KAMPALA INTERNATIONAL UNIVERSITY
KIU
Journal of Science, Engineering and Technology

KJSET Research Article

Assessment of the State-of-the-Art of electric vehicle charging stations: Classifications and design

B. Joshua, A. N. Shuaibu and A. B. Kunya
Department of Electrical, Telecom. and Computer Engineering, Kampala International University – Uganda
joshua.bakenge@studwc.kiu.ac.ug

Corresponding Author: joshua.bakenge@studwc.kiu.ac.ug

Paper history:
Received 22 April 2026
Accepted in revised form 30 May 2026

Keywords
Design Architectures, Energy Storage, EV charging stations, Smart Charging, Vehicle-to-Grid.

Abstract
The rapid growth of electric mobility is increasing the demand for resilient, interoperable, and grid-integrated Electric Vehicle Charging Stations (EVCSs). However, large-scale EV deployment introduces major technical challenges related to grid stability, charging coordination, renewable integration, interoperability, and infrastructure scalability, particularly in developing countries with weak distribution networks. This paper presents a critical review of state-of-the-art EVCS technologies, focusing on charging classifications, converter architectures, smart charging control strategies, communication standards, and renewable energy integration. The study comparatively evaluates AC/DC charging systems, wired and wireless charging methods, and centralized, decentralized, distributed, and hierarchical control architectures using key performance indicators including efficiency, scalability, grid impact, communication complexity, and deployment feasibility. In addition, major interoperability standards such as IEC 61851, ISO/IEC 15118, OCPP, and IEC 63110 are reviewed in the context of smart charging and Vehicle-to-Grid (V2G) applications. The paper further examines the integration of photovoltaic systems and Battery Energy Storage Systems (BESS) for sustainable EV charging under weak-grid conditions. Key findings indicate that hybrid PV–BESS-assisted EVCS architectures and intelligent charging coordination strategies can significantly improve grid flexibility, operational reliability, and energy sustainability. Finally, the paper identifies critical research gaps related to interoperability, cybersecurity, renewable intermittency, and real-world deployment in sub-Saharan Africa, providing future directions for scalable and context-aware EV charging infrastructure development.

Nomenclature and units

EV	Electric Vehicle
EVCS	Electric Vehicle Charging Station
BESS	Battery Energy Storage System
V2G	Vehicle-to-Grid
EMS	Energy Management System
SoC	State of Charge
THD	Total Harmonic Distortion
PFC	Power Factor Correction
SiC	Silicon Carbide
GaN	Gallium Nitride

1.0 INTRODUCTION

The global transition toward sustainable transportation has accelerated the adoption of Electric Vehicles (EVs) as countries seek to reduce greenhouse gas emissions, dependence on fossil fuels, and urban air pollution. Rapid advancements in battery technologies, declining lithium-ion battery costs, and supportive energy policies have further intensified the deployment of EVs across residential, commercial, and public transportation sectors[1]. Consequently, Electric Vehicle Charging Stations (EVCSs) are emerging as critical components of modern smart-grid infrastructure, enabling reliable, efficient, and scalable electrified mobility systems.

Despite these advancements, large-scale EV integration presents significant technical and operational challenges to existing power distribution networks. Uncoordinated charging can increase feeder congestion, transformer overloading, voltage deviations, and network power losses, particularly in weak-grid and rapidly urbanizing regions [2]. Furthermore, the increasing penetration of renewable energy sources such as solar photovoltaic (PV) systems introduces additional variability and uncertainty into charging operations, requiring intelligent coordination between charging demand, distributed generation, and energy storage systems [3]. As a result, modern EVCSs are evolving from conventional standalone charging points into grid-interactive, communication-enabled, and renewable-integrated energy systems.

EV charging infrastructure encompasses a broad range of technologies including low-power residential AC chargers, high-power DC fast chargers, wireless charging systems, and emerging megawatt charging platforms for heavy-duty transportation [4]. The operational performance of these systems depends not only on charging hardware, but also on converter architectures, communication standards, interoperability frameworks, and advanced control strategies capable of supporting smart charging and Vehicle-to-Grid (V2G) services. International standards such as IEC 61851, ISO/IEC 15118, OCPP, and IEC 63110 have therefore become increasingly important for enabling secure, interoperable, and bidirectional charging ecosystems [5].

In parallel, significant research attention has been directed toward intelligent charging coordination using optimization and artificial intelligence techniques including Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Model Predictive Control (MPC), and machine-learning-based energy management systems [6]. These approaches aim to minimize charging costs, flatten load demand, improve renewable utilization, and enhance grid stability. However, most existing studies remain simulation-oriented with limited real-world validation under weak-grid conditions common in developing countries. Additionally, many review studies focus primarily on charging technologies without providing integrated comparative analysis of control architectures, interoperability, renewable integration, and deployment feasibility within emerging economies.

In sub-Saharan Africa, the deployment of EVCS infrastructure faces additional constraints related to limited grid capacity, unreliable communication infrastructure, inadequate regulatory frameworks, and high capital investment costs. Nevertheless, the region possesses strong renewable energy potential, particularly solar irradiance, which creates significant opportunities for PV-assisted EV charging systems integrated with Battery Energy Storage Systems (BESS) [7]. Such hybrid charging architectures can improve energy resilience, reduce operational costs, and support sustainable transportation development under semi-decentralized power systems.

Therefore, this paper presents a critical review of state-of-the-art EV charging station technologies with emphasis on charging classifications, design architectures, smart charging control strategies, communication and interoperability standards, and renewable energy integration. Unlike previous descriptive reviews, this study comparatively evaluates EVCS technologies based on charging efficiency, scalability, grid impact, communication complexity, deployment feasibility, and suitability for developing-country applications. The paper further identifies critical research gaps related to interoperability, cybersecurity, renewable intermittency, and real-world implementation challenges in sub-Saharan Africa.

The major contributions of this review are summarized as follows:

1. Comparative evaluation of AC, DC, wired, and wireless EV charging technologies based on technical and operational performance indicators.
2. Critical analysis of centralized, decentralized, distributed, and hierarchical smart charging control architectures.
3. Review of major communication and interoperability standards supporting smart charging and V2G applications.
4. Assessment of renewable-integrated EVCS architectures incorporating PV systems and BESS under weak-grid conditions.
5. Identification of key deployment challenges, research gaps, and future directions for scalable EVCS implementation in developing countries.

The remainder of this paper is organized as follows. Section II presents the classification and comparative analysis of EV charging stations. Section III discusses EV architectures, charging principles, and converter topologies. Section IV reviews smart charging control strategies and optimization techniques. Section V examines communication standards and interoperability frameworks. Section VI discusses renewable energy integration and techno-economic considerations for EVCS deployment. Section VII highlights research gaps and future directions, while Section VIII concludes the paper.

2.0 CLASSIFICATION OF EV CHARGING STATIONS

EVCSs can be classified according to charging power level, installation environment, charging method, grid connectivity, and control capability. A structured classification framework is essential for utilities, policymakers, and system planners to align charging infrastructure deployment with grid capacity, transportation demand, and operational reliability requirements [8], [9], [10]. As EV penetration increases, charging classification increasingly influences power quality, energy management, interoperability, and charging scalability within modern smart-grid environments.

A. Classification by Charging Power Level

EV charging systems are commonly classified into Level 1, Level 2, and Level 3 charging according to charging power, voltage level, and charging duration [11]. Charging level directly influences infrastructure cost, grid impact, charging flexibility, and deployment suitability.

Level 1 charging typically operates below 3.6 kW using single-phase AC supply and is mainly suited for residential overnight charging due to its low power demand and minimal grid impact. However, long charging duration limits its applicability for commercial mobility systems.

Level 2 charging operates within 7–22 kW and is widely deployed in workplaces, public parking areas, and semi-commercial environments. It provides improved charging flexibility with moderate infrastructure requirements, although uncontrolled simultaneous charging may contribute to feeder congestion and voltage deviations.

Level 3 charging, commonly referred to as DC fast charging, operates within 50–350 kW, while emerging Megawatt Charging Systems (MCS) exceed 1 MW for heavy-duty transport applications [12]. External power conversion enables rapid charging but introduces higher infrastructure cost, harmonic distortion, transformer loading, and peak demand challenges.

Table 1: Summary of the operational characteristics of major EV charging levels.

Charging Level	Power Range	Charging Duration	Typical Application	Grid Impact
Level 1	≤ 3.6 kW	8–12 hrs	Residential	Low
Level 2	7–22 kW	2–6 hrs	Workplace/Public	Moderate
Level 3 DC Fast Charging	50–350 kW	20–60 mins	Highway/Fleet	High
Megawatt Charging System	≥ 1 MW	< 30 mins	Heavy-duty Transport	Very High

B. Comparative Evaluation of AC and DC Charging Systems

EV charging systems are broadly categorized into AC and DC charging according to the location of power conversion and charging power capability [13]. AC charging supplies alternating current to the onboard vehicle charger, making it suitable for residential and workplace applications due to lower installation cost and moderate grid impact. However, charging speed is limited by onboard converter ratings and battery thermal constraints.

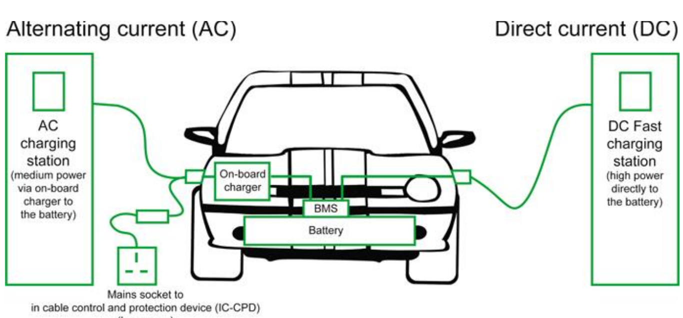


Figure 1. AC and DC charging modes*[14]*

In contrast, DC charging performs AC/DC conversion externally within the charging station, enabling high-power charging with significantly reduced charging duration. DC fast chargers are therefore preferred for commercial fleets, public transport, and highway charging corridors. Despite their operational advantages, high-power DC chargers impose greater stress on distribution networks through increased peak demand, harmonic distortion, and transformer loading.

Table 2: Comparison of the operational characteristics of AC and DC charging systems

Parameter	AC Charging	DC Charging
Power Range	3–22 kW	50–350 kW
Charging Duration	2–12 hrs	20–60 mins
Infrastructure Cost	Low	High
Efficiency	90–94%	94–98%
Grid Impact	Moderate	High
Harmonic Distortion	Lower	Higher
Typical Application	Residential	Commercial/Fleet

The Overall, AC charging remains more suitable for low-demand applications, while DC charging is essential for high-utilization transport systems. Future EVCS deployment will likely combine both approaches through coordinated smart charging and renewable-assisted energy management strategies.

C. Classification by Application and Deployment Context

EV charging stations are also classified according to installation environment, accessibility, and operational purpose [15]. Deployment context significantly influences charger rating, utilization rate, communication requirements, and grid interaction.

1. Residential Charging. Residential charging primarily utilizes Level 1 or Level 2 AC chargers installed in private homes or apartment complexes. These systems benefit from low installation cost and overnight charging flexibility but may contribute to residential peak demand if charging remains unmanaged.

2. Public Charging. Public charging stations are deployed in commercial centers, highways, parking facilities, and urban transport hubs. These installations commonly support multiple charging standards such as CCS, CHAdeMO, and Type 2 connectors to improve interoperability and user accessibility. Public charging infrastructure requires advanced metering, billing, and communication systems to support high utilization and coordinated operation.

3. Fleet and Depot Charging. Fleet charging systems support buses, taxis, logistics vehicles, and commercial transport fleets operating under scheduled charging conditions. These systems typically employ high-power DC charging with centralized or hierarchical energy management strategies to minimize downtime and optimize operational efficiency. However, large fleet charging installations may impose severe stress on local distribution networks without coordinated charging control and local energy storage integration.

4. Highway and Corridor Charging. Highway charging corridors utilize ultra-fast DC charging systems designed to support long-distance transportation. These systems prioritize charging speed and availability but require substantial grid reinforcement, high-capacity transformers, and advanced thermal management infrastructure.

Table 3: Summary of the major EVCS deployment categories and their operational characteristics.

Deployment Context	Typical Charger Type	Power Range	Main Application	Infrastructure Requirement
Residential	Level 1 / Level 2 AC	≤ 22 kW	Home charging	Low
Public Charging	AC/DC Mixed	7–150 kW	Urban mobility	Moderate
Fleet/Depot	DC Fast Charging	50–350 kW	Commercial fleets	High
Highway Corridors	Ultra-fast DC Charging	≥ 150 kW	Long-distance travel	Very High

The suitability of each deployment category depends strongly on traffic density, charging demand, grid capacity, and communication infrastructure availability [16]. In developing regions, hybrid PV–BESS-assisted charging stations present a practical approach for reducing grid dependency while improving charging reliability under weak-grid conditions

D. Wired and Wireless Charging Technologies

EV charging technologies are broadly categorized into wired (conductive) and wireless (inductive) charging systems based on the method of power transfer [17]. The selection of charging technology influences charging efficiency, infrastructure complexity, user convenience, and deployment cost.

1. Wired Charging. Wired charging remains the dominant EV charging approach due to its high efficiency, technological maturity, and relatively low implementation cost. Power is transferred through conductive connectors using AC or DC charging configurations. AC charging is typically limited to low and medium power applications, while DC charging supports high-power fast charging for commercial and transport systems.

Conductive charging systems commonly achieve efficiencies above 95%, making them suitable for large-scale deployment. However, frequent physical connection may increase connector wear and maintenance requirements.

2. Wireless Charging. Wireless charging transfers power through electromagnetic coupling between ground and vehicle coils, typically operating within frequencies of 20–85 kHz [17]. These systems improve automation, user convenience, and charging flexibility, particularly for autonomous mobility applications and smart-city transport systems.

Despite these advantages, wireless charging currently exhibits lower transfer efficiency and higher infrastructure cost compared to conductive charging. Additional concerns include electromagnetic field shielding, coil alignment sensitivity, and foreign object detection requirements.

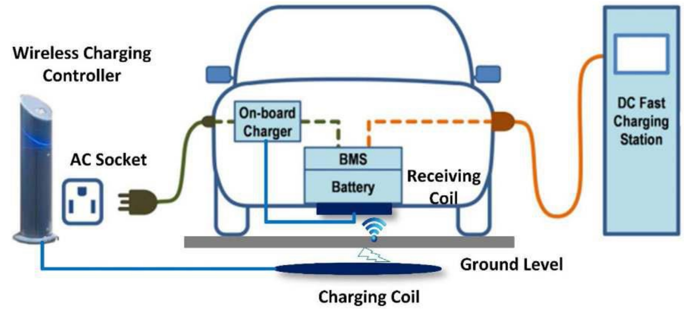


Figure 2. Charging means of EV Vehicle

Wireless charging is therefore still largely limited to pilot-scale and low-power applications, although ongoing advances in resonant inductive coupling and dynamic charging technologies may improve future commercialization potential.

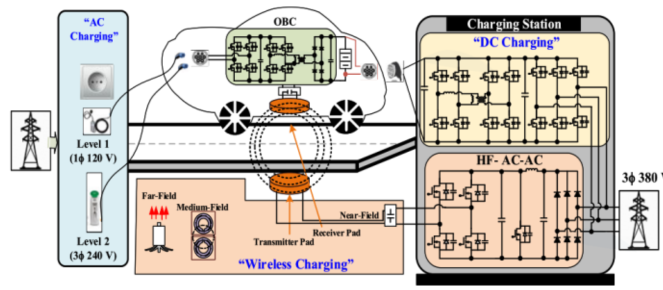


Figure 3. Overall charging system for BEVs using wired/wireless charging technologies *[12]*.

Table 4. The major characteristics of wired and wireless charging technologies *[17]*.

Parameter	Wired Charging	Wireless Charging
Power Transfer Method	Conductive	Electromagnetic Coupling
Typical Power Capacity	Up to 400 kW	Up to 22 kW
Efficiency	95–98%	85–92%
Infrastructure Cost	Lower	Higher
User Convenience	Moderate	High
Maintenance Requirement	Moderate	Low
Commercial Maturity	High	Moderate
Deployment Status	Commercial	Pilot/Emerging

E. Grid Connectivity and Smart Charging Capability

Based on grid interaction and operational control, EV charging stations can be categorized as on-grid, off-grid, hybrid, conventional, or smart charging systems [4], [18]. These classifications determine charging flexibility, energy management capability, and grid support functionality.

1. On-Grid Charging Systems. On-grid EVCSs are directly connected to utility distribution networks and rely primarily on grid power for charging operation. These systems are widely deployed in urban and commercial environments due to their operational simplicity and continuous power availability.

However, uncontrolled charging may increase feeder loading, voltage instability, and peak demand.

2. Off-Grid and Hybrid Charging Systems. Off-grid charging stations operate independently using local renewable generation and Battery Energy Storage Systems (BESS). Hybrid EVCS architectures combine grid supply with renewable energy sources such as solar PV to improve reliability and reduce grid dependency. These systems are particularly suitable for weak-grid and rural applications where utility infrastructure remains limited.

3. Conventional Charging. Conventional or "dumb" charging systems operate without communication or charging coordination. Charging begins immediately after vehicle connection, regardless of grid conditions or electricity pricing. Although simple to implement, uncontrolled charging may intensify peak demand and distribution network congestion.

4. Smart Charging. Smart charging enables coordinated charging operation through real-time communication, load management, and energy optimization techniques. Smart EVCSs dynamically regulate charging power based on Grid conditions, Electricity tariffs, Renewable generation availability, Battery state of charge, and user demand.

Advanced smart charging systems support Vehicle-to-Grid (V2G) services, enabling bidirectional power exchange between EV batteries and the grid for peak shaving, frequency regulation, and ancillary services.

Table 5. EVCS classifications based on grid connectivity and control capability.

EVCS Type	Energy Source	Communication Capability	Grid Interaction	Typical Application
On-Grid	Utility Grid	Limited/Moderate	Direct	Urban/Public Charging
Off-Grid	PV + BESS	Moderate	Independent	Rural Charging
Hybrid	Grid + Renewable	High	Coordinated	Smart Charging Networks
Conventional Charging	Grid	None	Passive	Residential Charging
Smart Charging	Grid + EMS	High	Bidirectional	Smart Grids/V2G

The transition from conventional charging toward intelligent grid-interactive charging systems is essential for supporting large-scale EV integration. In developing regions, hybrid smart charging architectures integrated with PV and BESS offer significant potential for improving charging reliability, reducing operational cost, and minimizing grid stress under constrained distribution infrastructure

F. Charging Standards and Interoperability Considerations

Interoperability is a critical requirement for scalable EV charging infrastructure, enabling compatibility between EVs, charging stations, utilities, and backend management systems [19], [20]. The growing diversity of EV manufacturers and charging technologies has accelerated the development of standardized communication and connector frameworks to ensure safe, secure, and coordinated charging operation.

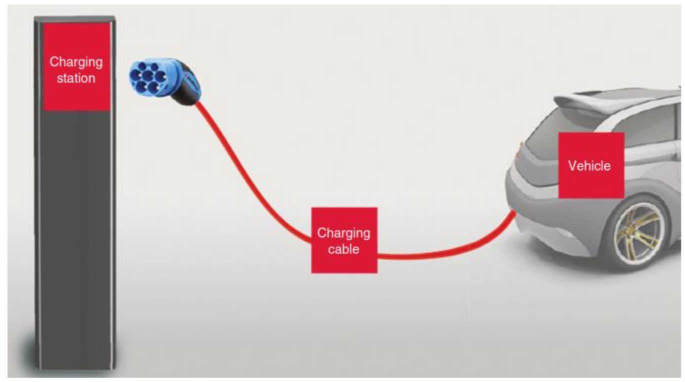


Figure 4. Case A: The charging cable is permanently connected to the vehicle

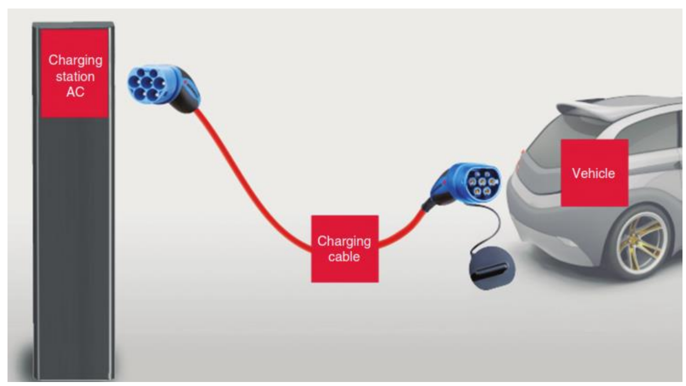


Figure 5. Case B: The charging cable is not permanently connected to the vehicle or the charging station

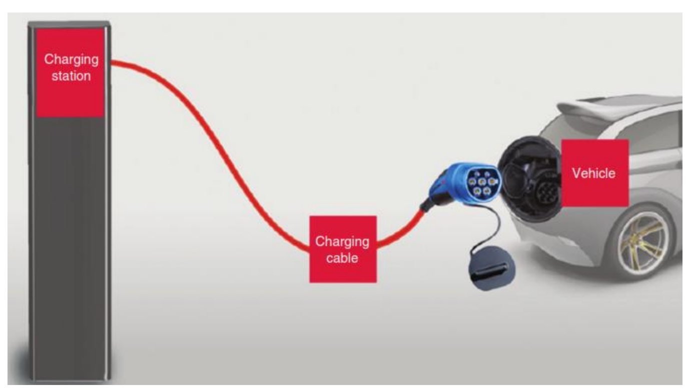


Figure 6. Case C: The charging cable is permanently connected to the charging station.

Major charging standards include:

i. IEC 61851 for conductive charging systems,

ii. ISO/IEC 15118 for Plug & Charge and V2G communication,
iii. OCPP for EVCS-backend communication, and
iv. IEC 63110 for charging infrastructure management.

Connector standards such as CCS, CHAdeMO, GB/T, Type 1, and Type 2 vary across regions and charging applications. Although CCS is increasingly dominant in Europe and North America, interoperability fragmentation remains a major deployment challenge globally [11], [21].

Table 6. Major EV charging standards and their operational characteristics

Standard / Protocol	Primary Function	Key Feature	Typical Application
IEC 61851	Conductive charging	Charging safety/control	AC/DC charging
ISO/IEC 15118	EV-EVCS communication	Plug & Charge, V2G	Smart charging
OCPP	EVCS-backend communication	Remote monitoring/control	Charging networks
IEC 63110	Infrastructure management	Smart grid integration	Large-scale EVCS
CCS	Charging connector standard	AC/DC combined charging	Public fast charging
CHAdeMO	DC charging protocol	Bidirectional charging	Fast charging
GB/T	Chinese charging standard	National interoperability	China market

Despite ongoing standardization efforts, interoperability challenges persist due to protocol fragmentation, legacy charging infrastructure, cybersecurity concerns, and inconsistent regional adoption policies.

These challenges are more pronounced in developing regions where communication infrastructure, interoperability certification systems, and regulatory frameworks remain limited. Consequently, scalable EVCS deployment increasingly requires harmonized standards, secure communication architectures, and coordinated policy development to support smart charging and V2G integration.

Table 7. Comparative Analysis of EV Charging Technologies

Parameter	AC Charging	DC Fast Charging	Wireless Charging
Typical Power Range	3–22 kW	50–350 kW	Up to 22 kW
Charging Duration	2–12 hrs	20–60 mins	3–10 hrs
Charging Efficiency	90–94%	94–98%	85–92%
Infrastructure Cost	Low	High	Very High
Grid Impact	Moderate	High	Moderate
Harmonic Distortion	Lower	Higher	Moderate
User Convenience	Moderate	Moderate	High
Deployment Maturity	Commercial	Commercial	Emerging
Typical Application	Residential/Workplace	Fleet/Highway	Smart Cities/Autonomous EVs
Major Limitation	Slow charging	Grid stress and cost	Low efficiency and cost

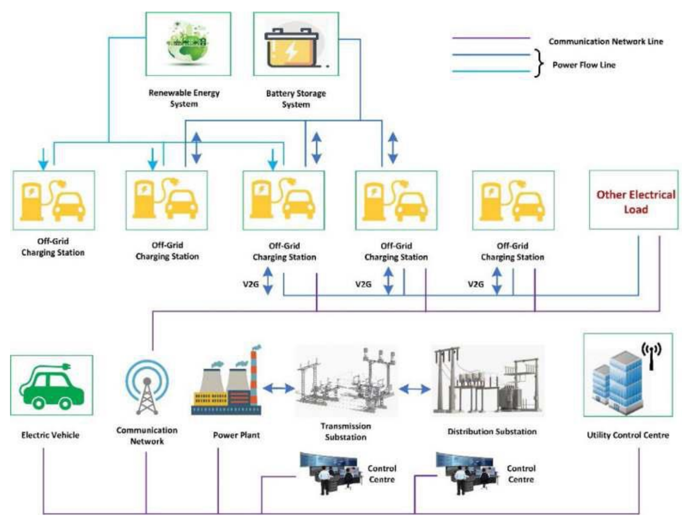


Figure 7. Charging infrastructure for EV

G. Deployment Challenges in Developing Regions

The deployment of EV charging infrastructure in developing regions faces significant technical, economic, and regulatory constraints despite increasing interest in electric mobility [22], [23]. Weak distribution networks, limited grid redundancy, and inadequate charging infrastructure remain major barriers to large-scale EV integration, particularly in sub-Saharan Africa.

High-power EV charging can intensify transformer loading, feeder congestion, and voltage instability in poorly reinforced distribution systems. In addition, limited communication infrastructure constrains the implementation of smart charging, remote monitoring, and interoperability frameworks required for coordinated charging operation [24], [25].

Economic limitations also affect EVCS deployment. High capital investment cost, dependence on imported charging equipment, and limited financing mechanisms continue to slow infrastructure expansion [26]. Furthermore, low EV penetration reduces charging station utilization rates, negatively affecting investment recovery and commercial viability.

Regulatory and standardization gaps present additional challenges. Many developing countries lack:

- EV charging standards,
- interoperability certification frameworks,
- V2G regulations, and
- coordinated e-mobility policies.

The shortage of skilled technical personnel in EV infrastructure design, cybersecurity, and power electronics further limits deployment capability.

Despite these constraints, developing regions possess strong renewable energy potential, particularly solar resources, which can support hybrid PV–BESS-assisted charging systems. Such architectures can reduce grid dependency, improve charging reliability, and enhance energy access under weak-grid conditions.

Consequently, scalable EVCS deployment in developing countries will require grid modernization, renewable-assisted charging integration, supportive regulatory frameworks, local technical capacity development, and investment in communication infrastructure.

These measures are essential for enabling resilient, interoperable, and economically sustainable EV charging ecosystems within emerging transportation markets.

3.0 EV DESIGN ARCHITECTURES AND POWER CONVERSION

A. *Electric Vehicle Architectures*

Electric vehicles are commonly classified into Battery Electric Vehicles (BEVs), Hybrid Electric Vehicles (HEVs), Plug-in Hybrid Electric Vehicles (PHEVs), and Fuel Cell Electric Vehicles (FCEVs) according to their propulsion and energy supply systems [9], [27]. These architectures significantly influence charging requirements, converter design, grid interaction, and charging infrastructure deployment.

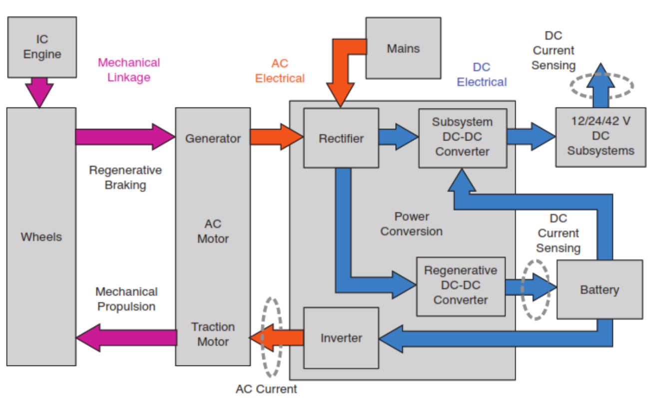


Figure 8. EV block diagram main components

1. Battery Electric Vehicles (BEVs). BEVs operate entirely using electrical energy stored in rechargeable battery packs and represent the dominant architecture in modern electric mobility systems. Major components include battery pack, inverter, electric motor, Battery Management System (BMS), and onboard charger.

BEVs support bidirectional power flow and are therefore highly compatible with smart charging and Vehicle-to-Grid (V2G) applications. However, large battery capacities increase charging demand and may intensify grid stress during simultaneous charging operation.

2. Hybrid Electric Vehicles (HEVs). HEVs combine an internal combustion engine with electric propulsion to improve fuel efficiency and reduce emissions. Depending on drivetrain configuration, HEVs may operate as:

- series hybrids,
- parallel hybrids,
- or series-parallel hybrids.

Although HEVs reduce charging dependency compared to BEVs, their limited electric-only operation restricts long-term zero-emission capability.

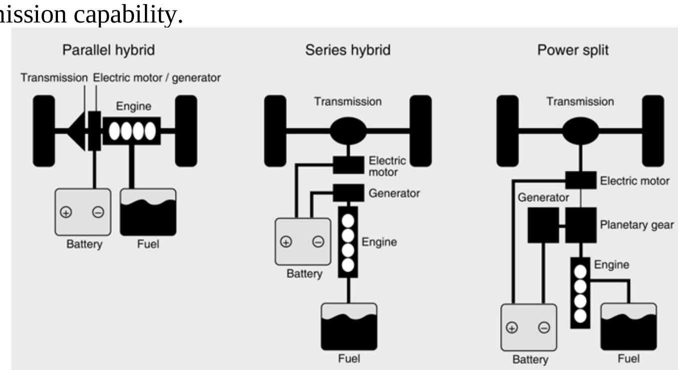


Figure 9. Types of hybrid vehicles (parallel, series, power split)

3. Plug-in Hybrid Electric Vehicles (PHEVs). PHEVs integrate rechargeable battery systems with conventional fuel-based propulsion, enabling both grid charging and hybrid operation. Compared to conventional HEVs, PHEVs offer greater electric driving range and lower fuel consumption. However, dual propulsion systems increase system complexity, weight, and maintenance requirements.

4. Fuel Cell Electric Vehicles (FCEVs). FCEVs generate electricity onboard using hydrogen fuel cells combined with electric propulsion systems. These vehicles provide extended driving range and rapid refueling capability but require specialized hydrogen infrastructure and high-cost fuel cell technologies. Consequently, large-scale deployment remains limited compared to battery-based EV architectures.

Table 8. The major EV architectures and their charging implications *[14]*.

Parameter	BEV	HEV	PHEV	FCEV
Primary Energy Source	Battery	Battery + ICE	Battery + ICE	Hydrogen Fuel Cell
Grid Charging Requirement	High	Low	Moderate	Low
Tailpipe Emission	Zero	Low	Low	Zero

Charging Infrastructure Need	High	Minimal	Moderate	Hydrogen Infrastructure
V2G Compatibility	High	Limited	Moderate	Limited
System Complexity	Moderate	High	High	Very High

Among these architectures, BEVs remain the most compatible with future smart-grid and renewable-integrated charging systems due to their full electrification and bidirectional charging capability. However, widespread BEV deployment will require coordinated charging control, advanced converter technologies, and scalable charging infrastructure to minimize distribution network impacts.

B. Power Conversion Topologies

Power conversion topology plays a critical role in EV charging performance, efficiency, thermal management, and grid interaction [28]. EV charging systems primarily employ AC/DC rectifiers and DC/DC converters to regulate voltage, current, and bidirectional power flow between the grid and vehicle battery.

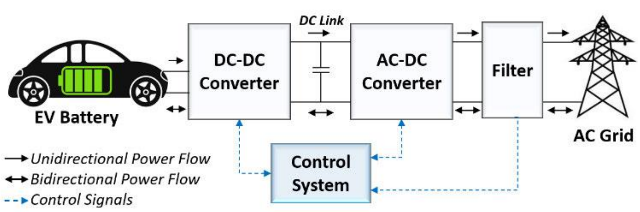


Figure 10. Block diagram of conventional EV charging system.

1. AC/DC Conversion. AC charging systems utilize onboard rectifiers with Power Factor Correction (PFC) to convert grid AC power into regulated DC power for battery charging. Converter efficiency, switching frequency, and thermal losses significantly affect charging performance and energy utilization.

2. DC/DC Conversion. DC fast charging systems employ high-power DC/DC converters to match charging station output voltage with battery charging requirements, typically within 200–800 V operating ranges. These converters enable rapid charging but require advanced cooling systems and high-efficiency semiconductor switching devices to minimize power losses.

3. Bidirectional Converters. Bidirectional converters support both Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) operation, enabling EV batteries to provide ancillary grid services such as peak shaving, frequency regulation, and energy arbitrage. Although bidirectional charging improves grid flexibility, it increases converter complexity, communication requirements, and battery degradation concerns.

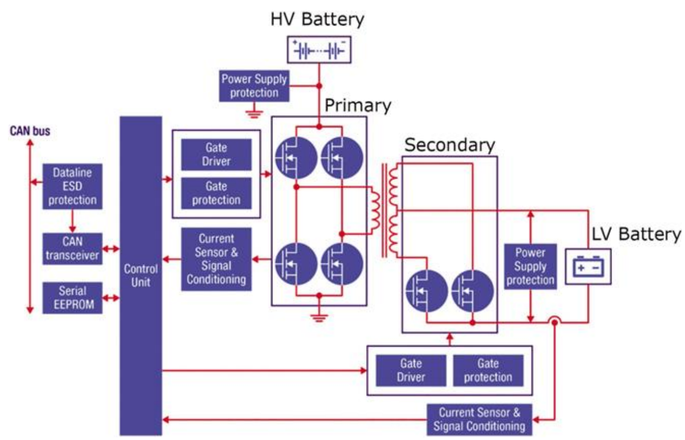
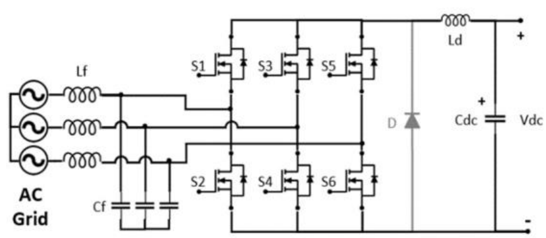
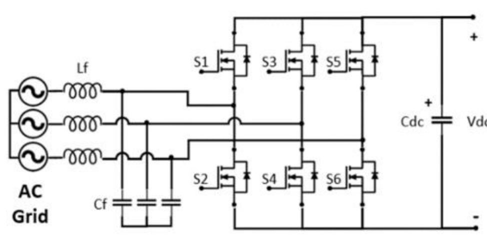


Figure 11. DC–DC bi-directional converter

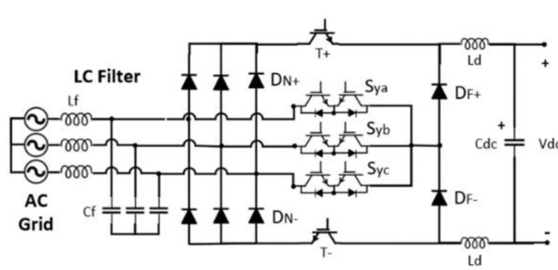
Converter efficiency remains a major performance indicator in EVCS design because higher losses increase thermal stress, operational cost, and cooling requirements. Modern fast-charging converters commonly achieve efficiencies above 95% through advanced semiconductor technologies such as Silicon Carbide (SiC) and Gallium Nitride (GaN) devices EV



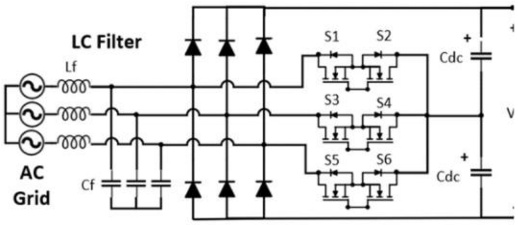
(a)



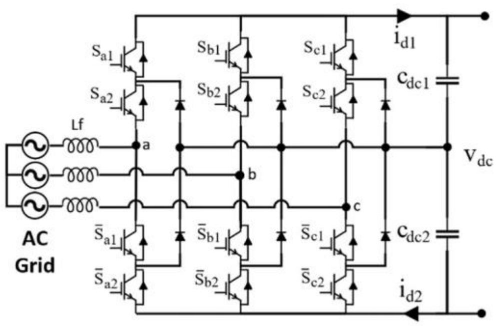
(b)



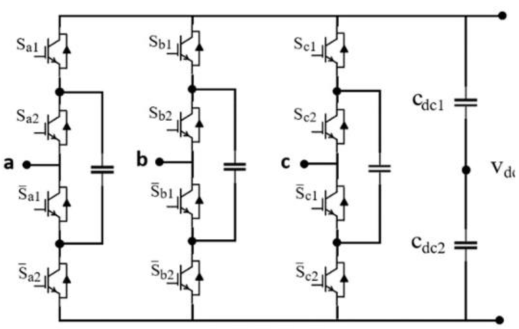
(c)



(d)



(e)



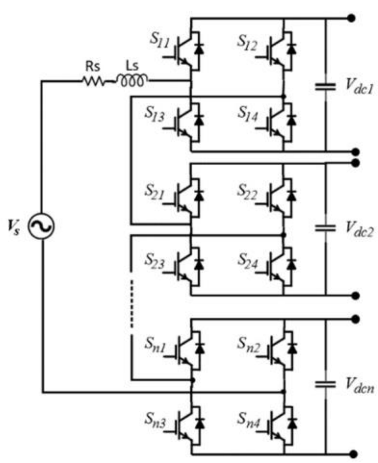


Figure 12. AC-DC converter configurations (a) Three-phase six-switch buck-type converter, (b) Three-phase six-switch boost converter, (c) Three-phase Swiss converter, (d) Vienna converter (e) Three-level neutral point clamped (NPC) converter *[12]*.

Table 9. Major EV charging converter topologies and their characteristics.

Converter Topology	Main Function	Typical Application	Merits	Limitations
AC/DC Rectifier	AC to DC conversion	Level 1/2 Charging	Simple, mature	Limited charging speed
DC/DC Converter	Voltage regulation	DC Fast Charging	High charging power	Thermal complexity
Bidirectional Converter	G2V/V2G operation	Smart Charging	Grid support capability	Higher cost/ complexity
Isolated Converter	Electrical isolation	High-safety charging	Improved protection	Larger size
Non-Isolated Converter	Direct conversion	Compact EVCS	Higher efficiency	Reduced isolation

The selection of converter topology depends on charging power level, efficiency requirements, safety standards, and intended grid interaction capability. Future EVCS development increasingly favors high-efficiency bidirectional converter architectures capable of supporting renewable integration and intelligent energy management within smart-grid environments.

C. *Charging Control and Battery Management*

Efficient EV charging requires coordinated control between the charging station, power converter, and Battery Management System (BMS) to ensure safe, reliable, and optimized charging operation [29], [30]. Charging control directly affects battery lifespan, charging efficiency, thermal stability, and grid interaction.

Most EV charging systems employ Constant Current–Constant Voltage (CC–CV) charging, where charging initially occurs at constant current until a voltage threshold is reached, followed by constant voltage operation with gradually decreasing current.

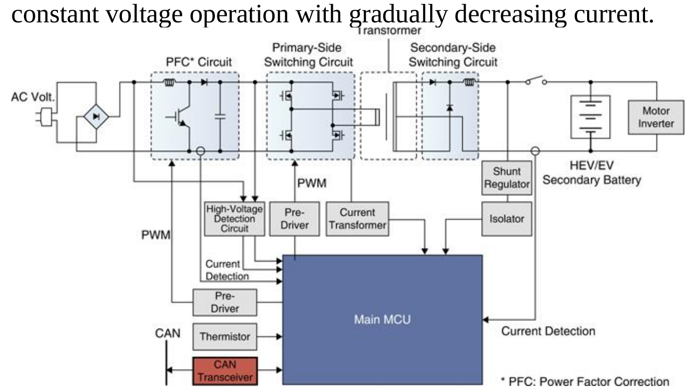


Figure 13. Battery charger circuit and control *[29]*.

The BMS continuously monitors battery voltage, charging current, temperature, and State of Charge (SoC) to prevent overcharging, overheating, and battery degradation. Advanced BMS platforms further support cell balancing, fault detection, and predictive battery health estimation.

Smart charging systems integrate Energy Management Systems (EMS) and communication protocols to dynamically regulate charging power according to grid demand, electricity pricing, renewable energy availability, and user charging preferences [18], [25].

Optimization-based charging control is commonly formulated as

$$min \sum_{t=1}^{T} \left(P_{grid,t} + P_{EV,T}\right)^2 \qquad (1)$$

where $P_{grid,t}$ represents grid load demand and
$P_{EV,t}$ represents EV charging demand at time t.
This objective minimizes peak loading and improves load profile flattening within distribution systems.

Advanced charging coordination increasingly utilizes:

- Genetic Algorithms (GA),
- Particle Swarm Optimization (PSO),
- Model Predictive Control (MPC), and
- Machine-learning-based EMS frameworks

to improve charging efficiency, renewable utilization, and grid stability.

Although intelligent charging significantly enhances operational flexibility, its effectiveness depends on reliable communication infrastructure, cybersecurity protection, and accurate real-time system monitoring. These requirements remain challenging in weak-grid and low-connectivity environments common in many developing regions

D. Harmonic and Power Quality Considerations

Large-scale EV charging can significantly affect power quality within distribution networks due to nonlinear converter operation and fluctuating charging demand [31]. High-power charging systems, particularly DC fast chargers, introduce harmonic distortion, reactive power consumption, voltage fluctuations, and transformer overloading.

Harmonic distortion generated by power electronic converters may increase feeder losses, reduce equipment lifespan, and interfere with sensitive electrical loads. Total Harmonic Distortion (THD) is commonly used to evaluate charging-induced waveform distortion and is regulated under IEEE 519 power quality standards [5], [32].

Uncontrolled simultaneous EV charging may also produce voltage deviation, transformer thermal stress, feeder congestion, and increased network losses [31],

These impacts become more severe under weak-grid conditions where distribution infrastructure capacity remains limited.

Advanced mitigation techniques include Active Power Factor Correction (PFC), Harmonic filtering, Coordinated smart charging, Reactive power compensation, And local Battery Energy Storage System (BESS) integration.

Smart charging strategies can further reduce grid stress by shifting charging demand away from peak-load periods and coordinating charging schedules according to feeder loading condition

Table 10. Major EV charging power quality challenges and mitigation approaches.

Power Quality Issue	Cause	Impact on Grid	Mitigation Technique
Harmonic Distortion	Power electronic converters	Increased losses	Harmonic filters/PFC
Voltage Deviation	Simultaneous charging	Voltage instability	Smart charging
Transformer Overloading	High charging demand	Thermal stress	Load coordination
Reactive Power Demand	Converter operation	Reduced power factor	Reactive compensation
Peak Demand Increase	Fast charging clusters	Feeder congestion	EMS/BESS integration

E. Comparative Converter Performance Analysis

The performance of EV charging converters is commonly evaluated based on efficiency, switching losses, power density, thermal management, bidirectional capability, and grid interaction performance [22]. Converter selection directly affects charging speed, operational cost, reliability, and scalability of EV charging infrastructure.

Conventional silicon-based converters remain widely deployed due to their lower cost and mature manufacturing processes. However, high-power fast charging increasingly utilizes wide-bandgap semiconductor technologies such as Silicon Carbide (SiC) and Gallium Nitride (GaN) devices because of their higher switching frequency, reduced conduction losses, and improved thermal performance.

Bidirectional converter architectures further enhance charging flexibility by enabling Vehicle-to-Grid (V2G) operation and renewable-assisted energy exchange. Despite these advantages, bidirectional systems require more advanced control algorithms, communication coordination, and battery degradation management.

Table 11. Converter technologies used in EV charging systems.

Converter Type	Efficiency	Power Density	Bidirectional Capability	Typical Application	Limitation
Silicon-Based Converter	90–94%	Moderate	Limited	Conventional AC Charging	Higher switching losses

SiC-Based Converter	95–98%	High	Excellent	DC Fast Charging	Higher cost
GaN-Based Converter	96–98%	Very High	Excellent	Ultra-fast Charging	Thermal sensitivity
Bidirectional Converter	94–97%	High	Full V2G Support	Smart Charging	Control complexity
Isolated Converter	92–96%	Moderate	Moderate	High-safety EVCS	Larger size

Comparative analysis indicates that wide-bandgap semiconductor converters provide superior efficiency and power density for next-generation fast charging systems. However, deployment cost and thermal management requirements remain major practical considerations, particularly within developing regions with constrained infrastructure and limited technical support capacity.

Future EVCS architectures will increasingly integrate high-efficiency bidirectional converters, intelligent control systems, and renewable-assisted energy management to support scalable, grid-interactive charging ecosystem.

4.0 SMART CHARGING CONTROL STRATEGIES AND OPTIMIZATION

A. Centralized Charging Control

Centralized charging control utilizes a single control entity or aggregator to coordinate charging activities across multiple EVs and charging stations [2], [24]. The controller collects real-time information related to charging demand, grid conditions, electricity pricing, and battery state of charge to optimize charging schedules and minimize grid stress.

Centralized architectures are widely applied in fleet charging systems, commercial charging hubs, and utility-managed smart charging networks because they provide global system visibility and coordinated decision-making capability.

Centralized charging offers several advantages including:

- Global optimization capability,
- Effective peak-load management,
- Improved renewable coordination, and
- Enhanced demand response participation.

However, centralized systems also exhibit significant limitations such as:

- High communication dependency,
- Computational burden,
- Scalability constraints, and
- Vulnerability to single-point failure.

As EV penetration increases, centralized control may become difficult to scale efficiently due to increased data exchange and real-time processing requirements. In developing regions, unreliable communication infrastructure and limited smart-grid capability further constrain large-scale centralized implementation.

B. Decentralized Charging Control

Decentralized charging control allows individual EVs or charging stations to independently determine charging behavior based on local information such as electricity price, battery state of charge, and user charging preference [2]. Unlike centralized systems, decentralized architectures do not rely on a single control entity, thereby improving scalability and operational flexibility.

In decentralized charging, each EV autonomously optimizes its charging schedule while responding to external signals including dynamic pricing, grid loading conditions, and renewable energy availability.

This approach reduces communication burden and computational dependency compared to centralized control frameworks.

Decentralized charging offers several advantages including:

- Improved scalability,
- Lower communication requirements,
- Enhanced fault tolerance, and
- Greater user flexibility.

However, independent charging decisions may produce suboptimal system-wide coordination and increase the risk of feeder congestion during simultaneous charging periods. In addition, limited global visibility reduces the ability to perform coordinated demand response and large-scale grid optimization.

Decentralized charging is therefore more suitable for residential charging, small commercial charging networks, and weak communication environments where fully centralized infrastructure may be impractical.

C. Distributed and Hierarchical Control

Distributed and hierarchical charging architectures combine local charging autonomy with coordinated grid-level supervision to improve scalability, resilience, and operational efficiency [25], [33]. These approaches are increasingly considered suitable for large-scale smart charging networks with high EV penetration.

1. Distributed Charging Control. Distributed control utilizes multiple regional controllers or aggregators that coordinate charging operation through peer-to-peer communication. Each controller manages a subset of EVs while exchanging limited operational information with neighboring controllers to maintain system stability and load balancing.

Distributed architectures improve scalability, fault tolerance, and regional energy coordination compared to purely centralized systems. However, distributed charging requires reliable communication infrastructure and synchronization mechanisms to ensure coordinated operation among multiple controllers.

2. Hierarchical Charging Control. Hierarchical charging control combines centralized supervision with decentralized local decision-making using multi-layer control structures. Higher control layers manage global optimization, grid coordination, and

energy market interaction, while lower layers regulate local charging operation and user-level control.

Hierarchical architectures provide improved balance between:

- scalability,
- optimization capability,
- communication efficiency,
- and operational flexibility.

These systems are particularly suitable for smart cities, utility-scale charging networks, and renewable-integrated EVCS infrastructures.

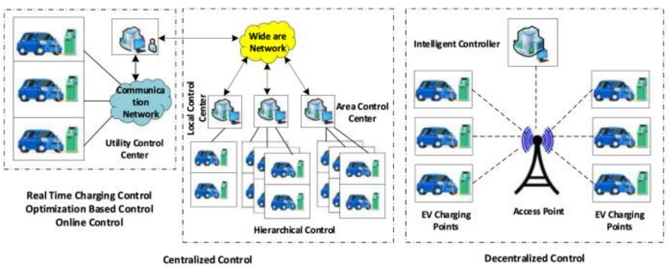


Figure 14. EV Charging system with centralized and decentralized charging.

D. *Comparative Analysis of Charging Control Architecture*

The effectiveness of smart charging systems depends strongly on the selected control architecture, communication capability, computational complexity, and grid coordination strategy [34]. Centralized, decentralized, distributed, and hierarchical control frameworks each present distinct advantages and operational limitations.

Centralized control provides superior global optimization and demand response capability but suffers from scalability limitations and high communication dependency. In contrast, decentralized charging improves scalability and fault tolerance but offers limited system-wide coordination.

Distributed and hierarchical architectures provide a compromise between local flexibility and global optimization by enabling coordinated multi-level charging management. These approaches are increasingly preferred for large-scale smart-grid environments due to their improved adaptability and resilience under high EV penetration.

Table 12. Evaluation of major charging control architectures.

Parameter	Centralized	Decentralized	Distributed	Hierarchical
Optimization Scope	Global	Local	Regional	Global + Local
Scalability	Moderate	High	High	Very High
Communication Requirement	High	Low	High	Moderate
Computational Complexity	High	Moderate	High	Moderate
Fault Tolerance	Low	High	High	High
Grid Coordination	Excellent	Limited	Good	Excellent
Cybersecurity Risk	High	Moderate	Moderate	Moderate
Typical Application	Fleet Charging	Residential Charging	Smart Microgrids	Utility-scale Networks

From a deployment perspective, centralized charging remains effective for small and medium charging networks, whereas decentralized architectures are more practical under limited communication infrastructure [25]. However, future EV ecosystems with high charging density will increasingly require hierarchical and distributed frameworks capable of balancing scalability, real-time coordination, renewable integration, and grid stability.

In developing regions, hierarchical smart charging combined with local renewable-assisted energy management presents a promising approach for reducing grid congestion while improving charging reliability under constrained infrastructure conditions.

E. *Optimization and AI-Based Charging Coordination*

Optimization and artificial intelligence (AI) techniques are increasingly applied in EV charging coordination to improve charging efficiency, reduce operational cost, and enhance grid stability [35]. These approaches enable adaptive charging control under dynamic grid conditions, renewable intermittency, and varying charging demand.

Conventional optimization methods commonly applied in EV charging include:

- Genetic Algorithms (GA),
- Particle Swarm Optimization (PSO),
- Mixed Integer Linear Programming (MILP),
- and Model Predictive Control (MPC).

These methods are widely used for charging scheduling, charging station placement, load balancing, renewable energy coordination, and peak demand reduction.

Optimization objectives typically include minimizing:

- charging cost,
- power loss,
- voltage deviation,
- and peak demand.

The charging optimization objective can be expressed as:

$$min \sum_{t=1}^{T}\left(C_t P_{EV,t} + \gamma P_{loss}\right) \quad (2)$$

where C_t represents electricity price,
$P_{EV,t}$ represents EV charging demand,

$P_{loss,t}$ represents network power loss, and
λ is the weighting factor.

AI-based charging coordination further improves adaptability through machine learning, reinforcement learning, artificial neural networks (ANN), and predictive energy management systems.

These approaches enable:

- Real-time charging adaptation,
- Charging demand forecasting,
- Renewable generation prediction,
- Autonomous charging coordination.

Compared to conventional optimization methods, AI-driven charging systems provide improved flexibility under uncertain operating conditions [11], [16]. However, they require large training datasets, higher computational capability, and reliable communication infrastructure

Table 13. Optimization and AI techniques applied in EV charging coordination.

Technique	Main Application	Strength	Limitation
GA	Charging scheduling	Global optimization	High computation time
PSO	EVCS placement	Fast convergence	Local optimum sensitivity
MILP	Load management	Accurate optimization	Computational complexity
MPC	Predictive charging control	Real-time adaptability	Model dependency
ANN	Demand forecasting	Learning capability	Data intensive

Future EV charging systems will increasingly integrate AI-driven control, predictive analytics, and renewable-aware optimization to support intelligent, scalable, and grid-interactive charging infrastructures. However, practical deployment will depend on cybersecurity readiness, communication reliability, and availability of real-time operational data, particularly within developing smart-grid environments.

Table 14. Comparative Analysis of Smart Charging Architectures

Parameter	Centralized	Decentralized	Distributed	Hierarchical
Optimization Scope	Global	Local	Regional	Global + Local
Scalability	Moderate	High	High	Very High
Communication Requirement	High	Low	High	Moderate
Computational Complexity	High	Moderate	High	Moderate
Fault Tolerance	Low	High	High	High
Grid Coordination Capability	Excellent	Limited	Good	Excellent
Cybersecurity Risk	High	Moderate	Moderate	Moderate
Typical Application	Fleet Charging	Residential Charging	Smart Microgrids	Utility-scale Networks
Main Advantage	Global optimization	Scalability	Regional flexibility	Balanced coordination
Main Limitation	Single-point failure	Limited coordination	Communication dependency	Complex implementation

5.0 COMMUNICATION AND INTEROPERABILITY STANDARDS

A. EV Charging Communication Architecture

Modern EV charging systems rely on communication architectures that enable coordinated interaction among EVs, charging stations, aggregators, and utility networks [24]. Communication capability is essential for smart charging, billing, remote monitoring, demand response, and Vehicle-to-Grid (V2G) operation.

EV charging communication generally operates through three main layers:

1. EV-to-EVCS Communication. Enables authentication, charging control, battery status exchange, and charging parameter coordination between the EV and charging station.
2. EVCS-to-Backend Communication. Supports remote monitoring, billing, load management, firmware updates, and charging network supervision through cloud-based or utility-managed platforms.
3. Backend-to-Grid Communication. Connects charging operators with utilities and energy management systems to support demand response, grid coordination, and energy market participation.

Real-time communication enables charging systems to dynamically regulate charging power according to grid loading conditions, electricity pricing, renewable energy availability, and user charging demand.

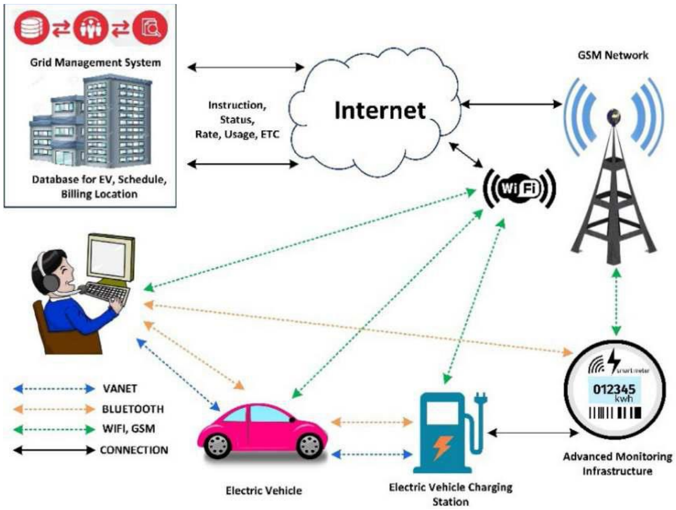


Figure 15. Communication network for EVCS *[25]*.

The communication architecture of smart EVCS networks therefore plays a major role in charging reliability, interoperability, cybersecurity, and large-scale EV integration.

As EV penetration increases, communication systems must support low-latency, secure, and scalable data exchange capable of coordinating thousands of charging devices simultaneously. Consequently, communication architecture has become a foundational requirement for future smart-grid-integrated EV charging ecosystems.

B. *Major EV Charging Standards and Protocols*

Standardized communication and interoperability protocols are essential for ensuring compatibility among EVs, charging stations, utilities, and backend management systems [25], [36]. These standards support secure charging operation, coordinated energy management, and scalable smart-grid integration.

1. IEC 61851. IEC 61851 defines conductive charging system requirements including charging modes, safety mechanisms, and operational control for AC and DC charging systems. The standard forms the foundation for conventional EV charging infrastructure deployment.

2. ISO/IEC 15118. ISO/IEC 15118 enables advanced communication between EVs and charging stations, supporting:

Plug & Charge authentication,
automated billing,
smart charging,
and Vehicle-to-Grid (V2G) operation.

The standard further enables bidirectional energy exchange and secure digital communication using Public Key Infrastructure (PKI).

3. Open Charge Point Protocol (OCPP). OCPP is an open communication protocol used between charging stations and backend management systems. It supports remote monitoring, charging control, firmware updates, fault diagnostics, and charging network management.

OCPP has become widely adopted due to its interoperability and vendor-independent architecture.

4. IEC 63110. IEC 63110 focuses on charging infrastructure management and smart-grid coordination. The protocol supports large-scale EVCS management, energy market participation, demand response, and distributed charging coordination.

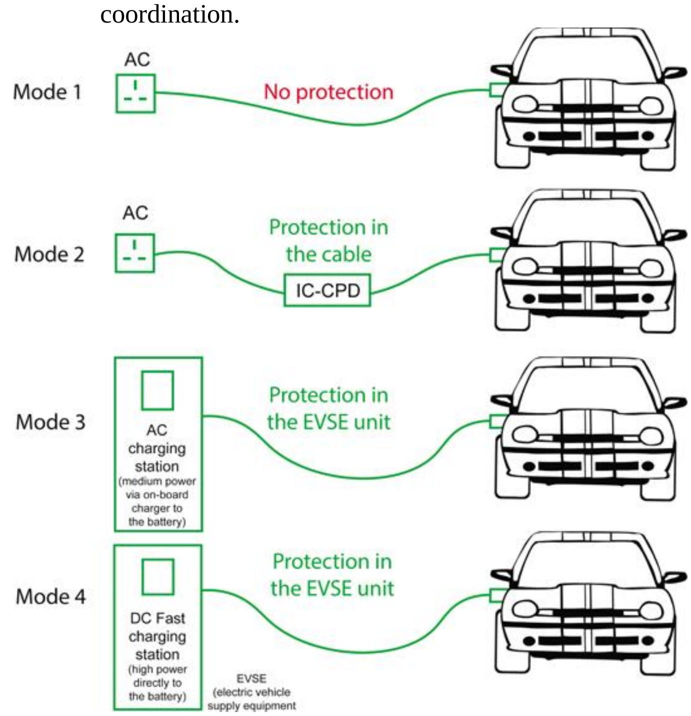


Figure 16. Charging modes and a summary of each *[29]*.

Table 15. EV charging standards and their primary applications.

Standard/Protocol	Primary Function	Key Feature	Application
IEC 61851	Conductive charging control	Charging safety/modes	AC/DC Charging
ISO/IEC 15118	EV-EVCS communication	Plug & Charge, V2G	Smart Charging
OCPP	EVCS-backend communication	Remote monitoring/control	Charging Networks
IEC 63110	Infrastructure management	Smart-grid integration	Large-scale EVCS

Despite significant progress in standardization, interoperability challenges persist due to:

- Fragmented regional standards,
- Legacy charging infrastructure,
- Firmware incompatibility, and

- Inconsistent protocol implementation.

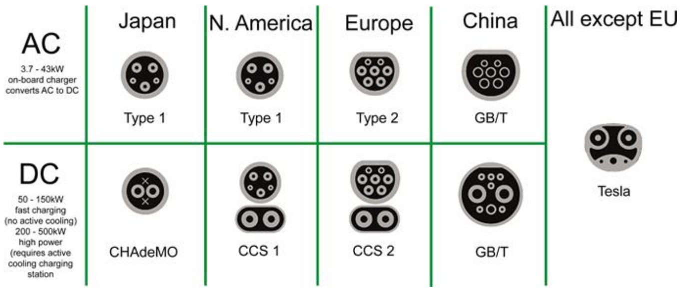


Figure 17. Current charging methods *[11]*.

Consequently, harmonized communication standards remain essential for enabling secure, interoperable, and scalable EV charging ecosystems capable of supporting future smart-grid and V2G applications.:

C. *Cybersecurity and Data Protection*

The increasing digitalization of EV charging infrastructure has introduced significant cybersecurity and data privacy challenges [25]. Smart charging systems continuously exchange operational and user data among EVs, charging stations, aggregators, and utility networks, making secure communication essential for reliable system operation.

Cybersecurity threats in EVCS networks include unauthorized charging access, data interception, malware attacks, false data injection, and denial-of-service attacks.

Such vulnerabilities may compromise charging coordination, billing systems, and grid stability, particularly under large-scale V2G operation.

ISO/IEC 15118 incorporates Public Key Infrastructure (PKI) to enable secure authentication and encrypted communication between EVs and charging stations. Additional cybersecurity measures commonly applied in smart charging systems include:

- end-to-end encryption,
- role-based access control,
- secure firmware updates,
- and anomaly detection mechanisms.,

Despite ongoing advances in EVCS cybersecurity, implementation challenges remain significant, particularly in developing regions with limited cybersecurity infrastructure and technical expertise. Consequently, future smart charging ecosystems will require stronger security frameworks capable of supporting secure, scalable, and interoperable charging operation under increasingly connected smart-grid environments [26].

D. *Interoperability Challenges*

Despite advances in EV charging standards, interoperability remains a major barrier to large-scale EVCS deployment [18], [37]. Differences in charging protocols, connector standards, communication frameworks, and backend management systems continue to limit seamless charging operation across regions and manufacturers.

One major challenge is protocol fragmentation among charging standards such as CCS, CHAdeMO, GB/T, and proprietary charging systems.

This fragmentation complicates cross-platform compatibility and increases infrastructure deployment complexity.

Legacy charging infrastructure presents additional limitations because many older charging stations lack firmware capability to support Plug & Charge, V2G communication, and advanced smart charging functions.

Consequently, interoperability upgrades often require costly hardware replacement or software retrofitting.

Communication incompatibility between charging stations and backend systems may further reduce charging reliability and network coordination efficiency. Differences in protocol implementation across manufacturers can also create synchronization and authentication challenges during real-time charging operation [5].

Interoperability challenges are particularly significant in developing regions where charging infrastructure expansion is still emerging and standardization frameworks remain limited. Therefore, future EVCS deployment will increasingly depend on harmonized communication protocols, vendor-independent architectures, and coordinated international standardization efforts to support scalable and reliable smart charging ecosystems

E. *Communication Infrastructure Challenges in Developing Regions*

The implementation of smart EV charging infrastructure in developing regions is constrained by limited communication capability, weak grid infrastructure, and inadequate digital support systems [8]. Reliable communication is essential for smart charging, remote monitoring, interoperability, and V2G coordination; however, many emerging economies still face significant connectivity limitations.

Unstable internet connectivity and limited broadband penetration reduce the effectiveness of cloud-based charging management, real-time monitoring, and remote firmware updates.

These limitations may compromise charging coordination and reduce the reliability of smart charging services.

In addition, limited deployment of advanced metering infrastructure, SCADA systems, and utility communication platforms restricts large-scale charging coordination within distribution networks [25]. This challenge becomes more severe under high EV penetration where real-time data exchange is required for dynamic load management.

Economic constraints further affect communication infrastructure deployment. High implementation costs associated with:

- Smart meters,
- Communication gateways,
- Cybersecurity systems,
- And backend servers remain major barriers for many developing countries

Table 16. Key communication infrastructure challenges affecting EVCS deployment in developing regions.

Challenge	Impact on EVCS Operation	Possible Mitigation
Unreliable Internet Connectivity	Reduced smart charging capability	Hybrid local control systems
Limited Smart Grid Infrastructure	Poor charging coordination	Grid modernization
High Communication Cost	Slow infrastructure expansion	Public-private investment
Weak Cybersecurity Readiness	Increased cyber vulnerability	Security framework development
Limited Technical Expertise	Poor system maintenance	Capacity building and training

Despite these challenges, hybrid control architectures combining local intelligence with limited centralized coordination may provide practical solutions for weak-grid environments. Furthermore, ongoing investments in smart-grid modernization, renewable energy systems, and digital infrastructure are expected to improve future EVCS deployment capability across developing regions.

Consequently, scalable EV charging implementation in emerging economies will require integrated development of:

- communication infrastructure,
- smart-grid systems,
- cybersecurity frameworks,
- and technical workforce capacity

to support reliable and interoperable charging ecosystems

6.0 RENEWABLE ENERGY AND ENERGY STORAGE INTEGRATION

A. Renewable-Assisted EV Charging Architectures

Renewable-assisted EV charging systems integrate solar PV, wind energy, and Battery Energy Storage Systems (BESS) with EVCS infrastructure to reduce grid dependency, operational cost, and carbon emissions [13], [18]. Among these, solar PV-assisted charging remains the most practical solution due to high solar availability and modular deployment capability.

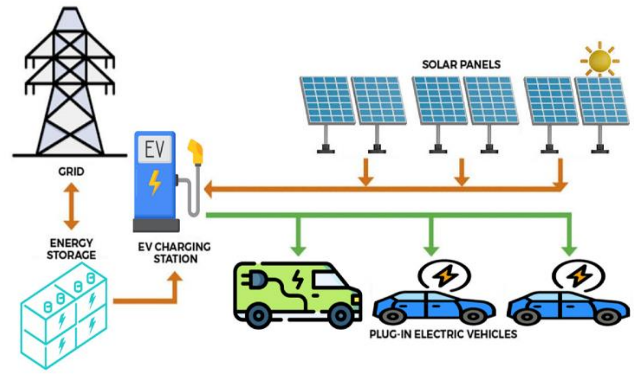


Figure 18. PV system with BESS to support EVCS.

Renewable-integrated EVCS architectures are commonly classified as:

- On-grid PV-EVCS,
- Off-grid PV-EVCS,
- Hybrid PV-BESS-grid systems.

On-grid systems export excess renewable energy to the utility grid, while off-grid systems rely on local generation and storage for autonomous operation. Hybrid systems combine grid support with renewable generation to improve charging reliability and operational flexibility [38].

Table 17. Renewable-assisted EVCS configurations.

Configuration	Main Components	Typical Application	Key Advantage
On-Grid PV-EVCS	PV + Grid	Urban charging	Reduced grid energy demand
Off-Grid PV-EVCS	PV + BESS	Rural charging	Energy independence
Hybrid PV-BESS EVCS	PV + BESS + Grid	Smart charging networks	Improved reliability
PV-Wind Hybrid EVCS	PV + Wind + BESS	Large charging hubs	Enhanced energy security

Renewable-assisted charging significantly improves sustainability and charging resilience, particularly in weak-grid regions. However, renewable intermittency and storage sizing remain major operational challenges requiring intelligent energy management and coordinated charging control.

Table 18. Comparative Analysis of EV Charging Converter Technologies

	Efficiency	Switching Frequency	Power Density	Typical Application	Key Limitation
Silicon-Based Converter	90–94%	Moderate	Moderate	Conventional EVCS	Higher switching losses

Silicon Carbide (SiC)	95–98%	High	High	DC Fast Charging	High cost
Gallium Nitride (GaN)	96–98%	Very High	Very High	Ultra-fast Charging	Therma l sensitiv ity
Bidirecti onal Convert er	94–97%	High	High	V2G Charging	Control comple xity
Isolated Convert er	92–96%	Modera te	Moder ate	High-safety EVCS	Large size

B. Battery Energy Storage Systems (BESS)

Battery Energy Storage Systems (BESS) improve EVCS reliability, renewable utilization, and grid stability by storing excess energy and supplying power during peak charging periods [33]. BESS integration is particularly important for fast-charging stations and weak-grid environments with fluctuating renewable generation.

Major functions of BESS in EVCS operation include:

- Peak shaving,
- Load balancing,
- Renewable smoothing,
- Backup power support,
- Energy arbitrage.

Battery storage sizing depends on charging demand, renewable generation profile, and required autonomy period

Lithium-ion batteries remain the dominant storage technology due to:

- High energy density,
- Fast response time,
- High charging efficiency.

However, battery degradation, thermal management, and high investment cost remain major limitations for large-scale deployment.

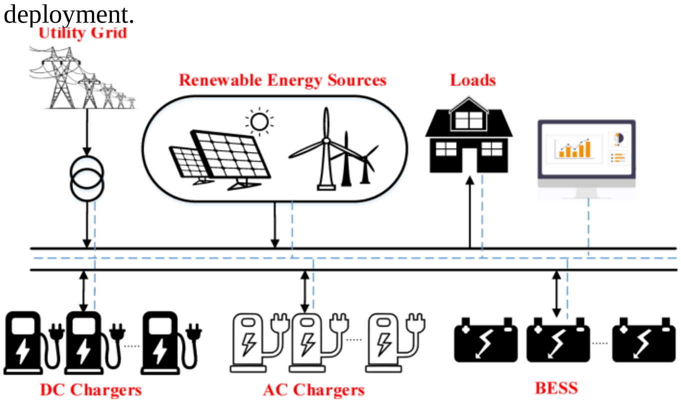


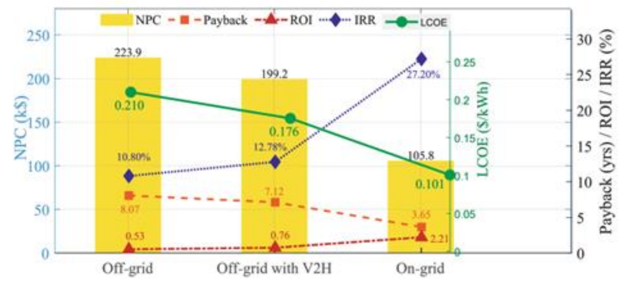
Figure 19. Configuration of EVCS powered by RESs

BESS-assisted charging systems are increasingly becoming essential for renewable-integrated and smart-grid EVCS deployment, particularly in regions with unstable utility infrastructure and high solar energy potential.

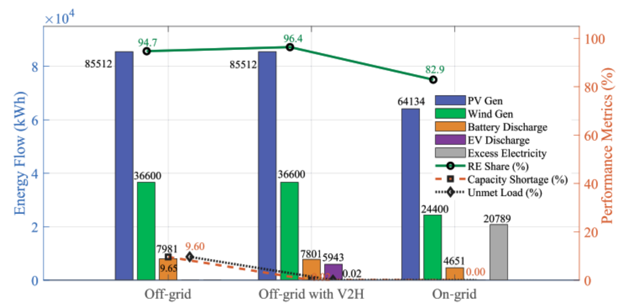
C. Techno-Economic Evaluation

The economic viability of EVCS deployment depends on charger rating, utilization level, renewable integration, electricity tariff, and energy management strategy [26]. High-power DC charging stations generally provide faster investment recovery due to higher charging throughput, although they require greater capital investment and grid reinforcement.

Hybrid PV-BESS-assisted charging systems can significantly reduce operational cost by minimizing grid energy consumption and peak demand charges [29]. However, system profitability strongly depends on charging demand, battery lifecycle, renewable generation variability, and local tariff structure.



(a)



(b)

Figure 20. (a) Annual energy flow and key performance metrics for off-grid, off-grid with V2H, and on-grid configurations. (b) Comparison of key financial indicators across off-grid, off-grid with V2H, and on-grid configurations [39]

Table 19. Typical techno-economic characteristics of EVCS deployment categories.

EVCS Category	Charg er Rating	CAPE X Level	Payback Period	Typical Applicatio n
Residenti al AC Charging	≤ 7 kW	Low	Long	Home charging
Commerc ial Level 2 Charging	7–22 kW	Modera te	Moderate	Public parking
DC Fast Charging	50–350 kW	High	Short/Moder ate	Fleet/highw ay charging

Hybrid PV-BESS EVCS	Variable	High	Moderate	Smart charging networks

Large-scale DC charging stations generally achieve better economic performance under high utilization conditions, while hybrid renewable-assisted systems improve long-term operational sustainability and grid resilience.

Consequently, techno-economic optimization remains essential for developing scalable EVCS infrastructure capable of balancing charging performance, investment cost, and grid stability.

D. Renewable Intermittency and Energy Management

Renewable energy intermittency remains a major challenge in PV-assisted EV charging systems due to fluctuations in solar irradiance and charging demand [18]. Variations in renewable generation may cause unstable charging operation, reduced charging availability, and increased dependency on utility grids.

Energy Management Systems (EMS) are therefore used to coordinate renewable generation, battery storage, grid supply, and EV charging demand.

Common EMS strategies include:

- Rule-based control,
- Predictive energy management,
- Load-following control,
- Ai-based optimization.

Smart EMS platforms dynamically schedule charging according to electricity pricing, solar generation forecasts, battery state of charge, and feeder loading conditions [40].

Effective energy management significantly improves charging reliability, renewable utilization, and grid stability. Consequently, intelligent EMS integration is becoming essential for future renewable-assisted smart charging infrastructures

E. Renewable-Integrated EVCS Deployment in Developing Regions

Renewable-assisted EV charging presents significant opportunities for developing regions with weak-grid infrastructure and high solar energy potential [30]. Hybrid PV-BESS EVCS architectures can reduce dependence on unstable utility networks while improving charging reliability and energy accessibility.

In sub-Saharan Africa, abundant solar irradiance supports the deployment of decentralized and semi-autonomous charging systems for Urban mobility, Electric motorcycles, public transport, and rural electrification.

However, deployment challenges remain significant due to:

- Limited grid capacity,
- High infrastructure cost,
- Low ev penetration,
- Inadequate regulatory frameworks

Despite these limitations, renewable-integrated EVCS systems remain a promising solution for sustainable transportation development in emerging economies. Future deployment will depend on coordinated investment in renewable energy systems, smart-grid infrastructure, energy storage, and supportive policy frameworks

7.0 RESEARCH GAPS AND FUTURE DIRECTIONS

A. Technical and Operational Gaps

Despite significant advances in EV charging technologies, several technical and operational challenges continue to limit large-scale EVCS deployment [41]. Most smart charging and optimization frameworks remain simulation-based with limited real-world validation under practical grid conditions.

Major technical gaps include:

- Limited scalability of centralized charging architectures,
- Inadequate harmonic mitigation under high-power charging,
- Insufficient renewable intermittency management,
- Limited integration of real-time grid analytics.

Battery degradation during fast charging and V2G operation also remains insufficiently addressed, particularly under high charging frequency and variable operating conditions.

Operational limitations further arise from:

- Communication latency,
- Interoperability mismatch,
- Cybersecurity vulnerability,
- Inaccurate charging demand forecasting.

In weak-grid environments, uncontrolled fast charging may still produce voltage instability, transformer overloading, and feeder congestion despite existing smart charging approaches.

Addressing these challenges will require Scalable control architectures, Advanced harmonic mitigation, AI-driven predictive charging, Real-time grid-aware energy management systems capable of supporting large-scale smart charging ecosystems.

B. Interoperability and Cybersecurity Gaps

Interoperability remains a major limitation in EVCS deployment due to fragmented charging standards, inconsistent protocol implementation, and limited compatibility among charging platforms [25]. Differences in connector standards and backend communication frameworks continue to hinder seamless charging operation across regions and manufacturers.

Cybersecurity challenges are also increasing with the expansion of connected charging networks. Existing EVCS systems remain vulnerable to unauthorized access, false data injection, malware attacks, and communication interception.

In many developing regions, cybersecurity implementation is constrained by limited technical expertise and weak digital infrastructure.

Future research should prioritize harmonized interoperability frameworks, secure communication architectures, lightweight cybersecurity solutions, and standardized certification mechanisms to support scalable and secure EV charging ecosystems.

C. Economic and Policy Gaps

The large-scale deployment of EV charging infrastructure remains constrained by significant economic and regulatory challenges, particularly in developing regions [29]. High capital investment associated with fast chargers, renewable integration, and communication infrastructure continues to limit commercial scalability.

Low EV penetration in emerging economies further reduces charging station utilization rates, negatively affecting investment recovery and long-term profitability. In addition, many techno-economic studies rely on generalized assumptions that do not reflect Local tariff structures, Renewable resource variability, Financing conditions, and weak-grid operational constraints [19].

Policy and regulatory limitations also remain significant. Many countries still lack EV charging standards, V2G regulations, Interoperability certification frameworks, and coordinated e-mobility policies.

The absence of clear regulatory structures increases deployment uncertainty and slows private-sector investment.

Future research and policy development should focus on Localized techno-economic modeling, Supportive financing frameworks, Standardized charging regulations, and incentive-based renewable-assisted evcs deployment to improve the scalability and sustainability of smart charging infrastructure.

D. Priority Research Directions

Future EVCS research should prioritize technologies and deployment strategies capable of improving scalability, interoperability, grid stability, and renewable integration under real operating conditions. Particular emphasis is required for weak-grid and developing-region applications where infrastructure limitations remain significant.

Key priority research areas include AI-driven smart charging coordination, renewable-aware energy management, scalable V2G implementation, cybersecurity-enhanced charging systems, and real-time grid-support services.

Hybrid PV-BESS charging systems integrated with predictive EMS frameworks are expected to become increasingly important for reducing grid stress and improving charging reliability.

Future research should increasingly focus on pilot-scale deployment validation, adaptive charging coordination, localized techno-economic assessment, and resilient smart-grid integration to support reliable and scalable EV charging ecosystems under high EV penetration conditions.

E. Future Outlook

EV charging infrastructure is rapidly evolving from standalone charging facilities toward intelligent, renewable-integrated, and grid-interactive energy systems. Future EVCS networks will increasingly combine smart charging, bidirectional power flow, AI-driven energy management, and renewable-assisted charging coordination to support sustainable transportation and smart-grid operation.

Hierarchical and distributed control architectures are expected to dominate future large-scale charging ecosystems due to their improved scalability, resilience, and grid coordination capability. Similarly, wide-bandgap converter technologies such as Silicon Carbide (SiC) and Gallium Nitride (GaN) are expected to improve charging efficiency and enable ultra-fast charging applications.

In developing regions, hybrid PV-BESS charging systems present a practical pathway for expanding EV infrastructure under weak-grid conditions. However, successful deployment will depend on grid modernization, harmonized interoperability standards, cybersecurity readiness, supportive policy frameworks, and local technical capacity development.

Future EVCS deployment will therefore require coordinated advancement in power electronics, communication systems, renewable integration, artificial intelligence, and smart-grid infrastructure.

These developments are expected to accelerate the transition toward resilient, scalable, and low-carbon electric mobility ecosystems worldwide.

8.0 CONCLUSION

This paper presented a critical review of EVCS technologies with emphasis on charging classifications, converter architectures, smart charging control strategies, interoperability standards, and renewable energy integration. Comparative analysis showed that high-power DC charging, bidirectional converter technologies, and intelligent charging coordination are becoming essential for large-scale EV integration and smart-grid operation.

The review further demonstrated that centralized, decentralized, distributed, and hierarchical control architectures each present unique trade-offs in terms of scalability, communication requirement, computational complexity, and grid coordination capability. In addition, AI-driven optimization techniques and predictive energy management systems are increasingly improving charging efficiency, renewable utilization, and operational flexibility.

Renewable-assisted EVCS architectures incorporating photovoltaic systems and Battery Energy Storage Systems (BESS) were identified as promising solutions for reducing grid dependency and improving charging reliability, particularly under weak-grid conditions. However, major challenges related to interoperability, cybersecurity, harmonic distortion, infrastructure cost, and renewable intermittency continue to limit large-scale deployment.

For developing regions such as sub-Saharan Africa, hybrid PV-BESS charging systems provide significant opportunities for sustainable and decentralized EV infrastructure development. Nevertheless, successful deployment will require supportive policy frameworks, communication infrastructure modernization, standardized interoperability protocols, and local technical capacity development.

Overall, future EV charging ecosystems will increasingly depend on intelligent control, renewable integration, secure communication, and scalable smart-grid coordination to support resilient and low-carbon transportation systems. This review provides a structured analytical foundation for future research and practical deployment of next-generation EV charging infrastructure.

REFERENCES

T. Denton, H. Pells, and H. Pells, "Electric and Hybrid Vehicles".

A. R. Bhatti *et al.*, "Electric vehicle charging stations and the employed energy management schemes: a classification based comparative survey," *Discov. Appl. Sci.*, vol. 6, no. 10, p. 503, Sep. 2024, doi: 10.1007/s42452-024-06190-9.

I. Aretxabaleta, I. M. De Alegria, J. Andreu, I. Kortabarria, and E. Robles, "High-Voltage Stations for Electric Vehicle Fast-Charging: Trends, Standards, Charging Modes and Comparison of Unity Power-Factor Rectifiers," *IEEE Access*, vol. 9, pp. 102177–102194, 2021, doi: 10.1109/ACCESS.2021.3093696.

M. E. El-hawary, "The Smart Grid—State-of-the-art and Future Trends," *Electr. Power Compon. Syst.*, vol. 42, no. 3–4, pp. 239–250, Mar. 2014, doi: 10.1080/15325008.2013.868558.

L. Wang, Z. Qin, T. Slangen, P. Bauer, and T. Van Wijk, "Grid Impact of Electric Vehicle Fast Charging Stations: Trends, Standards, Issues and Mitigation Measures - An Overview," *IEEE Open J. Power Electron.*, vol. 2, pp. 56–74, 2021, doi: 10.1109/OJPEL.2021.3054601.

M. Nurmuhammed, O. Akdağ, and T. Karadağ, "A novel modified Archimedes optimization algorithm for optimal placement of electric vehicle charging stations in distribution networks," *Alex. Eng. J.*, vol. 84, pp. 81–92, Dec. 2023, doi: 10.1016/j.aej.2023.10.055.

F. M. Tiburtini, F. Lo Franco, and M. Ricco, "Multi-Objective Sizing Method for Pv-Bess Integration with Ev Charging Stations and Analysis Across Different Parking Scenarios," 2025, *SSRN*. doi: 10.2139/ssrn.5107053.

H. M. Hussein *et al.*, "State-of-the-Art Electric Vehicle Modeling: Architectures, Control, and Regulations," *Electronics*, vol. 13, no. 17, p. 3578, Sep. 2024, doi: 10.3390/electronics13173578.

T. Denton, *Electric and Hybrid vehicles*. Milton Park, Abingdon, Oxon ; New York, NY: Routledge, 2016.

Modern Electric, Hybrid Electric, and Fuel Cell Vehicles, Third Edition. CRC Press, 2018. doi: 10.1201/9780429504884.

S. M. Arif, T. T. Lie, B. C. Seet, S. Ayyadi, and K. Jensen, "Review of Electric Vehicle Technologies, Charging Methods, Standards and Optimization Techniques," *Electronics*, vol. 10, no. 16, p. 1910, Aug. 2021, doi: 10.3390/electronics10161910.

M. A. H. Rafi and J. Bauman, "A Comprehensive Review of DC Fast-Charging Stations With Energy Storage: Architectures, Power Converters, and Analysis," *IEEE Trans. Transp. Electrification*, vol. 7, no. 2, pp. 345–368, Jun. 2021, doi: 10.1109/TTE.2020.3015743.

S. Ali Qasem Mohammed, S. Saleh Hakami, M. Kassas, and M. M. Almuhaini, "Critical Review on Powertrain Technologies for Electric Vehicles: Classification, Broadly Adopted Topologies, and Future Challenges," *IEEE Access*, vol. 13, pp. 71755–71772, 2025, doi: 10.1109/ACCESS.2025.3561577.

M. Waseem, E. Sreeshobha, K. Shashidhar Reddy, and T. Donateo, "State-of-the-Art and Advancement of Charging Infrastructure in Electric Mobility: An Integrated Review," *Energies*, vol. 17, no. 23, p. 6137, Dec. 2024, doi: 10.3390/en17236137.

T. Muthusamy, U. Meyyappan, S. B. Thanikanti, and M. Khishe, "Enhancing distribution system performance by optimizing electric vehicle charging station integration in smart grids using the honey badger algorithm," *Sci. Rep.*, vol. 14, no. 1, p. 27341, Nov. 2024, doi: 10.1038/s41598-024-78569-y.

M. Z. Zeb *et al.*, "Optimal Placement of Electric Vehicle Charging Stations in the Active Distribution Network," *IEEE Access*, vol. 8, pp. 68124–68134, 2020, doi: 10.1109/ACCESS.2020.2984127.

S. A. Q. Mohammed and J.-W. Jung, "A Comprehensive State-of-the-Art Review of Wired/Wireless Charging Technologies for Battery Electric Vehicles: Classification/Common Topologies/Future Research Issues," *IEEE Access*, vol. 9, pp. 19572–19585, 2021, doi: 10.1109/ACCESS.2021.3055027.

G. Rajendran, R. Raute, and C. Caruana, "A Comprehensive Review of Solar PV Integration with Smart-Grids: Challenges, Standards, and Grid Codes," *Energies*, vol. 18, no. 9, p. 2221, Apr. 2025, doi: 10.3390/en18092221.

P. Bhosale, S. A, R. Kumar, and R. C. Bansal, "Electric Vehicle Charging Infrastructure, Standards, Types, and Its Impact on Grid: A Review," *Electr. Power Compon. Syst.*, pp. 1–25, Apr. 2024, doi: 10.1080/15325008.2024.2315206.

M. A. Hannan, Md. M. Hoque, A. Hussain, Y. Yusof, and P. J. Ker, "State-of-the-Art and Energy Management System of Lithium-Ion Batteries in Electric Vehicle Applications: Issues and Recommendations," *IEEE Access*, vol. 6, pp. 19362–19378, 2018, doi: 10.1109/ACCESS.2018.2817655.

S. S. G. Acharige, Md. E. Haque, M. T. Arif, N. Hosseinzadeh, K. N. Hasan, and A. M. T. Oo, "Review of Electric Vehicle Charging Technologies, Standards, Architectures, and Converter Configurations," *IEEE Access*, vol. 11, pp. 41218–41255, 2023, doi: 10.1109/ACCESS.2023.3267164.

H. Wouters and W. Martinez, "Bidirectional Onboard Chargers for Electric Vehicles: State-of-the-Art and Future Trends," *IEEE Trans. Power Electron.*, vol. 39, no. 1, pp. 693–716, Jan. 2024, doi: 10.1109/TPEL.2023.3319996.

Y. Zhang, Y. Wang, F. Li, B. Wu, Y.-Y. Chiang, and X. Zhang, "Efficient Deployment of Electric Vehicle Charging Infrastructure: Simultaneous Optimization of Charging Station Placement and Charging Pile Assignment," *IEEE Trans. Intell. Transp. Syst.*, vol. 22, no. 10, pp. 6654–6659, Oct. 2021, doi: 10.1109/TITS.2020.2990694.

A. Arancibia and K. Strunz, "Modeling of an electric vehicle charging station for fast DC charging," in *2012 IEEE International Electric Vehicle Conference*, Greenville, SC, USA: IEEE, Mar. 2012, pp. 1–6. doi: 10.1109/IEVC.2012.6183232.

B. Wang, P. Dehghanian, S. Wang, and M. Mitolo, "Electrical Safety Considerations in Large-Scale Electric Vehicle Charging Stations," *IEEE Trans. Ind. Appl.*, vol. 55, no. 6, pp. 6603–6612, Nov. 2019, doi: 10.1109/TIA.2019.2936474.

T. K. Roy, "Techno-economic assessment of Hybrid Renewable Energy Systems with advanced EMS and renewable energy-based EV charging with V2H integration for remote and grid-edge Australian communities," *Energy Convers. Manag.*, vol. 348, p. 120725, Jan. 2026, doi: 10.1016/j.enconman.2025.120725.

M. Ehsani, K. V. Singh, H. O. Bansal, and R. T. Mehrjardi, "State of the Art and Trends in Electric and Hybrid Electric Vehicles," *Proc. IEEE*, vol. 109, no. 6, pp. 967–984, Jun. 2021, doi: 10.1109/JPROC.2021.3072788.

D. Savio Abraham *et al.*, "Electric Vehicles Charging Stations' Architectures, Criteria, Power Converters, and Control Strategies in Microgrids," *Electronics*, vol. 10, no. 16, p. 1895, Aug. 2021, doi: 10.3390/electronics10161895.

H. Wu, "A Survey of Battery Swapping Stations for Electric Vehicles: Operation Modes and Decision Scenarios," *IEEE Trans. Intell. Transp. Syst.*, vol. 23, no. 8, pp. 10163–10185, Aug. 2022, doi: 10.1109/TITS.2021.3125861.

J. Van Mierlo *et al.*, "Beyond the State of the Art of Electric Vehicles: A Fact-Based Paper of the Current and Prospective Electric Vehicle Technologies," *World Electr. Veh. J.*, vol. 12, no. 1, p. 20, Feb. 2021, doi: 10.3390/wevj12010020.

S. M. A. Elazim *et al.*, "Enhancing stability and power quality in electric vehicle charging stations powered by hybrid energy sources through harmonic mitigation and load management," *Sci. Rep.*, vol. 15, no. 1, p. 28077, Aug. 2025, doi: 10.1038/s41598-025-14143-4.

S. S. Sayed and A. M. Massoud, "Review on State-of-the-Art Unidirectional Non-Isolated Power Factor Correction Converters for Short-/Long-Distance Electric Vehicles," *IEEE Access*, vol. 10, pp. 11308–11340, 2022, doi: 10.1109/ACCESS.2022.3146410.

S. Deeum *et al.*, "Optimal Placement of Electric Vehicle Charging Stations in an Active Distribution Grid with Photovoltaic and Battery Energy Storage System Integration," *Energies*, vol. 16, no. 22, p. 7628, Nov. 2023, doi: 10.3390/en16227628.

S. Chakraborty, H.-N. Vu, M. M. Hasan, D.-D. Tran, M. E. Baghdadi, and O. Hegazy, "DC-DC Converter Topologies for Electric Vehicles, Plug-in Hybrid Electric Vehicles and Fast Charging Stations: State of the Art and Future Trends," *Energies*, vol. 12, no. 8, p. 1569, Apr. 2019, doi: 10.3390/en12081569.

M. Muzammal Islam *et al.*, "Improving Reliability and Stability of the Power Systems: A Comprehensive Review on the Role of Energy Storage Systems to Enhance Flexibility," *IEEE Access*, vol. 12, pp. 152738–152765, 2024, doi: 10.1109/ACCESS.2024.3476959.

S. M. Shariff, D. Iqbal, M. Saad Alam, and F. Ahmad, "A State of the Art Review of Electric Vehicle to Grid (V2G) technology," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 561, no. 1, p. 012103, Oct. 2019, doi: 10.1088/1757-899X/561/1/012103.

A. M. Foley, I. J. Winning, and B. P. O Gallachoir, "State-of-the-art in electric vehicle charging infrastructure," in *2010 IEEE Vehicle Power and Propulsion Conference*, Lille, France: IEEE, Sep. 2010, pp. 1–6. doi: 10.1109/VPPC.2010.5729014.

F. M. Tiburtini, F. Lo Franco, and M. Ricco, "Multi-Objective Sizing Method for Pv-Bess Integration with Ev Charging Stations and Analysis Across Different Parking Scenarios," 2025, *SSRN*. doi: 10.2139/ssrn.5107053.

V. N. Saraswathi and V. P. Ramachandran, "A comprehensive review on charger technologies, types, and charging stations models for electric vehicles," *Heliyon*, vol. 10, no. 20, p. e38945, Oct. 2024, doi: 10.1016/j.heliyon.2024.e38945.

R. Çakmak, G. Bayrak, and M. Koç, "A Fuzzy Logic-Based Energy Management Approach for Fuel Cell and Photovoltaic Powered Electric Vehicle Charging Station in DC Microgrid Operations," *IEEE Access*, vol. 13, pp. 49905–49921, 2025, doi: 10.1109/ACCESS.2025.3552253.

S. Deeum *et al.*, "Optimal Placement of Electric Vehicle Charging Stations in an Active Distribution Grid with Photovoltaic and Battery Energy Storage System Integration," *Energies*, vol. 16, no. 22, p. 7628, Nov. 2023, doi: 10.3390/en16227628.