

Multi-Energy Microgrids for Sustainable Electric Vehicle Infrastructure: A Systematic Review of Hybrid Architectures, V2X Flexibility Services, and Hydrogen Sector Coupling

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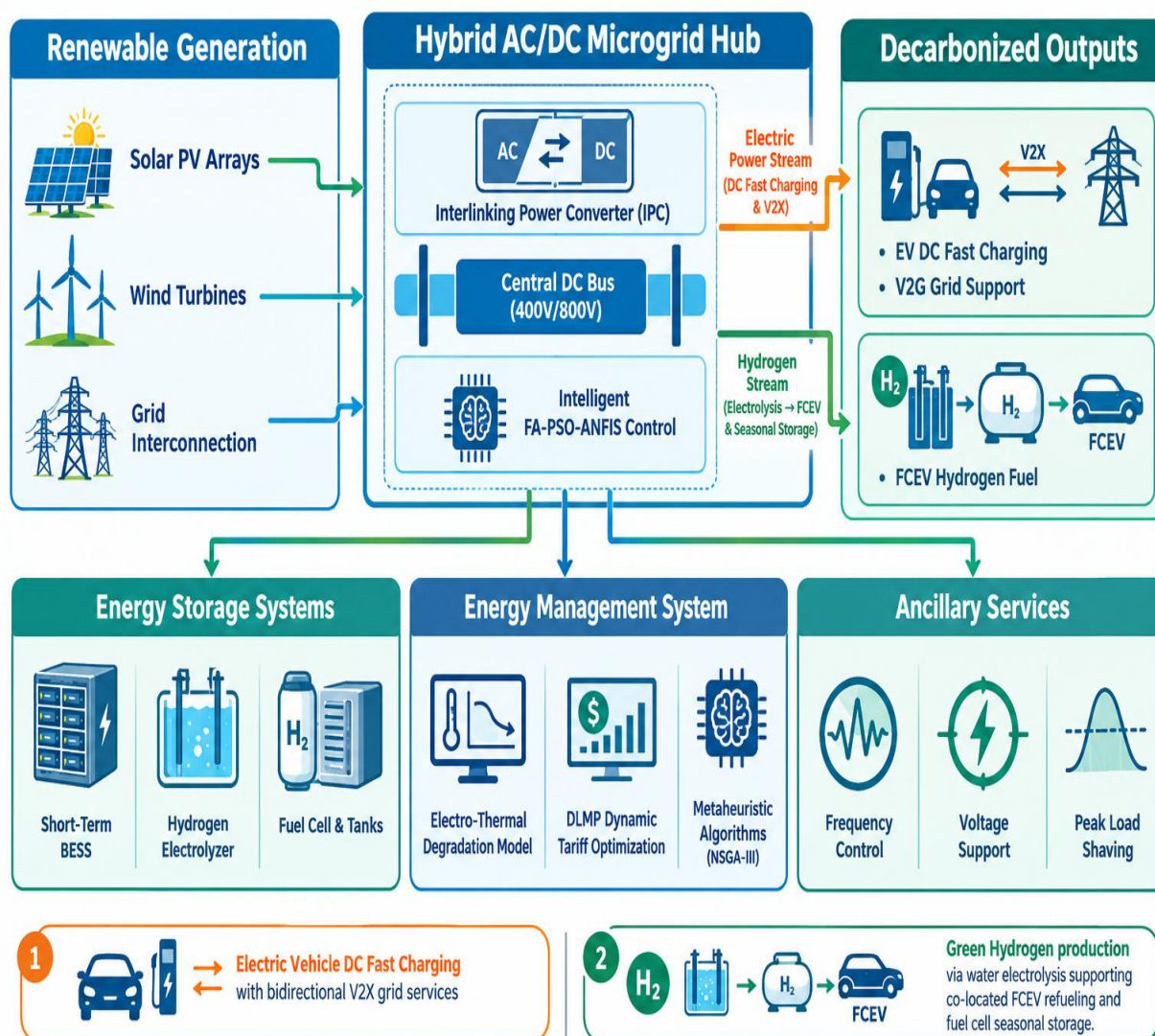
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Abstract

The accelerated worldwide deployment of electric vehicles is profoundly reshaping electrical distribution systems, introducing significant operational constraints regarding network stability while simultaneously unlocking novel paradigms for distributed energy resource management. Uncoordinated Level 3 direct current fast charging (DCFC) and megawatt-level fleet hubs introduces localized transformer thermal overloading, voltage unbalance, and severe harmonic distortion. To mitigate these impacts, multi-energy microgrids (MEMGs) integrating solar photovoltaics (PV), wind generators, battery energy storage systems (BESS), and green hydrogen vectors (electrolyzers and fuel cells) are emerging as essential infrastructure. This paper presents a systematic review of multi-energy EV charging microgrids following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol, synthesizing literature published between 2018 and 2026. A comprehensive taxonomy has been established across three primary domains: (1) power electronic converter topologies and hybrid AC/DC microgrid architectures, evaluating control strategies for constant power load (CPL) stability; (2) Vehicle-to-Everything (V2X) flexibility services, analysing aggregator market mechanics and Distribution Locational Marginal Pricing (DLMP); and (3) green hydrogen sector coupling, evaluating co-located Fuel Cell Electric Vehicle (FCEV) refuelling hubs and seasonal storage dynamics. Furthermore, this review examines non-linear electro-thermal battery degradation modelling within multi-objective energy management systems (EMS) and metaheuristic optimization algorithms (e.g., NSGA-III, MOROA, HOMER). Finally, critical research gaps are identified in low-inertia Virtual Synchronous Generator (VSG) control, cybersecurity against False Data Injection (FDI) attacks, and Inter-industry regulatory alignment.

Keywords: Electric vehicle charging; multi-energy microgrid; Vehicle-to-Grid (V2G); Green hydrogen; Battery degradation; Power electronics

Graphical Abstract



Highlights

- Systematic PRISMA review of multi-energy EV microgrid literature (2018–2026).
- Comparative taxonomy of AC, DC, and hybrid AC/DC converter bus topologies.
- V2X flexibility mechanics for frequency regulation and DLMP dynamic pricing.

- Green hydrogen sector coupling for seasonal storage and FCEV refuelling hubs.
- Electro-thermal battery degradation integration in multi-objective EMS.

1. Introduction and PRISMA Survey Methodology

The rapid global electrification of transport has driven a fundamental paradigm shift in electrical distribution networks. As analysed in comprehensive reviews by Acharige et al. (2023), Mastoi et al. (2022), and Yousuf et al. (2024), electric vehicle charging stations (EVCS), once operated as passive, unpredictable electrical loads, are evolving into active prosumer nodes integrated into multi-energy microgrids (MEMG). Uncoordinated, high-power EV charging—especially Level 3 direct current fast charging (DCFC) and megawatt-level fleet charging—introduces severe power quality and operational challenges to low- and medium-voltage distribution feeders. As documented by Li and Jenn (2024), Zhang et al. (2025), and Sarda et al. (2024), these challenges include localized power transformer thermal overloading, accelerated insulation aging, voltage sags, phase unbalance, and harmonic distortion exceeding standard grid limits.

To alleviate grid congestion while advancing decarbonization objectives, modern electric vehicle charging infrastructure increasingly incorporates localized distributed energy resources (DERs). Integrating solar photovoltaics (PV), wind turbine generators (WTG), battery energy storage systems (BESS), and green hydrogen vectors (electrolyzers and fuel cells) convert charging hubs into resilient microgrid systems (Dimitriadou et al., 2023; Rachid et al., 2023; Zhao et al., 2025). These integrated systems can operate in both grid-connected and islanded modes, providing clean energy for EV charging while buffering grid peak loads.

1.1. PRISMA Systematic Review Protocol

To uphold methodological rigor, transparency, and reproducibility, this review adheres to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, following recommendations from recent systematic literature (Ghanbari Motlagh and Li, 2026; Rashid et al., 2024; Yuvaraj et al., 2024). To identify relevant literature published between 2018 and 2026, a structured four-stage screening procedure was executed across major indexing databases, specifically Scopus, IEEE Xplore, Web of Science, and ScienceDirect.

1. **Identification Stage:** Initial search queries utilized Boolean combinations of primary keywords: ("Electric Vehicle Charging Station" OR "EVCS" OR "DC Fast Charging") AND ("Microgrid" OR "Hybrid AC/DC" OR "Multi-Energy System") AND ("Vehicle-to-Grid" OR "V2G" OR "V2X" OR "Ancillary Services") AND ("Hydrogen" OR "Electrolyzer" OR "Fuel Cell"). This broad query yielded an initial pool of 1,482 database records.
2. **Screening Stage:** Following automated deduplication and title-abstract screening, 1,070 records were excluded. Disqualified items comprised non-peer-reviewed preprints, industry and trade publications, policy briefs lacking quantitative technical modeling, and studies addressing isolated battery chemistry with no grid-interaction component.
3. **Eligibility Stage:** The remaining 412 full-text articles underwent rigorous assessment against strict technical inclusion criteria:
 - We selected studies that incorporated explicit power converter architectures or validated energy management algorithms for microgrid environments.
 - Inclusion of quantitative technical metrics (e.g., total net present cost [TNPC], levelized cost of energy [LCOE], total harmonic distortion [THD], voltage deviation indices, or loss of power supply probability [LPSP]).
 - Eligible studies were required to present direct modelling of multi-source DER integration alongside EV load dynamics; 326 articles failing to satisfy these criteria were excluded with documented rationales.
4. **Inclusion Stage:** A finalized corpus of primary studies was compiled to establish the taxonomy, state-of-the-art converter assessments, control benchmarks, and techno-economic comparative tables presented in this review.

1.2. International Standards and Regulatory Grid Codes

As summarized by Acharige et al. (2023), Sagar et al. (2023), and Zhao et al. (2025), deploying and integrating multi-energy EV charging microgrids requires strict compliance with international standards. These regulatory frameworks establish mandatory requirements for power quality thresholds, safety interlock mechanisms, conductive and wireless power transfer protocols, and grid interconnection guidelines.

Organization	Standard Reference	Focus Area and Operational Scope
IEEE	IEEE 519-1992 / 2014	Voltage and current harmonic control limits in electrical power systems.
IEEE	IEEE 1159-1995	Recommended practice for monitoring electric power quality.
IEEE	IEEE 1547-2018	Standard for interconnecting distributed energy resources with electric power systems ($PCC \leq 10$ MVA).
SAE	SAE J1772	AC Level 1/2 and DC Fast Charging conductive charge couplers and electrical ratings.
SAE	SAE J2293	Power requirements, system architecture, and communication for conductive/inductive EV charging.
SAE	SAE J2847	Communication requirements between electric vehicles and utility grid interfaces for smart charging/V2G.
IEC	IEC 61851-1 / 23 / 24	Conductive EV charging systems, DC fast charging requirements, and digital communication protocols.
IEC	IEC 61980	System requirements and safety standards for wireless/inductive power transfer (WPT) systems up to 1000V AC / 1500 V DC.
IEC	IEC 62196	Plugs, socket-outlets, vehicle connectors, and vehicle inlets for conductive charging.
UL / NEC	UL 2231 / NEC 625	Safety protection systems for EV supply equipment (EVSE) and national electrical installation codes.

2. Hybrid AC/DC Microgrid Architectures and Advanced Power Conversion

2.1. Architectural Classification: AC, DC, and Hybrid AC/DC Buses

The structural architecture of an EV charging microgrid determines its conversion efficiency, control complexity, power density, and DER integration flexibility (Acharige et al., 2023; Rachid et al., 2023; Singh et al., 2024b). Microgrids are broadly

categorized into common AC bus, common DC bus, and hybrid AC/DC bus configurations.

Common AC Bus Architectures

In conventional AC bus architectures, all energy sources, energy storage systems, and EV chargers' interface at a centralized AC distribution bus (typically operating at 230 V / 400 V or medium voltage 11 kV / 20 kV). Because solar PV arrays, batteries, and EV batteries operate natively in DC, each unit requires an independent AC/DC or DC/AC conversion stage. As highlighted by Senapati et al. (2024), this multi-stage power conversion chain increases capital cost, reduces overall round-trip efficiency (due to accumulated conversion losses), and complicates system synchronization. Furthermore, uncoordinated rectifiers connected to the AC bus can inject low-order current harmonics, degrading system power factor and requiring bulky passive or active harmonic filters.

Common DC Bus Architectures

A common DC bus microgrid typically employs a single high-efficiency, grid-connected AC/DC converter, also known as an active front-end (AFE) rectifier, to regulate and maintain a stable central DC bus at standard voltage levels such as 400 V, 750 V, or 1000 V DC. DC-native energy sources, such as photovoltaic (PV) systems and fuel cells, together with energy storage technologies including battery energy storage systems (BESS) and supercapacitors, are interfaced directly with the DC bus through either isolated or non-isolated DC/DC converters. This architecture eliminates unnecessary AC/DC conversion stages, thereby reducing conversion losses, improving overall system efficiency, and simplifying power management. EVs connect via high-power DC/DC buck/boost regulators, as demonstrated by Senapati et al. (2024), Rachid et al. (2023), and Kumar et al. (2024), this architecture increases system efficiency, reduces weight and footprint, simplifies control by eliminating reactive power and frequency synchronization constraints on the internal bus, and facilitates rapid bidirectional energy transfer. However, the implementation of common DC bus architectures necessitates the use of specialized protection technologies, including fast-acting DC circuit breakers and solid-state switching devices, to effectively detect, isolate, and extinguish high-energy DC arc faults. These protection requirements arise from the absence of natural current zero crossings in DC systems, which makes fault interruption significantly more challenging than in conventional AC networks.

Hybrid AC/DC Bus Microgrids

Hybrid AC/DC microgrids combine the operational maturity of AC distribution with the efficiency of DC fast-charging networks. The AC bus connects directly to the utility grid, conventional AC loads, and wind turbine generators, while the DC bus aggregates solar PV, BESS, fuel cells, and EV chargers. A bidirectional Interlinking Power Converter (IPC) links the AC and DC buses, controlling active and reactive power flow between the two domains. This hybrid configuration provides maximum operational flexibility and superior fault isolation, though it requires sophisticated hierarchical control algorithms to manage the interlinking converter (Acharige et al., 2023; Yuvaraj et al., 2024).

Feature / Dimension	Common AC Bus Microgrid	Common DC Bus Microgrid	Hybrid AC/DC Bus Microgrid
Conversion Efficiency	Moderate (82% - 88%) due to multiple AC/DC/AC conversion stages.	High (90% - 96%) through direct DC-AC coupling of PV, BESS, and EVs.	Optimal (88% - 94%), balancing localized DC efficiency with grid coupling.
Control Complexity	High: Requires frequency, phase, and voltage synchronization across all nodes.	Moderate: Eliminates frequency/phase control; requires tight DC bus voltage regulation.	Complex: Requires coordinated multi-variable control of interlinking converters and sub-busses.
Power Quality & Harmonics	High harmonic distortion; requires active filtering and power factor correction (PFC).	Minimal AC-side harmonics when equipped with a central active front-end rectifier.	Isolated DC-side harmonics; high power quality maintained at the Point of Common Coupling (PCC).
Protection Systems	Standard, low-cost AC circuit breakers and protective relays.	Specialized, high-cost DC protection (solid-state relays, fast arc-extinguishing breakers).	Dual-zone protection: Standard AC breakers combined with specialized DC protection devices.
RES & ESS Integration	Requires individual grid-tied inverters for	Direct coupling via streamlined DC/DC buck	Plug-and-play integration of both

	each DC source.	or boost converters.	AC-native (wind) and DC-native (PV, BESS) sources.
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2.2. Power Converter Topologies for Bidirectional Charging

Efficient bidirectional EV charging requires specialized power electronic topologies for both the AC/DC rectification stage and the DC/DC voltage regulation stage (Acharige et al., 2023; Rachid et al., 2023; Sagar et al., 2023).

Front-End AC/DC Rectifiers

For Level 3 DCFC and high-power microgrid interfaces, three-phase bidirectional AC/DC converters are standard. Advanced topologies reviewed by Acharige et al. (2023) and Rachid et al. (2023) include:

- **Vienna Rectifiers:** A three-phase, three-switch, three-level active power factor correction (PFC) circuit. It offers high power density, low total harmonic distortion (THD < 3%), and reduced switch voltage stress (handling half the total DC link voltage). However, it is inherently unidirectional, restricting its application to Grid-to-Vehicle (G2V) charging.
- **Neutral Point Clamped (NPC) Multilevel Inverters/Rectifiers:** Three-level diode-clamped topologies capable of bidirectional power flow. NPC converters synthesize a low-distortion staircase voltage output, drastically reducing filter inductor sizing and electromagnetic interference (EMI) while handling elevated DC bus voltages (> 800V).
- **Modular Multilevel Converters (MMC):** Constructed from cascaded half-bridge or full-bridge submodules. MMCs are the benchmark topology for ultra-high-power megawatt charging hubs connected directly to medium-voltage distribution feeders without step-down transformers. MMCs offer modular redundancy, high voltage scalability, and low harmonic distortion.

Back-End DC/DC Converters

The interface between the intermediate DC link and the EV battery pack requires isolated or non-isolated bidirectional DC/DC converters:

- **Non-Isolated Interleaved Buck-Boost Converters:** Multiphase interleaved topologies operate with designated phase displacement to mitigate input and output current ripples, reduce current stresses across passive inductive components, and enhance transient dynamics. Consequently, these

architectures offer high volumetric power density and operational efficiency, making them particularly well-suited for both onboard and offboard DC fast-charging applications.

- **Dual Active Bridge (DAB) Converters:** An isolated bidirectional DC/DC topology comprising a primary full-bridge, a high-frequency (HF) isolation transformer, and a secondary full-bridge. As formulated by Rachid et al. (2023), power transfer magnitude and direction are controlled by modulating the phase-shift angle (ϕ) between the primary and secondary square-wave AC voltages:

$$P_{DAB} = \frac{V_1 V_2}{2\pi^2 f_s L_{leak}} \phi \left(1 - \frac{|\phi|}{\pi} \right) \text{ where } V_1 \text{ and } V_2$$

represent primary and secondary DC voltages, f_s is the switching frequency, and L_{leak} is the leakage inductance of the high-frequency transformer. DAB converters provide galvanic isolation, zero-voltage switching (ZVS) across a wide load range, and high-power density.

2.3. Intelligent Control Strategies for DC Microgrid Stability

DC microgrids with integrated EV fast chargers face stability challenges due to low physical inertia, solar PV and wind power variability, and the constant power load (CPL) characteristics of fast-charging converters. CPLs exhibit negative incremental impedance ($\frac{dv}{di} < 0$), which can induce undamped voltage oscillations and destabilize the main DC bus during severe power transients.

In landmark research by Senapati et al. (2024), advanced intelligent control frameworks were established to stabilize the DC bus voltage under dynamic loading conditions. The representative architecture consists of an islanded multi-source DC microgrid featuring a dual-voltage distribution topology. A low-voltage (450 V) DC link coordinates distributed generation and storage assets—including photovoltaic arrays, permanent magnet synchronous generator (PMSG) wind turbines, solid oxide fuel cells (SOFCs), water electrolyzers, and a battery energy storage system (BESS). A centralized boost converter interfaces this primary sub-network with a high-voltage (660 V) DC distribution bus dedicated to feeding non-linear electric vehicle fast-charging infrastructure.

To maintain stable DC bus voltages under rapid solar irradiance, drop ($1000 \text{ W/m}^2 \rightarrow 150 \text{ W/m}^2$) and step load variations ($10 \text{ kW} \rightarrow 13 \text{ kW}$), Senapati et al. (2024) developed a hybrid optimization algorithm combining soft-computing controllers with fractional-order calculus:

- **Hybrid Firefly Algorithm-Particle Swarm Optimization (FA-PSO):** The proposed metaheuristic framework autonomously optimizes the membership function geometries and corresponding operational gains for Adaptive Neuro-Fuzzy Inference Systems (ANFIS), Takagi–Sugeno Fuzzy Inference Systems (TSFIS), and Fractional-Order PID (FO-PID) controllers.
- **Fractional-Order PID (FO-PID) Formulation:** Introduces fractional integration (λ) and differentiation (μ) orders, providing additional degrees of freedom over conventional integer-order PID controllers:

$$C(s) = K_p + \frac{K_i}{s^\lambda} + K_d s^\mu$$

Small-Signal Stability Analysis (SSSA): State-space modelling of converter dynamics evaluates system eigenvalues under bus capacitance (C_d) uncertainty, proving that hybrid FA-PSO-tuned ANFIS-FO-PID controllers achieve faster settling times ($t_s < 2.5$ ms) and minimal peak-to-peak overshoot ($\Delta V_{dc} < 1.2\%$) compared to classical PI and fuzzy controllers (Senapati et al., 2024).

- **Advanced Non-Linear Approaches:** Backstepping Lyapunov-based adaptive schemes and Linear Quadratic Regulator (LQR) output-feedback mechanisms ensure robust bus-voltage stabilization under incomplete state observation, effectively counteracting parametric variations in battery internal resistance and point-of-connection grid impedance (Rachid et al., 2023).

3. Vehicle-to-Everything (V2X) Flexibility Services and Ancillary Grid Support

3.1. Taxonomies and Operational Mechanics of V2X

Vehicle-to-Everything (V2X) embodies an integrated operational paradigm wherein electric vehicles function as mobile, decentralized energy storage assets capable of bidirectional grid interaction and localized load balancing. (Acharige et al., 2023; Rachid et al., 2023; Tayri and Ma, 2025). As classified by Mastoi et al. (2022) and Zhao et al. (2025), energy stored in traction batteries can be discharged back to specific endpoints through bidirectional power electronics:

- **Vehicle-to-Grid (V2G):** Bidirectional power exchange between aggregated electric vehicle fleets and distribution or transmission system operators enables the provision of utility-scale ancillary services, notably primary frequency containment, spinning reserve allocation, and peak-demand shaving.

- **Vehicle-to-Building (V2B):** EVs discharge power directly to commercial facilities (offices, shopping malls, supermarkets) during peak demand hours, reducing commercial building demand charges and enhancing localized microgrid self-consumption.
- **Vehicle-to-Home (V2H):** Individual EV batteries supply residential household loads during peak electricity tariff periods or utility power outages, operating as an uninterruptible power supply (UPS).
- **Vehicle-to-Load (V2L):** Onboard inverter power delivery to off-grid electrical appliances, power tools, or emergency equipment (1.9 kW – 7.2 kW AC).
- **Vehicle-to-Vehicle (V2V):** Direct energy transfer from one EV to another to provide emergency roadside range extension.

3.2. Ancillary Grid Support Mechanisms

Through centralized or distributed fleet aggregation, bidirectional EV storage assets function as high-bandwidth balancing resources, providing distribution and transmission system operators with prompt, agile ramping flexibility (Tayri and Ma, 2025; Yuvaraj et al., 2024).

Primary and Secondary Frequency Regulation

EV batteries react almost instantaneously (≤ 100 ms) to grid frequency deviations, outperforming conventional thermal generators with long governor delay times.

- **Over-Frequency Events ($f > 50.0$ Hz/60.0 Hz):** The aggregator ramps up EV charging rates (G2V mode), absorbing excess generation and restoring grid frequency balance.
- **Under-Frequency Events ($f < 50.0$ Hz/60.0 Hz):** EV charging is throttled, or bidirectional discharging (V2G mode) is initiated, injecting active power back into the feeder. Advanced architectures implement adaptive droop control (P-f droop) directly at the charger controller level:

$$P_{inj} = P_{scheduled} - K_{droop}(f_{measured} - f_{nominal})$$

Voltage Support and Reactive Power Compensation

Bidirectional AC/DC converters can independently regulate active power (P) and reactive power (Q) using four-quadrant operation. In addition to active power

injection, EV chargers can absorb or supply reactive power (leading or lagging power factor) to regulate feeder voltage profiles, compensate for local line inductive losses, and prevent over-voltage conditions induced by high rooftop PV penetration without depleting the EV's state of charge (SoC) (Yuvaraj et al., 2024).

Peak Shaving and Spinning Reserves

By coordinating fleet charge schedules, aggregators flatten feeder load profiles through "valley filling" (charging during off-peak night hours) and "peak shaving" (discharging during evening peak hours). Aggregated EV fleets also serve as non-spinning and spinning reserves, providing immediate backup power capacity to cover sudden generator outages or renewable ramp loss.

3.3. Aggregator Market Mechanics and Dynamic Tariff Paradigms

Individual EVs cannot participate directly in wholesale electricity markets due to minimum capacity thresholds (typically 1 MW). EV aggregators function as specialized market intermediaries that pool hundreds or thousands of EVs into a single controllable energy resource (Tayri and Ma, 2025; Triviño-Cabrera et al., 2019).

Aggregators operate using bi-level optimization frameworks:

- **Upper-Level Problem:** The objective is to maximize aggregator profitability across multi-interval wholesale electricity markets—including day-ahead, hour-ahead, and real-time frequency regulation—while maintaining cost competitiveness against conventional generation companies (GENCOs).
- **Lower-Level Problem:** Minimizes charging costs for individual EV owners, respecting user-defined constraints including arrival time (t_{arr}), departure time (t_{dep}), minimum required departure state-of-charge (SoC_{req}), and battery degradation preferences.

To incentivize user participation, utilities implement dynamic pricing mechanisms:

- **Time-of-Use (TOU) Tariffs:** Static, pre-defined price blocks that encourage off-peak charging.
- **Real-Time Pricing (RTP):** Dynamic tariffs that mirror hourly wholesale market price fluctuations.
- **Distribution Locational Marginal Pricing (DLMP):** Spatially and temporally varying price signals that reflect localized feeder congestion, transformer voltage limits, and distribution losses. DLMP incentivizes EVs to charge in

regions with excess local PV generation and discharge in congested grid branches (Li and Jenn, 2024; Tayri and Ma, 2025).

4. Hydrogen Sector Coupling and Multi-Energy Integration

4.1. Co-Location of BEV Fast-Charging and FCEV Hydrogen Refueling Hubs

While Battery Electric Vehicles (BEVs) dominate light-duty passenger transport, Fuel Cell Electric Vehicles (FCEVs) offer compelling advantages for heavy-duty freight trucks, long-haul transit buses, and intensive commercial fleets due to rapid refuelling time (3 – 5 minutes) and high gravimetric energy density (Dimitriadou et al., 2023; Rachid et al., 2023; Zhao et al., 2025). Co-locating BEV fast-charging infrastructure with FCEV Hydrogen Refuelling Stations (HRS) establishes a multi-energy microgrid that links the electricity and gas sectors.

A co-located multi-energy hub incorporates:

- **On-Site Renewable Generation:** High-capacity solar PV arrays and Permanent Magnet Synchronous Generator (PMSG) wind turbines.
- **Water Electrolyzer Unit:** Polymer Electrolyte Membrane (PEM) or Alkaline electrolyzers (operating at efficiencies around 85%) that convert excess renewable electricity into green hydrogen.
- **High-Pressure Hydrogen Storage:** Multi-stage compression systems feeding dual-pressure buffer storage tanks operating at 350 bar (for heavy-duty trucks/busses) and 700 bar (for light-duty FCEVs).
- **Solid Oxide Fuel Cell (SOFC) / PEM Fuel Cell Systems:** Stored hydrogen is reconverted into zero-emission electricity to maintain critical microgrid operation during multi-day grid outages and extended periods of low renewable availability.
- **Battery Energy Storage System (BESS):** To prevent dynamic grid destabilization, high-power lithium-ion buffer architectures absorb sharp, second-to-second charging spikes, delivering localized surge suppression and mitigating transformer thermal stress at extreme fast-charging plazas.

4.2. Short-Term BESS vs. Long-Term Hydrogen Storage Dynamics

By coupling distinct storage media across localized timescales—ranging from millisecond transient buffers to long-duration chemical storage—multi-energy

microgrids achieve comprehensive operational flexibility and grid resilience. (Dimitriadou et al., 2023; Rachid et al., 2023; Senapati et al., 2024):

- **Short-Term Storage (BESS):** High round-trip efficiency (85% - 95%) and rapid response times (≤ 10 ms), but high capital cost per kWh and significant self-discharge/degradation over extended periods. BESS handles intra-day power smoothing, dynamic voltage stabilization, and transient peak-shaving during high-power EV plug-in events.
- **Long-Term / Seasonal Storage (Hydrogen Vector):** Lower electrical round-trip efficiency (40% - 50% Power-to-Gas-to-Power), but very low energy storage cost per kWh and zero self-discharge over months. Hydrogen acts as a flexible, controllable load sink: during periods of excess renewable generation or negative grid prices, excess power is diverted to electrolyzers rather than curtailed. Stored hydrogen provides seasonal energy security, supplies FCEV transport fuel, and powers fuel cells during severe winter grid shortages.

4.3. Operational Dispatch Strategies: Load Following vs. Cycle Charging

The economic performance of multi-energy charging hubs depends on the dispatch strategy implemented within the Energy Management System (EMS) (Dimitriadou et al., 2023; Rachid et al., 2023):

- **Load Following (LF) Strategy:** Under the load-following (LF) dispatch paradigm, primary generation assets (photovoltaics, wind, and the upstream utility) are prioritized to directly track dynamic electric vehicle charging loads. Complementary storage assets—specifically battery energy storage systems (BESS) and water electrolyzers—function reactively to clear residual power imbalances. Consequently, this control strategy curtails redundant conversion stages, minimizes running hours on electrochemical units (fuel cells and electrolyzers), and lowers leveled operational expenditures under time-varying electricity tariffs.
- **Cycle Charging (CC) Strategy:** Backup generation and fuel cell systems are triggered to operate at full rated capacity whenever activated. Excess power beyond immediate EV demand is directed to fully charge the BESS or produce hydrogen until storage setpoints are achieved. While CC maximizes generator operating efficiency, it increases fuel consumption and leads to higher operating costs in solar-rich microgrid applications.

Comparative field studies across regional microgrids by Rachid et al. (2023) demonstrate that LF strategies achieve superior techno-economic feasibility (e.g., achieving levelized energy costs as low as 0.0215kWh in solar-rich regions like Adana, Turkey) compared to CC strategies.

5. Electro-Thermal Battery Degradation and Techno-Economic Optimization

5.1. Mechanics of Battery Degradation in V2X Operations

While V2G operation provides substantial grid flexibility, repeated bidirectional micro-cycles accelerate irreversible capacity fade and internal resistance growth in vehicular lithium-ion batteries. (Tayri and Ma, 2025). Battery degradation proceeds through two primary mechanisms:

1. **Calendar Aging:** Capacity loss over time, independent of usage, driven by storage temperature, ambient thermal stress, and elevated State of Charge (SoC). Prolonged storage at 100% SoC accelerates solid electrolyte interphase (SEI) layer growth at the anode.
2. **Cycling Aging:** Mechanically driven degradation caused by lithium insertion/extraction during charge/discharge cycles. Cycling aging depends heavily on Depth of Discharge (DoD), C-rate (charging/discharging current magnitude), temperature variations, and cumulative Ah throughput.

Omitting non-linear battery degradation models from microgrid optimization frameworks results in an underestimation of real operational costs by approximately 30%. Accurate operational models must incorporate empirical or electro-thermal degradation cost functions (C_{deg}) into the real-time V2G bidding objective function (Tayri and Ma, 2025):

$$C_{deg}(t) = C_{bat_replace} \times \left(\frac{\Delta SoC(t) \cdot Cap_{bat}}{2 \cdot N_{cycle}(DoD) \cdot Cap_{bat} \cdot EoL} \right) \cdot f(T_{cell})$$

where $C_{bat_replace}$ is battery replacement cost, $N_{cycle}(DoD)$ is cycle life as a function of Depth of Discharge, EoL is end-of-life capacity threshold (typically 80% remaining capacity), and $f(T_{cell})$ accounts for thermal stress multipliers.

5.2. Mathematical Formulation of Multi-Objective Microgrid Optimization

The design and operation of multi-energy EV charging microgrids represent complex multi-objective, non-linear optimization problems balancing economic, technical, and environmental objectives (Çelik and Ok, 2024; Dimitriadou et al., 2023; Rachid et al., 2023; Singh et al., 2024a).

Primary Objective Functions

1. Minimization of Total Net Present Cost (TNPC):

$$\min \text{TNPC} = C_{\text{capital}} + C_{\text{O\&M}} + C_{\text{replacement}} + C_{\text{grid_purchase}} - S_{\text{salvage}}$$

2. Minimization of Levelized Cost of Energy (LCOE):

$$\min \text{LCOE} = \frac{\sum_{t=0}^N \frac{C_{\text{cap},t} + C_{\text{O\&M},t} + C_{\text{fuel},t}}{(1+r)^t}}{\sum_{t=0}^N \frac{E_{\text{EV_served},t}}{(1+r)^t}}$$

3. Minimization of Loss of Power Supply Probability (LPSP):

$$\min \text{LPSP} = \frac{\sum_{t=1}^{8760} \max(0, P_{\text{load}}(t) - (P_{\text{PV}}(t) + P_{\text{WT}}(t) + P_{\text{BESS_dis}}(t) + P_{\text{grid_max}}(t)))}{\sum_{t=1}^{8760} P_{\text{load}}(t)}$$

4. Minimization of Carbon Emissions and Grid Losses: Co-optimizes active power losses ($\sum I^2 R$) across distribution feeder branches and greenhouse gas emissions (kg CO₂/kWh) associated with grid energy purchases (Kumar et al., 2024; Singh et al., 2024a).

5.3. Optimization Paradigms, Metaheuristics, and Software Tools

Solving multi-energy microgrid dispatch and sizing problems requires robust computational optimization tools (Kumar et al., 2024; Rachid et al., 2023; Senapati et al., 2024; Wang et al., 2022):

- **Metaheuristic Algorithms:** Multi-objective metaheuristic frameworks—notably the Multi-Objective Remora Optimization Algorithm (MOROA), Multi-Objective Particle Swarm Optimization (MOPSO), Non-dominated Sorting Genetic Algorithms (NSGA-II and NSGA-III), and Hybrid Genetic Algorithm–Simulated Annealing (GA-SAA)—are widely employed to generate Pareto-optimal fronts that resolve trade-offs among total lifecycle expenditure, power system reliability metrics, and operational carbon emissions (Kumar et al., 2024).
- **Techno-Economic Software Tools:** Techno-economic simulation platforms, most notably HOMER Pro and HOMER Grid, are extensively utilized to assess lifecycle economic feasibility, optimize component capacities, and execute multi-variable tariff sensitivity analyses across heterogeneous multi-energy microgrid architectures. (Dimitriadou et al., 2023; Rachid et al., 2023).

Optimization Method / Tool	Core Capabilities	Primary Strengths	Limitations
HOMER Pro / HOMER Grid	Lifecycle simulation, component sizing, sensitivity analysis, TOU tariff modelling.	High commercial maturity; rapid evaluation of LCOE, TNPC, and renewable fraction.	Limited short-term dynamic stability modeling (≤ 1 second transient limits omitted).
NSGA-II / NSGA-III	Multi-objective genetic algorithms for complex non-convex Pareto optimization.	Effectively resolves non-continuous objective landscapes and discrete component sizing constraints.	Computationally intensive; sensitive to crossover/mutation parameter selection.
MOPSO / MOROA	Swarm-intelligence metaheuristics for rapid convergence on multi-dimensional fronts.	High convergence speed; effective for dynamic power dispatch and daily EMS scheduling.	Susceptible to premature convergence in highly constrained topological search spaces.
Mixed-Integer Non-Linear Programming (MINLP)	Exact mathematical programming formulations for centralized deterministic dispatch.	Ensures global optimality when microgrid power and energy balance formulations are convexified.	Requires linearization approximations; struggles with stochastic solar/wind uncertainties.

6. Open Challenges, Regulatory Frameworks, and Future Research Directions

While rapid progress has accelerated the development of multi-energy EV microgrids, widespread commercial adoption is substantially hindered by persistent challenges spanning system-level integration, high capital expenditure, and fragmented policy frameworks.

6.1. High-Frequency Power Electronic Stability and Harmonics

The aggregation of multiple high-frequency switching converters (AC/DC rectifiers, DAB converters, solar inverters) connected to a common bus introduces complex

harmonic resonance and cross-talk interactions (Acharige et al., 2023; Rachid et al., 2023). Non-linear EV loads induce low-order current harmonics (5th, 7th, 11th) that propagate upstream into low-voltage distribution transformers. Future research must focus on adaptive active power filters (APFs), broad-bandwidth LCL filter optimization, and advanced active damping control algorithms to ensure strict compliance with IEEE 519 harmonic standards under dynamic charging loads.

6.2. Low-Inertia Grid Dynamics and Virtual Synchronous Generators (VSG)

As microgrids transition toward 100% inverter-based resource (IBR) penetration dominated by solar photovoltaics and DC fast chargers, the intrinsic physical rotational inertia (H) asymptotically approaches zero. Consequently, sudden megawatt-scale EV connection transients or rapid solar irradiance intermittency induce steep rate-of-change-of-frequency (RoCoF) excursions, heightening the risk of localized voltage collapse and nuisance protective relay tripping. Embedding Virtual Synchronous Generator (VSG) algorithms within bidirectional EV charging interfaces—thereby emulating the rotor swing dynamics and damping characteristics of conventional synchronous machines via grid-forming control—has emerged as a critical paradigm for reinforcing microgrid frequency stability (Senapati et al., 2024; Zhao et al., 2025).

6.3. Cybersecurity, Privacy, and False Data Injection Attacks

Smart EV charging infrastructure relies heavily on bi-directional communication channels (e.g., Open Charge Point Protocol [OCPP], ISO 15118, and Modbus) linking EVs, charging stations, aggregators, and DSOs. This high digital connectivity introduces vulnerability to cyber-physical threats, including False Data Injection (FDI) attacks, Denial of Service (DoS), and man-in-the-middle manipulation of pricing signals. Malicious manipulation of EV fleet charge/discharge commands can intentionally destabilize feeder voltage profiles or trigger wide-scale blackout events. Developing communication-efficient Federated Learning frameworks, blockchain-enabled peer-to-peer (P2P) energy trading architectures, and intrusion detection systems is essential to protect user location privacy and grid integrity (Ghanbari Motlagh and Li, 2026; Rashid et al., 2024; Tayri and Ma, 2025).

6.4. Battery Degradation Compensation and Standardized Business Models

V2G commercialization is constrained by a fundamental misalignment: aggregators monetize wholesale market flexibility, while EV owners bear uncompensated battery degradation. Establishing dynamic Distribution Locational Marginal Pricing (DLMP) that integrates real-time electro-thermal aging costs—supported by structured

multi-party revenue-sharing contracts—is critical to driving broad consumer adoption of bidirectional charging. (Li and Jenn, 2024; Tayri and Ma, 2025).

6.5. Cross-Sector Regulatory Policies and Interoperability

Fragmented policy governance across the power, transport, and gas domains severely stifles multi-energy microgrid scalability. Power-to-gas electrolyzers remain burdened by standard industrial utility tariffs, preventing microgrids from monetizing low-cost surplus renewable generation. Concurrently, protocol discrepancies among SAE J2847, ISO 15118-20, and CHAdeMO continue to create severe vendor lock-in and hardware incompatibility. Synthesizing cross-sector regulatory incentives, streamlining grid-tie interconnection frameworks, and mandating universal bidirectional communication standards represent indispensable steps toward operationalizing multi-energy charging ecosystems. (Acharige et al., 2023; Mastoi et al., 2022; Yousuf et al., 2024; Zhao et al., 2025).

7. Conclusion

This systematic review establishes a comprehensive taxonomy and critical comparative assessment of multi-energy electric vehicle charging microgrids. Through a rigorous synthesis of 1,482 identified records refined under the PRISMA framework, the findings demonstrate that re-architecting EV charging infrastructure from passive demand sinks into dispatchable, multi-energy prosumer nodes constitute an indispensable pathway toward grid-level decarbonization and distribution network resilience. Key insights established in this survey include:

1. **Architectural Optimization:** Common DC bus and hybrid AC/DC bus microgrid architectures achieve superior round-trip conversion efficiency (88% - 96%) compared to traditional common AC bus networks, provided that CPL negative incremental impedance instabilities are mitigated using FA-PSO-tuned ANFIS and fractional-order (FO-PID) controllers.
2. **V2X Flexibility Services:** Bidirectional V2G, V2B, and V2H operations provide fast-acting frequency regulation (<100ms) and reactive power compensation. However, commercial viability requires bi-level aggregator market formulations and DLMP dynamic pricing that compensate vehicle owners for cycling-induced battery capacity fade.
3. **Hydrogen Sector Coupling:** Co-locating BEV DC fast-charging with FCEV hydrogen refuelling hubs creates a symbiotic multi-energy ecosystem where

water electrolyzers absorb excess renewable power, hydrogen tanks provide seasonal zero-self-discharge storage, and fuel cells guarantee multi-day grid resilience.

4. **Research Frontiers:** Addressing remaining open challenges requires urgent research into Virtual Synchronous Generator (VSG) grid-forming controls for low-inertia microgrids, privacy-preserving federated learning architectures against FDI cyber-attacks, and harmonized cross-sector regulatory tariffs.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

No new primary empirical dataset was created during this systematic literature review. All data analysed were extracted from published scientific literature cited within the manuscript.

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