

Review

New Energy Vehicles and Charging and Battery-Swapping Infrastructure: Development Patterns, Policy Drivers, and the Evolution of Vehicle–Grid Interaction

Bo Zhao ¹, Zhihang Ren ¹, Zhibin Liu ^{1,*}, Peng Yang ¹, Zhiheng Liu ¹, Changpeng Hu ¹, Nahan Hao ¹, Xiaoyin Ding ² and Lei Li ³

¹ College of Electronic and Information Engineering, Hebei University, Baoding 071002, China

² Quzhou Power Supply Company, State Grid Zhejiang Electric Power Co., Ltd., Quzhou 324000, China

³ Marketing Service Center of State Grid Tianjin Electric Power Company, Hexi District, Tianjin 300221, China

* Correspondence: liuzhibin@hbu.edu.cn

Abstract

The rapid expansion of electric mobility is reshaping both transport infrastructure and power-system operation. This narrative and critical review examines the connected evolution of new energy vehicle (NEV) markets, charging and battery-swapping infrastructure, policy mechanisms, and vehicle-to-grid (V2G) systems. In this paper, NEV includes battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and fuel-cell electric vehicles (FCEVs); conventional non-plug-in hybrid electric vehicles are discussed only where regional statistics require clarification. Peer-reviewed studies, official statistics, policy documents, market reports, and technical standards available through June 2026 are synthesized thematically and compared across China, Europe, the United States, and selected emerging markets. The review distinguishes verified 2025 observations from scenario-based projections, evaluates policy instruments by their outcomes and limitations, and extends the V2G discussion to bidirectional charger requirements, interoperability, aggregation, DSO-TSO coordination, battery degradation, cybersecurity, and economic viability. Unlike reviews centered on a single technology or region, the proposed market–infrastructure–policy–V2G framework explains how market structure, infrastructure governance, standards, and electricity-market design jointly shape commercialization pathways. The synthesis indicates that infrastructure scale alone is insufficient: utilization, grid hosting capacity, interoperable communication, credible revenue stacking, and equitable access determine whether charging, battery swapping, and V2G can deliver system-level value.

Keywords: new energy vehicles; charging and battery-swapping infrastructure; development patterns; vehicle–grid interaction (V2G); policy drivers and mechanisms



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1. Introduction

The decarbonization of road transport has become a central component of global energy-transition strategies [1–3]. Electric mobility can reduce direct petroleum use and tailpipe emissions, but its system-level benefits depend on the electricity mix, battery supply chain, charging behavior, and the capacity of local distribution networks. Accordingly, vehicle deployment and charging infrastructure should be assessed as a coupled transport-energy system rather than as independent markets.

Existing reviews provide substantial knowledge on charging-station planning, battery swapping, grid impacts, V2G control, or policy design, but these themes are often treated

separately. This fragmentation makes it difficult to explain why similar technical solutions produce different outcomes across regions, or why rapid infrastructure expansion does not necessarily lead to high utilization, interoperability, or commercial V2G participation. A critical review is therefore needed to connect market scale, infrastructure configuration, policy implementation, technical readiness, and business-model viability.

The review addresses four questions: (1) how did actual 2025 market and charging developments differ across major regions; (2) which structural factors explain divergent charging and battery-swapping models; (3) how do policy instruments translate into measurable outcomes and unintended limitations; (4) which technical and economic conditions are necessary for scalable V2G. The resulting contribution is an integrated market–infrastructure–policy–V2G analytical chain, a cross-regional comparison of development logics, and an outcome-oriented agenda for research and policy.

1.1. Terminology and Scope Definitions

For consistency, this review uses NEV as an umbrella term for BEVs, PHEVs, and FCEVs. Conventional hybrid electric vehicles without external charging capability are excluded from the main quantitative comparisons, except where national statistics or regional transition pathways explicitly group them with NEVs. V2G refers specifically to controlled bidirectional electricity exchange between an EV and the grid; unidirectional managed charging is denoted V1G. The key terminology and scope definitions adopted throughout this review are summarized in Table 1.

Table 1. Nomenclature and scope definitions used in this review.

Abbreviation	Definition	Scope Note
NEV	New energy vehicle	BEV, PHEV, and FCEV in this review
EV	Electric vehicle	Generic term; the included powertrain is stated where data definitions differ
BEV	Battery electric vehicle	Externally charged and propelled only by an electric drivetrain
PHEV	Plug-in hybrid electric vehicle	Externally chargeable vehicle with electric and combustion propulsion
FCEV	Fuel-cell electric vehicle	Electric drivetrain supplied primarily by a fuel-cell system
HEV	Hybrid electric vehicle	Non-plug-in hybrid; excluded from main NEV comparisons unless explicitly noted
EVSE	Electric vehicle supply equipment	Charging equipment and associated control/protection interfaces
DCFC/HPC	DC fast charging/high-power charging	Public or fleet charging with direct-current power conversion
V1G	Managed unidirectional charging	Charging power is scheduled but electricity does not flow back to the grid
V2G	Vehicle-to-grid	Controlled bidirectional electricity exchange between EVs and the power system
V2H/V2B	Vehicle-to-home/vehicle-to-building	Behind-the-meter bidirectional energy services
VPP	Virtual power plant	Digital aggregation of distributed resources for coordinated operation or markets
BaaS	Battery-as-a-Service	Battery leasing or vehicle–battery separation business model
DSO	Distribution system operator	Operates the local distribution network and manages hosting constraints
TSO	Transmission system operator	Operates the bulk power system and system-level balancing services

1.2. Positioning and Novelty Compared with Recent Reviews

Recent reviews have made important contributions, but most are organized around a specific layer of the electric-mobility system. Mastoi et al. [4] provide a broad assessment of charging-station infrastructure and policy implications, whereas Ghanbari Motlagh et al. [5] concentrate on charging-station operation under market dynamics and grid interaction. Anggraini et al. [6] examine charging business models under grid constraints, mainly from

the perspective of European electricity markets. Kumbhar and Kalkhambkar [7] focus on the coordinated planning and operation of charging and battery-swapping stations. At the grid-interaction level, Kumar et al. [8] map the evolution of V2G research through a large-scale bibliometric review, while Tayri and Ma [9] synthesize distribution-grid impacts and technical mitigation strategies.

These studies provide valuable depth within their respective domains; however, the relationships among global NEV market development, charging and battery-swapping deployment modes, policy instruments and their implementation outcomes, and the commercial evolution of V2G remain fragmented. To address this gap, the present review adopts a unified comparative framework that follows the full causal and developmental chain of market growth → infrastructure configuration → policy-driven coordination → V2G technology and business-model evolution → energy-system impacts. The overall structure and analytical framework of this review are illustrated in Figure 1. Table 2 summarizes the distinction between representative recent reviews and the present study.

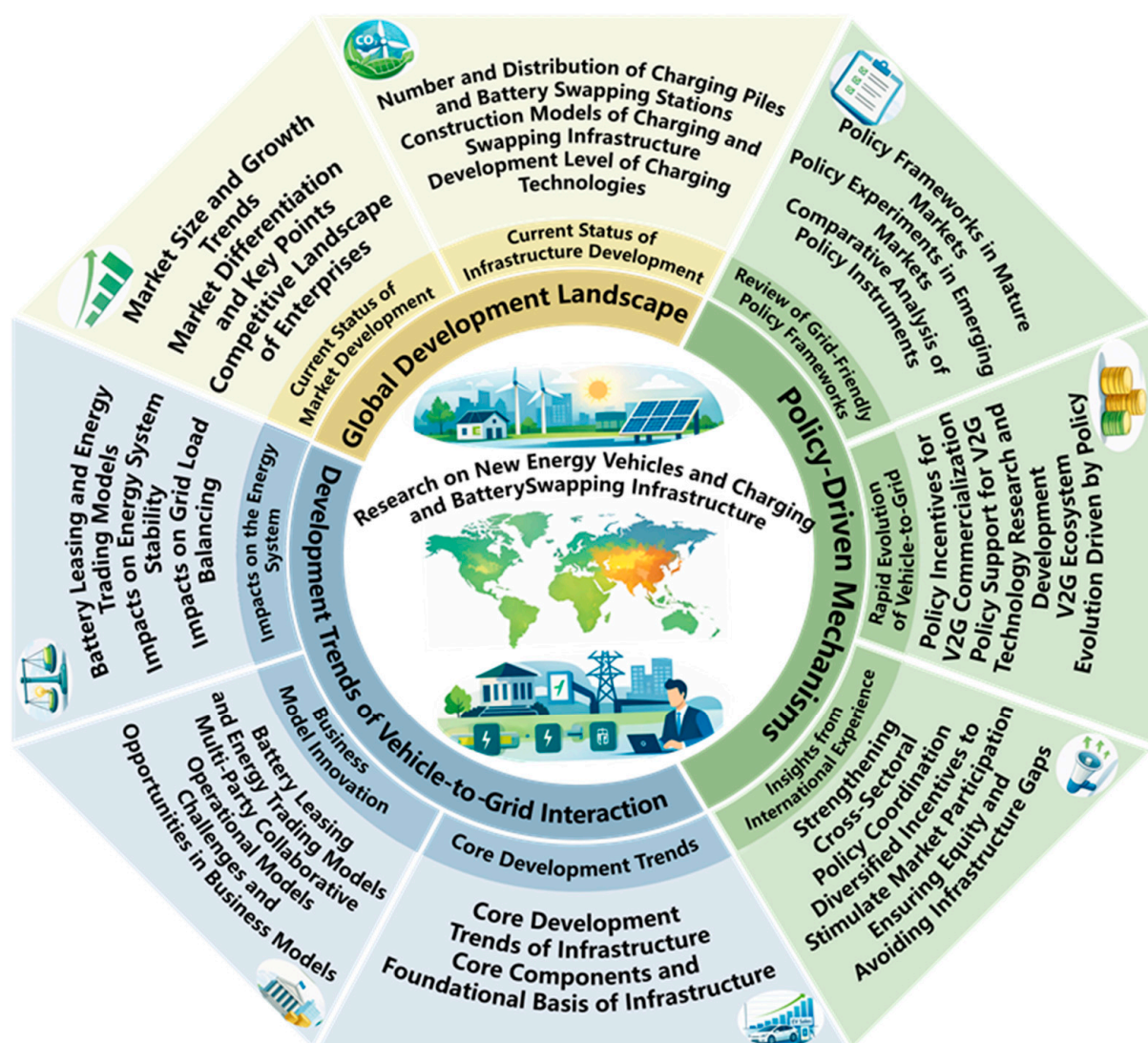


Figure 1. Structure of the review. Source: Authors' synthesis.

Table 2. Comparison of this review with representative recent review studies.

Study	Primary Focus	Analytical Scope	Main Distinction/Gap Relative to This Review
Mastoi et al. [4]	Charging infrastructure, policies, and future trends	Broad infrastructure review; charging centered	Does not jointly trace battery swapping, policy outcomes, and V2G commercialization
Ghanbari Motlagh et al. [5]	Charging-station operation, pricing, scheduling, and grid interaction	Operational and market-oriented	Limited treatment of global market evolution, battery swapping, and cross-regional policy comparison
Anggraini et al. [6]	Charging business models under grid limitations	European electricity-market perspective	Region- and business-model-specific; does not integrate swapping infrastructure or global policy pathways
Kumbhar and Kalkhambkar [7]	Coordination of charging and battery-swapping stations	Planning, operation, ownership, and grid integration	Limited analysis of policy implementation effectiveness and the wider V2G ecosystem
Kumar et al. [8]	Bibliometric evolution of V2G research	Global research trends and collaboration networks	Maps the knowledge landscape rather than linking infrastructure deployment to policy and commercialization
Tayri and Ma [9]	Distribution-grid impacts of EV charging and mitigation	Technical grid-performance perspective	Limited coverage of battery swapping, policy mechanisms, and market/business-model evolution
Present review	NEV market, charging and battery swapping, policy drivers, V2G infrastructure, and business models	Global, cross-regional, and multidimensional	Integrates market–infrastructure–policy–V2G evolution and converts the synthesis into a multidimensional policy evaluation and differentiated recommendations

2. Global Development Landscape of New Energy Vehicles and Charging and Battery-Swapping Infrastructure

This section uses verified 2025 observations to compare market growth and infrastructure deployment, then interprets the structural factors behind regional differences. Market size is considered together with charging density, dwelling and parking conditions, grid governance, industrial structure, and policy continuity. This avoids treating sales or charger counts as stand-alone measures of transition quality. The analytical framework for evaluating the global development landscape of new energy vehicles and charging and battery-swapping infrastructure is illustrated in Figure 2.

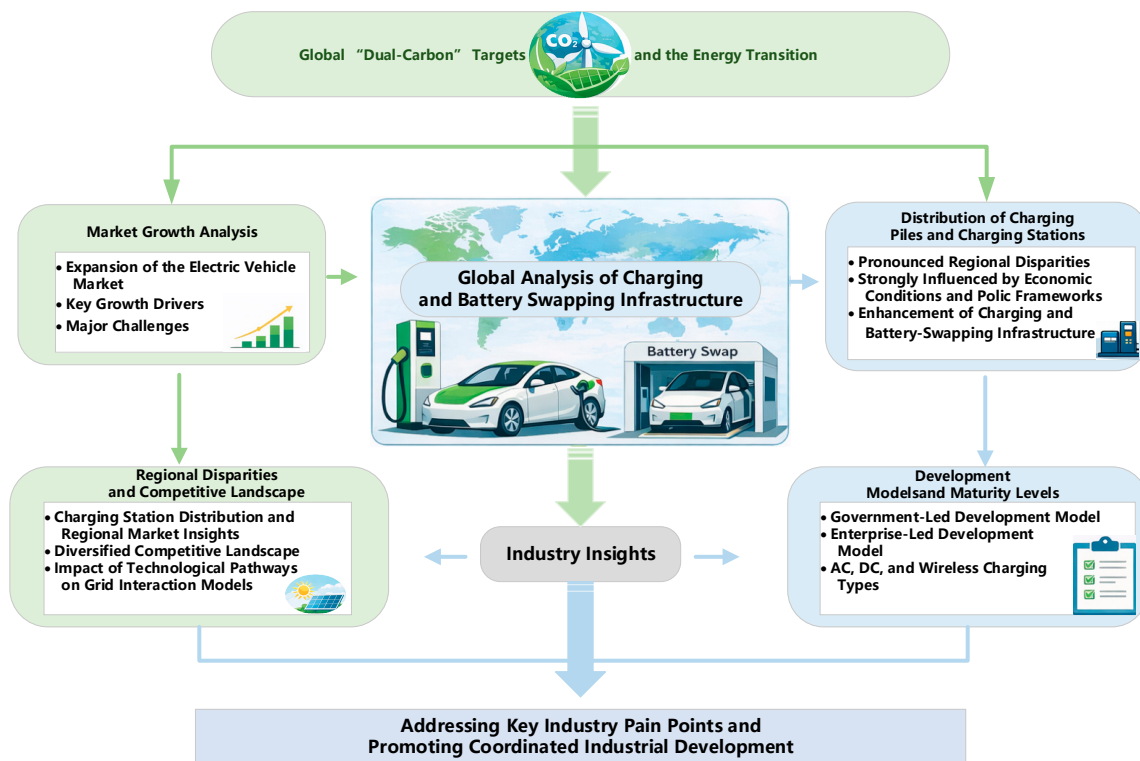


Figure 2. Analytical framework for global charging and battery-swapping infrastructure. Source: Authors’ synthesis.

2.1. Current Status of the New Energy Vehicle Market

2.1.1. Global Market Scale and Growth

Global electric car sales reached approximately 21 million in 2025, more than 20% above 2024, and represented about one-quarter of new car sales worldwide [10]. These are observed full-year data, not forecasts. The IEA series used for Figure 3 defines electric cars as BEVs and PHEVs; FCEVs remain within this review’s broader NEV definition but are not included in that particular time series. The growth rate moderated relative to the early post-pandemic expansion, indicating a transition from an initial scale-up phase to more differentiated regional competition.

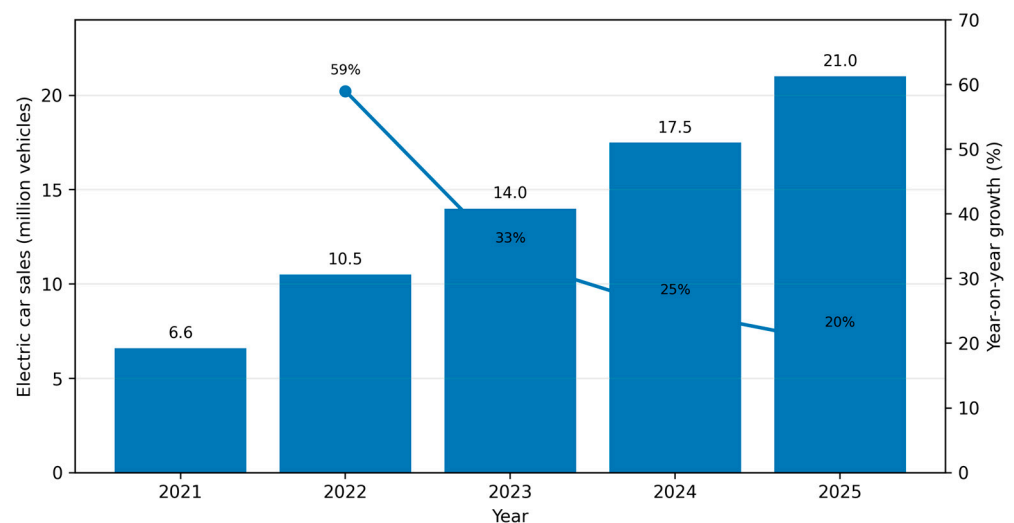


Figure 3. Global electric-car sales and year-on-year growth, 2021–2025. Source: Authors’ original visualization based on data from the IEA Global EV Outlook 2026 [10].

Technology learning, wider model availability, falling battery costs, and policy support remain important growth drivers. However, their effects are conditional. Purchase incentives can accelerate adoption but may create demand discontinuities when withdrawn; high-power charging improves convenience but can increase connection costs and local peak demand; and lower vehicle prices do not eliminate barriers related to home parking, public charging reliability, or consumer confidence [11]. The relevant policy question is therefore not only how to increase sales, but how to align adoption with infrastructure utilization and grid readiness. The representative national policy instruments, together with their implementation features and potential limitations, are summarized in Table 3.

Table 3. Representative NEV policy instruments and implementation features. Source: Authors' compilation and synthesis based on Refs. [10,12].

Country/Region	Representative National Policy Instruments	Implementation Features and Cautions
China	Purchase-tax support continues through 2027, with a lower benefit ceiling from 2026; trade-in incentives support vehicle replacement.	Local license, parking, electricity-tariff, and infrastructure measures vary. The policy focus is shifting from rapid installation toward reliability, utilization, and grid coordination.
United States	Federal vehicle incentives changed substantially in 2025; state purchase, utility, and infrastructure programs remain heterogeneous.	HOV access, registration fees, tariffs, and grants differ by state. Policy volatility can weaken alignment between vehicle demand and long-lived charging investment.
Germany	Company-car tax treatment, vehicle incentives, and charging-infrastructure support are used within the EU regulatory framework.	Municipal access and parking benefits vary. AFIR supports corridor deployment, while grid-connection lead times remain important.
United Kingdom	The zero-emission vehicle mandate and a 2025 grant for eligible lower-priced BEVs support market development.	Congestion, parking, and charging benefits are partly local. Implementation depends on private investment and distribution-network connections.
Norway	Long-standing BEV tax advantages are being gradually narrowed as the market matures.	Road toll, ferry, parking, and lane benefits vary by locality; the policy challenge is maintaining adoption while reducing fiscal cost.

The growing environmental consciousness among consumers is equally noteworthy. As global attention to climate change and pollution intensifies, an increasing number of people are opting for eco-friendly and low-carbon transportation options. NEVs perfectly meet this demand, as consumers hope to contribute to reducing carbon emissions and improving environmental quality through their purchases [13,14].

2.1.2. Regional Market Differences and Structural Drivers

Electric car adoption in 2025 remained highly uneven across regions, reflecting differences in policy stringency, vehicle prices, domestic manufacturing, housing and parking patterns, and charging availability [10]. The comparative characteristics of major regional NEV markets are summarized in Figure 4.

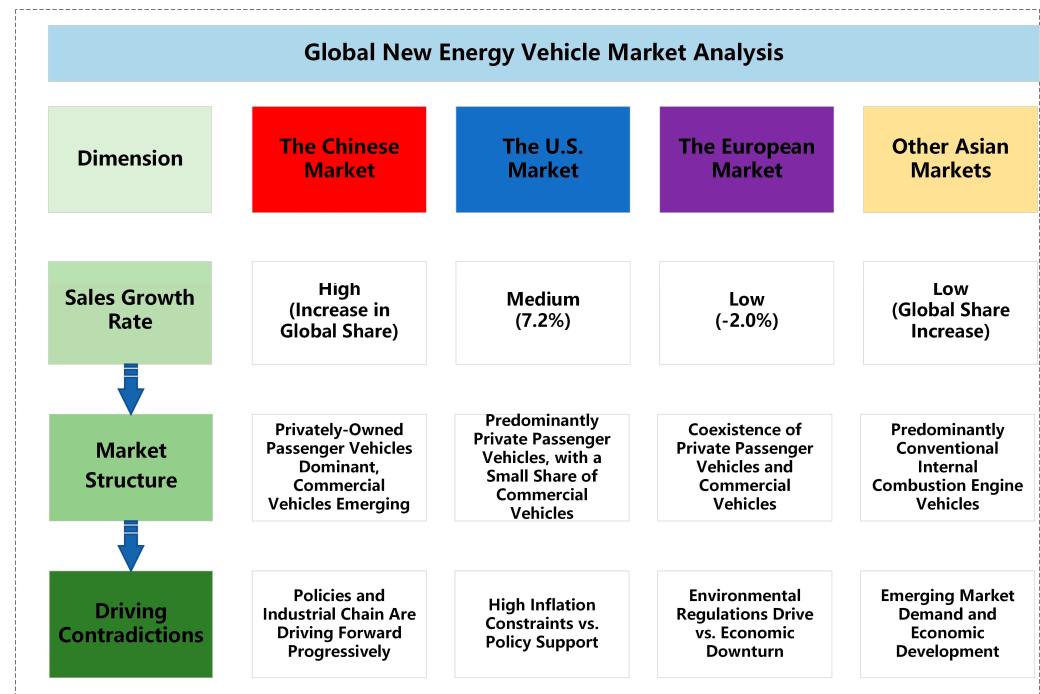


Figure 4. Analytical overview of the global NEV market. Source: Authors' synthesis based on the cited market evidence.

China sold more than 13 million electric cars in 2025, accounting for approximately six in ten global electric-car sales, while the electric share of new car sales approached 55% [10]. This scale was supported by a mature battery and vehicle supply chain, intense price competition, trade-in incentives, and rapid public-charging deployment. The same scale creates second-order challenges: local distribution capacity, uneven charger utilization, and interoperability between vehicle, charging, swapping, and grid platforms.

Europe recorded about 4.2 million electric-car sales in 2025, equivalent to 28% of new car sales, following tighter CO₂ standards and renewed growth in major national markets. By contrast, US electric-car sales were approximately 1.5 million and the sales share was around 10%; policy changes late in 2025 increased uncertainty despite continued infrastructure investment [10]. These contrasting outcomes show that regulatory credibility and model availability can be as influential as headline subsidy levels.

Outside China, Europe, and the United States, electric-car sales reached approximately 2 million in 2025. Southeast Asia exceeded half a million sales and approached a one-fifth sales share, while India reached about 165,000 sales and a share near 4%. Japan remained below 3% for plug-in electric cars, although conventional hybrids represented a much larger share [10]. Rapid growth in later-entry markets is associated with lower-cost imports and local manufacturing incentives, but charging finance, grid reliability, and standards remain binding constraints.

The comparison indicates that adoption is shaped by a system of mutually reinforcing conditions rather than a single policy lever. China combines industrial scale and coordinated infrastructure; Europe relies more heavily on regulation and interoperability;

the United States reflects decentralized federal-state governance; and emerging markets balance affordability and industrial policy against infrastructure and financing gaps. To highlight the regional disparities in electric-car adoption, Figure 5 compares the shares of electric cars in new car sales across selected markets in 2025.

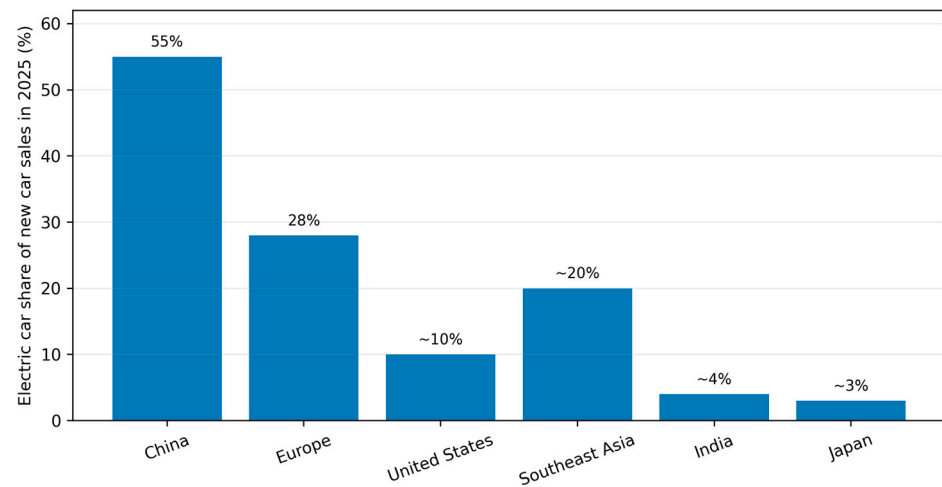


Figure 5. Electric car share of new car sales in selected markets in 2025. Source: Authors' original visualization based on data from the IEA Global EV Outlook 2026 [10].

2.1.3. Competitive Landscape of Major Enterprises

Enterprise competition is relevant to this review only where it changes infrastructure architecture or grid interaction. Automakers influence connector ecosystems, charging network access, battery-pack standardization, software control, and the availability of bi-directional functions. Proprietary integration can improve user experience and deployment speed, but it may also increase switching costs and reduce cross-brand interoperability [15].

The grid effect of an automaker's strategy depends less on brand market share than on the spatial concentration, rated power, and control capability of the associated charging network. Unmanaged high-power clusters can create local capacity constraints, whereas managed charging, storage-assisted stations, and interoperable V2G interfaces can convert part of the same load into a flexible resource [16,17].

Accordingly, corporate comparisons should emphasize open access, standards compliance, battery and thermal-management capability, and participation in grid services rather than product positioning alone. Table 4 provides an illustrative infrastructure-focused comparison; it is not intended as a ranking of manufacturers.

Table 4. Illustrative comparison of manufacturer strategies relevant to charging infrastructure and V2G.

Infrastructure-Relevant Dimension	Tesla	BYD	Volkswagen Group
Energy-replenishment strategy	Large proprietary fast-charging network with increasing third-party access in some markets	Combination of conductive charging, high-power platforms, and selected battery/energy-service partnerships	Multi-brand charging partnerships and standards-based public-network access
Vehicle/battery integration	Tightly integrated vehicle, software, and charging ecosystem	Vertically integrated battery and vehicle manufacturing; broad vehicle portfolio	Modular vehicle platforms across multiple brands and regions
V2G/interoperability implication	Strong software integration, but functions and market availability vary by vehicle and region	Potential scale advantages; cross-brand and grid-service interoperability require verification	Standards alignment supports multi-brand deployment; implementation varies by platform and market

2.2. Current Status of Charging and Battery-Swapping Infrastructure Development

2.2.1. Global Deployment and Spatial Distribution of Public Charging Points and Battery-Swapping Stations

Public charging expanded rapidly in 2025, but the distribution remained concentrated. China increased its public charging stock from about 3.4 million points at the end of 2024 to more than 4.7 million at the end of 2025, representing over 65% of the global stock and more than three-quarters of annual additions [18]. Approximately ten electric light-duty vehicles were served per public charging point, although this national ratio masks substantial differences in utilization and location.

Europe's public charging stock grew by roughly 20% in 2025. The Netherlands, Germany, and France had approximately 210,000, 196,000, and 185,000 public points, respectively, while the United Kingdom reached about 116,000 [19]. Binding corridor requirements and national incentives supported expansion, but grid-connection queues, permitting, and unequal coverage continue to constrain rated power and accessibility.

The United States had approximately 70,000 fast and ultra-fast public points and more than 160,000 slower public points at the end of 2025 [19]. Its public charging stock represented only about 3% of the global total despite a larger share of the electric-vehicle fleet. Interstate and metropolitan deployment improved, but state-level policy differences, rural coverage, and reliability remain important sources of spatial inequality.

These observations show why charger counts must be interpreted together with power rating, uptime, utilization, access, and local grid capacity. A region can simultaneously exhibit rapid infrastructure growth and persistent service gaps. Figure 6 therefore reports traceable end-2025 public-point counts rather than an unsupported global-share estimate.

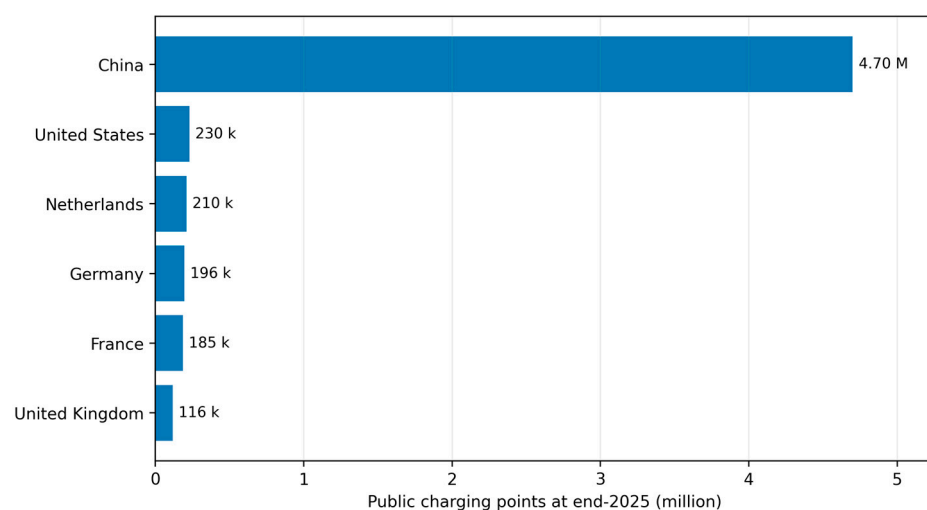


Figure 6. Public charging points in selected markets at the end of 2025. Source: Authors' original visualization based on data from the IEA Global EV Outlook 2026 [18].

2.2.2. Construction Models of Charging and Battery-Swapping Infrastructure

At present, global charging and battery-swapping infrastructure development primarily follows multiple models, including government-led, enterprise-led, and private capital participation. In the government-led model, public authorities played a dominant role in planning, investment, and construction, coordinating infrastructure deployment through policy regulations, financial subsidies, and land support to ensure public service needs and guide the development of the NEV industry [19]. This model was commonly applied in public transportation sectors, such as buses and taxis. For example, in Beijing, government investment in dedicated bus charging stations effectively supported the electrification of the urban bus fleet.

From the perspective of policy outcomes, the government-led model facilitated comprehensive planning and rapid deployment of infrastructure, allowing priority coverage of public services and strategic regions. Its limitations, however, included substantial fiscal burdens and relatively constrained operational efficiency and technological innovation incentives. Therefore, this model is particularly suitable for large-scale charging and battery-swapping infrastructure projects in public transportation systems, power grid coordination scenarios, or those requiring unified planning [20]. The comparative characteristics, advantages, limitations, and applicable scenarios of the three construction models are summarized in Table 5.

Table 5. Comparative characteristics of charging and battery-swapping infrastructure construction models.

Construction Model	Key Participants	Typical Cases	Advantages	Disadvantages	Applicable Scenarios
Government-Led	Government	Dedicated bus charging stations in Beijing	1. Rational macro-level planning, ensuring public demand is met 2. Faster construction speed	1. High fiscal burden on the government 2. Lower operational efficiency	Public sectors such as buses and taxis, rural or low-revenue areas
Enterprise-Led	Vehicle manufacturers, energy companies, and charging/swapping service operators	Tesla Supercharger network	1. Precisely matches market demand 2. Rapid technological innovation	1. Limited coverage in remote areas 2. Potential formation of technological barriers	Urban core areas, highway service areas
Private Capital Participation	Financial institutions, real estate developers, commercial enterprises, and charging service operators	Charging stations in Chinese commercial complexes	1. Broad sources of funding 2. Cross-industry integration and innovation	1. Lack of unified standards 2. Challenges in coordinating interests among stakeholders	Commercial areas, residential neighborhoods, office buildings

In the enterprise-led model, vehicle manufacturers, energy companies, or specialized charging and swapping operators led infrastructure investment and construction based on their market strategies. Tesla's Supercharger network served as a typical example, in which high-power charging stations were independently planned and constructed to enhance user experience and strengthen vehicle sales competitiveness [21]. The advantages of the enterprise-led model included a close alignment between deployment decisions and market demand, high operational efficiency, and the capacity for ongoing technological innovation and service optimization. However, investments were primarily profit-driven, potentially resulting in insufficient infrastructure provision in remote areas or regions with low short-term returns. Consequently, this model was more suitable for application scenarios with clear market demand and enterprises possessing strong capital resources and strategic planning capabilities [22].

In the private capital participation model, multiple stakeholders-including financial institutions, real estate developers, and commercial enterprises-were involved in the construction of charging and battery-swapping infrastructure. Common implementations included deploying charging facilities in parking areas through collaborations between commercial complexes and operators. This model expanded financing channels, improved construction efficiency, and promoted cross-industry collaborative innovation. However, the participation of multiple stakeholders increased coordination costs and often resulted in non-uniform construction standards and more complex operational management. It was therefore more suitable for areas with stable customer flows and commercial value, such as business districts and residential communities [23].

Overall, different infrastructure development models exhibited distinct advantages and limitations in terms of efficiency, equity, and sustainability. Most countries and regions adopted parallel or combined strategies tailored to regional conditions and stages of development, in order to achieve efficient deployment and long-term operation of charging and battery-swapping infrastructure [24]. To further illustrate the interaction mechanisms and evolution pathways among different infrastructure construction models, Figure 7 presents the conceptual framework developed in this review.

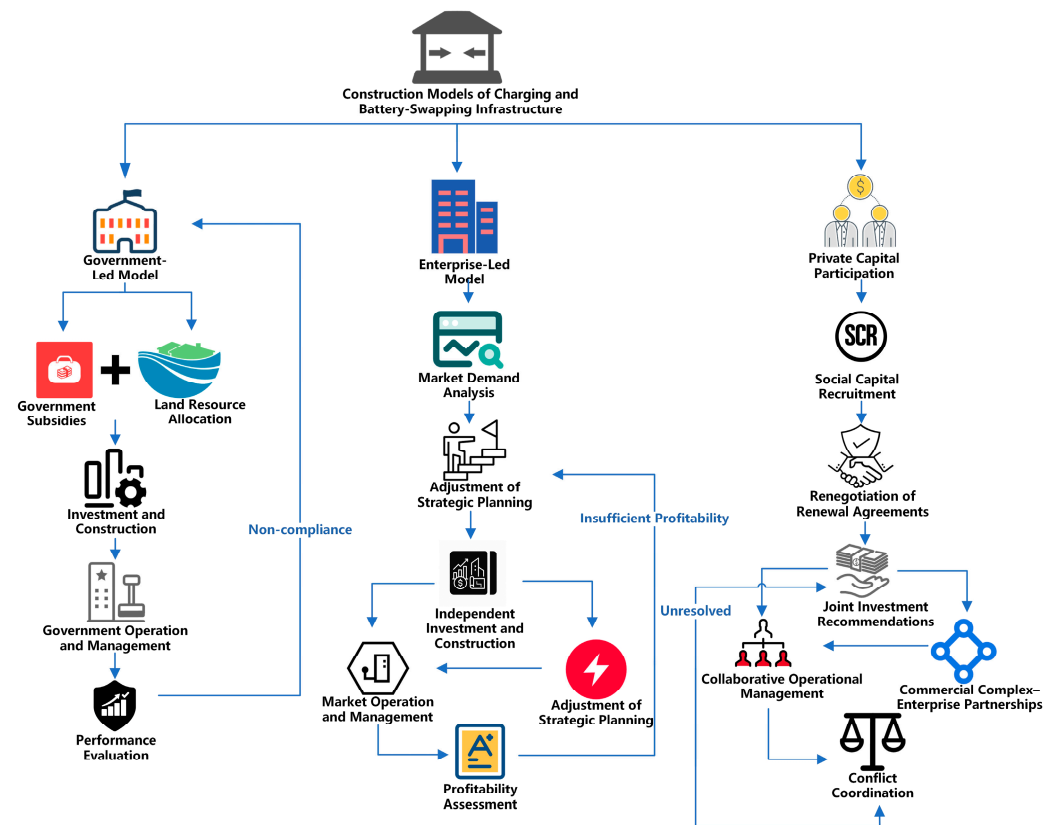


Figure 7. Construction models for charging and battery-swapping infrastructure. Source: Authors' synthesis.

2.2.3. Development Level of Charging Technologies

EV charging infrastructure can be grouped into AC conductive charging, DC fast/high-power charging, and wireless charging. Their suitability depends on dwell time, required energy, connection capacity, efficiency, equipment cost, and interoperability [25]. To provide a comprehensive comparison of different charging technologies, Figure 8 summarizes the characteristics, typical applications, and development features of AC, DC, and wireless charging systems.

AC charging is well suited to homes, workplaces, and long-dwell parking because the grid connection and equipment are comparatively simple. Typical powers range from approximately 3.7 to 22 kW, so charging time depends strongly on vehicle battery size and onboard-charger rating. Its main system value is the large controllable dwell window available for V1G [26].

DC fast charging moves power conversion offboard and supports substantially higher power. Contemporary public systems span roughly 50 kW to more than 350 kW, with higher-power liquid-cooled systems deployed in selected locations. The benefit is shorter dwell time; the trade-offs are higher capital cost, thermal-management requirements, connection demand, and the possibility of low asset utilization outside high-traffic sites [27].

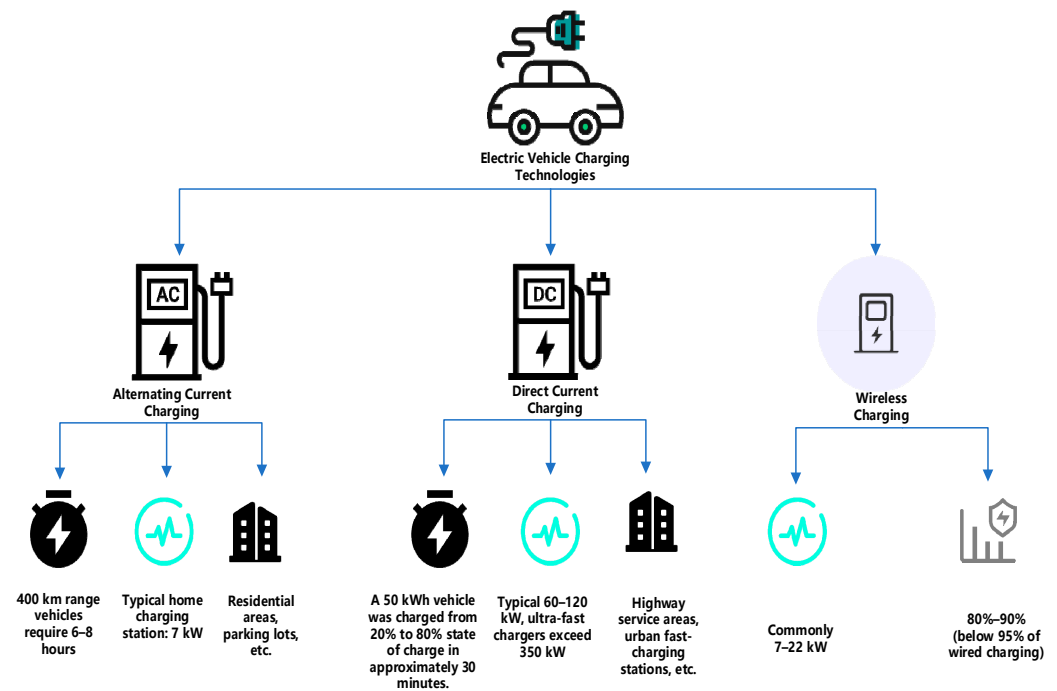


Figure 8. Comparative overview of AC, DC, and wireless EV charging technologies. Source: Authors' compilation and synthesis based on Refs. [10,12].

Wireless charging is based primarily on inductive wireless power transfer, in which a ground-side converter and compensation network energize a transmitting pad that couples magnetically with a receiving coil and rectifier on the vehicle. The technology can be implemented as static charging in parking bays, semi-dynamic charging at stops, or dynamic charging through embedded road segments [28,29].

Deployment readiness differs sharply by pathway. Static systems are closest to commercialization because alignment, communication, foreign-object detection, and electromagnetic-field control can be managed within a fixed bay. Dynamic systems may reduce onboard battery requirements and extend operating range, but they add pavement integration, segment control, maintenance, metering, and capital-cost challenges. Interoperability is being supported by SAE J2954, ISO 19363, ISO 5474-4:2025, and IEC 61980-2, yet cross-manufacturer conformance and real-world misalignment tolerance remain critical [30–33].

The principal technical trade-offs involve transfer efficiency across the air gap, coil geometry and compensation topology, tolerance to lateral and vertical misalignment, thermal performance, electromagnetic exposure, and cybersecurity of authentication and billing. Consequently, wireless charging should be treated as a scenario-specific complement to conductive charging rather than as a near-term universal replacement.

High-power charging is progressing through higher-voltage vehicle platforms, liquid-cooled cables, improved power modules, and local energy-management systems. Storage-assisted stations can reduce the required grid connection or manage short peaks, but they add conversion losses, asset cost, and control complexity. Reported peak charger power should therefore not be interpreted as the continuously deliverable power of a site [34].

Across all charging pathways, the key research issue is system integration: Charging speed, battery temperature and life, grid hosting capacity, utilization, standards, and user access must be optimized jointly [35]. A technology that improves the individual charging event may still increase system cost if it requires extensive grid reinforcement or remains underused.

2.2.4. Battery-Swapping Operational Efficiency, Economics, and Constraints

Battery swapping can deliver short and predictable energy-replenishment times and is particularly attractive for high-utilization fleets, taxis, ride-hailing vehicles, and logistics depots. Operational performance, however, depends on demand concentration, battery inventory, station throughput, pack-state balancing, and reliable automated handling. A nominally fast swap does not guarantee high system efficiency when station utilization is low, or battery inventory is excessive [20,36].

Its economics differ fundamentally from plug-in charging. In addition to land, power connection, and station equipment, the operator must finance a pool of batteries and manage depreciation, maintenance, insurance, and residual value. Vehicle–battery separation and BaaS can reduce the vehicle purchase price and create lifecycle value, but profitability is highly sensitive to lease pricing, daily turnover, battery standardization, and the allocation of degradation risk [37–41].

The main barriers are cross-brand pack compatibility, mechanical and electrical interface standards, battery ownership and state-of-health transparency, safety during storage and exchange, and the possibility that synchronized battery charging creates a new local peak. Coordinated scheduling, onsite storage, and participation in demand response can mitigate grid impacts, but they increase data, control, and market-integration requirements. Battery swapping is therefore most viable in standardized, high-throughput use cases rather than as a universal substitute for charging [42].

2.3. Cross-Regional Synthesis of Development Models

Four structural variables explain much of the cross-regional divergence. First, dwelling type and access to private parking determine the balance between home and public charging. Second, distribution-network governance and connection procedures determine whether high-power sites can be commissioned at their rated capacity. Third, policy continuity and capital-market depth affect long-lived infrastructure investment. Fourth, the domestic vehicle, battery, and equipment ecosystem shapes cost, standards, and the feasibility of battery swapping or V2G integration.

These variables also limit policy transferability. A dense, government-coordinated network model cannot be copied directly into a decentralized electricity market, while a market-led model may underprovide service in low-income or rural areas. Effective strategies therefore combine a common interoperability and safety baseline with region-specific instruments for finance, siting, grid upgrades, and utilization.

3. Policy-Oriented Support Mechanisms for Charging and Battery-Swapping Infrastructure and V2G Development

Charging and battery-swapping policy corrects several market failures: network externalities, uncertain early demand, land and grid–connection coordination, and incomplete valuation of flexibility. The relevant analytical question is not whether policy support exists, but whether it produces reliable, well-used, interoperable, and equitably distributed infrastructure without creating long-term subsidy dependence. To integrate the policy drivers, international experiences, and future optimization directions discussed above, Figure 9 presents a conceptual framework for coordinated charging, battery-swapping infrastructure, and V2G development.

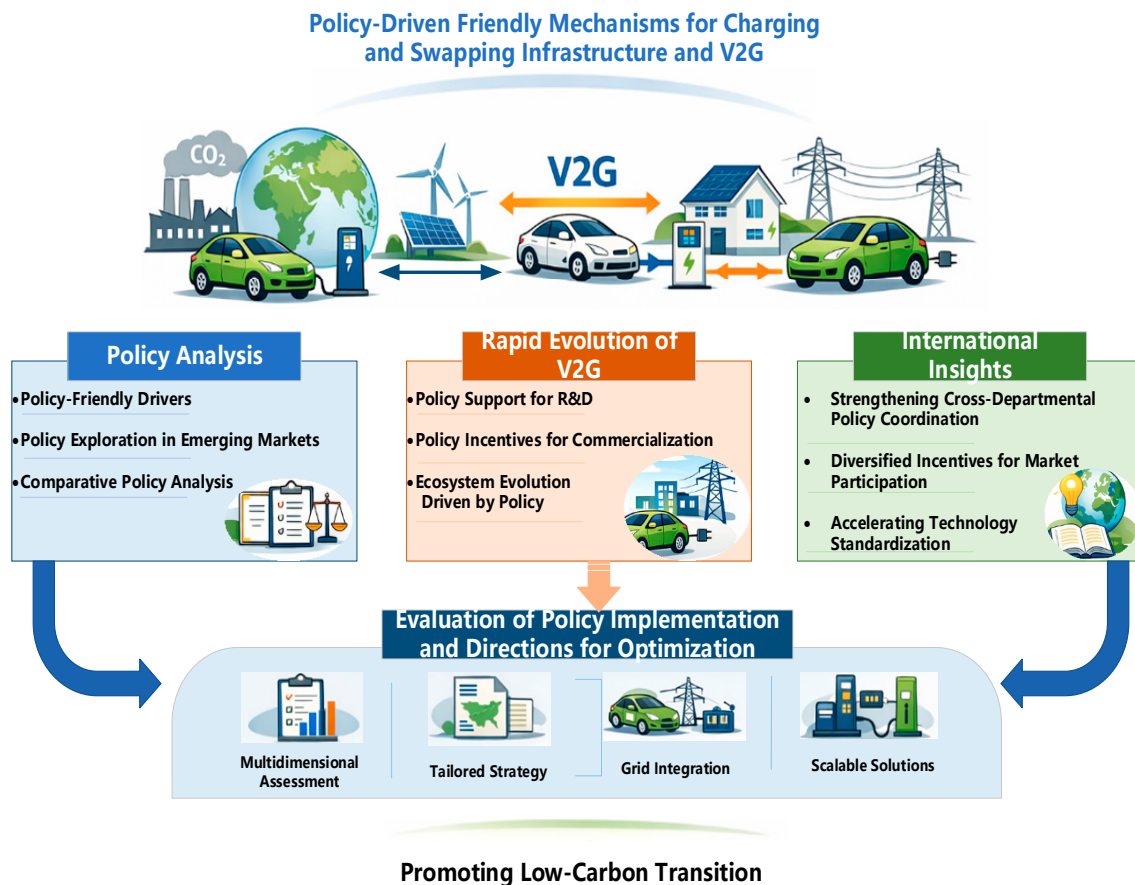


Figure 9. Policy mechanisms for coordinated charging, battery swapping, and V2G development. Source: authors' synthesis.

This section therefore compares policy design with observed outcomes and implementation constraints. Infrastructure expansion, market participation, grid readiness, standardization, and distributional effects are assessed separately so that a high charger count is not mistaken for overall policy effectiveness.

3.1. Review of Supportive Policies for Charging and Battery-Swapping Infrastructure

The formulation of global charging and battery-swapping infrastructure policies has gradually shifted from “quantity expansion” to “quality enhancement and network optimization”, with distinct characteristics in policy tools, coverage scope, and implementation intensity across different regions [43].

3.1.1. Policy Frameworks in Mature Markets

In the European Union, the policy framework combines vehicle CO₂ standards with the Alternative Fuels Infrastructure Regulation (AFIR), which establishes binding coverage and power requirements along the trans-European transport network. This regulatory approach improves cross-border predictability and interoperability, but implementation still depends on national permitting, grid connections, and the commercial utilization of high-power sites. The 20% growth in European public points in 2025 coexisted with country-level gaps and connection delays [18].

The United States combines federal corridor and community funding with state incentives, utility programs, and local siting rules. This layered governance can support experimentation, but it also produces heterogeneous access and policy uncertainty. In 2025, the public charging stock expanded while federal vehicle incentives and compliance signals

changed substantially, illustrating the risk that infrastructure investment and vehicle-demand policy may move on different timelines [10,18].

3.1.2. Policy Initiatives in Emerging Markets

China's model is characterized by national targets, local implementation, state-grid participation, and a strong domestic equipment and vehicle industry. It has delivered unmatched deployment speed and supported battery-swapping pilots, but the next policy challenge is to shift from installation counts toward utilization, reliability, rural service quality, and coordinated distribution-grid planning. Performance-based support is more appropriate than uniform construction subsidies once basic network scale has been achieved [44].

India and other emerging markets combine purchase support, manufacturing policy, public procurement, and private charging investment. These measures can accelerate a late-entry market, yet weak site economics, limited distribution capacity, and fragmented technical standards may prevent announced infrastructure from becoming dependable service. Policies should therefore link capital support to commissioning, uptime, interoperability, and verified use rather than to equipment installation alone [45].

3.1.3. Comparative Analysis of Policy Instruments

Across regions, financial incentives are effective for overcoming early capital barriers, regulatory mandates are effective for minimum coverage and interoperability, and market mechanisms are required for sustained operation. None is sufficient alone. Subsidies without utilization criteria can create idle assets; mandates without grid planning can produce sites that cannot deliver rated power; price liberalization without competition or consumer protection can reduce affordability.

Table 6 combines actual 2025 market and charging evidence with the dominant governance logic and remaining constraints. The comparison shows that policy effectiveness depends on sequencing: establish safety and interoperability, coordinate land and grid connection, support initial investment where network externalities are strongest, and then expose mature services to performance and market signals.

Table 6. Cross-regional comparison of market, infrastructure, policy logic, and remaining constraints in 2025. Source: Authors' compilation and comparative synthesis based on Refs. [10,18].

Region	2025 Market Evidence	2025 Infrastructure Evidence	Dominant Development Logic	Critical Constraints
China	>13 million electric-car sales; ~55% new-car share	>4.7 million public points; >65% of global stock	National planning, industrial scale, trade-in support, grid-enterprise participation	Utilization and regional imbalance; local grid capacity; multi-platform interoperability
Europe	4.2 million sales; 28% new-car share	Public points grew ~20%; leading national stocks in Netherlands, Germany, and France	CO ₂ standards, AFIR coverage rules, national incentives, interoperability focus	Connection and permitting delays; country heterogeneity; high-power site economics
United States	~1.5 million sales; ~10% new-car share	~70,000 fast/ultra-fast plus >160,000 slower public points	Federal-state-utility mix; corridor and community programs	Policy volatility; uneven state access; reliability and rural coverage
Emerging markets outside the three major markets	~2 million sales; Southeast Asia >0.5 million; India ~165,000	Rapid but heterogeneous deployment; limited comparable public-point data	Affordability, import/manufacturing policy, public procurement, private investment	Financing, grid reliability, standards, and low early utilization

3.2. Accelerated Evolution of V2G Under Policy Incentives

V2G can provide peak management, frequency response, reserve, renewable-energy balancing, and local network support, but these services require more than a bidirectional

power stage. Commercial deployment depends on certified interconnection, interoperable communication, aggregation and telemetry, DSO-TSO coordination, battery-health constraints, cybersecurity, and settlement rules. Policy support should therefore be evaluated against the complete service chain rather than the number of demonstration chargers.

3.2.1. Policy Support for V2G Technology Research and Development

European research and demonstration programs have supported bidirectional charging, interoperability, renewable integration, and fleet aggregation. Their most transferable contribution is not a single funding amount, but the creation of test environments in which vehicles, EVSE, aggregators, DSOs, TSOs, and market operators can validate communication, metering, and service qualification. The remaining challenge is to translate project-specific interfaces and exemptions into repeatable commercial rules.

In the United States, federal laboratories, utilities, states, and school-bus or fleet demonstrations have tested bidirectional charging and grid services. The decentralized structure supports diverse use cases but complicates certification and market access because interconnection procedures, tariffs, and aggregator rules differ by jurisdiction. Technical progress therefore needs parallel reform of utility approval and compensation mechanisms.

3.2.2. Policy Incentives for V2G Commercialization

Economic feasibility usually requires value stacking rather than reliance on a single service. Energy arbitrage alone is often insufficient after charger losses, communication and aggregation costs, battery degradation, availability constraints, and customer compensation are included. Capacity, frequency-response, demand-charge management, resilience, and behind-the-meter services can improve the business case, but simultaneous commitments must respect physical and market constraints [46,47].

Demonstration programs in the United Kingdom, Japan, and other markets show that clear eligibility, baseline, telemetry, and settlement rules are as important as hardware subsidies. Standard contracts can reduce transaction costs, while time-varying tariffs and ancillary-service access can create revenue opportunities. However, reported project revenues are not directly transferable across electricity markets, fleet duty cycles, or battery warranties.

3.2.3. Policy-Driven Evolution of the V2G Ecosystem

Policy-driven V2G ecosystems require coordinated roles. Automakers provide vehicle capability and battery warranties; EVSE manufacturers provide certified bidirectional conversion; aggregators forecast availability and submit market bids; DSOs manage local voltage, thermal, and congestion constraints; and TSOs procure system-level balancing. Without a mechanism for exchanging constraints and dispatch signals, a TSO-level service can unintentionally aggravate a distribution-network bottleneck.

The key institutional transition is therefore from isolated pilots to standardized qualification, data exchange, and settlement. Public policy can accelerate this transition by funding conformance testing, defining aggregator responsibility, enabling flexibility markets, and ensuring that customer consent and battery-health limits are enforceable.

3.3. *International Lessons for the Development of Charging and Battery-Swapping Infrastructure and V2G*

Cross-regional comparison yields lessons, but also reveals limits to direct policy transfer. Instruments must be evaluated against local housing, grid, market, and institutional conditions. The following lessons therefore distinguish broadly transferable principles from context-dependent implementation choices.

3.3.1. Strengthening Cross-Sector Policy Coordination

The transferable principle is coordinated planning across transport, energy, land use, and digital infrastructure. The implementation form can differ: centralized planning may accelerate corridor or fleet deployment, whereas decentralized systems may rely on hosting-capacity maps, standardized connection queues, and utility performance regulation. Coordination should be judged by connection time, delivered power, and service reliability rather than by the existence of an interdepartmental plan.

3.3.2. Activating Market Participation Through Diversified Incentive Mechanisms

Public support is most defensible where network externalities or equity objectives are strong. As markets mature, incentives should shift toward co-investment, availability payments, verified utilization, and competitive service procurement. For V2G, participation depends on transparent revenue allocation and protection against uncompensated degradation; overly complex market entry can exclude small fleets and households even when technical capability exists.

3.3.3. Accelerating Technological Standardization to Reduce Barriers

A common safety and communication baseline reduces integration cost, but formal publication of a standard does not guarantee field interoperability. Conformance testing, certificate management, version compatibility, cybersecurity updates, and clear responsibility for failed transactions are required. Regional standards can coexist, yet vehicle-EVSE and EVSE-backend interfaces must be mapped explicitly to prevent proprietary lock-in.

3.3.4. Ensuring Equity to Prevent “Infrastructure Blind Spots”

Equity should be evaluated through travel needs, dwelling type, income, disability access, and reliability, not only distance to the nearest charger. Targeted support for multifamily housing, rural corridors, public fleets, and low-income communities can reduce access gaps. However, subsidizing construction without maintenance obligations may leave nominally covered communities with unreliable service.

3.4. Evaluation of Policy Implementation Outcomes and Directions for Optimization

An outcome-oriented evaluation framework should separate inputs (funding and equipment), outputs (commissioned capacity and coverage), outcomes (use, reliability, affordability, and grid value), and distributional effects. This distinction reduces the risk of attributing market growth to a single policy or reporting infrastructure announcements as operating performance.

3.4.1. A Multidimensional Evaluation Framework for Policy Implementation Effectiveness

A rigorous assessment combines quantitative indicators with institutional evidence and states the observation year, geographic boundary, vehicle definition, and data status. Comparable metrics include public points per electric vehicle, delivered rather than nameplate power, uptime, utilization, connection lead time, private co-investment, service revenue, interoperability test results, and access for underserved users.

(1) Infrastructure Dimension: From Coverage Scale to Operational Efficiency

Infrastructure performance should be evaluated by spatial coverage, rated and delivered power, uptime, utilization, queueing, and distribution-network hosting capacity. A rapid increase in installed points can coexist with low use, congestion at a few high-demand sites, or chargers that operate below nameplate power because grid reinforcement is incomplete.

(2) Market Ecology Dimension: From Policy Dependence to Endogenous Cycles

Market performance should distinguish private investment from sustainable cash flow. Relevant indicators include operating margin, customer acquisition, utilization, price transparency, aggregator entry, and the diversity of revenue sources. High participation during a subsidized pilot does not demonstrate bankability after incentives end.

(3) Technology Development Dimension: From Pilot Demonstrations to Standard Implementation

Technology outcomes should include conformance and field interoperability, bidirectional efficiency, response accuracy, battery-health impact, communication availability, and cybersecurity incident management. Pilot success with one vehicle–EVSE pair is insufficient evidence of cross-brand scalability.

(4) Social Value Dimension: From Carbon Reduction to Equity and Inclusiveness

Social value includes lifecycle emissions, renewable-energy integration, resilience, affordability, and distributional access. Carbon benefits depend on charging time and grid mix, while resilience benefits depend on islanding capability and customer priorities. Equity indicators should therefore be reported independently from aggregate charger density.

3.4.2. Targeted Directions for Policy Optimization

Policy optimization should follow the identified failure mode rather than apply a universal subsidy. Five priorities emerge: performance-based finance, market access for flexibility, interoperable standards, proactive equity, and lifecycle governance.

(1) Optimization of Fiscal Instruments: From Universal Subsidies to Performance-Oriented Support

Capital support should be linked to commissioning, uptime, utilization, delivered power, interoperability, and service in priority locations. Grants, concessional loans, guarantees, and co-investment can be selected according to risk, while automatic sunset and review clauses reduce long-term dependence.

(2) Development of Market Mechanisms: From Administrative Control to Value Realization

Time-varying tariffs and flexibility markets should expose the value of location and timing, but customer compensation, baseline methods, and revenue sharing must be transparent. Aggregators require clear access rules and should be responsible for performance without being exposed to unmanageable local-network constraints.

(3) Coordination of Technical Standards: From Regional Fragmentation to Global Integration

Policy should support conformance laboratories, certificate and software-version management, open interfaces, and mutual recognition where technically justified. Coordination among ISO 15118-20, OCPP/IEC 63584, regional interconnection rules, and utility requirements is more useful than declaring a nominal percentage of compatibility [48,49].

(4) Ensuring Equity: From Passive Gap-Filling to Proactive Imbalance Prevention

Equity instruments should target multifamily housing, rural and low-income areas, public transport, and users without private parking. Funding should include operation and maintenance obligations, accessibility requirements, and transparent reporting of downtime and prices.

(5) Regulatory System Improvement: From single point inspection to system governance.

Lifecycle governance should cover equipment certification, installation, operation, data protection, software updates, battery safety, and end-of-life responsibility. Cross-agency data standards and auditability can reduce duplication while preserving accountability.

4. Analysis of Trends in V2G Interaction Infrastructure Development

This section moves from descriptive technology trends to the requirements that determine whether V2G can operate safely and profitably at scale. The analysis covers system architecture, interconnection and communication standards, aggregation, DSO-TSO coordination, battery degradation, cybersecurity, market settlement, and conditional energy-system impacts.

4.1. Core Development Trends of V2G Interaction Infrastructure

4.1.1. System Architecture and Actor Roles

(1) End-to-End Architecture

A V2G service chain contains the vehicle battery and battery-management system, an onboard or offboard bidirectional charger, EVSE protection and metering, a charging-station management system, an aggregator or VPP platform, and interfaces to the DSO, TSO, retailer, and market operator. The physical power path and the digital control path must both be available; a bidirectional charger without secure dispatch, metering, and settlement cannot provide a bankable grid service. To integrate the system architecture, technical requirements, policy mechanisms, and optimization pathways discussed in this section, Figure 10 presents a comprehensive framework for V2G infrastructure analysis.

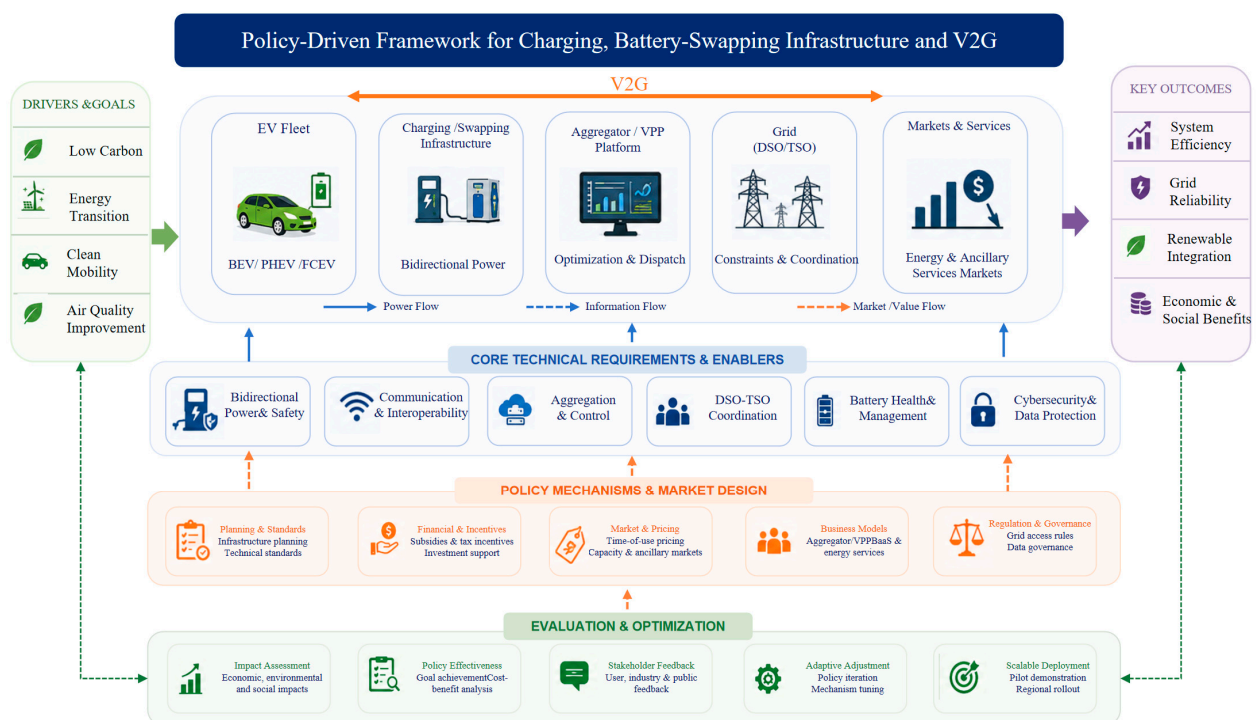


Figure 10. Framework for V2G infrastructure analysis. Source: authors' synthesis.

(2) Actor Responsibilities and Coordination

Automakers define battery limits and vehicle availability; EVSE suppliers implement conversion, protection, and communication; aggregators forecast flexibility and manage customer portfolios; DSOs validate local thermal and voltage constraints; TSOs procure

system-wide services. Operational rules must specify which actor can curtail or override a dispatch, how conflicts are resolved, and how non-delivery is allocated.

The central coordination challenge is that a fleet may be valuable to the TSO while being located behind a constrained distribution feeder. DSO-TSO coordination therefore requires constraint exchange, location-aware bids, or hierarchical dispatch so that system-level activation does not create local overload or voltage violations [50].

4.1.2. Technical Requirements, Interoperability, and Control

(1) Bidirectional Charger and Grid Interconnection

A grid-capable bidirectional charger requires controlled four-quadrant power conversion, galvanic isolation where required, anti-islanding, overcurrent and residual-current protection, power-quality compliance, accurate bidirectional metering, and defined behavior during abnormal voltage and frequency. Interconnection requirements are governed by regional grid codes and standards such as IEEE 1547 and SAE J3072 in relevant US applications [51,52]. Certification must address both the charger and the vehicle-integrated inverter configuration.

Power rating alone does not determine service value. Round-trip efficiency, minimum stable power, ramp rate, response latency, standby consumption, thermal limits, and simultaneous charging needs determine the dispatchable envelope. These characteristics should be measured at the point of grid connection and reported separately from nominal hardware ratings.

Aggregation platforms translate thousands of uncertain vehicle schedules into a reliable flexibility product. Required functions include customer consent, availability and state-of-charge forecasting, baseline construction, optimization under mobility constraints, telemetry, dispatch, exception handling, settlement, and audit. The platform must also communicate local DSO constraints and prevent the same flexibility from being sold to incompatible services.

(2) Communication and Interoperability

ISO 15118-20 defines vehicle-EVSE messages for bidirectional power transfer, while OCPP 2.0.1/IEC 63584 supports communication between charging stations and management systems [48,49,53]. These interfaces address different layers and must be implemented consistently with metering, tariff, certificate, and utility requirements. Compatibility claims should therefore be based on conformance and cross-vendor testing rather than protocol names alone.

Interoperability also includes connector and power-stage compatibility, Plug and Charge certificate management, firmware versioning, roaming, and mapping between aggregator commands and grid-code functions. Legacy fleets and chargers create a transition problem because OCPP versions are not fully interchangeable and bidirectional capability is not implied by ordinary smart-charging support.

(3) Battery Degradation, Control, and Cybersecurity

Battery degradation is governed by both calendar and cycle aging. Depth of discharge, average state of charge, C-rate, temperature, dwell time at high state of charge, and cell chemistry influence incremental wear. V2G control should therefore optimize revenue net of degradation and preserve mobility and warranty constraints; a fixed cost per discharged kilowatt-hour can be misleading across climates and duty cycles [47].

Hierarchical control can combine local charger protection, aggregator optimization, DSO constraint management, and TSO dispatch. Forecast errors and customer opt-outs require reserve margins and real-time re-optimization. Reported simulation benefits should

be interpreted in relation to fleet size, availability, feeder topology, market rules, and baseline assumptions.

Cybersecurity spans vehicle identity, Plug and Charge certificates, station-backend communication, aggregator APIs, and grid control interfaces. Mutual authentication, encrypted communication, least-privilege access, secure software updates, logging, incident response, and privacy-preserving data aggregation are required. A compromised fleet could create synchronized load changes, making cybersecurity a power-system reliability issue as well as a data-protection issue [54]. The key technical requirements and unresolved challenges associated with V2G deployment are summarized in Table 7.

Table 7. Technical requirements and unresolved challenges for V2G deployment.

Layer	Minimum Functional Requirement	Relevant Standard/Mechanism	Unresolved Challenge
Bidirectional power conversion	Four-quadrant control, protection, metering, power quality, abnormal-grid response	Grid codes; IEEE 1547; SAE J3072 [51,52]	Certification across onboard/offboard architectures and regions
Vehicle-EVSE communication	Negotiation of charging/discharging limits, authorization, schedules, and metering data	ISO 15118-20 [48]	Cross-vendor conformance, certificate lifecycle, legacy compatibility
EVSE-backend/aggregator	Device management, secure transactions, smart charging, telemetry, and remote control	OCPP 2.0.1/IEC 63584 [49,53]	Version incompatibility, cybersecurity, vendor-specific extensions
Aggregation and market interface	Forecasting, baseline, dispatch, settlement, audit, and customer override	VPP and flexibility-market rules	Uncertain availability, minimum bids, double commitment, transaction cost
DSO-TSO coordination	Exchange of local constraints and system-service activation	Hierarchical or location-aware dispatch	TSO activation can conflict with feeder voltage or thermal limits
Battery health	SOC, temperature, C-rate, depth-of-discharge, warranty, and mobility constraints	BMS limits; degradation-aware optimization	Transferable degradation cost and long-term field evidence
Cybersecurity and privacy	Authentication, encryption, least privilege, secure updates, logging, incident response	PKI/TLS; DER cybersecurity guidance	Fleet-scale synchronized attacks and sensitive mobility data
Economic settlement	Revenue stacking, loss and degradation accounting, transparent customer compensation	Tariffs, ancillary services, local flexibility	Market-specific profitability and incomplete cost reporting

4.2. Innovation in V2G Infrastructure Business Models

4.2.1. Battery Leasing and Energy Trading Models

Battery Leasing and Energy Trading Models: A Key Lever for V2G Commercialization

The battery leasing and energy trading model leverages a “vehicle–battery separation with bidirectional energy flow” approach. This model reduces the upfront cost of electric vehicle ownership while simultaneously activating the energy storage and trading potential of EV batteries, positioning it as a critical commercial pathway connecting transportation and energy systems. Existing studies have primarily focused on transaction algorithms, community-level applications, supply chain coordination, and full lifecycle management.

In the domain of energy trading and dispatch algorithms, studies generally aim to maximize user profits or minimize electricity procurement costs by constructing optimization models that accommodate uncertainties in electricity prices, load demand, and renewable energy fluctuations. Real-time decision-making approaches based on Lyapunov optimization have demonstrated strong adaptability in bidirectional transactions between end-users and the grid, owing to their low computational complexity and lack of reliance on a priori statistical information [50]. Furthermore, when integrated with vehicle-to-home (V2H) scenarios, this approach enables multi-level energy trading across households, com-

munities, and the grid while accounting for battery degradation costs, thereby extending energy interactions from a “user-grid” paradigm to a “user–user-grid” framework [37].

In the realm of supply chain and business strategy design, research has focused on the strategic interactions among automakers, battery asset holders, and service operators. The findings indicate that different power structures and collaboration models significantly affect the profits of each stakeholder: under certain conditions, cooperative strategies facilitate the maximization of overall supply chain returns, while the duration of consumer battery leases emerges as a critical factor influencing the sustainability of battery-swap models. From the perspective of promoting the “vehicle–battery separation” paradigm, consumer acceptance and battery utilization efficiency are key drivers of model diffusion. Appropriately regulating lease pricing and subsidy levels is essential to prevent users from reverting to traditional vehicle ownership models.

In terms of extracting value across the full battery lifecycle, second-life utilization and recycling mechanisms have been identified as critical factors for enhancing the economic viability of battery leasing. Studies have demonstrated that integrating recycling and reuse within the Battery-as-a-Service (BaaS) model contributes to lowering lease prices, expanding market demand, and increasing corporate profits. Simultaneously, the lease duration exerts a decisive influence on the battery’s ultimate disposition, providing a quantitative basis for asset management decisions [55]. Furthermore, the introduction of performance guarantees and collaboration with third-party Battery Asset Companies (BACs) can improve manufacturer cash flows and risk-sharing structures, particularly under conditions of high battery maintenance costs [56].

In the domain of operation and maintenance optimization, studies progressively incorporated asset-liability management and user behavior modeling tools. By predicting battery replacement behaviors and optimizing maintenance scheduling, these approaches enhanced the operational efficiency of battery swapping and leasing systems. Relevant models indicated that refined maintenance strategies combined with behavior prediction significantly improved the profitability of swapping stations and the efficiency of resource allocation.

Overall, battery leasing and energy trading can support V2G commercialization only when asset ownership, degradation, residual value, and dispatch rights are contractually aligned. Algorithmic revenue estimates should therefore be stress-tested against price volatility, charger downtime, user opt-outs, battery warranties, and regional market rules.

4.2.2. Multi-Stakeholder Collaborative Operation Models

Large-scale V2G depends on collaboration among automakers, EVSE suppliers, grid operators, aggregators, retailers, and customers. The technical platform centralizes distributed flexibility, but governance must define data access, dispatch priority, customer override, liability, and revenue sharing. Without these rules, a technically successful pilot cannot be replicated commercially.

Demonstrations in fleets, school buses, depots, and virtual power plants show that aggregated EVs can provide grid services, but project results vary with vehicle availability, market prices, feeder conditions, and subsidy design. Claims of aggregate capacity should therefore distinguish enrolled battery capacity from continuously available and market-qualified power.

The likely development path is gradual: captive fleets with predictable schedules can establish operational evidence; aggregators can then extend services to mixed fleets as standards and settlement mature. The principal scaling barriers are not only device cost, but also transaction complexity, data governance, and inconsistent interconnection approval.

4.2.3. Challenges and Opportunities in Commercial Models

Commercial viability is constrained by uncertain availability, bidirectional-charger premiums, efficiency losses, degradation, customer compensation, qualification tests, telemetry costs, and market minimums. Revenue stacking can improve economics, but overlapping service commitments must be physically feasible and accepted by the relevant DSO and TSO.

V2G should therefore be framed as a portfolio of use cases rather than a single universal business model. Fleet peak-demand management, resilience, local flexibility, and frequency services have different technical and institutional requirements. Scalable deployment will occur first where high vehicle availability, clear market access, and avoided network or demand costs create a sufficiently robust value proposition.

4.3. Impacts of V2G Infrastructure on the Energy System

4.3.1. Impacts on Grid Load Balancing

V2G can reduce net-load peaks and charging-induced ramps, but the magnitude is study- and system-specific. Optimization studies report meaningful peak reduction under favorable availability and price signals, yet results depend on the assumed fleet participation, baseline, feeder constraints, and whether battery degradation and customer mobility are included [57]. These values should not be generalized as universal percentages.

Advanced forecasting and control can improve frequency response, phase balancing, and photovoltaic hosting, but cross-study comparison remains difficult because datasets, network models, control horizons, and performance metrics differ [58–61]. Future empirical studies should report no-V2G, V1G, and V2G baselines under the same operating conditions.

4.3.2. Enhancement of Energy Storage and Utilization Efficiency

Aggregated EV batteries can provide distributed flexibility during parked periods, with advantages in response speed and geographic dispersion. The usable resource is smaller than the installed battery stock because mobility needs, connection probability, state of charge, charger rating, and customer preferences limit availability [62].

VPP aggregation can support renewable integration and reduce curtailment in some systems, but benefits depend on location and coincidence. Discharging from a congested or carbon-intensive part of the grid may provide less value than predicted by system-wide energy balances. Locational constraints and marginal emissions should therefore be included in evaluation.

4.3.3. Impact on Energy System Stability

Uncoordinated charging and discharging can worsen voltage deviation, phase imbalance, or congestion, whereas coordinated V2G can provide active and reactive power support. The direction of impact depends on feeder topology, control settings, and communication reliability [63].

Hierarchical and model-predictive control can improve regulation accuracy, but simulation performance does not by itself demonstrate field reliability. Latency, packet loss, device heterogeneity, forecast error, and cybersecurity events should be included in hardware-in-the-loop and field validation.

Three safeguards are consistently required: location-aware aggregation to respect distribution constraints; fast local protection and fallback control; and continuous monitoring of battery, charger, communication, and grid states. Market activation should be blocked or derated when these safeguards are not available.

V2G is therefore a conditional grid resource rather than automatically available storage. Its long-term contribution will be determined by the share of vehicles with certified

bidirectional capability, customer participation, network hosting capacity, and viable market products. Future capacity estimates should be reported as scenarios with explicit assumptions rather than definitive forecasts.

5. Conclusions and Outlook

5.1. Research Summary

- (1) Verified 2025 evidence confirms continued scale growth but stronger regional differentiation. Global electric-car sales reached about 21 million and a 25% sales share. China exceeded 13 million sales and approached a 55% share; Europe reached 4.2 million and 28%; the United States remained near 1.5 million and 10%. These differences reflect industrial structure, regulation, affordability, and infrastructure conditions rather than a single adoption driver [10].
- (2) Public charging expansion is necessary but not sufficient. China exceeded 4.7 million public points at the end of 2025, Europe grew by about 20%, and the United States reached roughly 230,000 public points [17]. The critical performance variables are delivered power, uptime, utilization, spatial equity, and connection lead time. Battery swapping is economically credible mainly in standardized, high-throughput fleets and requires explicit battery-asset management.
- (3) V2G commercialization is constrained by an end-to-end coordination problem. Certified bidirectional conversion, ISO 15118-20 and backend interoperability, aggregation, DSO-TSO coordination, battery-health-aware control, cybersecurity, and transparent settlement must operate together [48]. Revenue stacking can improve profitability, but project results cannot be generalized without common baselines and full cost accounting.

5.2. Future Development Prospects

(1) Market and Infrastructure: From Counts to Service Performance

Future market and infrastructure pathways should be treated as scenarios conditioned on policy, cost, and macroeconomic assumptions. Under continued electrification, investment should prioritize network reliability, high-utilization locations, multifamily housing, rural access, and grid reinforcement rather than pursue charger counts alone. Public reporting should distinguish operational points from announced projects and nameplate power from delivered power.

Charging and battery swapping will coexist. Conductive home and destination charging remains cost-effective for long dwell times; high-power DC charging serves corridors and rapid-turnover use; wireless charging is most plausible in automated or high-frequency fixed-route applications; and swapping is strongest in standardized fleets. Regional portfolios should reflect local travel, parking, land, and grid conditions.

Cross-regional balance requires targeted finance and planning rather than uniform replication. Hosting-capacity information, transparent connection queues, minimum reliability standards, and operation and maintenance obligations can reduce the gap between nominal coverage and usable service.

(2) Policy Optimization: Outcome-Based and Adaptive Governance

Policy should move from broad installation subsidies toward verified outcomes: commissioning, uptime, utilization, interoperability, delivered power, and service in underserved areas. Market access for aggregators and V2G should be paired with clear baselines, customer compensation, DSO constraints, and auditability. Periodic evaluation is necessary because vehicle incentives, electricity prices, and technology costs change rapidly.

(3) V2G Research: Interoperability, Degradation, and Field Evidence

Priority research areas are cross-vendor conformance testing, battery degradation under real dispatch profiles, location-aware DSO-TSO coordination, cybersecurity of aggregated fleets, and profitability under complete cost accounting. Standard alignment should be evaluated through test results and deployed compatibility, not an unsupported target percentage.

Field trials should publish vehicle availability, state-of-charge limits, charger efficiency, communication failures, customer opt-outs, feeder constraints, market prices, and degradation assumptions. These data are necessary to compare V1G, V2G, stationary storage, and network reinforcement on a consistent basis.

AI and optimization can improve forecasting and dispatch, but model accuracy should be reported on representative out-of-sample data and linked to operational value. Privacy-preserving learning and robust control are promising, although their communication, verification, and failure-mode requirements need field validation.

The forward-looking statements in this section are scenarios and research priorities rather than deterministic forecasts. Their realization depends on policy continuity, technology cost, market design, customer participation, and grid investment.

Research Gaps and Future Directions

The following critical evidence gaps identified by this review are:

1. Empirical quantification of incremental battery degradation and warranty risk under different V2G services, climates, and chemistries.
2. Scalable, location-aware coordination among vehicles, aggregators, DSOs, TSOs, and electricity markets under uncertain availability.
3. Cross-vendor interoperability, cybersecurity, and privacy validation across vehicle-EVSE-backend-grid interfaces.

Future work should prioritize open field datasets, harmonized performance metrics, hardware-in-the-loop and multi-vendor demonstrations, and scenario analysis under extreme weather or communication failures. These steps would convert the field from isolated demonstrations and descriptive forecasts toward reproducible evidence for investment and policy decisions.

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