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Advancing Sustainable Transportation: The Critical Role of Electric Vehicles and Supporting Infrastructure

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Abstract

Electric vehicles (EVs) have emerged as a central pathway for decarbonizing transport, yet sustained adoption depends on coordinated progress in technology, infrastructure, and policy. This mini-review synthesizes recent evidence on environmental performance, market growth, and enabling systems for large-scale electrification. First, it consolidates technical and life-cycle findings that indicate lower greenhouse gas emissions and higher energy-conversion efficiency for EVs relative to internal combustion engine vehicles, with advantages strengthening as grids decarbonize. Second, it examines charging infrastructure typologies and deployment patterns, highlighting the complementary roles of Level 2 and DC fast charging and the need for reliability, interoperability, and grid-aware siting. Third, it analyzes policy instruments—financial incentives, regulatory mandates, and planning frameworks—and compares national approaches to illustrate how instrument mixes shape outcomes. Persistent challenges include upfront affordability, uneven access to charging, grid integration under peak demand, and battery material sustainability. The review identifies future directions in managed and bidirectional charging, data-driven planning, AI-enabled operations, and circular economy practices for batteries, alongside equity-focused governance. Collectively, these insights outline a coherent agenda for scaling EV adoption while aligning climate mitigation with resilient and inclusive mobility.

Keywords: Electric Vehicles; Sustainable Transportation; Charging Infrastructure; Vehicle-To-Grid; Policy Frameworks; Life-Cycle Assessment; Equity

1. Introduction

The transportation sector is a major contributor to greenhouse gas (GHG) emissions, air pollution, and dependence on finite fossil fuels. Developing sustainable mobility solutions is therefore critical to mitigating climate change, improving urban air quality, and advancing global environmental goals. Among the emerging technologies, electric vehicles (EVs) are increasingly recognized as a pivotal solution for reducing emissions and enabling the transition to sustainable transportation systems [1, 2].

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Table 1: Global EV market indicators, 2020–2024. Source: BloombergNEF (2024), IEA (2024), and industry reports [17, 18].

Indicator	2020	2021	2022	2023	2024
Global EV Sales (millions)	3.2	6.6	10.3	13.0	14.0
Market Share (% of new sales)	4.2	8.3	13.2	16.8	18.0
Average Battery Cost ($/kWh)	140	132	115	105	98
Median EV Range (miles)	234	256	275	295	310
Public Charging Points (millions)	1.3	1.8	2.2	2.6	2.8
Countries with >10% EV Market Share	4	8	13	17	21

The adoption of EVs has accelerated in recent years, driven by advancements in battery technologies, reductions in cost, and stronger policy incentives. EVs offer multiple benefits compared to internal combustion engine (ICE) vehicles, including zero tailpipe emissions, higher energy conversion efficiency, and the potential to integrate renewable energy into mobility systems [3, 4]. However, their widespread deployment depends on the availability of robust supporting infrastructure, such as charging networks, grid integration, and recycling frameworks. At the same time, policy decisions—including purchase incentives, stricter emissions regulations, and subsidies for R&D—play an instrumental role in shaping adoption trajectories [5]. This mini-review aims to synthesize the current state of EV adoption and infrastructure, focusing on three major dimensions: (i) environmental benefits and market growth, (ii) infrastructure requirements and smart grid integration, and (iii) policy frameworks and future research directions. By combining evidence from technical, infrastructural, and policy perspectives, this review highlights both the opportunities and challenges in advancing EVs as a cornerstone of sustainable transportation systems. In line with sustainable mobility paradigms [6, 7], the analysis adopts a multi-dimensional lens, evaluating not only environmental performance but also issues of social equity, resilience, and systemic integration within transport-energy systems [8, 9]. Similar calls for integrated approaches can be found in broader reviews of sustainable mobility transitions [10, 11], which stress the role of shared mobility, equity considerations, and systemic policy support in ensuring that electrification contributes to long-term sustainability goals.

2. Electric Vehicles in Sustainable Transportation

The adoption of electric vehicles (EVs) has accelerated significantly in recent years, driven by advancements in battery technologies, reductions in cost, and stronger policy incentives. EVs consistently demonstrate environmental advantages over internal combustion engine (ICE) vehicles, including zero tailpipe emissions, improved energy conversion efficiency, and integration potential with renewable energy systems [3, 4, 12]. Life-cycle assessments confirm that even when upstream electricity emissions are included, EVs deliver lower overall greenhouse gas (GHG) outputs compared with ICE vehicles, particularly as renewable shares in power grids increase [13, 14]. From an energy efficiency perspective, EVs achieve wheel-to-power efficiencies of 60–77%, far surpassing the 17–21% conversion rates typical of ICE vehicles [12]. Technologies such as regenerative braking and optimized power electronics further enhance their performance and sustainability [15, 16]. Moreover, EV adoption contributes to energy security by diversifying national energy portfolios and reducing reliance on imported petroleum. Market adoption has expanded rapidly. Global EV sales rose from 3.2 million in 2020 to 14 million in 2024, with market share increasing from 4.2% to 18% [17, 18]. One of the strongest drivers of this growth has been the sharp decline in battery pack prices—nearly 90% since 2010—which has enabled mass-market adoption [19]. At the same time, life-cycle assessment studies confirm that EVs consistently outperform internal combustion engine vehicles in terms of greenhouse gas (GHG) emissions, particularly when upstream electricity relies increasingly on renewable sources [20]. Table 1 summarizes key indicators, including sales, market share, battery costs, and charging infrastructure. Figure 1 illustrates the rising trajectory of sales volume and market penetration, while Figure 2 highlights the dual trend of declining battery costs and increasing vehicle range. Figure 1 illustrates the corresponding trajectory, where global EV sales grew more than fourfold between 2020 and 2024. The upward slope of both sales volume and market share highlights the rapid mainstreaming of EVs within the global automobile market, supported by declining battery costs and stronger policy incentives.

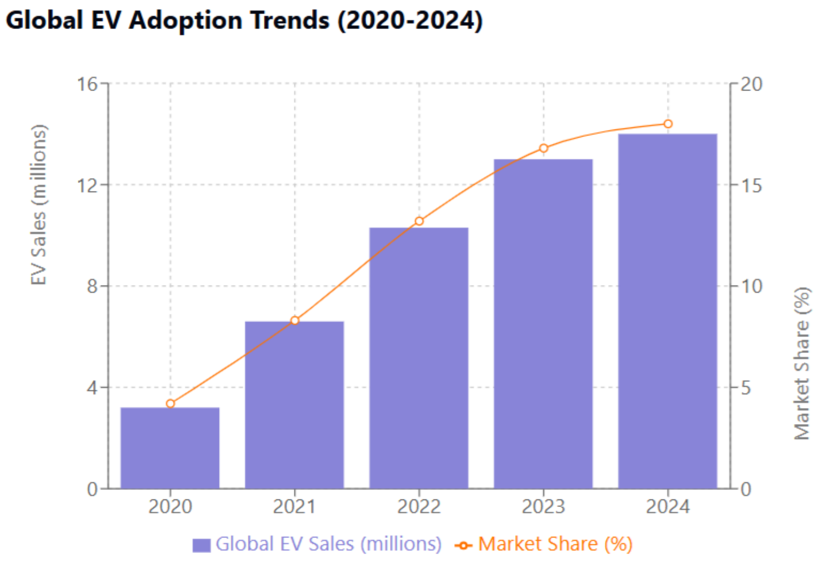

Figure 1: Global EV adoption trends from 2020 to 2024, showing steady growth in both absolute sales and market share. Source: compiled from BloombergNEF (2024) and IEA (2024) [17, 18].

Figure 2 demonstrates the technological progress underpinning adoption, with average battery pack costs falling from 140 to 98 $/kWh between 2020 and 2024, while median EV range increased from 234 to 310 miles. This dual trend highlights the reinforcing cycle of affordability and performance that has accelerated market uptake.

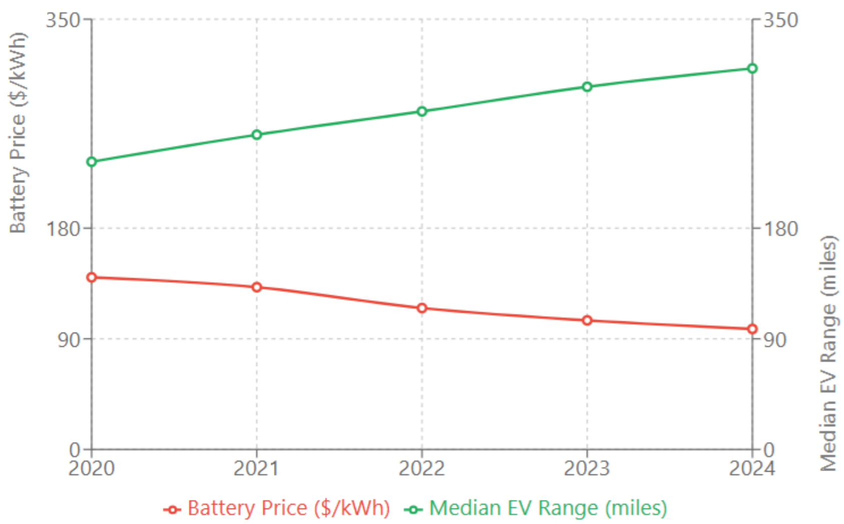

Figure 2: Battery prices and median EV range, 2020–2024. Source: BloombergNEF (2024) and IEA (2024) [17, 18].

The characteristics of charging systems vary considerably across technologies, influencing cost, convenience, and deployment context. Level 1 AC charging is typically confined to residential use due to its low power output and slow speed, while Level 2 AC charging dominates global installations by offering a balance of moderate charging times and feasible installation costs for both residential and public environments. In contrast, DC fast charging provides rapid replenishment but remains a smaller share of deployments given higher capital costs and siting constraints. Table 2 summarizes the key attributes and global deployment shares. As shown in Figure 3, the number of global public charging points more than doubled between 2020 and 2024, paralleling a sharp increase in the number of countries surpassing 10% EV market share. This demonstrates the strong positive feedback between infrastructure provision and adoption, emphasizing that charging availability is one of the most decisive enablers of EV market growth.

Table 2: Charging infrastructure comparison by type. Source: compiled from ICCT (2023), DOE (2024), and industry reports [21, 12].

Charging Type	Power Output	Charging Speed	Installation Cost	Typical Locations	Share of Global Installations
Level 1 (AC)	1.4–1.9 kW	2–5 miles/hour	$300–$600	Residential	N/A (primarily private)
Level 2 (AC)	3.3–19.2 kW	10–30 miles/hour	$2,000–$10,000	Residential, Workplace, Public	79%
DC Fast Charging	50–350+ kW	3–20 miles/minute	$20,000–$150,000	Public, Highway Corridors	21%

3. Policy Frameworks and Incentives

Policy interventions have been instrumental in shaping the trajectory of electric vehicle (EV) adoption worldwide. Governments employ a mix of financial and non-financial incentives to encourage the transition from internal combustion engine vehicles to EVs, while simultaneously investing in the infrastructure required to sustain long-term adoption. Financial instruments include direct purchase subsidies, tax credits, preferential loans, and registration fee reductions, all of which reduce the upfront cost barrier that remains one of the most significant obstacles to widespread EV uptake. Non-financial incentives, such as high-occupancy vehicle (HOV) lane access, preferred parking privileges, exemptions from tolls and congestion charges, and exemptions from low-emission zone restrictions, further enhance consumer willingness to shift toward EV ownership [9, 15]. Beyond consumer-focused incentives, regulatory mechanisms play a critical role in accelerating adoption. Many jurisdictions have implemented zero-emission vehicle (ZEV) mandates that require automakers to gradually increase the share of EVs in their fleets, coupled with increasingly stringent fuel economy and emissions standards. These policies not only drive supply-side transformation but also stimulate research and development in next-generation batteries, charging technologies, and grid integration systems. The cumulative effect has been a global acceleration in EV innovation, supported by both targeted government interventions and private-sector participation [22–24].

The effectiveness of EV policy frameworks varies widely across regions, reflecting differences in institutional capacity, industrial priorities, and social contexts. While some countries emphasize fiscal incentives, others rely on centralized planning or regulatory mandates. The diversity of these approaches highlights that no single strategy is universally applicable, underscoring the importance of policy alignment with local conditions and long-term sustainability goals. Section **??** examines these differences in greater detail through comparative national experiences.

Critics argue that heavy reliance on subsidies is not sustainable in the long run, as fiscal constraints eventually necessitate their phase-out once market maturity is achieved. This raises important questions about the timing and design of transition strategies. Ideally, governments should taper subsidies as EV prices converge with ICE vehicles, while simultaneously strengthening non-financial incentives and regulatory frameworks to maintain momentum. Additionally, equity concerns must be addressed to ensure that benefits are not disproportionately concentrated in urban or affluent regions but are accessible to all segments of society [11]. Integrating EV adoption with broader climate, energy, and social policies, as emphasized by Gudmundsson et al. in their sustainability performance frameworks, offers a pathway to harmonize environmental effectiveness with social inclusivity [9].

4. Case Studies and Comparative Insights

Comparative experiences across countries provide valuable evidence on how different policy mixes, infrastructure strategies, and market dynamics shape electric vehicle (EV) adoption. Norway remains the global leader in EV penetration, where sustained policy support has enabled EVs to surpass 80% of all new car sales in 2024. A consistent package of fiscal and non-fiscal measures—including purchase tax exemptions, road toll waivers, and dense charging deployment—has been key to this transition [25, 18, 17]. The case illustrates how long-term, consistent policy frameworks combined with infrastructure deployment can create a self-reinforcing cycle of adoption, where economies of scale and consumer trust accelerate transition. China represents another instructive example but with a different approach. As the world's largest EV market, China accounted for nearly 60% of global sales in 2024. Centralized planning, industrial strategy integration, and massive infrastructure rollout—including battery swapping stations—have defined its success [26, 27, 22]. Standardization of interfaces, mandatory EV-ready infrastructure in new construction projects, and strong coordination between government agencies and private firms have further accelerated deployment.

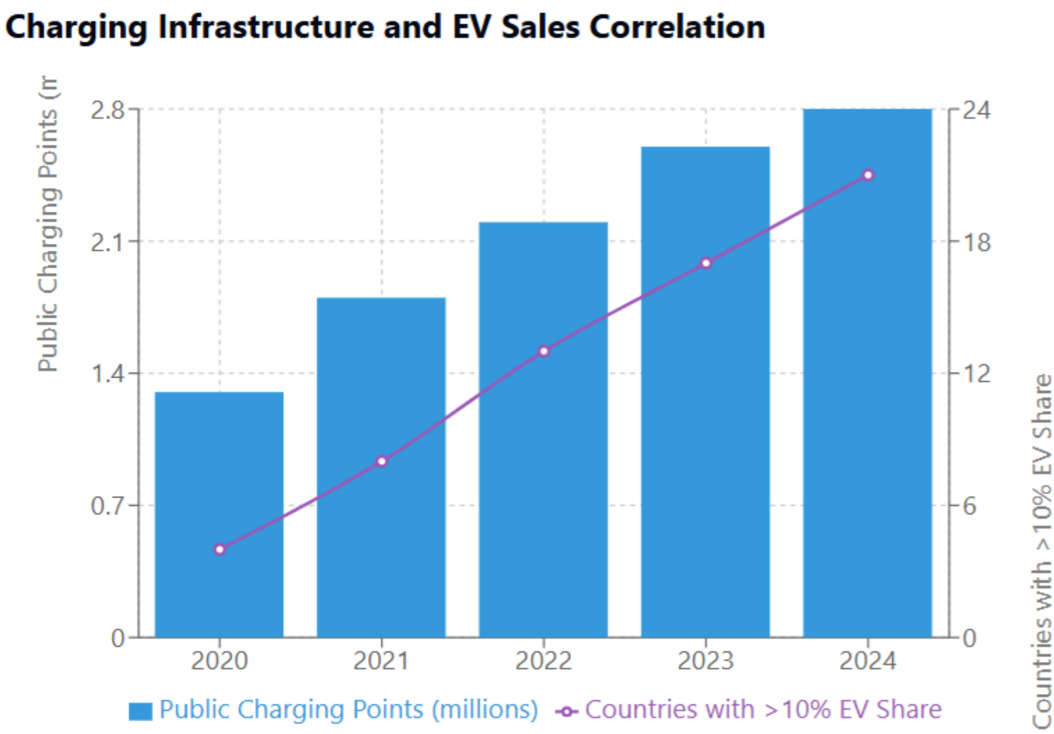

Figure 3: Correlation between growth in public charging infrastructure and EV adoption from 2020 to 2024. As charging points expanded from 1.3 to 2.8 million units worldwide, the number of countries exceeding a 10% EV share increased fivefold. Source: compiled from BloombergNEF (2024) and IEA (2024) [17, 18].

The European Union (EU) and North America, though less advanced in terms of penetration rates compared to Norway and China, present hybrid models where regulatory mandates combine with targeted subsidies. Germany and the Netherlands have pursued aggressive charging deployment alongside tax incentives, while the United States has seen fragmented state-level programs under a weaker federal framework [28, 29, 23]. These cases underscore the importance of policy alignment across scales of governance to avoid fragmented outcomes. The diversity of experiences demonstrates that there is no universal pathway to electrification. Rather, successful strategies are context-dependent, influenced by institutional capacity, market maturity, and socio-economic conditions. Gudmundsson et al. emphasize that performance should be evaluated not only in terms of adoption numbers but also against broader sustainability indicators, including equity of access, integration with renewable energy, and long-term resilience of transport systems [9]. This perspective aligns with the Transportation 5.0 paradigm proposed by Shamsuddoha et al., which argues that future mobility transitions must integrate technology, policy, and inclusivity to create sustainable, people-centered systems [22]. Table 3 highlights cross-national differences in adoption metrics. Norway continues to lead the world with more than 80% of new car sales being electric, supported by dense charging infrastructure and the highest policy strength index. The Netherlands and Sweden also report high penetration rates alongside robust public charging provision. China, despite a lower market share than Norway, accounts for the largest absolute CO_2 reductions due to its market size and rapid infrastructure expansion. By contrast, the United States exhibits relatively low adoption and weaker infrastructure density, illustrating the uneven global progress toward electrification. As illustrated in Figure 4, there is a clear correlation between strong policy environments and high adoption rates. Norway, the Netherlands, and Sweden, which maintain the highest policy strength indices, also exhibit the highest EV market shares. By contrast, countries such as the United States, with relatively modest policy interventions, lag significantly behind despite their large market potential. This underscores the pivotal role of sustained policy commitment in driving large-scale adoption.

5. Challenges and Research Gaps

Despite significant progress in the adoption of electric vehicles (EVs) and supporting infrastructure, multiple challenges persist that constrain the full realization of their sustainability potential. One of the foremost barriers remains affordability. While lifetime costs of EVs are declining due to falling battery prices and efficiency gains, the initial purchase cost continues to be higher than that of conventional internal combustion engine vehicles, particularly in developing markets. This creates equity concerns, as the benefits of electrification risk being concentrated among wealthier urban consumers, while rural and low-income communities face limited access to both vehicles and charging

Table 3: Comparative EV adoption metrics across leading markets in 2024. The Policy Strength Index combines financial incentives, infrastructure investment, and regulatory frameworks into a composite score (0–10). CO_2 reduction values are estimated cumulative impacts. Source: compiled from IEA (2024), BloombergNEF (2024), and national transportation agencies [18, 17].

Country/Region	EV Market Share (%)	Public Chargers per 100 EVs	Public Fast Chargers per 100 km Highway	Policy Strength Index (0–10)	CO_2 Emissions Reduction (MT)
Norway	83	9.2	7.8	9.5	1.8
Netherlands	62	8.3	6.2	8.7	2.3
Sweden	55	7.1	5.5	8.2	2.0
China	39	7.8	5.8	8.8	48.6
Germany	32	6.5	4.2	7.5	7.2
UK	30	5.3	3.8	7.1	5.1
France	28	5.7	3.5	7.3	4.3
US	12	3.2	1.6	6.2	22.4
Global Average	18	5.1	2.8	6.3	108.5

infrastructure [30, 9].

Charging infrastructure itself presents several persistent gaps. Deployment is heavily concentrated in urban centers and along major highways, while rural areas, multi-unit dwellings, and underserved neighborhoods remain inadequately equipped. This uneven distribution exacerbates range anxiety and reinforces patterns of exclusion from clean mobility benefits. Even in regions with substantial infrastructure, reliability challenges such as malfunctioning chargers, incompatible payment systems, and inconsistent standards hinder user confidence [30]. Addressing these gaps requires not only technical solutions but also governance mechanisms that prioritize accessibility and fairness.

The integration of EVs into existing electricity grids is another critical challenge. Without demand management, simultaneous charging can exacerbate peak load demand and necessitate costly grid reinforcements. Duan et al. demonstrate that unmanaged charging in high-adoption regions can diminish the net climate benefit of electrification by increasing reliance on fossil-based peaking power [31]. Smart charging systems, vehicle-to-grid (V2G) technologies, and dynamic pricing strategies offer potential solutions but require large-scale investment and regulatory adaptation. Ensuring compatibility with renewable energy systems is equally important for maximizing environmental gains.

Battery production and recycling raise long-term sustainability questions. The extraction of lithium, cobalt, and nickel has significant ecological and social impacts, including land degradation, water use, and labor concerns in mining regions. Life-cycle assessment studies confirm that while EVs offer reduced operational emissions, upstream production of batteries remains carbon-intensive [13, 14, 29]. Research has emphasized that effective recycling and second-life applications are essential to mitigate these impacts. Studies by Gaines [32] and Neubauer et al. [33] demonstrate the technical and economic feasibility of recycling and repurposing EV batteries for grid storage. Without advances in these areas, EV expansion risks shifting environmental burdens rather than eliminating them.

From a governance perspective, the absence of harmonized international standards for charging connectors, cybersecurity protocols, and grid integration frameworks continues to slow progress. Policy support often remains unstable, with incentives fluctuating in response to fiscal pressures or political shifts, creating uncertainty for industry stakeholders. Equity concerns also remain critical, as access to EVs and charging infrastructure is unevenly distributed across socio-economic groups and regions. Sovacool [34] highlights how poorly designed transitions risk reinforcing social inequalities, while Gudmundsson et al. [9] emphasize that sustainability performance should be evaluated through indicators that capture resilience, equity, and systemic integration. Together, these perspectives underline the importance of coordinated and inclusive governance mechanisms.

Future research should therefore address several pressing areas. First, there is a need for optimized models for siting and scaling charging networks, informed by behavioral data on user charging patterns and regional energy availability. Second, more work is required on circular economy approaches to battery lifecycle management, encompassing sustainable mining, efficient recycling, and integration of secondary-use applications. Third, socio-technical studies should investigate equity in EV adoption, focusing on how infrastructure provision, pricing, and policy can be designed to avoid reinforcing existing inequalities. Finally, systemic research is needed on the interaction between EVs, renewable energy integration, and emerging mobility paradigms such as connected autonomous vehicles, in line with the broader vision of Transportation 5.0 [22]. Together, these areas define the critical frontiers for ensuring that EVs deliver not only technological progress but also comprehensive and inclusive sustainability outcomes.

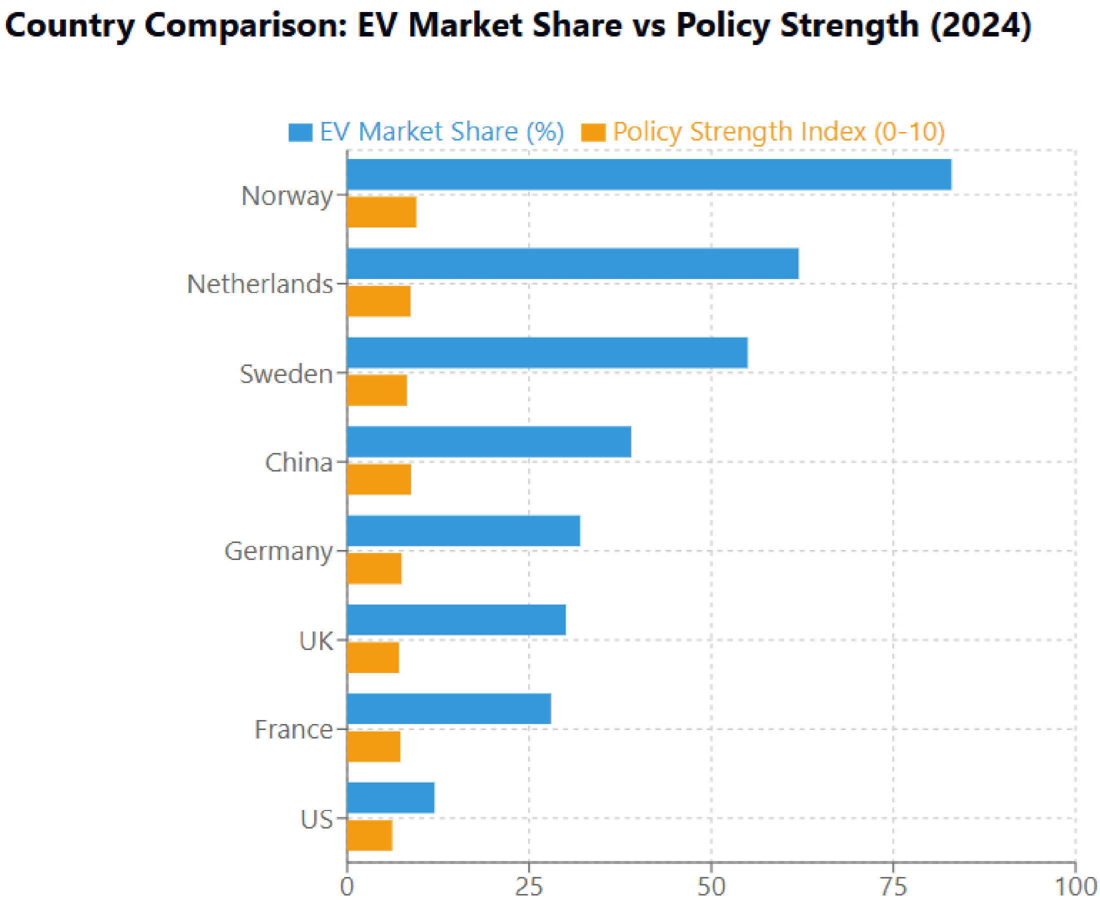

Figure 4: Comparison of EV market share and policy strength index across leading countries in 2024. Strong policy frameworks in Norway, the Netherlands, and Sweden correlate with higher EV penetration, while weaker policy environments in the US and France align with lower adoption levels. Source: compiled from IEA (2024), BloombergNEF (2024), and national transportation agencies [18, 17].

6. Future Directions

Deeper integration with smart grids hinges on bidirectional and scheduled charging. Vehicle-to-grid (V2G) systems, enabled by such technologies, can transform EVs into active components of the energy system, supplying power during peak demand and stabilizing renewable energy fluctuations. Studies show EV fleets can provide capacity and frequency support while generating revenue streams if supported by appropriate tariffs and aggregators [24, 35, 23]. To reduce user friction, emerging infrastructure such as high-power DC charging, wireless inductive charging, and even dynamic in-motion charging corridors should be evaluated for efficiency and cost at scale [36, 37]. Planning models should also co-optimize charger siting with distribution network constraints and renewable energy availability to maximize both grid stability and consumer convenience [38]. Artificial intelligence will coordinate charging, routing, and traffic control across modes. Evidence from connected and automated vehicles indicates substantial energy-saving potential from predictive eco-driving and cooperative signal timing [39]. When paired with shared autonomous fleets, AI can reduce empty miles and right-size supply to demand, complementing mass transit rather than competing with it [40]. Another important future direction concerns material sustainability and circular economy approaches. Research into solid-state batteries, sodium-ion technologies, and sustainable mining practices is advancing rapidly, but equally important is the development of efficient recycling infrastructures. Closed-loop systems that recover lithium, cobalt, and nickel for reuse will be essential to mitigate environmental impacts and resource dependency. Gudmundsson et al. highlight the need to evaluate such transitions against long-term sustainability indicators, ensuring that short-term gains in decarbonization do not result in new systemic vulnerabilities [9]. Equity and accessibility will remain central challenges for the coming decades. Without intentional design, infrastructure and policy frameworks risk deepening inequalities by concentrating benefits in urban or high-income regions. Addressing this requires deliberate strategies to expand rural infrastructure, subsidize access for disadvantaged groups, and integrate EV planning into broader social and economic development goals [30]. By aligning EV adoption with the Sustainable Development Goals, policymakers can ensure that the transition contributes not only to emissions reductions but also to social inclusion and resilience.

Long-term projections from BloombergNEF and the International Energy Agency suggest that EVs may account for 30–40% of global new vehicle sales by 2030, with continued growth thereafter [18, 17]. Yet achieving this trajectory depends on resolving the challenges of affordability, infrastructure deployment, and grid integration. Future research must therefore be multidisciplinary, bridging engineering, economics, environmental science, and social policy to build coherent strategies for scaling EV adoption. In summary, the future of EVs will be defined not only by continued technological progress but also by advances in governance, planning, and integration with emerging mobility systems. Priorities for the coming decade include scaling smart charging and V2G applications, accelerating circular economy approaches to battery materials, and ensuring equity in infrastructure access. Addressing these frontiers will determine whether EV adoption evolves into a genuinely transformative pathway for climate mitigation and sustainable urban mobility.

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Declaration of Competing Interests

The authors declare no known competing financial interests or personal relationships.

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Author Contributions

First Author: Conceptualization, Supervision, Data Analysis, Writing – Review and Editing; **Second Author**: Methodology, Validation, Investigation, Writing – Original Draft; **Third Author**: Software, Visualization, Investigation

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