Transportation Electrification and Grid Integration: Environmental Benefits, Operational Challenges, and Fleet-Level Implications

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ABSTRACT

Electrification offers significant benefits in transportation by lowering emissions and costs, especially when paired with shared mobility and automation. This paper comprehensively synthesizes recent advances in electric vehicle (EV) adoption, charging infrastructure planning, and vehicle-grid integration (VGI). Smart-charging strategies amplify EV fleets' benefits, cutting greenhouse gas (GHG) emissions. Strategic charging infrastructure planning is key to scaling EV fleet development. This work contributes by synthesizing EV charging station planning strategies and summarizing optimization-based siting and sizing approaches, comparing objectives, constraints, and algorithms. It also details the role of smart-charging strategies in lowering energy consumption and emissions, and improving grid stability. Building on this synthesis, the paper identifies challenges and outlines future research avenues, including integrated infrastructure-grid planning, behavioral shifts in emerging mobility systems, and real-time operational strategies aligned with energy market dynamics.

1. Introduction

United States energy consumption is dominated by transportation and industrial sectors, which together account for nearly three-quarters of total end-use energy, at 28 quadrillion British thermal units (Btu) (37.4%) and 26.1 quadrillion Btu (34.9%), respectively, in 2023 (1). As the global economy rapidly expands, understanding the impacts of advances in transportation technologies, especially electrification and transportation automation, on energy demand and carbon emissions becomes crucial for long-term planning. While GDP-per-capita growth is generally a key driver of energy demand, many cities and nations have decoupled that relationship. For example, Austin, Texas set a carbon neutrality goal in 2007 and reduced its carbon footprint by 75% over the following 9 years (2). This highlights the potential of coordinated policy, innovation, and energy system changes to mitigate increasing emissions despite rapid population expansion and GDP growth.

In addition, growing use of energy-intensive technologies, like artificial intelligence (AI), adds demand to the power grid. For instance, Lawrence Berkeley National Laboratory (LBNL) reported that data centers consumed 4.4% of U.S. electricity in 2023 and are predicted to consume 6.7% to 12% by 2028 (3). Dallas-Fort Worth held 141 of Texas' 279 data centers in 2024, demanding up to 0.565 GW power in 2023 simultaneously (4). These trends emphasize the need for smarter grid management to ensure reliability and integrate renewable resources, while accommodating rising demands (from vehicle and heating electrification, data centers, and industrial loads).

The shift toward EVs requires significant infrastructure upgrades and smart grid strategies to mitigate excessive pressure on already inefficient systems. It also offers a promising solution to reduce emissions, especially when integrated with renewable energy resources. Renewables are a fast-growing energy source, contributing 24% of U.S. electricity generation in early 2022, with Texas leading national renewable energy production (5). Smart-charging strategies, such as day-ahead charging and vehicle-to-grid integration, have gained attention in recent studies for their potential to optimize EV charging by aligning with renewable energy availability and dynamic grid load (6, 7). These strategies reduce emissions, mitigate grid stress, and enhance overall system efficiency.

EVs are viewed as less environmentally harmful than internal-combustion-engine (ICE) vehicles, and produce roughly half the lifetime emissions of comparable ICE designs due to embodied emissions during battery and vehicle manufacture (8, 9). Automation, electrification, and sharing technologies are impacting vehicle ownership, mode choices and travel patterns (10). Such technologies have given rise to shared autonomous vehicles (SAVs) and shared autonomous all-electric vehicles (SAEVs), which offer convenient door-to-door services as a potential alternative to conventional privately owned vehicles (POVs) (11). Meanwhile, ride-hailing platforms are transitioning to all-electric fleets in alignment with zero-emission goals and government regulations. For example, Uber is now offering SAEVs (via Waymo) in Los Angeles and Austin, and aims to expand to other cities across the U.S., Canada, and Europe by 2030, with 100% of rides and deliveries globally in zero-emission vehicles by 2040 (12). Similarly, Lyft committed to transitioning to 100% EVs to lead the shift toward zero emissions (13).

Despite these advances, transportation electrification and autonomous vehicles remain in their early stages. Considerable uncertainty remains regarding the optimal smart-charging strategies to improve total system efficiency, their impacts on energy consumption trends and environment, and appropriate policies to support the development. There is a lack of comprehensive studies on the combined impacts of ride-hailing fleet electrification, charging infrastructure, and smart-charging strategies on grid stability and emissions. This research addresses these gaps by exploring the following research questions (RQs):

RQ1: What are the environmental benefits and challenges of private vehicle and fleet electrification?

RQ2: What siting and sizing charging infrastructure methods can support large-scale EV adoption while considering operational and environmental impacts?

RQ3: What smart charging strategies can be applied, and how do they contribute to emission reduction and grid stability?

The contributions of this work are threefold. First, it provides a comprehensive review of alternative fuel vehicles' environmental impacts and delineates how emerging technologies and innovative strategies shape energy consumption and emissions. Second, it summarizes the potential of smart-charging strategies, such as day-ahead charging and vehicle-to-grid approaches, to optimize fleet operations, reduce emissions, and enhance grid stability. Third, it proposes future research directions to bridge gaps in charging infrastructure planning, fleet electrification, and integration of renewable energy resources. By exploring the interplay among those elements, this work supports policymakers, fleet operators, and researchers in designing strategies that enhance grid resilience, reduce emissions, and accelerate the transition to a sustainable and low-emission transportation future.

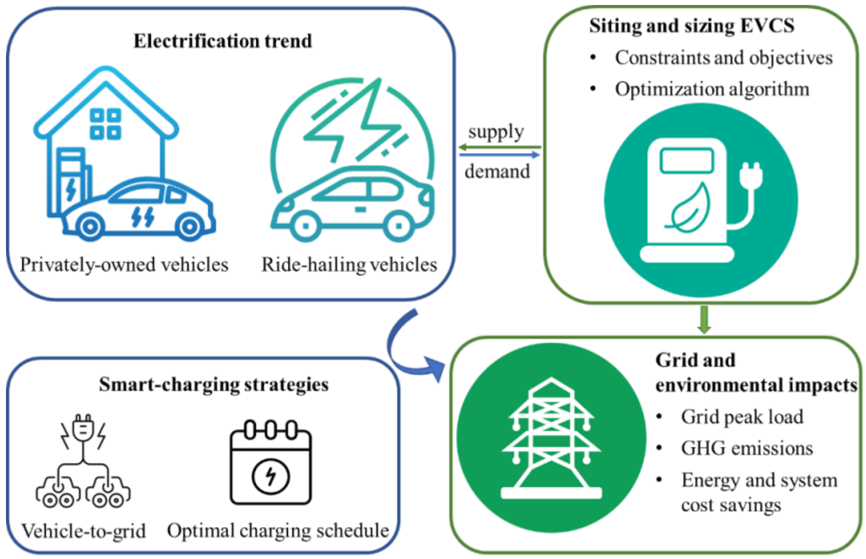

Figure 1. Contents of Paper Review

Figure 1 illustrates the structure of this review. The following section provides an overview of transportation electrification trends, focusing on privately owned vehicles, the integration of automation in ride-hailing, and their environmental impacts. Section 3 discusses charging infrastructure planning strategies, covering key constraints considered, objectives, and optimization methods for siting and sizing EVCS. Section 4 reviews smart-charging strategies and their impacts on grid performance, energy, and the environment. Section 5 outlines future research opportunities and potential solutions, followed by conclusions and recommendations summarized in Section 6.

2. Transportation Electrification Trend and Impacts on the Environment

This section explores the electrifying trend in transportation, focusing on both POVs and ride-hailing fleets. Advances in technology, policy incentives, and shifting consumer preferences are driving EV adoption, but challenges like infrastructure gaps, grid integration, and lifecycle emission persist. The following subsections highlight the opportunities and challenges associated with widespread electrification by synthesizing recent adoption trends, environmental impacts, and operational considerations.

2.1 Electrification of Privately Owned Vehicles

The electrification of POVs is an important component of transportation decarbonization, driven by advances in battery technology, financial and government incentives, and growing infrastructure support. The global EV market is expanding rapidly, with nearly 14 million new EVs registered in 2023, with 95% of them in China, Europe, and the United States, bringing the total to 40 million worldwide (14).

Battery electric vehicles (BEVs) offer significant environmental benefits compared to internal combustion engine (ICE) vehicles, primarily by greatly reducing fossil fuel dependence. The U.S. Department of Energy (15) highlights the efficiency advantage of electric motors, which convert over 77% of grid electricity into usable power, compared to gasoline vehicles, which achieve only 12-30% of the energy stored in gasoline to power at the wheels. Despite the growing adoption trend, consumer hesitation persists. Several factors influence the pace of POV electrification, including vehicle costs, charging accessibility, range anxiety, and consumer attitudes. (16) highlighted that while EV adoption has progressed significantly over the past decade, many consumers still prefer gasoline-powered vehicles due to concerns over range and charging infrastructure. Based on a U.S. stated preference survey of over 1,300 respondents, it was found that perceived advantages of BEVs and range anxiety have a statistically significant impact on purchase intentions. Similarly, (17) emphasized that BEVs will become acceptable to most households when three key conditions are met: an all-weather range exceeding 500 km (300 miles), convenient Level 2 overnight charging at home, and accessible fast charging for long journeys. Under these conditions, up to 98% of conventional vehicles could be replaced, electrifying 90% of personal vehicle travel. (18) estimated that private EVs with uncontrolled charging can reduce GHG emissions by 46% compared to gasoline vehicles, while controlled charging can achieve a 49% reduction and reduce peak charging demand by 53%. In addition, (19) results showed that fully managed charging can reduce system costs by 2% with relatively lower need for battery storage compared to unmanaged charging. Furthermore, (20) projected that EV adoption, coupled with grid decarbonization, could reduce CO_2 emissions per mile to between 84 g and 93 g by 2035, depending on adoption rates.

Despite these benefits, battery production, end-of-life recycling, and clean energy sourcing remain major concerns (21, 22). (23) identified driving and charging obstacles, as well as consumer willingness to pay, as additional key barriers to EV adoption. (24) further categorized these challenges into infrastructure, cost, energy transition, and market-related issues. For instance, the sparse charging network and higher upfront costs of EVs compared to ICEVs continue to hinder widespread adoption. Additionally, the integration of EVs into the electricity grid poses operational challenges. (20) warned that rapid EV adoption could increase peak net electricity demand by up to 25% by 2035, with a 50% increase under full electrification scenarios. This underscores the need for optimized charging controls and infrastructure build-out to mitigate grid strain.

POV electrification brings environmental benefits, including reduced GHG emissions and improved energy efficiency. However, addressing operational challenges such as grid stability, renewable resources integration, and consumer adoption barriers, is essential to fully realizing its potential. With continued advancements in battery performance, policy support, and grid integration strategies, POV electrification is expected to play an important role in achieving net-zero emission targets.

2.2 Emerging Technology with Ride-hailing Fleet Electrification

Synergy among sharing, automation, and electrification drives significant reduction in GHG emissions in the transportation sector. According to the McKinsey ACES survey, 56% of consumers are willing to replace private vehicle trips with shared autonomous vehicles (11). This shift is already underway; for example, Waymo has partnered with Uber's platform to serve ride requests with SAEVs in Austin and Atlanta city, and has operated 24/7 in San Francisco, Phoenix, and Los Angeles (25). The environmental benefits brought by this transition are substantial, including clear reductions in CO2 emissions, reduced noise pollution, and decreased energy consumption (26)

SAVs simplify vehicle access, avoid parking cots, and reduce fleet size, enabling them to meet diverse travel demands and remaining competitive in the ride-hailing market (27). Electrification further enhances these benefits, as EVs are more energy-efficient, reliable, and environmentally friendly, especially when paired with renewable energy resources (27, 28). (29) demonstrated that widespread SAV adoption accelerated EV market penetration, largely lowering costs and emissions. (30) found that each SAV could replace around 10 conventional vehicles, reducing energy use by 16% and volatile organic compound (VOC) emissions by 48% per person-trip. Further work by (31) estimated that energy use could decline by 55% with widespread SAV deployment. Additionally, (32) predicted the strategic development of an electrified autonomous fleet in Austin, Texas could slash cumulative energy and GHG emissions by up to 60%. (33) expanded on these findings, showing that appropriate SAV pricing strategies could reduce PM2.5 emissions and energy consumption by 56% to 64% and 53% to 61%, respectively, with electrification boosting these reductions to 76% and 74%.

Centrally managed SAEV fleets could deliver services comparable to those conventional ride-hailing companies, but at lower costs and significantly reduced GHG emissions. (34) found that a 200-mile range

SAEV could replace 5.5 POV, serving 96% to 98% of trips requests with an average wait time of 7 to 10 minutes. Similarly, (18) estimated that an SAEV fleet just 9% the size of existing active vehicle fleet could meet travel request, lowering lifecycle costs to 41% of a private EV fleet while cutting GHG emissions by 70%.

Table 1, along with Figure 2, compares CO_2 across various transportation modes, highlighting the benefits of electrified transportation. Among passenger modes, air travel has higher emissions–business class emits roughly 1.28 lb of CO_2 (triple than that of economy), and first class emitting roughly 4 times as much (35). In contrast, e-bikes are ideal choice for short trips, emitting just 0.05 lb CO_2/VMT (36) due to minimal electricity consumption. While BEVs may produce no tailpipe emissions, their manufacturing and charging processes still generate GHG. On average, gasoline cars emit 0.77 lb CO_2/VMT, while BEVs (0.44 lb CO_2/VMT) and plug-in hybrid EVs (0.57 lb CO_2/VMT) emit less (37). Traditional ride-hailing services in the U.S. and Canada produce 0.75 lb CO_2/PMT, while Europe's higher proportion of EVs reduces this to 0.43 lb (38). Diesel transit buses average 0.34 lb CO_2/PMT (emissions fall as occupancy rises), whereas the electric buses emit less at 0.26 lb CO_2/PMT on average (39). It's important to note that diesel vehicles and coal-based electricity cause significant PM2.5-related health damages, worsening their environmental impacts. In contrast, simulations in the Austin 6-county region, Texas showed that SAEVs can achieve zero-carbon mobility when paired with renewable energy, offering a significant advantage over gasoline-powered vehicles and traditional ride-hailing services (28).

Table 1. CO2 emissions by transportation mode

Mode Type	**Specific Mode**	**CO2 (lb) per passenger- (or vehicle-) mile**	**Notes**	**Source**
Car	Gasoline car	0.77/VMT	•Location: US •Avg vehicle occupancy (AVO): 1.5 •Life-cycle emissions	(37, 40)
	Plug-in hybrid EV	0.57/VMT		
	BEV	0.44/VMT		
Rail	Diesel passenger train	0.319/PMT	•Location: Europe •Avg occupancy rate (AOR): 35%	(39, 41)
	Electric passenger train	0.174/PMT		
Ride-hailing	Ride-hailing (Uber in US and Canada)	0.75/PMT	•Location: US and Canada	(38)
	Ride-hailing (Uber in Europe)	0.43/PMT	•Location: Europe	
Air	First class	1.76/PMT	•Location: Europe •Avg occupancy rate: 70%	(35, 41)
	Business class	1.28/PMT		
	Economy class	0.44/PMT		
Bike	E-bike	0.05/VMT	•Life-cycle emissions	(36)
	Motorbike	0.4/VMT	•Average size •Avg occupancy: 1.2	(40, 42)
Bus	Electric bus	0.26/PMT	•Location: Europe •Avg bus occupancy: 7.5	(39, 40)
	Diesel bus	0.34/PMT		

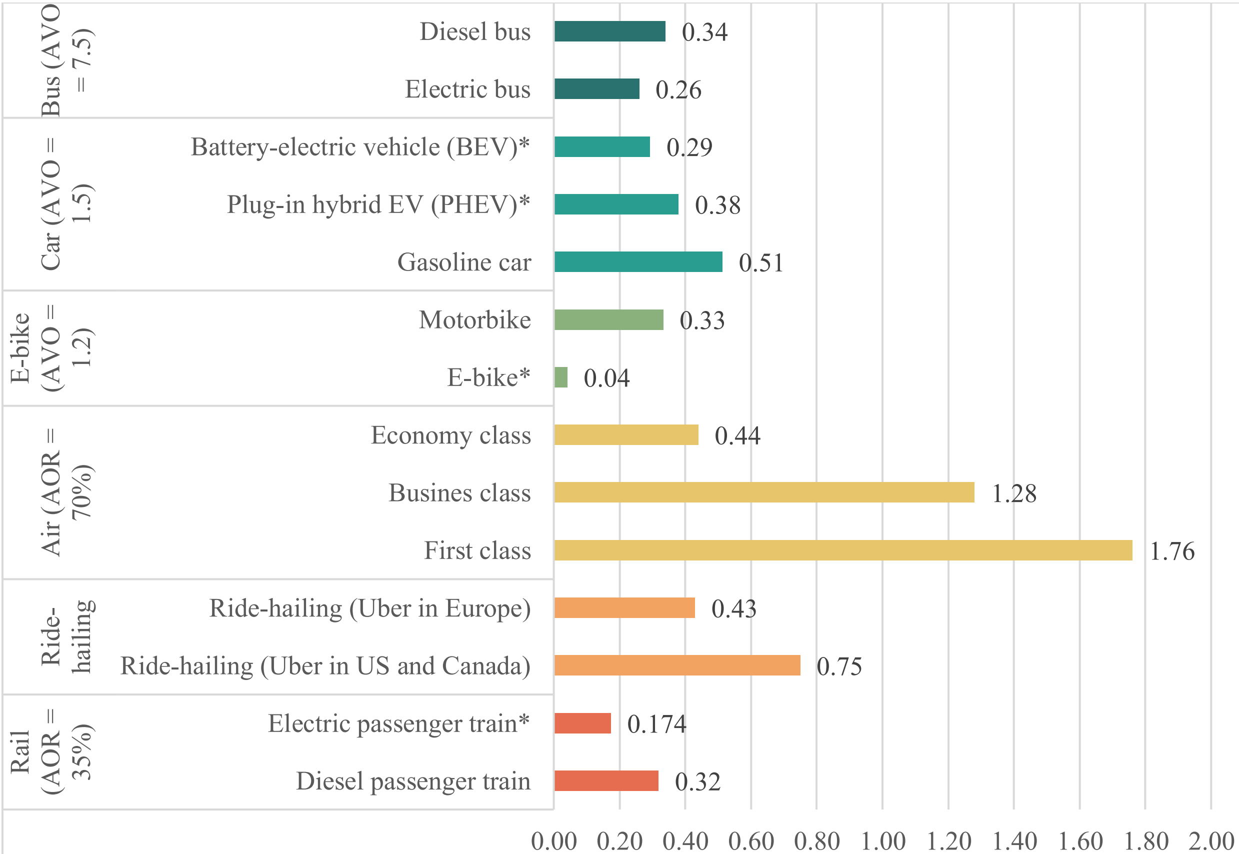

Figure 2. CO2 emissions in pounds per passenger-mile traveled by mode (* asterisked modes are life-cycle emissions)

3. Siting and Sizing Charging Infrastructure

Figure 3 shows a typical workflow for siting and sizing charging infrastructures, widely used in recent literature. Infrastructure planning involves integrating multi-dimensional inputs, including spatial data (e.g., land use patterns, road networks, points of interest), socio-economic factors (e.g., EV adoption rates and household data), and energy system parameters (e.g., power supply information). These inputs shape key constraints like candidate site locations, land use regulations, budget limits, service levels (e.g., queuing length and wait time), and grid capacity. Planners typically aim to minimize total development and operation costs while maximizing operator benefits, enhancing service efficiency and quality, and improving environmental outcomes. Optimization is achieved through heuristic or analytical methods (e.g., genetic algorithms, GIS-based modeling, or multi-criteria decision analysis), yielding EVCS locations and their outfitted plugs, cost estimations, and performance metrics.

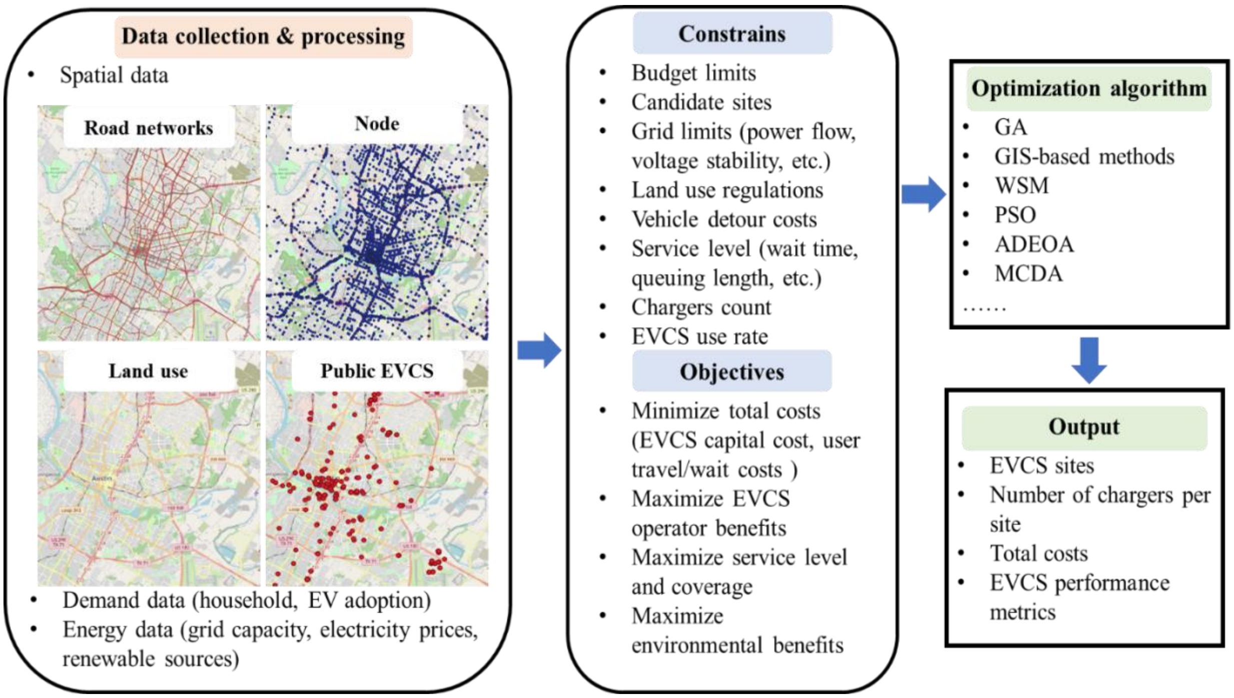

Figure 3. EV Charging Station (EVCS) siting and sizing optimization flowchart (with Austin, Texas in 4 example images)

This generalized workflow is adaptable to various strategic siting approaches as summarized in Table 2. Expanding EV charging access by sharing chargers at electric bus (e-Bus) depots, households, and multi-unit dwellings (MUDs) can enhance charger use, reduce reliance and congestion at public EVCS, and bridge residential charging gaps. Co-location strategies, including integration with streetlights, public EVCS, parking lots adjacent to shopping and workplaces, and gas stations, can lower deployment cost, increase convenience, and promote efficient land use. Highway fast-charging corridors further support long-distance travel. Each strategy brings distinct benefits, collectively fostering a more accessible and user-friendly charging ecosystem.

Table 2. EV Charging Station (EVCS) siting strategies

Strategic approaches	Place	Description	Benefits	References
Shared charger access	e-Bus depots	Opening e-Bus depots & chargers to public to maximize use.	• No disruption to e-bus operations. • Extra revenue for e-bus operators. • Meet >97% of private EVs' charging demand.	• (43)
	Household	Encourage households to open & share their private chargers to public.	• Increase parking events with charging access. • Reduce private EV users' reliance on public EVCS. • Complementary role with public fast-charging EVCS.	• (44) • (45)
	Multi-unit/multi-family dwellings (MUDs)	Introduce community charging hubs in parking lots with shared chargers to address home-charging barriers for residents.	• Faster charging hub turnover with compact schedule. • Bridge charging supply gap.	• (46)

Co-location with existing infrastructure	Streetlights	Integrate chargers with streetlights to reduce installation costs & use existing grid connections in urban areas where space is limited.	• Expand charging access for residents without private parking. • Require solutions for power supply limitations.	• (47)
	Battery swapping stations (BSS)	Co-construction BSS & charging piles.	• Support rapidly adoption of BEVs & provide forward-looking insights for battery swapping services.	• (48)
	Public EVCS	Co-locate fleet-owned charging stations with existing public EVCS to achieve cost-sharing during construction & cord-sharing during use.	• Enable more simultaneous charges & reduce charging congestion at public EVCS. • Minimize charging delays for both private EVs & EV fleets. • Avoid duplicate infrastructure (save huge investment costs).	• (49) • (50)
	Parking lots	Install chargers in commercial/public parking lots to serve drivers while they park.	• Optimize revenue while enhancing customer convenience. • Increase property value & attract potential investors.	• (510
	Gas stations	Integrate EV chargers with gas station to use existing public infrastructure.	• Use high-traffic locations & existing amenities (e.g., quick-service stores, restrooms). • Align existing consumers' refueling habits. • Balance decline of gas station services while ensuring efficient use of public infrastructure.	• (52) • (53)
	Workplaces	Deploy chargers at workplace to support employee EV adoption & daytime charging demand.	• Building energy savings (e.g., daylighting control) can facilitate EV charging alongside office building loads. • Supports employees, especially renters, by providing daytime charging when renewable energy is sufficient. • Alleviate range anxiety, making EV adoption more practical.	• (54) • (55)
Long-distance & mobility hub charging	Highways as fast-charging corridors	Deploy DC fast chargers along major travel corridors.	• Ensure a seamless long-distance travel experience for EV drivers. • Establish a convenient & reliable national EV charging network for all drivers. • Minimize recharge downtime & help save travel time.	• (56)

Charging infrastructure siting methods are typically categorized into node-based, path-based, and tour-based approaches (57, 58). Node-based models are the most widely used, placing stations at candidate sites to serve demand at network nodes. Commonly applied methods include the set covering location model (SCLM), maximum covering location model (MCLM), and p-median model. For instance, (59) applied the p-median model to minimize average distance between demand points and the nearest station, while (60) integrated SCLM, MCLM, and the flow intercept location model (FILM) to optimize station placement along the United Arab Emirates (UAE) highways for maximum coverage with minimal infrastructure. The second is path-based models, which locate stations along high-flow routes using origin-destination (OD) data rather than node demand. (61) introduced the flow capturing location model (FCLM) to capture the maximum flow between OD pairs, later extended by (62) into the flow refueling location model (FRLM) to account for multiple charging stops. The tour-based models rely on the user behavior data, such as vehicle routes and waiting times; for example, (63) used truck trip GPS data from southeast Queensland with MCLM to site charging stations for a short-haul electric truck fleet. However, tour-based approaches are often challenging to scale for nationwide infrastructure planning due to data availability and privacy concerns (58). Table 3 summarizes typical methods for siting and sizing EVCS, highlighting their subtypes, strengths, and limitations. Recent studies applying those methods for facility location are summarized in Table 4. The optimization phase in studies typically involves multi-objective functions, aiming to minimize costs (e.g., infrastructure, detour, waiting) while maximizing coverage and benefits, as demonstrated by studies using methods like genetic algorithm (GA) (64, 65), weighted-sum method (WSM) (66), particle swarm optimization (PSO) (67), and multi-criteria decision analysis (MCDA) (68).

Table 3. Typical methods for siting and sizing EVCS

Category	Subtypes	Advantages	Disadvantages
Optimization-Based Methods	• Linear Programming (LP) • Mixed-Integer Linear Programming (MILP) • Nonlinear Programming (NLP) • Multi-objective Optimization	• Optimal solutions under constraints • Handles multi-objective tradeoffs • Suitable for grid load limit, budget-constrained, and location-specific planning	• Computationally expensive for large networks • Requires accurate input data • Classical models (e.g., LP, MILP) may oversimplify real-world dynamics & uncertainty
Heuristic and Metaheuristic Methods	• Genetic Algorithm (GA) • Particle Swarm Optimization (PSO)	• Scalable & easy to solve large-scale problems • Flexible & adaptable • Finds good solutions quickly	• No global optimality guarantees • Depends on parameter tuning
Geographic and Demand-Based Methods	• GIS-based methods • Set Covering models • P-median & p-center models • Clustering	• Intuitive & spatially rich • Useful for maximizing coverage • Support visualization	• Lack of temporal or behavioral dynamics • Limited grid capacity consideration
Simulation-Based Approaches	• Agent-Based Simulation • Travel Demand Simulation • Distribution Power Flow Simulation	• Captures dynamic interactions • Enables scenario testing under policy, travel mode, or pricing changes	• Computationally intensive • Data-hungry • Not inherently optimization-driven
Machine Learning Methods	• Regression • Clustering Algorithms (e.g., K-means) • Neural Networks (NN)	• Learn patterns from real-world data • Adaptive to behavioral trend • Effective demand forecasting	• Needs large & high-quality datasets • limited interpretability • Not inherently constraint-aware or optimal

Table 4. Modeling approaches for EVCS siting and sizing in recent studies

Candidate sites	Objective	Constrains considered	Method	References
Yes	Maximize the weighted sum of the EVCS siting selection criteria	• Distance between two EVCS	WSM (weighted-sum method)	(66)
Yes	Minimize upper-level cost (infrastructure, distance and queueing waiting costs)	• Finite queue length • Charging detour distance	Genetic algorithms (GA)	(64)

No	Place EVCS to the road segment with top ranked utility	• Available EV range • Installation preferences	Multi-crit. decision analysis (MCDA)	(68)
No	Maximize EVCS benefits, minimize voltage deviation rate, users' wait time, and detour costs	• System power flow • Node voltage amplitude • Service radius • Charging queuing time • Number of EVSEs in each EVCS • EV user charging requirement	Adaptive differential evolution optimization algorithm (ADEOA)	(69)
Yes	Minimize the costs (capital expenditure + charging costs) and maximize the coverage	• Demand • Distance between the charging station • Number of facilities in each charging station	GIS-based multi-objective PSO	(67)
No	Minimize the average distance between charging demand points and the nearest station	• Station capacity • reachability	K-means and hierarchical clustering algorithm	(59)
No	Minimize total building cost, charging cost, and environmental costs	• Charging demand and power supply • Charging detour distance • Charging station use	Genetic algorithms (GA)	(65)

4. Impacts of Smart-Charging Strategies on Grid and Emissions

Transportation systems and energy networks are deeply interconnected, each shaping the other's efficiency, sustainability, and resilience. As the transportation sector increasingly shifts toward electrification, its reliance on energy systems grows. Meanwhile, EVs can serve as flexible energy storage units through technologies like smart-charging to support grid stability. The integration of diverse renewable energy resources, such as solar and wind, enhances grid flexibility, making the cooperation between transportation and energy important for sustainable development.

EVs typically operate under three charging modes: disorderly charging (V0G), scheduled unidirectional orderly charging (V1G), and bidirectional charging and discharging (V2G) (70). V0G is commonly seen in residential settings, where users plug in their EV immediately upon arrival, potentially causing grid demand spikes. V1G introduces smart scheduling (e.g., shift charging to off-peak periods when renewable energy is abundant), while V2G allows EVs to feed energy back to the grid during peak demand or power shortages. In a typical residential community with 100 EVs per 1000 people, disorderly charging can increase the peak load by 17.1%, whereas V2G, even with a participation ratio of 30%, significantly reduces the load range by 74.8% (70). Aligning these smart-charging strategies with renewable resource generation is important to reduce carbon emissions and achieve less unsustainable energy management. For instance, (71) applied the EVI-Pro Lite model to project EV charger requirements in Texas, showing how solar photovoltaics (PV) and wind turbines (WT) can meet the energy demands of EV charging infrastructure, achieving net-zero energy performance. (72) found that V2G encourages EVs to charge during low-price periods and discharge during high-price periods, thereby mitigating electricity price fluctuations. This mode can substitute 22.2% to 30.1% of energy storage and accelerate the phase-out of coal-fired power. However, V2G becomes viable only when the renewable energy penetration rate reaches 80%, and it notably reduces the peak net load during the early morning and night while increasing the valley load at night. Increasing the fast-charging infrastructure development will further strengthen these benefits.

The environmental and economic advantages of V2G are substantial. (73) highlighted that SAEV fleets, particularly those with larger battery capacities, can save up to 35.8% in GHG emissions and 41.4% in energy consumption compared to traditional AV fleets. Providing V2G service with a 75-kWh battery can save an average of 66.5 tons of GHG emissions per vehicle annually, while a 25-kWh battery can reduce energy use by 46.8%. Prior study also shows that SAEV fleets could reduce both charging costs and emissions, charging costs by at least 10% and emissions by at least 16% (74).

From an economic standpoint, V2G offers substantial financial incentives, with (73) estimating V2G implementation to yield $2,272 per SAEV annually. (6) simulated how SAEVs reduce peak electricity demand and emissions using a multi-stage optimization that integrated day-ahead charging schedules with real-time vehicle dispatch decisions. Their integration allowed fleet operators to align vehicle charging and discharging activities with fluctuating electricity prices and grid emissions. Simulation results showed how price-agnostic charging strategies added 29.6 MW (1.05% of peak demand) to the Austin, Texas power grid. In contrast, their multi-stage charging and discharging strategy reduced peak demand by 38%, avoiding the daily release of up to 43.6kg CO_2 per SAEV, on average. (75) predicted EV market share and assessed V2G revenues and emissions across five independent system operator (ISO) or regional transmission organization (RTO) regions. Their results in the PJM region showed that if 1% of EVs provided V2G services by 2030, the regional CO_2 emissions would be reduced by 500,000 tons per year.

(76) used real trajectory data with 19,900 electric taxis (ETs) in Shenzhen, China for V2G potential and resilience analysis. Their ET-V2G system was able to deliver flexible power outputs (e.g., 20 to 50 MW for 1 to 3 hours) while recovering within the next 2 to 3 hours without disrupting the fleet's regular operations. They also found at least 20% of the ET fleets always remained connected to the grid, with a peak of 50% during the morning peak hours. This highlights the potential of V2G to enhance grid resilience and support renewable energy integration. Overall, the growing interdependencies between transportation and energy systems underscore the important role of EVs and smart-charging strategies. While their benefits are widely recognized, implementation remains hindered by technical limitations and regulatory challenges (77, 78).

5. Future Research Directions

The rapid electrification of transportation and its integration with power grids present numerous opportunities for innovation. Despite this, several critical research gaps remain. Addressing these gaps can enhance grids' resilience, optimize infrastructure deployment, and maximize environmental benefits. This section outlines promising directions for future work.

5.1 Integrate Infrastructure Planning and Dynamic Fleet Sizing

Recent studies often treat fleet size as an exogenous variable, relying on empirical data or assumptions rather than dynamic system interactions. Future work can integrate system dynamics (SD) modeling with simulation frameworks to endogenously estimate fleet sizes in response to socio-economic trends, travel pattern changes, and charging behavior shifts. The feedback loop between fleet simulation and infrastructure planning can iteratively adjust fleet size and charging requirements until system convergence is achieved. This approach would provide insights into cost-effective optimal fleet configurations and infrastructure settings, and long-term system equilibrium under varying policy and behavioral scenarios.

5.2 Behavioral Shifts and Environmental Trade-offs in Emerging Mobility Systems

The rise of SAVs and SAEVs may trigger significant changes in travel behavior, including mode and charging patterns shifts, and increased vehicle-miles traveled (VMT). However, studies examining the behavioral and environmental implications of these changes remain limited. Future research should explore the interplay of traveler preferences, travel and charging patterns, and system-wide modal shifts, particularly under mixed conditions involving human-driven, electric, and autonomous vehicles. For example, integrating activity-based travel demand models with life-cycle assessments (LCAs) to evaluate how SAEV adoption influences emissions, energy consumption, and charging infrastructure needs under different adoption scenarios.

5.3 Optimal Charger Mix Considers Charging Behavior

While DCFC is essential for efficient fleet operations and long-distance travel, high costs may deter private EV owners from frequent use. Conversely, Level 2 charging is more economical but may not meet fleet efficiency requirements (e.g., lower charging downtime) to remain competitive in the ride-hailing market. Future research should assess how to optimize charging infrastructure, especially at shared charging facilities, considering fleet charging schedules, private EV user preferences and willingness to pay, and grid impact and infrastructure costs. Multi-objective optimization framework can balance cost, user satisfaction, and grid stability while determining the ideal charger mix.

5.4 Integrated Planning of Power Grid and Charging Infrastructure

Many existing studies on EVCS planning lack detailed grid constraints or overlook the feasibility of grid upgrades; similarly, power system models often fail to include practical EVCS demand predictions and urban spatial limitations (79, 80). An integrated planning approach is needed that jointly considers fleet and private EV charging demand, grid hosting capacity, and siting and sizing charging infrastructure. Such co-planning ensures that charging infrastructure expansion aligns with grid modernization efforts to enhance deployment feasibility and grid resilience.

5.5 Smart Operational Strategies for EV-Grid Integration

While day-ahead charging and discharging strategies have shown promise in aligning EV behavior with electricity markets, real-time operational models for EV-grid integration remain underdeveloped. A promising direction lies in developing real-time decision-support tools that dynamically respond to grid emissions, electricity price fluctuations, and renewable energy availability. Incorporating short-term forecasts of renewable generation, traffic conditions, and grid contingencies (e.g., outages or congestion) can significantly enhance the resilience and effectiveness of EV fleet operations, enabling them to provide more responsive and robust grid support services.

5.6 SAEVs' Penetration within Ride-hailing Fleets

Conventional vehicles, SAVs, and SAEVs offer distinct advantages in meeting ride-hailing demand. Conventional vehicles and SAVs, often powered by ICE or hybrid systems, alleviate concerns about range limitations and are well-suited for long-distance trips. In contrast, SAEVs lower emissions and operational costs while enabling integration with grid services. SAEVs can also be optimized for scheduled charging and energy market participation, potentially offsetting charging downtime with revenue-generating grid services.

The penetration rate of SAEVs, defined as the proportion of these vehicles within the total ride-hailing fleet, is an important factor influencing the fleet operation. High SAEV penetration may bring environmental benefits and cost savings, but also intensifies demand for charging infrastructure and grid power. Conversely, lower penetration levels may reduce these challenges but limit system-wide benefits. Future research should optimize fleet compositions by balancing SAEV sustainability benefits against ICE vehicles’ flexibility under varying service demand patterns, grid constraints, and technology adoption scenarios to assess their implications on fleet efficiency, cost, and performance.

6. Conclusions

This paper synthesizes recent advances and ongoing challenges associated with EVs, from the adoption trend to charging infrastructure planning and smart-grid integration, while identifying key research gaps for future investigation. Recent studies show that ride-hailing fleets composed of autonomous and all-electric vehicles further amplify benefits transportation electrification, reducing cumulative energy use and emissions.

Smart-charging strategies present huge potential in enhancing these gains. Ride-hailing EV fleets with V2G capabilities can achieve reductions in GHG emissions and energy use compared to the conventional fleet, and optimized charging schedules can further mitigate grid peak demand. However, V2G's attractiveness depends on high renewable energy penetration (≥80%), highlighting the need for improving grid-transportation coordination. This work categorizes optimization approaches for siting and sizing of EVCS, along with strategic planning methods, which are important to scale EV adoption cost-effectively. Integrating these strategies with dynamic fleet operations and real-time market conditions remains challenge. The future research directions outlined in this paper, ranging from optimal charger mix and behavioral modeling to integrated infrastructure planning with the grid, highlight the need for solutions that span transportation planning, power grid, and data-driven optimization.

Overall, achieving a sustainable and resilient EV system will require coordinated planning efforts across sectors and scales. Aligning transportation electrification with renewable energy supply, technological evolution, and grid upgrade could unlock environmental benefits while enhancing mobility services in both urban and regional contexts.

7. Author Statement

Lin Su: Writing – Original draft, resources, conceptualization. **Kara M. Kockelman**: Writing – Review & editing, Supervision, Funding acquisition, Conceptualization.

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