

The Energy Efficiency of Electric Vehicle Charging Stations with Minimal Grid Impact

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Introduction

Electric mobility has emerged as a pivotal component of global decarbonization and sustainable transport strategies. Beyond the replacement of internal combustion engines with electric drivetrains, it represents a profound systemic transformation—a reconfiguration of the relationships between energy systems, transportation networks, and urban infrastructures. This transition demands a holistic perspective that integrates engineering innovation, energy policy, behavioral adaptation, and spatial planning.

The global electric vehicle (EV) market continues to expand at an unprecedented pace. With more than 14 million units sold in 2023, EVs accounted for nearly 18% of all new car sales worldwide [1,2]. This rapid growth reflects a convergence of structural drivers [1]:

- **Technological progress:** The technological evolution underpinning electric mobility has been nothing short of transformative. At the heart of this progress lies the rapid advancement in battery technology, particularly lithium-ion cells. Over the past decade, battery costs have plummeted by nearly 90%, dropping from over USD 1000 per kilowatt-hour in 2010 to less than USD 130/kWh in 2023. This cost reduction, coupled with improvements in energy density, has enabled EVs to achieve ranges exceeding 500 km on a single charge—once considered unattainable for mainstream vehicles [3,4]. Beyond cost and range, charging speed has emerged as a critical innovation driver. Ultra-fast DC chargers now deliver up to 350 kW, reducing charging times to under 20 min for most modern EVs [5,6]. This technological leap addresses one of the primary consumer concerns: convenience. Simultaneously, advancements in thermal management systems and solid-state battery research promise even greater safety, longevity, and performance in the near future. Complementing battery improvements are breakthroughs in power electronics and drivetrain efficiency. High-efficiency inverters, silicon carbide (SiC) semiconductors, and regenerative braking systems have collectively enhanced energy utilization, reducing losses and improving overall vehicle performance. These innovations not only extend driving range but also lower operational costs, reinforcing the economic case for EV adoption. Puma-Benavides et al. [7] proposed a methodology to enhance Extended-Range Electric Vehicles (EREVs) through the integration of an auxiliary power unit and an advanced control strategy based on the Equivalent Consumption Minimization Strategy (ECMS). Rather than increasing battery size—which adds cost and weight—their approach optimizes the entire powertrain to improve efficiency and extend range. Experimental results show that ECMS-based control can increase driving distance by up to 39% under standardized cycles, while maintaining low emissions and fuel



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consumption. This work illustrates how intelligent energy management and modular hardware integration can overcome range limitations, reinforcing the imperative of system-level optimization for sustainable mobility.

- **Regulatory pressure:** Regulatory frameworks have been one of the most decisive forces accelerating the transition to electric mobility. Governments worldwide are implementing stringent emission standards that limit greenhouse gas outputs from internal combustion engine (ICE) vehicles. These standards often escalate annually, making compliance increasingly costly for manufacturers and incentivizing the shift toward zero-emission alternatives [8,9]. In parallel, zero-emission vehicle (ZEV) mandates have emerged as powerful policy instruments. Jurisdictions such as California and the European Union require automakers to achieve specific quotas of ZEV sales or face substantial penalties. These mandates create a predictable market signal, encouraging investment in EV technologies and infrastructure. Another critical lever is carbon pricing, which internalizes the environmental cost of fossil fuel consumption. Through mechanisms like carbon taxes or cap-and-trade systems, governments make ICE vehicles less economically attractive compared to EVs. This approach not only reduces emissions but also generates revenue that can be reinvested in clean transportation initiatives. Beyond direct regulation, incentive schemes amplify the impact of these measures [8]. Purchase subsidies, tax credits, and exemptions from road tolls or congestion charges lower the upfront cost barrier for consumers. Meanwhile, fleet electrification targets for public transport and corporate fleets accelerate adoption at scale. Finally, long-term bans on ICE vehicles—already announced by several countries for 2035 or earlier—send a clear signal to markets and consumers: the future of mobility is electric [9]. These regulatory pressures collectively create a robust policy environment that complements technological progress and societal awareness, ensuring that EV adoption is not just a trend but an irreversible trajectory toward decarbonization.
- **Societal awareness:** Societal awareness has emerged as a powerful catalyst for the global transition to electric mobility [10]. Increasing public concern over climate change, air quality, and energy security has reshaped consumer preferences, making sustainability a key determinant in purchasing decisions [11,12]. This shift is reinforced by the growing visibility of environmental issues—wildfires, extreme weather events, and urban pollution—which have heightened the urgency for low-carbon solutions. Environmental consciousness is not limited to individual choices; it influences corporate strategies and public policy. Companies are adopting ESG (Environmental, Social, and Governance) principles, committing to carbon-neutral operations and electrified fleets. Similarly, cities and municipalities are promoting clean transportation through low-emission zones and incentives for EV adoption, aligning local actions with global climate targets. Energy security concerns also play a critical role [13]. Geopolitical tensions and volatility in oil markets have underscored the vulnerability of fossil fuel dependence. EVs offer a pathway to reduce reliance on imported petroleum, leveraging domestic renewable resources and enhancing resilience against supply disruptions. This narrative resonates strongly in regions seeking to balance environmental goals with economic stability. Moreover, the rise of digital platforms and social media amplifies awareness campaigns, accelerating behavioral change. Consumers are increasingly informed about lifecycle emissions, battery recycling, and the broader sustainability implications of their choices. This transparency fosters trust and drives demand for cleaner technologies, creating a feedback loop that reinforces market growth.

However, the accelerating electrification of transport also poses systemic challenges that extend beyond the automotive sector. The surge in electricity demand for vehicle charging introduces unprecedented stresses on grid operation, requiring utilities to manage higher peak loads and maintain voltage stability. This challenge is compounded by the temporal mismatch between renewable generation—often intermittent and weather-dependent—and the dynamic consumption patterns of EV users. Without effective coordination, these discrepancies can lead to inefficiencies, curtailment of renewable energy, and increased reliance on fossil-based backup generation, undermining decarbonization goals [14].

In addition to grid-related concerns, the intensifying competition for critical raw materials such as lithium, nickel, and cobalt raises questions about supply chain resilience and geopolitical dependencies. These materials are essential for battery production, yet their extraction and processing carry significant environmental and social impacts. As demand escalates, ensuring sustainable sourcing and ethical practices becomes imperative. Furthermore, the end-of-life management of batteries is emerging as a central issue within the circular economy paradigm. Recycling technologies, second-life applications, and closed-loop systems must advance rapidly to prevent resource depletion and minimize waste [15].

Historically, approaches to EV infrastructure have prioritized the quantitative expansion of charging points—measured in sheer numbers. While this strategy addressed early adoption barriers, it is no longer sufficient. As EV penetration grows, qualitative evolution becomes critical. Charging infrastructure must transition from static installations to smart, adaptive, and interoperable networks. These networks should dynamically interact with both the power grid and mobility systems, leveraging real-time data, predictive algorithms, and distributed energy resources to optimize charging schedules, reduce peak demand, and integrate renewable energy effectively [16].

The future of EV infrastructure lies in intelligence and flexibility. Smart charging stations equipped with communication protocols, demand-response capabilities, and vehicle-to-grid (V2G) functionalities can transform EVs from passive loads into active grid assets. This paradigm shift requires not only technological innovation but also supportive regulatory frameworks and market mechanisms that incentivize grid-friendly behaviors. Ultimately, the success of electrified transport depends on harmonizing infrastructure development with systemic resilience—ensuring that the transition to electric mobility strengthens, rather than destabilizes, the broader energy ecosystem.

Without intelligent coordination, uncontrolled EV charging can significantly amplify peak electricity demand by as much as 25% in high-penetration scenarios [2]. This surge occurs because most users tend to charge their vehicles during evening hours, coinciding with residential peak loads. The result is a sharp increase in demand that stresses distribution transformers, feeders, and substations, often beyond their design capacity.

Such demand spikes trigger local congestion in distribution networks, leading to thermal overloads and accelerated aging of grid assets. Voltage instabilities are another critical consequence: as load rises abruptly, voltage drops propagate through the network, compromising power quality and potentially damaging sensitive equipment. In extreme cases, these conditions can cascade into outages or require emergency load shedding [17].

To maintain reliability under these circumstances, utilities are forced to invest in costly grid reinforcements, such as upgrading transformers, expanding feeder capacity, and installing voltage regulation devices. These capital expenditures can amount to billions of dollars globally, eroding the economic benefits of electrification if not managed proactively.

Javier Martínez-Gómez [18] on the review on EV charging stations in Latin America emphasized that technological progress alone cannot drive the transition to electric

mobility. The review identifies critical challenges—such as fragmented regulations, high infrastructure costs, and limited public awareness—while highlighting opportunities through integrated policies, public–private collaboration, and renewable energy integration. Successful cases in Chile, Costa Rica, and Colombia show that long-term planning and coherent governance are essential. Ultimately, charging infrastructure must evolve as an intelligent, resilient, and inclusive energy system, ensuring equitable access and financial sustainability across the region. The article highlights that successful implementation depends on coherent governance and public–private collaboration. Countries such as Chile and Costa Rica demonstrate that long-term strategies, tax incentives, and integration with renewable energy policies can accelerate infrastructure deployment. Conversely, nations lacking clear regulations or incentives face slower progress, reinforcing the need for harmonized standards and streamlined permitting processes. Financing emerges as a critical barrier: high installation costs for fast-charging stations and grid upgrades demand innovative business models—such as subscription schemes or battery-swapping—and support from international development banks.

Moreover, uncontrolled charging undermines the integration of renewable energy. Solar generation typically peaks at midday, while EV charging demand peaks in the evening—creating a temporal mismatch that increases reliance on fossil-based generation during critical hours. This not only raises emissions but also inflates operational costs for grid operators. The solution lies in intelligent coordination: deploying smart charging systems that align EV demand with grid flexibility, leveraging dynamic pricing, demand-response programs, and V2G capabilities. By transforming EVs into controllable loads and even distributed energy resources, these strategies can flatten demand curves, stabilize voltage profiles, and defer costly infrastructure upgrades—turning a potential liability into a strategic asset for the energy transition [19].

Achieving this vision requires more than advanced hardware and algorithms; it demands a holistic approach that spans multiple dimensions of the electrification ecosystem. Energy systems, transportation networks, and digital platforms must converge to create a resilient and adaptive infrastructure capable of supporting large-scale EV integration. This multidimensional integration encompasses energy, mobility, and planning domains, each with distinct challenges and opportunities.

Saleh's et al. [20] contribution introduces a user-centric decision-making framework that combines the Best–Worst Method (BWM) with Grey Relational Analysis (GRA) to optimize charging station selection. This approach is significant because it operationalizes the behavioral and planning dimension highlighted in the introduction. By systematically incorporating user preferences—such as proximity, cost, and charging speed—alongside technical and network constraints, the method ensures that infrastructure planning is not solely driven by engineering considerations but also by social responsiveness. This dual perspective addresses a critical gap in conventional deployment strategies, which often prioritize grid efficiency at the expense of user convenience. Furthermore, the integration of BWM and GRA provides a robust mechanism for handling uncertainty and multi-criteria trade-offs, making it particularly relevant in dynamic urban environments where energy demand, traffic patterns, and user expectations fluctuate. Ultimately, this work exemplifies the need for decision-support tools that harmonize technical optimization with human-centric design, reinforcing the notion that sustainable mobility depends on aligning infrastructure intelligence with user engagement.

The energy dimension of mobility electrification introduces profound changes in how power systems operate. Electric vehicles reshape traditional load profiles, adding significant temporal variability that challenges grid stability. Charging demand often peaks during evening hours, coinciding with residential consumption, while renewable

generation—particularly solar—peaks at midday. Bridging this mismatch requires advanced forecasting algorithms, energy storage systems, and flexible integration of distributed renewable resources. By coupling EV charging with localized microgrids and energy communities, operators can optimize resource utilization and reduce reliance on fossil-based backup generation, reinforcing the sustainability of the energy transition [21].

Beyond energy, the transportation dimension reflects the spatial and operational impacts of electric mobility. Charging infrastructure influences traffic dynamics, parking availability, and urban form. The strategic placement of charging stations determines accessibility and convenience for users, while shaping land-use efficiency and equity across neighborhoods. Poorly planned deployment risks creating “charging deserts” in underserved areas, exacerbating social disparities. Conversely, well-integrated networks can support multimodal transport systems, reduce congestion, and enhance urban livability.

Finally, the planning and digitalization dimension underpins the entire ecosystem. Effective integration demands robust digital platforms capable of predictive control, real-time data analytics, and cybersecure communication between vehicles, grids, and users. These platforms enable dynamic pricing, demand-response programs, and vehicle-to-grid (V2G) services, transforming EVs into active participants in energy markets. Digitalization also facilitates interoperability across charging networks, ensuring seamless user experiences and efficient grid coordination.

The synergy between mobility electrification and renewable energy unlocks significant sustainability gains when supported by localized microgrids, distributed storage, and community-based energy models. This convergence not only mitigates technical challenges but also fosters resilience, equity, and economic efficiency—hallmarks of a truly sustainable transport paradigm [22].

Technological innovation alone is insufficient without coherent policy frameworks that guide and coordinate systemic change. Regulatory instruments play a pivotal role in shaping the conditions for successful electrification of mobility. One critical aspect is the promotion of interoperability and standardization, which ensures seamless integration across manufacturers, charging networks, and regions. Without common protocols and technical standards, fragmentation can hinder user experience and slow infrastructure deployment.

Equally important is the introduction of incentives for grid-friendly behaviors. Time-of-use tariffs, flexibility markets, and dynamic pricing schemes can encourage consumers to charge during off-peak hours, reducing stress on the grid and aligning demand with renewable generation patterns. These mechanisms transform charging from a passive activity into an active component of energy system optimization.

Public–private partnerships represent another cornerstone of effective policy. Collaboration between governments, utilities, and private operators accelerates infrastructure deployment, particularly in underserved areas where market forces alone may not guarantee equitable access. Such partnerships can leverage shared investment models and coordinated planning to ensure that charging networks expand inclusively.

In addition, electric mobility represents far more than a technological evolution; it is a profound societal transformation. Its success depends on aligning innovation with systemic resilience, equity, and sustainability. This transition cannot be achieved through isolated efforts—it requires coordinated action across multiple disciplines, including engineering, economics, behavioral science, and policy design. Only through such collaboration can we ensure that EV adoption strengthens rather than burdens the energy ecosystem [23].

A future where electric vehicles operate as integral, intelligent components of a decarbonized energy system is within reach. Achieving this vision demands an inclusive and interdisciplinary approach—one that embraces complexity as a foundation for flexibility, efficiency, and sustainability. By harmonizing technological progress with ro-

bust governance frameworks and social engagement, we can create a mobility paradigm that not only reduces emissions but also enhances energy security, urban livability, and economic opportunity.

Ultimately, the transition toward energy-efficient and grid-friendly electric mobility will not be achieved solely through technological deployment but through systemic integration. The contributions gathered in this Special Issue demonstrate how the multifaceted challenges—ranging from demand forecasting and power-flow optimization to bidirectional V2G interaction—are being addressed through approaches that combine advanced control algorithms, energy storage systems, renewable energy coupling, and innovative business models. Collectively, these studies confirm that electric vehicle charging infrastructure can evolve from a passive electricity load into a dynamic asset for the power system, contributing to flexibility, stability, and decarbonization.

To fully unlock this potential, an equally innovative framework of governance and regulation is required. Interoperability standards, dynamic pricing schemes that reward flexibility, and urban planning strategies that integrate land use, mobility, and energy considerations must all converge. Only through the combined efforts of engineering, economics, user behavior, and public policy—in a truly interdisciplinary approach—can we ensure that large-scale electrification strengthens, rather than strains, the grid. This Special Issue invites readers to explore the presented contributions as stepping stones toward a new generation of intelligent, efficient, and grid-aware charging infrastructures that support sustainable mobility and resilient energy systems.

Looking ahead, we hope that this collection will inspire continued collaboration among researchers, policymakers, and industry practitioners. The path toward decarbonized transport is both a technological and societal endeavor, demanding creativity, coordination, and a shared vision of sustainability. By advancing the frontiers of energy efficiency, grid integration, and smart infrastructure design, the studies featured here lay the groundwork for an equitable and adaptive electromobility paradigm—one that harmonizes innovation with resilience for the decades to come.

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