Beyond Transport: V2X Integration Turning EVs into Smart Energy Assets

Bojie Shen
Monash University
Melbourne, Australia
bojie.shen1@monash.edu

Jinchun Du
Monash University
Melbourne, Australia
jinchun.du@monash.edu

Muhammad Aamir Cheema
Monash University
Melbourne, Australia
aamir.cheema@monash.edu

Abstract

Electric Vehicles (EVs) are increasingly recognized not only as key assets for sustainable transportation but also as flexible, distributed energy resources. This dual role is enabled by the emergence of Vehicle-to-Everything (V2X) technologies, which allow EVs to bidirectionally charge and discharge energy across various domains, such as the grid, homes, buildings, other vehicles, and mobile devices. As global momentum builds toward decarbonizing both transportation and energy systems, the integration of V2X positions EVs at the intersection of these domains, offering new opportunities to enhance energy efficiency, grid resilience, and environmental sustainability. This tutorial provides a comprehensive introduction to the potential of EVs as both transportation and energy storage solutions, focusing specifically on practical applications and recent advancements in V2X integration. Participants will explore foundational concepts and practical use cases across individual and fleet scenarios, including energy-aware EV routing, smart charging, and coordinated energy management. By bridging transportation and energy domains, the tutorial offers participants insights into leveraging EVs to enhance mobility, resilience, and energy efficiency.

CCS Concepts

• **Information systems → Spatial-temporal systems**; • **Computing methodologies → Planning and scheduling**; • **Applied computing → Transportation**.

Keywords

Electric vehicles, Transportation, Energy storage, Sustainability

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1 OVERVIEW

The global shift toward a sustainable future is closely linked to decarbonizing the transportation sector, one of the largest contributors to greenhouse gas (GHG) emissions and urban air pollution [49]. In 2022, transportation was responsible for approximately 16% of global GHG emissions, with road transport — predominantly fueled by internal combustion engine (ICE) vehicles—accounting for nearly 70% of that total [43]. Transitioning from ICE vehicles to electric vehicles (EVs) is a critical component of this transformation, as lifecycle assessments show that medium-sized EVs emit roughly 50% less GHG over their lifespan than comparable ICE models [38].

In addition to their role in reducing GHG emissions, EVs are increasingly recognized as valuable distributed energy resources through V2X technologies. V2X enables bidirectional electricity exchange between EVs and external systems, transforming vehicles from passive energy consumers into active participants in the energy ecosystem. Applications of V2X across multiple domains: Vehicle-to-Grid (V2G) allows EVs to discharge electricity back into the power grid, supporting grid stability and alleviating stress during peak demand; Vehicle-to-Home (V2H) enables households to draw on EV batteries during power outages or when electricity tariffs are high; Vehicle-to-Building/Premises (V2B/V2P) extends these capabilities to commercial or institutional facilities, providing on-site energy management and peak shaving; and Vehicle-to-Load (V2L) facilitates direct power supply to external devices and equipment, offering portable, off-grid energy solutions. These capabilities position EVs as “batteries-on-wheels” that not only provide backup power and load balancing but also store surplus renewable energy, enhancing both sustainability and grid resilience. The growing EV battery capacity could soon exceed that of stationary storage, unlocking significant opportunities for cost-effective, decentralized energy management and broader participation in a cleaner, smarter energy ecosystem [11].

This tutorial introduces these transformative functions through two complementary lenses. The first part focuses on individual EV applications, such as energy-aware routing, smart charging integration with homes (V2H), and economically optimized scheduling for commercial users. The second part examines fleet-level scenarios in logistics, public transportation, and autonomous vehicle services, highlighting challenges and innovations in fleet routing, V2B energy coordination, transit electrification, and shared autonomous EV deployment. Drawing on current research, the tutorial equips participants with a comprehensive understanding of how V2X technologies enhance both mobility and energy systems.

2 TUTORIAL OUTLINE

This 90-minute tutorial introduces EVs as both transportation assets and distributed energy resources, focusing on recent advances in V2X technologies. We explore practical applications in EV routing, smart charging, and coordinated energy management across individual and fleet scenarios.

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2.1 Introduction to Electric Vehicles and V2X Potential

EVs are well-suited for V2X integration due to their substantial battery capacities (30–100 kWh) and long idle periods—most are parked 95% of the time and travel just 38 km per day on average [40]. Battery wear is relatively minor, with modern EVs maintaining 93% of their capacity after 280,000 km [46]. Ongoing advancements in infrastructure, such as fast and ultra-fast charging, in-road wireless charging, and battery swapping, are further enhancing the practicality of V2X applications [1, 14]. Real-world cases highlight its value: a vineyard in South Australia generated $2,500 annual profit via V2G [15]; UK modelling predicts $460 million in savings and 3 million tonnes of CO_2 reduction from 50,000 V2G-enabled EVs [37]; and International Renewable Energy Agency (IRENA) projects up to 61% emission and 42% cost reductions [22]. This session introduces EVs as both mobility and energy assets, laying the groundwork for the technical discussions to follow.

2.2 Enabling V2X Integration: From Individual Use to Fleet-Level Coordination

2.2.1 Individual EV Scenarios: Routing, Charging, and Scheduling.

Individual EV users must make spatial and temporal decisions that integrate travel needs, charging strategies, and economic considerations. We focus on three key areas: (i) energy-aware routing, (ii) V2H smart charging, and (iii) revenue-driven scheduling.

Energy-Constrained Routing Foundations. To fully realize the potential of V2X, EVs must be managed not only as transport assets but also as energy resources. Energy-aware routing helps reduce unnecessary consumption during trips, preserving battery capacity that can be redirected for V2X services like grid support or home backup. Unlike conventional vehicles, EV routing must account for limited battery capacity, charging infrastructure, and energy consumption influenced by terrain, speed, and driving behavior. Foundational work by Artmeier et al. [5] extended Dijkstra's algorithm to incorporate energy constraints, initiating a new class of energy-aware routing algorithms. Building on this, Storandt [47] and Baum et al. [8] modeled partial recharging and battery swapping strategies, and the same authors later [7] introduced speed-sensitive energy models. Most recently, Alam et al. [3] developed queue-aware and time-dependent routing approaches that consider real-world delays at charging stations and dynamic traffic conditions. Complementing such algorithmic innovations, the survey [18] provides a comprehensive taxonomy of eco-routing methods, situating EV-focused approaches within the broader context of sustainable transportation. Together, these contributions highlight the central role of spatiotemporal modeling in making EV routing practical and scalable, minimizing energy consumption and preserving battery capacity for V2X services.

Home-Integrated Smart Charging (V2H). V2H technologies enable private EVs to supply electricity to homes, transforming vehicles into mobile energy storage units. Integrated with home energy management systems (HEMS), V2H allows households to reduce costs, enhance reliability, and better utilize renewable energy. For example, EVs can serve as backup energy sources during power outages, particularly when combined with rooftop solar systems to form a self-sustained nano-grid [41]. In real-time pricing environments, HEMS platforms can schedule EV discharging to minimize electricity costs [29], while centralized control strategies optimize household loads and charging behavior. Some recent methods also help maximize renewable energy utilization without requiring dedicated battery storage [9, 10], instead leveraging virtual partitioning of EV batteries to allocate capacity for household energy support. Additionally, recent advances [4] demonstrate how spatiotemporal forecasting and smart charging approaches can reduce both energy costs and carbon emissions, further enhancing the value of V2H systems through informed trading and scheduling decisions. Despite these benefits, challenges remain, including control complexity, and renewable variability, which motivate further research into scalable, adaptive V2H systems.

Revenue-Aware Scheduling for Commercial EV Users. For individual EV owners engaged in ride-hailing or delivery, routing decisions must optimize both energy efficiency and economic returns. The Electric Vehicle Orienteering Problem (EVOP) provides a formal model where the EV selects a profitable subset of customer requests to serve within a time or energy budget, starting and ending at a depot. Recent studies have extended this framework in various ways: Lee et al. [27] incorporate charging delays; Wang et al. [51] introduce time-window constraints; and Chen et al. [13] address range anxiety under sparse infrastructure. These models integrate charging station locations, waiting times, and profit considerations into spatial-temporal planning. In contrast, traditional formulations like the Electric Vehicle Traveling Salesman Problem (EVTSP) [16] require visiting all customers while minimizing travel cost under energy constraints. EVOP, by enabling selective service, offers a more flexible and revenue-aware framework for real-world EV scheduling [17].

2.2.2 Fleet-Level Scenarios: Logistics, Transit, and V2X Coordination.

Fleet-scale EV deployment, across logistics, transit, and autonomous services introduces spatial and temporal coordination challenges beyond single-vehicle settings. This section highlights four key scenarios: (i) energy-aware routing for delivery fleets, (ii) coordinated V2B/V2P energy services, (iii) grid-integrated public transport systems, and (iv) real-time V2X control in shared Autonomous Electric Vehicles (AEVs) fleets.

Energy-Aware Routing for Commercial EV Fleets. Fleet-based Electric Vehicle Routing Problems (EVRPs) extend classical VRP formulations by incorporating the unique energy limitations and charging constraints of EVs. In these models, a fleet of EVs departs from and returns to depots while serving a set of customers, aiming to minimize total energy consumption or maximize operational efficiency. Given the limited driving range and long charging times of EVs, researchers have explored a variety of strategies to balance routing with energy management, such as full recharging at stations [2], partial charging to enhance flexibility [24], and battery swapping for faster turnaround [12]. Time-window constraints [44] further increase complexity by imposing strict delivery deadlines. Some formulations consider homogeneous fleets, where all vehicles have similar specifications, while others address heterogeneous fleets with varying capacities and energy profiles [50]. More recent extensions incorporate V2G functionality, allowing EVs to discharge energy back to the grid [31]. To better reflect real-world charging dynamics, Lam et al. [26] develop a branch-and-cut-and-price approach that jointly optimizes routing and station scheduling for large-scale EVRPs with piecewise-linear charging functions.

While standard EVRPs prioritize regional fleet efficiency, urban last-mile delivery involves dense, stop-intensive operations supported by micro-depots and parcel lockers. The Two-Echelon Electric Vehicle Routing Problem (2E-EVRP) extends the classical EVRP by introducing a two-stage distribution system, in which the second echelon, dedicated to last-mile delivery, is carried out by smaller electric vehicles. This structure better aligns with EV limitations by assigning shorter, urban-specific routes, thereby enhancing energy management and service reliability in complex urban environments [35].

Fleet-Based V2B / V2P Energy Services. Unlike single-EV V2H systems, where one vehicle supplies power to a private residence during outages or periods of high electricity prices, V2B and V2P strategies coordinate multiple EVs to support larger commercial or institutional energy needs. While V2H centers on individual energy resilience, V2B leverages the collective capacity of EV fleets to deliver services like peak shaving, load balancing, and backup power at scale [23, 32, 42]. Fleet-based V2B introduces additional spatial and temporal challenges, including variable EV availability, changing building demand, and fluctuations in renewable energy generation across different times and locations. To manage these dynamics, researchers have developed advanced scheduling and optimization approaches [36, 48]. Recent studies emphasize the importance of incorporating zone-specific capacity limits and dynamic pricing signals, demonstrating that optimized fleet scheduling can reduce costs while alleviating grid stress across metropolitan networks [28]. Furthermore, integrating V2B systems with solar generation has been shown to significantly lower peak electricity expenses and enhance the performance of nearly zero-energy buildings [33]. By extending the V2H concept to a broader, multi-vehicle scale, V2B and V2P enable smarter vehicle-building coordination to improve energy resilience and lower costs.

Electrified Public-Transport Fleets. EVs are significantly transforming public transport systems, with electric buses (EBs) and electric taxis (ETs) playing central roles in urban sustainability initiatives. Advances in V2G technologies enable dynamic interactions between EV fleets and the power grid, supported by novel scheduling models that address uncertainties in battery efficiency [52]. Battery swapping strategies have also been optimized under variable temperature conditions to enhance reliability [19], while semi-empirical models account for battery degradation influenced by weather and usage patterns [34]. Electric school buses are well-suited for V2G applications due to their regular and predictable idle periods [25]. Similarly, electric taxi fleets have demonstrated the ability to provide V2G services without compromising their operational demands [53]. Moreover, urban transit systems increasingly rely on stochastic optimization frameworks for coordinated dispatch and charging, achieving notable cost and energy savings [45]. Effective implementation of electrified public transport will continue to rely on intelligent scheduling, fleet coordination, and real-time integration with the grid.

Autonomous Electric Vehicles for V2X Integration. Autonomous Electric Vehicles (AEVs) equipped with V2X technologies offer unique advantages as both transport and grid-responsive assets. Unlike private EVs, centrally managed AEVs can actively support V2G services such as peak shaving and renewable integration [21, 30]. Their autonomy enables real-time optimization of dispatch, routing, and charging based on both mobility needs and grid conditions [6, 54]. Recent work proposes integrated optimization-simulation frameworks to support scalable smart charging and relocation of shared AEV fleets, enhancing system-wide efficiency and responsiveness [20]. As research increasingly demonstrates, AEVs are well-suited to support coordinated, system-level integration of energy and transport in future smart cities [39].

2.3 Emerging Research Opportunities and Open Challenges

In this final part of the tutorial, we highlight key emerging research directions and open challenges at the intersection of EV mobility and energy systems. Most existing work focuses on energy management while overlooking the need to integrate EV travel requirements. Future approaches should jointly optimize routing, charging, and discharging while handling uncertainties in traffic, prices, and charging availability. There is also a growing need for scalable, privacy-preserving coordination across independent EVs in shared spaces, and for strategies that balance cost, emissions, and travel reliability in dynamic, spatially diverse settings. Addressing these challenges calls for new spatiotemporal models, multi-objective optimization, and intelligent control techniques to unlock the full potential of EVs as both transport and energy assets.

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