Beyond the Commute: Unlocking the Potential of Electric Vehicles as Future Energy Storage Solutions (Vision Paper)

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ABSTRACT

Electric vehicles (EVs) have the potential to serve as energy storage solutions through bidirectional charging technology, which allows them to both draw power from and feed power back into the grid, homes, or other vehicles. This capability enables EVs to reduce emissions, optimize costs, and support the grid by storing energy during periods of high production and supplying it when demand is high. In this vision paper, we focus on unlocking the potential of EVs as energy storage solutions while ensuring they remain readily available for transportation, their primary purpose. A significant research gap exists in that most current studies prioritize energy management, often using simplistic approaches that inadequately address the travel needs of EV owners. We believe the database community can be instrumental in maximizing the dual role of EVs as transportation and energy storage. We present a non-exhaustive list of research directions for various EV stakeholders, including individual EV owners, groups of independent yet cooperative EVs, commercial EV fleets, and autonomous EVs, and hope to inspire the database community for further exploration.

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 MOTIVATION

Renewable energy sources, such as wind and solar power, are crucial to achieving the net-zero 2050 target. However, these are intermittent energy sources and do not produce a consistent energy supply. This intermittency can be addressed through the use of energy storage solutions such as batteries, which offer a range of benefits including: reducing carbon emissions by storing excess renewable energy during periods of high production and supplying it back when renewable energy production is lower than demand; minimising costs by storing energy when it is cheap and using it when prices are high; and enhancing grid stability by storing excess energy when demand is low and supplying it back when demand is high. However, the cost and capacity requirements of batteries present a significant challenge, e.g., achieving a zero-carbon future in the US by 2050 would require 6 TWh of energy storage [12].

Fortunately, electric vehicles (EVs) can assist in solving this challenge. In addition to serving as a means of transportation, EVs can function as energy storage devices, thanks to bidirectional charging technology [7] that allows power to be supplied from the vehicle to various sources, including the grid (V2G), home (V2H), other vehicles (V2V), and premises (V2P) - collectively known as vehicle to everything (V2X) [11]. As EVs are predicted to become more prevalent and eventually ubiquitous, they present an attractive option for energy storage needs without significant additional investment compared to standalone batteries. International Renewable Energy Agency (IRENA) anticipates that the future EV battery capacity may dwarf stationary battery capacity and, in 2050, around 14 TWh of EV batteries would be available to provide grid services, compared to 9 TWh of stationary batteries [5].

EVs have the potential to serve as future energy storage solutions while fulfilling transportation needs. For instance, consider a private EV owner who primarily uses their vehicle for commuting to work and running daily errands. When not need for travel, the EV can act as a home battery by charging during off-peak hours (or utilizing excess solar energy) and supplying power back to the home during peak hours. Companies with a large EV fleet can reduce their carbon footprint by charging their vehicles when excess renewable energy is available and sending power back to the grid when demand is high. This approach maximizes the use of clean energy, contributing to a reduction in overall emissions, while also supporting the grid and generating additional revenue. In areas prone to power outages, a network of interconnected EVs could act as a microgrid, providing backup power to critical infrastructure like hospitals or communication towers during emergencies.

2 FEASIBILITY AND BENEFITS

EVs offer the advantage of mobile energy storage (i.e., battery-on-wheels) with much larger energy storage capacity (ranging from 30-100 kWh) compared to residential batteries (typically 4-20 kWh). Furthermore, the energy storage capacity of EVs is often underutilized, e.g., the average Australian drives around 38 kms per day [16] and most cars remain parked for 95% of the time, giving drivers ample opportunity to make use of their idle batteries for bidirectional charging [4]. Additionally, the substantial investments made by governments and businesses in fast and ultra-fast charging stations and emerging technologies, such as in-road wireless charging [17], emergency vehicle-to-vehicle energy sharing, and battery swap services [1], are anticipated to address the concerns of EV owners who may experience range anxiety. Battery life is a common concern, but real-world data indicates that modern EV batteries maintain 93% of their capacity even after 280,000 kilometers and are projected to retain 80% capacity after 820,000 kilometers [19]. Numerous recent studies show the feasibility and benefits of using EVs as energy storage devices in various scenarios, taking into account factors such as battery degradation cost and charging/discharging efficiency (e.g., see [11] and references therein).

Cost and emission reduction. Bidirectional charging and EVs hold promise for significant environmental and economic benefits. A vineyard in South Australia transformed its 2,000 AUD annual electricity bill into an annual profit exceeding 2,500 AUD by utilising its Nissan Leaf for energy storage [6]. Modelling in the UK shows that even a low penetration of 50,000 EVs with bidirectional charging capability can result in substantial whole-system cost savings of over $460 million per year and CO_2 emission reductions of over 3 million tonnes per year [9]. An IRENA study estimates that the use of EVs and smart bidirectional charging have potential to reduce CO_2 emissions by up to 61% and marginal cost by up to 42% [10]. Additionally, V2X could cut EV ownership costs and emissions. UK trials [9] saw savings of $830-$1,660 per EV yearly, with bidirectional charging achieving negative emissions (-243 gCO_2/km). To provide context, average emission intensity for petrol-only passenger cars and light SUVs sold in Australia in 2021 was 164 gCO_2/km [14].

Grid support. Bidirectional charging and EVs have significant potential to support the grid and contribute to a greener environment. A recent study [15] found that if 13.9% of the New England light-duty vehicle fleet participated in bidirectional charging, it could displace 14.7 GWh of stationary storage, resulting in capital savings of almost $1 billion. The total system savings ranged from 2.2% to 20.3% ($180–1305 million) as the participation rate increased from 5% to 80%. Compared to traditional demand response schemes, even at modest participation rates of 5–10%, bidirectional charging yielded over 337% more savings and displaced storage tenfold. The UK Centre of Excellence for Low Carbon and Fuel Cell Technologies, cenex, has published a report that highlights the benefits of V2G technology based on a review of several European projects [3]. The report suggests that, by avoiding the curtailment of renewable energy generation alone, V2G could avoid network costs equating to an overall saving of $4.1 billion per year by 2040.

The future promises even greater benefits. We can expect significant improvements in battery technology, including increased durability, larger capacities, and faster (dis)charging times. Additionally, charging infrastructure will become more accessible and widespread. Finally, the growing adoption of renewable energy will further enhance the environmental benefits of EVs.

3 KEY RESEARCH GAP

In the previous sections, we have demonstrated the significant potential of EVs and bidirectional charging in driving a sustainable future. As a result, governments, businesses, and research organizations are heavily investing in this area. This multidisciplinary field involves numerous research communities working on various facets, such as developing better, larger, and more durable EV batteries, creating more efficient and accessible charging networks, and improving smarter charging solutions and grid integration techniques, to name a few. In this paper, we highlight a key research gap that the database community, particularly the spatial database community, is well-positioned to address.

Most existing research in this area focuses on designing charging strategies [2, 18] for EVs, often neglecting the potential of bidirectional charging and the role of EVs as energy storage units. While there is also considerable research on smart energy management for EVs considering bidirectional charging [13], which includes both charging and discharging strategies, a significant challenge remains in fully integrating EV travel with energy management. This integration is essential to ensure that EVs remain readily available for owners' transportation requirements while optimising their role in energy storage. Successfully addressing this challenge is crucial for promoting the adoption of EVs as dual-purpose vehicles for transportation and energy storage, necessitating the development of intelligent techniques that seamlessly integrate EV travel with energy storage requirements.

The current research in bidirectional charging for EVs (e.g., see [11] and references therein) is still in its infancy and it predominantly emphasises energy management techniques while neglecting the transportation aspect of EVs altogether. These studies tend to treat EVs primarily as energy storage devices, assuming that meeting transportation needs can be achieved through simplistic approaches like ensuring that the state of charge (SoC) never drops below a certain threshold [8, 11]. However, such solutions are too conservative and fail to adequately incorporate the complex and often unpredictable travelling needs of EVs. This necessitates next-generation travel **and** energy management techniques for EVs that take into account important travel- and energy-related factors such as uncertain travel patterns, structure and topology of the road network, historical and real-time traffic conditions and electricity prices, efficient and accurate computation of time and energy requirements for different routes, battery degradation cost, (dis)charging efficiency, and the availability, charging speeds, prices and waiting times for charging stations.

4 OUR VISION AND RESEARCH DIRECTIONS

Our vision is for the database community to address the above critical gap by designing intelligent travel and energy management techniques for EVs considering the potential of bidirectional charging. This includes innovative data management techniques, smart charging/discharging and routing strategies, novel optimization and machine learning algorithms, and innovative methods for energy trading in V2X scenarios. These approaches should prioritize both EV owner needs and grid stability. Ideally, they would:

- **Fulfill travel requirements:** Ensure EVs can effortlessly handle daily commutes, errands, and accommodate unexpected travel needs.
- **Optimize energy storage:** Maximize the contribution of EV batteries to reducing carbon emissions and lowering costs.
- **Enhance grid stability:** Minimize negative impacts on the electricity grid.

This area offers a wealth of exciting possibilities while presenting the research community with intriguing challenges. Our aim is not to provide an exhaustive list, but rather to showcase representative research directions. Our hope is to inspire the database community to further explore this area, imagine the exciting possibilities it brings, and work towards realizing them. There are various ways to categorize future research directions, such as by modes of energy trading (e.g., vehicle-to-grid, vehicle-to-home, vehicle-to-vehicle), travel patterns (e.g., regular vs. irregular) and desired benefits (e.g., emission reduction, cost optimization, grid stability). However, in this paper, we present several exciting research directions categorizing these by different EV stakeholders including:

(1) Individual EV owners.
(2) Groups of independent but cooperative EVs, such as those hosted by car parks, shopping centers, airports, and university campuses.
(3) EV fleets operated by single entities, such as transportation and logistics companies.
(4) Fully autonomous EVs.

Next, we discuss some representative research directions for each of these. Different modes of energy trading, travel patterns and desired benefits could all be considered in each of these directions.

4.1 Individual EV Owners

This section considers individual EV owners, highlighting private and business use, like ride-hailing or delivery services.

4.1.1 EVs for Private Use. Most EV owners use their vehicles for private purposes, such as daily commutes, running errands, etc. Their typical traveling needs are relatively easier to learn and predict, although unexpected long trips may be required occasionally. The goal is to consider information about traveling, traffic, renewable energy for charging, and dynamically changing price signals, which are often not available in advance, to design real-time techniques for travel and energy management. This involves keeping track of real-time data and using predictions for future values. Continuously monitoring and predicting the status of the EV (such as SoC, location, and traveling requirements) and the environment (including charging station availability, traffic, and weather conditions) can provide more accurate information to optimize the travel and energy schedule.

4.1.2 EVs for Business Use. Many individuals use EVs for business purposes, such as providing ride-hailing or delivery services. For example, an Uber driver needs to pick up and drop off customers or food at different locations. Such EVs have more complex and often more difficult-to-predict traveling requirements and routes. The uncertainties in complex trips and associated fares/costs make travel and energy management more challenging due to stochastic customer demand, traffic conditions affecting energy consumption and trip times, and other factors. Additionally, trip and behavioral forecasts are challenging, with no mature solutions available. Without careful travel and energy management, ride-hailing/delivery services may be interrupted, or charging costs/times may be high, thus impacting revenue. Thus, there is a need to design techniques to manage such complex trips by actively analyzing their impact on various factors, including costs, travel times, fares, and energy consumption, to ensure reliable hailing and delivery services while maximising a given objective value such as the total revenue.

4.2 Groups of Independent but Cooperative EVs

This section explores cooperation among EVs for mutual benefit. While independent, EVs can leverage coordination, incentivized by, for example, cheaper parking or electricity. We focus on two groups: 1) Co-located EVs: Parked together (airports, malls, offices), these EVs share space and potentially charging infrastructure, enabling coordinated charging and travel planning to reduce costs and/or emissions; 2) Dispersed EVs: Geographically spread, these EVs can still cooperate via central entities (grid operators) using optimized (dis)charging and routing schedules for objectives like reducing grid stress. Next, we discuss a sample application scenario for each.

4.2.1 Towards Net Zero Premises using Co-located EVs. Consider the premises with car parks that host a group of independent EVs such as shopping centers, airports, hospitals and university campuses. Assume that a certain number of EVs parked at such premises are willing to collaborate, potentially incentivised by offers such as reduced parking rates or cheap charging. These EVs and bidirectional charging can be used to achieve different goals, such as net zero premises. Given the estimated time-varying on-site renewable energy production and energy consumption requirements of the venue, the goal is to design effective travel and energy management techniques for the group of cooperative EVs to minimise carbon emissions and the overall operational cost while ensuring that the travel and energy constraints of each individual EV are respected.

4.2.2 Supporting Grid using a Group of Dispersed EVs. Assume that a group of EVs (not necessarily located at the same venue) are incentivised to collaborate in order to support the grid by providing ancillary services. We assume a central system that serves as intermediary entity and communicates with the EVs to manage their energy while respecting their individual travel and energy constraints. For a group of EVs with big enough aggregate battery capacity, ancillary services can be provided by charging and discharging EV batteries to the grid. For example, when the grid has a shortfall in energy supplies, EVs can be used to discharge their batteries to inject energy into the grid, such that the supply-demand mismatch in the grid is resolved. When the grid has excessive power injected from non-dispatchable renewable energy, EVs can charge to store excessive supply in the grid to harvest zero-carbon or low-carbon energy, which helps reduce emissions. Supporting the grid from a group of EVs is not trivial as it involves designing effective coordination algorithms considering dynamically varying grid conditions demanding charge or discharge from time to time, as well as restrictions on EVs' travel needs.

4.3 EV Fleets

This section looks at EV fleets used by delivery companies, government, and transport organizations, focusing on two key research directions, while acknowledging there are many others.

4.3.1 EV Fleets for Last-Mile Deliveries. This research direction involves optimizing the operations of a delivery company's fleet of EVs for last-mile deliveries, aiming to minimize costs and reduce carbon emissions using bidirectional charging. Techniques need to be developed to schedule delivery routes as well as energy management of the EV fleet, taking into account factors such as charging and discharging locations, electricity tariffs, delivery locations and times, and EV energy profiles.

4.3.2 Public Transport Fleets. Here, the focus is on optimizing the usage of EV fleets in public transport, particularly electric buses, which bring unique challenges and opportunities due to their larger batteries, higher energy consumption, and more predictable travel patterns. The objective is to design techniques that provide travel and energy planning for every vehicle in the fleet while minimizing a weighted sum of carbon emissions and operational costs, and satisfying relevant constraints such as arrival and departure times for each stop.

4.4 Fully Autonomous EVs

Consider futuristic scenarios for fully autonomous EVs, which present new opportunities as these driverless vehicles are not constrained by human drivers. For example, they can autonomously visit charging/discharging stations, are not necessarily bothered by wait times during charging/discharging, and can opt to travel on the most energy-efficient routes even if it takes longer to reach the destination. There are many interesting use cases for individual EVs as well as groups of EVs (independent EVs as well as EV fleets), each presenting unique opportunities and challenges.

Consider the example of a fleet used for the transportation of guests or employees, such as shuttle services offered by hotels or government fleets to transport officials and dignitaries. Such autonomous fleets present opportunities to generate revenue, reduce emissions, and support the grid, especially during low-demand periods such as the off-season for hotels or public holidays for government fleets. This can be achieved through V2X technology by selling energy to other vehicles, premises, and the grid, as well as by offering ride-hailing services without the need for employing human drivers. For example, during weekends or public holidays, excess renewable energy produced on-site can be used to charge government fleets. These autonomous fleets can then drive to nearby premises or vehicles to sell the excess energy or provide ride-hailing services.

5 CONCLUSIONS

We explore the exciting potential of EVs to go beyond transportation. EVs could become crucial tools in storing energy, a key element for achieving net zero emissions by 2050. However, this requires collaboration across various disciplines. We highlight some representative research areas where the database community can make significant contributions. Our aim is to spark the community's interest in this potential and encourage further exploration. Improvements in battery capacity, durability, cost and charging speeds will likely enhance V2G's viability. Additionally, the ongoing evolution of regulatory frameworks and infrastructure investments will support broader V2X adoption, underscoring the need for continuous research in this field to fully realize its potential benefits.

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