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Charge-on-the-move solutions for future mobility: A review of current and future prospects

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ABSTRACT

The electrification of transportation has emerged as a key focus area over the past decade, driven by the rise of electric vehicles (EVs) and supportive governmental policies. Conventional EV charging solutions, while foundational, face notable challenges such as high infrastructure costs, low flexibility, and underutilization. Simultaneously, emerging transportation modes such as autonomous vehicles, shared mobility, modular systems, and aerial vehicles, introduce additional complexities, demanding more innovative charging solutions. This review emphasizes the potential of charge-on-the-move systems referred to as dynamic charging, as a transformative approach to address these challenges. Dynamic charging enables EVs to recharge while in motion, presenting opportunities to minimize battery sizes, reduce emissions, and optimize operational efficiency. The study critically evaluates state-of-the-art dynamic charging technologies, including their benefits, limitations, and applicability to future mobility systems, while also comparing these solutions based on infrastructure costs, readiness, and scalability. The findings suggest that the future of EV charging will likely involve a hybrid approach, integrating both conventional and dynamic solutions. Key priorities for advancing dynamic charging include developing optimization models for infrastructure deployment, finding the balance between battery size and battery life, establishing interoperability standards, and enhancing energy transfer efficiency while ensuring safety and sustainability. By addressing these research challenges, dynamic charging systems have the potential to redefine EV infrastructure and support the broader transition to sustainable and efficient mobility ecosystems. This review serves as a guide for researchers and planners seeking to align charging technologies with evolving transportation needs.

Introduction

The rapid evolution of electric vehicles (EVs) has ushered in a new era of transportation, promising cleaner and more sustainable mobility solutions. As the world grapples with the challenges of climate change and the need to reduce greenhouse gas emissions, EVs have emerged as a crucial component of the transition to a greener future by decarbonizing the transportation sector. However, the successful integration of EVs into our daily lives hinges not only on the development of advanced electric propulsion technologies but also on the establishment of a robust charging infrastructure.

Compared with alternatives such as internal combustion and fuel cell vehicles, EVs perform better in terms of reducing primary energy consumption, CO2 emissions, and fuel costs (Sigle and Hahn, 2023). Recently, many studies also investigated the use of hydrogen as fuel, especially for freight transport. Reviews of recent developments and challenges of hydrogen fuel cell vehicles are presented in (Manoharan et al., 2019; Hosseini and Butler, 2020; Greene et al., 2020; Ajanovic and Haas, 2018; Jones et al., 2020). However, for the scope of this study, only battery electric vehicles are considered.

In tandem with the rise of EVs, the concept of Autonomous Vehicles (AVs) has gained considerable traction, and promises safer roads, reduced accidents, and enhanced mobility for individuals with limited access to transportation (Ahmed et al., 2022). Based on studies from Singapore (Sethuraman et al., 2019), Australia (Tirachini and Antoniou, 2020) and Japan (Abe, 2019), driver cost represents about 70 percent of the total bus operator cost, contingent on the bus type. Thus, autonomous vehicles have a great potential in making public transportation

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more cost-effective and accessible. The potential societal impact of AVs is vast, touching areas such as urban planning, traffic management, and overall transportation efficiency (Othman, 2022).

Beyond AVs, the landscape of future mobility encompasses shared mobility, modular vehicles and urban air mobility as shown in Fig. 1. Shared mobility solutions, such as ride-sharing services and communal vehicle usage allow for a more efficient use of vehicles. The collaborative use of these vehicles can potentially optimize resources and also address urban congestion and reduce the environmental footprint (Ata M. Khan, 2021). On the other hand, some studies also mention that without efficient ride-sharing and charging solutions, shared mobility may also increase congestion (Alonso-Mora et al., 2017; Liu et al., 2017).

Simultaneously, the advent of modular vehicles characterized by multiple pods forming variable length platoons (Hatzenbühler et al., 2023) and urban air mobility, enables increased flexibility and allows vehicles to cater to diverse passenger needs. Due to new technological advancements in the past decades, there has been a renewed interest in these aerial and modular transportation modes as they are expected to reduce congestion and travel time (Schindewolf et al., 2021; Chen et al., 2022; Bauranov and Rakas, 2021).

These future mobility systems are expected to be electricity-powered as the cost of EV technology has been decreasing, making it a more financially viable option when compared to combustion engines (Berckmans et al., 2017). For shared fleets that experience longer daily travel distances, EVs offer potential technical and economic advantages in terms of maintenance requirements (Weldon et al., 2018). While autonomy significantly improves driving efficiency and battery usage, EVs demand lower maintenance and considerably lower fuel expenses (Fournier et al., 2017).

To meet the energy demands of electric vehicles (EVs), including autonomous electric vehicles (AEVs), innovative charging solutions beyond conventional charging stations are emerging. One such concept is charge-on-the-move, referred to in this study as dynamic charging, which enables vehicles to recharge while in motion. This offers a transformative approach to addressing the limitations of existing charging methods. Dynamic charging not only supports energy needs but also mitigates environmental concerns. Studies indicate that particulate matter (PM) emissions from EVs, including tire and asphalt particles, are comparable to those from internal combustion engine vehicles (ICEVs) due to the increased weight of EV batteries (Timmers and Achten, 2016; Castiglione et al., 2023). By reducing the reliance on large batteries, dynamic charging has the potential to decrease vehicle weight and subsequently lower PM emissions.

The integration of autonomous driving technologies with dynamic charging systems presents profound implications for various industries. In emergency services, reductions in travel time facilitated by autonomous vehicles and dynamic charging could significantly improve response times, potentially decreasing mortality rates. For example, with a market penetration of 50 % for connected vehicles and 50 % for autonomous vehicles, emergency response times could be reduced by up to 68 % (Obenauf et al., 2019). Similarly, the freight industry stands to benefit from increased operational efficiency, potentially generating economic gains of up to $500 billion per year (Clements and Kockelman, 2017). In last-mile logistics, AEVs are anticipated to dominate, driven by their ability to reduce delivery times, lower operational costs, and meet growing customer demands in urban areas (Dabic-Miletic, 2023).

This review paper examines these emerging technologies, providing a comprehensive analysis of their effectiveness, challenges, and potential to shape the future of mobility. By examining the intersection of dynamic charging and autonomous systems, this study aims to highlight their transformative role in creating sustainable, efficient, and responsive transportation ecosystems.

The insights presented aim to guide researchers, policymakers, and industry stakeholders in identifying the most suitable charging solutions for specific applications. Additionally, this work facilitates comparisons between dynamic charging and alternative approaches, offering a robust foundation for informed decision-making in determining the optimal and efficient charging solutions.

With that aim, the main contributions of this study are as follows:

- The study develops a new framework for categorizing EV charging methods, distinguishing between stationary (idle) and dynamic (in-motion) charging solutions. Unlike existing studies, this framework systematically classifies dynamic charging technologies, offering a structured perspective on their implementation methods, challenges, and opportunities for future mobility. The study also integrates and analyzes the latest advancements in EV charging methods, addressing the gap in literature regarding rapidly evolving technologies. This ensures an up-to-date synthesis of dynamic charging innovations, making the findings relevant for current and future transportation needs.
- A comprehensive assessment of dynamic charging methods—charging lanes, vehicle-to-vehicle (V2V) charging, and dynamic battery swapping is conducted. These methods are compared across critical factors, such as infrastructure costs and potential reductions in battery capacity requirements, to evaluate their feasibility in addressing the energy needs of future mobility systems. This comparative analysis fills a significant gap in the literature, enabling informed decision-making for stakeholders.
- Unlike prior reviews, this study investigates the interplay between dynamic charging technologies and au- tonomous electric vehicles (AEVs), as well as emerging trends in transportation. It highlights potential benefits, challenges, and use cases, paving the way for the seamless integration of AEVs and dynamic charging systems.
- The study highlights existing technical, economic, and operational challenges in dynamic charging technologies while identifying knowledge gaps that hinder their widespread implementation. Furthermore, it outlines opportunities for innovation and integration, offering a robust foundation for future research and development efforts in this rapidly evolving field.

The remainder of the paper is organized as follows. Section 2 provides background and motivation for the review. Section 3 presents the methodology adopted for selection of literature. Section 4 briefly discusses different static charging methods to charge different types of EVs and their limitations. Section 5 discusses state-of-the-art dynamic charging solutions and provides a critical review of the proposed charging methods. Section 6 discusses the potential benefits and


(a) (b)

Fig. 1. Illustration of future mobility (a) Modular vehicle concept by NEXT (Next, 2023) (b) Urban Air Mobility concept (Pak et al., 2023).

challenges associated with dynamic chargers and Section 7 provides the conclusion.

Background and motivation

EVs typically face challenges pertaining to range anxiety and locating convenient charging locations to satisfy their energy needs. The charging stations require considerable investment and energy needs. The stock of home chargers is expected to reach about 135–145 million units and the number of public chargers for light-duty vehicles to around 13 million units worldwide by the year 2030. The total installed capacity of vehicle chargers is expected to grow to 2 TW during the same period and battery demand for buses is expected to reach 120 GWh, 160 GWh for two/three wheelers and 170 GWh for electric trucks as shown in Fig. 2 (International Energy Agency, 2023).

To circumvent the issue of large investment and energy requirements, charging-while-driving or dynamic charging solutions are being proposed in industry and academia alike. These solutions aim to recharge vehicles while in motion thereby spreading the energy demand during the day while reducing the required battery size. With the possibility of charging en route, vehicles can effectively reduce size and capacity of batteries by up-to one-fifth of original size (Yin et al., 2019), thereby reducing weight and energy needed for travel (Duarte et al., 2021). Moreover, these solutions can greatly extend driving range, thus overcoming range anxiety (Jansuwan et al., 2021), and can achieve infinite range in an ideal scenario (Machura et al., 2020).

Dynamic charging technology currently faces many issues and challenges due to high cost of deployment, low charging power and the need for low air gap for efficient transfer (Mahesh et al., 2021). The problem is especially dominant when charging on the move as the location of vehicles is constantly changing, which requires advanced control to reduce power loss and improve efficiency (Tavakoli and Pantic, 2017).

Autonomous driving technology offers a promising solution to address these challenges by enabling more reliable and efficient energy transfer (Panchal et al., 2018). Through energy-efficient driving techniques such as platooning and advanced control mechanisms, autonomous vehicles streamline traffic flow and reduce aerodynamic drag (Sheppard et al., 2021). Additionally, their ability to operate with smaller fleets and shorter travel distances while meeting equivalent demand further minimizes energy consumption (Pridemore et al., 2018).

Enhanced communication between vehicles and infrastructure facilitates the optimal deployment of dynamic charging systems, reducing associated costs (Tan et al., 2022). This integration enables the coordination of travel and charging schedules, offering increased control over traffic flow distributions to maximize the overall system's operational efficiency (Zhou et al., 2020). Furthermore, this coordinated approach mitigates peak demand, reduces power losses, and alleviates network congestion.

To harness the benefits offered by automation and dynamic charging, numerous innovative charging techniques are currently under exploration by both industry and academia. These charging methods employ autonomous vehicle capabilities to provide the same charging demand and services as other traditional charging methods, without requiring the costly infrastructure. Moreover, they allow EVs to charge while in motion through the use of charger vehicles (Nezamuddin et al., 2022), refurbished buses (Kosmanos et al., 2017), drones (Chakraborty et al., 2022) or by battery swapping drones (Chakraborty et al., 2023). Several potential realistic charging options were also identified in Villeneuve et al. (2020) using a micro-Delphi approach. The study consulted experts from various sectors and proposed conventional and new approaches, for example, tanker trucks, airborne feeding, valet charging and other methods as possible charging methods by year 2035.

It has become imperative to review, analyze, and categorize these charging methods in order to assess their benefits and challenges. An overview of state-of-the-art charging solutions with a focus on EV portable chargers is provided in Borgohain and Choudhury (2023). A comprehensive analysis of the factors influencing the adoption of EVs, focusing on charging infrastructure and energy resources, including a categorization of charging infrastructure based on location and technology and key features of EV batteries is studied in Aduama et al., (2023). Leijon and Boström, (2022) explores recent charging strategies for electric vehicles (EVs), including battery swapping, conductive charging, and inductive charging, while emphasizing the key factors influencing the suitability of these technologies for various types of EVs. The study suggests that the future of EV charging will not be dominated by a single technology. Instead, it will involve a combination of diverse solutions tailored to factors such as vehicle type, usage patterns, costs, and geographical context.

A comprehensive review of recent trends and emerging technologies in the field of electric vehicles (EVs) is provided by Mo et al. (2022), covering key areas such as wireless charging, vehicle-to-home (V2H), vehicle-to-grid (V2G), connected vehicles, and autonomous driving. The study highlights the opportunities and challenges associated with these technologies, offering insights into their potential and limitations. Similarly, Khalid et al. (2022) delivers an in-depth evaluation of advanced converter topologies and charging methods for EV applications, contributing to the understanding of power electronics in EV charging infrastructure. In addition, Arya and Saxena (2022) analyzes state-of-the-art and innovative solutions for dynamic charging, focusing on technologies that enable EVs to charge while in motion. Afshar et al. (2021) investigates mobile charging stations (MCSs), conceptualized as portable batteries or power banks capable of charging stationary EVs. The authors discuss the advantages and challenges of MCSs and propose future research directions to facilitate the adoption of flexible charging solutions.

Recent research on electric vehicle (EV) charging methods is

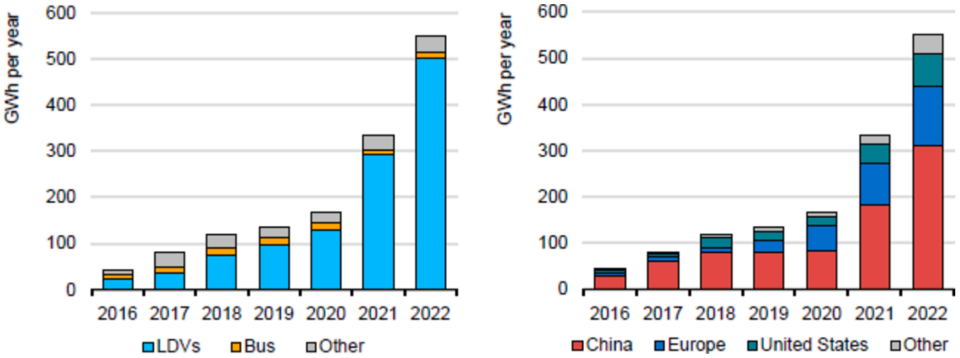


Fig. 2. Battery demand by mode and region from 2016 to 2022. Light duty vehicles (LDVs) include vehicles such as cars and vans. Medium and heavy-duty trucks as well as two/three-wheelers are classified as other (International Energy Agency, 2023).

comprehensively reviewed in Arif et al. (2021), encompassing battery swapping stations, wireless energy transfer, and conductive charging technologies. The study also examines EV standards and optimization techniques for determining the appropriate sizing and placement of charging stations. Complementing this work, Das et al. (2020) provides a detailed review of the current EV market, addressing key topics such as standards, charging infrastructure, and the implications for power grid operations. Additionally, Mouli et al. (2017) investigates five critical technologies shaping the future of EV charging: smart charging systems, vehicle-to-grid (V2G) integration, photovoltaic (PV)-based charging, contactless power transfer, and on-road charging solutions. The study delves into electromagnetic and power converter designs to support the development of contactless power transfer systems for future highway infrastructure.

The majority of recent literature reviews comparing EV charging methods only consider a broad categorization of conductive and wireless charging without mentioning the new innovative methods or the state of the vehicle (parked or moving) while charging (Mo et al., 2022; Khalid et al., 2022; Arya and Saxena, 2022; Mouli et al., 2017; Das et al., 2020; Zentani et al., 2024; Waseem et al., 2024). The review studies considering the future of EV charging do not mention the new developments in this field or provide the benefits or challenges of these charging methods (Leijon and Boström, 2022; Borgohain and Choudhury, 2023; Afshar et al., 2021; Mo et al., 2022). Interestingly, a few review studies propose mobile and portable chargers to be the dominant charging methods in the future (Borgohain and Choudhury, 2023; Afshar et al., 2021). Although many authors recognized the emergence of autonomous and shared mobility as a challenge to current charging infrastructure with possible different needs than current EVs, potential solutions were left as future research directions (Das et al., 2020; Mouli et al., 2017; Jog et al., 2021; Arif et al., 2021).

A summary of the recent review studies in EV charging infrastructure and the corresponding charging method mentioned in the review study is presented in Table 1. The table highlights that nearly all reviewed studies focus on fixed charging stations (FCS) and wireless charging lanes (CL(w)), likely due to the longer availability and maturity of these technologies. Mobile charging stations (MCS) and battery swapping stations (BS) follow as they represent comparatively newer approaches. In contrast, alternative methods such as wireless vehicle-to-vehicle charging (V2V(w)), conductive charging lanes (CL(c)), and dynamic battery swapping (DBS) receive minimal or no attention in the reviewed studies, reflecting their emerging or experimental status in the field.

Table 1
Selected review studies considering different EV charging technologies.

Ref	Charger classification							
	FCS	MCS	BS	V2V (c)	V2V (w)	CL (c)	CL (w)	DBS
Waseem et al. (2024)	✓		✓				✓	
Zentani et al. (2024)	✓		✓				✓	
Borgohain and Choudhury (2023)	✓	✓	✓			✓	✓	
Aduama et al. (2023)	✓		✓				✓	
Leijon and Boström (2022)	✓		✓		✓	✓	✓	
Mo et al. (2022)	✓						✓	
Khalid et al. (2022)	✓						✓	
Arya and Saxena (2022)	✓				✓		✓	
Afshar et al. (2021)	✓	✓	✓		✓		✓	
Arif et al. (2021)	✓		✓			✓	✓	
Jog et al. (2021)	✓	✓	✓					
Das et al. (2020)	✓						✓	
Mouli et al. (2017)	✓						✓	

While all of the studies included in Table 1 reviewed various aspects of conventional static chargers, dynamic charging technologies were dealt briefly and suggested as future works by a couple of studies (Das et al., 2020; Jog et al., 2021). This could be due to AEVs being in the development stage and wireless charging suffering from low efficiencies, low charging rate, and low distance required to transfer charge (Mohammed and Jung, 2021). With recent developments in autonomous vehicles where Waymo received its driver-less deployment permit from California Public Utilities Commission (CPUC) (Pan et al., 2024) and Mercedes Benz launching its software to allow Level 3 automation (Benz, 2023), these vehicle technologies could soon become commonplace. With the increased efficiency of wireless charging technologies (Tavakoli, 2023), recent studies are also considering the viability of V2V and DBS solutions (Chakraborty et al., 2022; Kosmanos et al., 2018), with companies such as Amazon already filing patents for charging EVs via drones as shown in Fig. 3 (Raj, 2018).

With the advent of modular vehicles designed to leverage the advantages of autonomous technologies (Next, 2023), innovative charging solutions such as wireless and conductive V2V charging are gaining attention as viable options (Ren et al., 2024). Additionally, advancements in drone technology and reductions in battery costs have spurred interest in dynamic battery swapping systems, which hold the potential for efficiently charging these emerging modular vehicle technologies (Chakraborty et al., 2023).

The following major research gaps are identified based on the survey of past review studies:

- Existing review studies do not comprehensively classify or analyze the various methods for implementing dynamic charging. Additionally, the challenges and opportunities associated with these methods, particularly in the context of future mobility systems, remain unexplored.
- As electric vehicle (EV) charging technologies evolve rapidly, recent advancements and innovations in charging methods are inadequately addressed in the existing body of literature, leaving a significant knowledge gap.
- While some studies mention autonomous electric vehicles (AEVs) and new trends in transportation as potential future directions, the interplay between AEVs and dynamic charging methods has not been thoroughly investigated. The possible benefits and synergies between these technologies are insufficiently explored.
- A comparative assessment of dynamic charging methods is missing in the literature. This gap hinders the ability to identify the most suitable charging methods for specific scenarios, conditions, or transportation requirements, thereby limiting practical decision-making and strategic planning in this domain.

Methodology

To address the identified research gaps in electric vehicle (EV) charging, this study classifies charging methods into two principal categories based on the operational state of the vehicle: static charging (vehicles are stationary) and dynamic charging (vehicles are in motion). The classification framework encompasses several subcategories as shown in Fig. 4 (expanded from Afshar et al. (2021)). Static charging includes fixed charging stations at designated locations, mobile charging stations offering flexible placement while still requiring stationary vehicles, and battery swapping stations where vehicles exchange depleted battery packs for charged ones. Dynamic charging methods are categorized into charging lanes, vehicle-to-vehicle (V2V) charging, and dynamic battery swapping. Charging lanes involve infrastructure installed along roads to charge vehicles conductively or inductively while in motion. V2V charging refers to the deployment of mobile charging vehicles that provide energy to moving EVs, while dynamic battery swapping replaces depleted batteries with charged ones without requiring vehicles to stop. Notably, dynamic chargers can also support

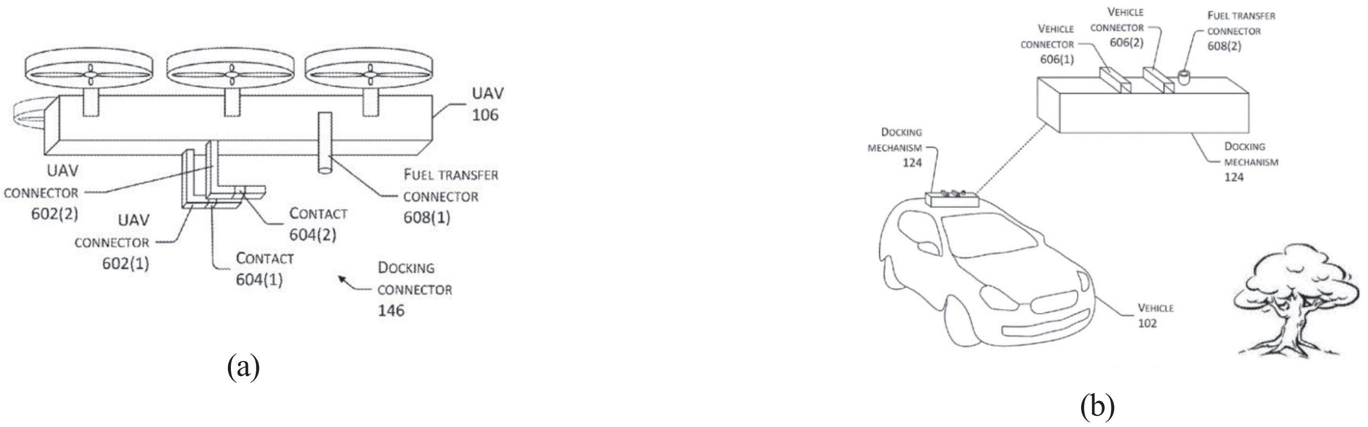


Fig. 3. Illustration of drone charging concept by Amazon (Raj, 2018).

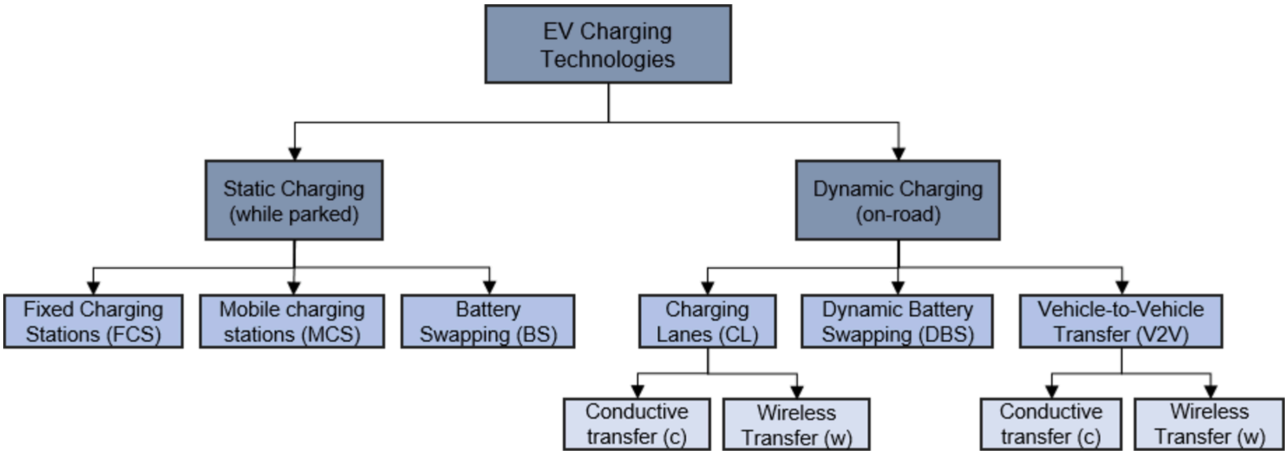


Fig. 4. Classification of EV charging technologies.

stationary vehicles with minor adjustments.

A systematic literature review was conducted to analyze trends in EV charging technologies. The search utilized databases such as Scopus, Web of Science, and Google Scholar, and was supplemented by AI-based tools including Semantic Scholar (Scholar, 2024), Sci-space (Sci-Space., 2024) and Research Rabbit (Rabbit, n.d.). A snowballing approach was employed to identify additional relevant studies. The search was restricted to peer-reviewed, English-language articles published since 2016 to ensure the inclusion of recent advancements (Van Den Bergh et al., 2023).

The search strategy used the following keywords: "(charging infrastructure OR charging station OR dynamic charg* OR V2V OR Vehicle-to-Vehicle OR inductive charg* OR wireless charge OR charging lane OR charge while driving OR mobile charg* OR ERS OR electric-road-system) AND (electric vehicles OR auto* mobility OR EVs).".

This query returned approximately 155,882 results across the three databases. A coarse-grained inclusion approach was adopted, stopping when 10 consecutive irrelevant titles appeared (Mualla et al., 2019). After removing duplicates, approximately 102 studies were identified as initial seeds for AI tools, leading to a total review of 115 studies focusing on EV charging technologies and applications.

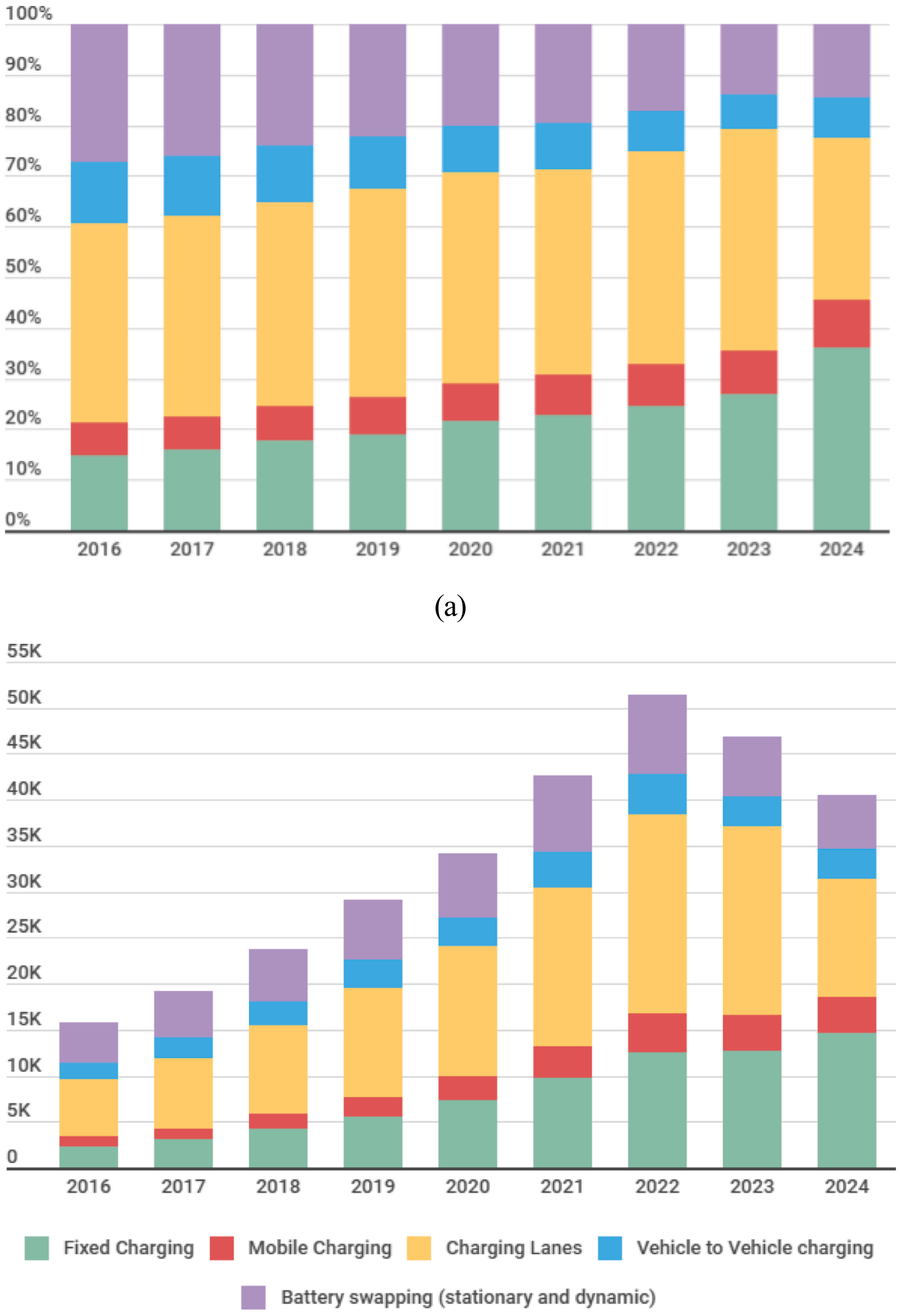
The distribution of research on charging methods was analyzed, revealing that charging lanes dominate the field, with steady publication trends as shown in Fig. 5. V2V charging, though currently less studied, is expected to gain attention due to emerging autonomous mobility. Studies on dynamic battery swapping remain sparse, necessitating broader inclusion of both static and dynamic methods for review. This analysis provides a foundation for identifying gaps, comparing charging technologies, and synthesizing insights for future developments in EV charging infrastructure.

Static charging for EVs

Static charging methods provide simple and highly efficient energy transfer and are currently the most popular methods for charging EVs (Rajendran et al., 2021). They require direct metal-to-metal contact for energy transfer and employ cables to charge the vehicle batteries while they are parked. The systems can be categorized based on the mobility of infrastructure as shown in Fig. 4 into fixed charging stations, which are installed in specific places and are connected directly to the grid or a local energy generator, and mobile charging stations, which correspond to charging stations that draw power from a large battery and are able to travel to where EVs are parked, similar to a mobile battery bank (Zhang et al., 2020). Battery swapping stations are dedicated stations to swap depleted batteries for a charged one. The fixed chargers are categorized based on location and power levels, while mobile chargers are categorized based on usage and working range (Afshar et al., 2021).

Fixed charging stations

Fixed charging stations can be categorized based on the power levels they can supply, which corresponds to the time it takes to charge a vehicle. They can supply power as alternating current (AC) or direct current (DC), depending on the charger location either on-board or off-board. The definition of charging levels can vary depending on different countries and international standards and can vary from level 1 to level



(a)

(b)

Fig. 5. Publications by topic in EV charging domain (a) Percentage of research per topic (b) Total number of publications per year.

3 with level 3 being the fastest (Dimitriadou et al., 2023). Based on their usage and power levels, which relates to charging duration, they are classified as home charging, public charging, workplace charging and depot charging.

Home charging

Home charging, also known as private and residential charging, relates to chargers installed at homes and residential facilities and are currently the most prevalent to charge EVs. They are the dominant type of charging and expected to reach 140 million units worldwide by 2030 (International Energy Agency, 2023). These facilities typically use Level 1 and Level 2 AC chargers, as they align with the convenience of overnight charging. This setup offers cost-effective flexibility due to the reduced equipment requirements. Recently, however, industries have begun exploring advanced alternatives, such as static wireless and robotic chargers, for residential applications (Evatran, 2021; Design, n.d.; Shariff et al., 2020).

Given that EV ownership is predominantly concentrated in urban centers where private garages are often unavailable (Kostian et al., 2023), a significant proportion of charging demand is anticipated to shift to workplace or public area charging facilities. To evaluate the feasibility of home charging, Jakobsson et al. (2016) analyzed multi-car households in Germany and Sweden under the assumption that vehicles charged exclusively at home. The study employed motion data to assess individual user patterns rather than relying on aggregate averages. The findings revealed that second cars in multi-car households required fewer adaptations and were more suitable for EV adoption compared to first cars in the same households or vehicles in single-car households. Wenig et al. (2019) further examined the trade-offs between battery capacity and charging infrastructure using a simulation-based approach with GPS data from approximately 1,000 vehicles. The results indicated that if only home charging at 22 kW is available, vehicles would require a battery capacity of approximately 112.8 kWh to meet all travel demands.

Public charging

Public chargers are installed in places that are easily accessible to public such as public parking lots, highways, petrol stations, parks and shopping centers. They are essential in dense urban areas where there is a lack of garages for home charging. As the time spent in these locations is shorter than time spent at home locations, public chargers usually employ level 2 AC and DC fast chargers and satisfy energy needs in less than half an hour.

Fast charging stations are rated from 50 kW to up to 3 MW, enabling vehicle charging in a matter of minutes. However, this rapid charging can negatively impact battery life due to the heat generated during the process. A study analyzing the effects of fast charging on the lifespan of batteries in heavy-duty electric vehicles found a direct correlation between higher charging power and increased battery degradation. One mitigation strategy involves increasing battery capacity; for instance, a 66 % increase in capacity was shown to extend battery life by 94 % (Al-Saadi et al., 2022). For private vehicles, a combination of home charging and public charging of up-to 50 kW is sufficient to meet travel demands with 56 kWh battery capacity (Wenig et al., 2019).

Despite their importance, public chargers face challenges, including lower utilization rates compared to home and workplace charging (LaMonaca and Ryan, 2022) and significant strain on existing grid infrastructure due to their high power requirements when in use (Meyer and Wang, 2018). Addressing these challenges necessitates improved planning and operational strategies to mitigate grid impacts and reduce deployment costs (Al-Ogaili et al., 2019; Ren et al., 2021; Chen et al., 2018).

Workplace charging

Workplace charging involves the deployment of charging stations at business and office complexes to provide convenient energy replenishment for employees and visitors. These stations predominantly utilize Level 2 AC chargers, supplemented by a limited number of DC fast chargers, and have been shown to significantly support the adoption of electric vehicles (EVs) (Garas et al., 2016).

In addition to promoting EV adoption, workplace charging can enhance the integration of renewable energy into the power grid. By aligning charging activities with daytime hours when renewable energy production is at its peak, workplace charging stations can contribute to cleaner energy consumption (Coignard et al., 2018). The predictability of work schedules further makes static wireless and mobile charging stations viable options for such environments (Flechl, n.d; Khan et al., 2022).

Access to workplace charging also has economic and practical benefits. It can marginally lower energy costs for users while enabling the adoption of smaller battery capacities. This is because the reduced distance between charging points (e.g., home-to-work) minimizes the need for larger energy reserves, leading to cost savings and potentially lighter, more efficient EV designs (Wu, 2018).

Depot charging

Depot charging is a critical solution for fleets of electric vehicles (EVs), including heavy-duty trucks and electric vehicles used in delivery and transportation services. These charging stations are typically located at fleet management hubs such as bus depots and logistics centers, where high-capacity Level 2 or Level 3 chargers are employed to meet the rapid turnaround and charging demands of EV fleets, as depicted in Fig. 6.

In addition to depot charging, opportunity charging has emerged as a supplementary solution, particularly for electric buses. This approach involves charging buses during the day at designated charging spots along their routes using fast or ultra-fast chargers. Opportunity charging can reduce the required size of battery packs; however, it currently represents a relatively small proportion of charging solutions, with an estimated installed capacity of approximately 1.2 GW (International Energy Agency, 2023). Comparative research on depot charging versus opportunity charging indicates a preference for depot charging, attributed to lower infrastructure costs, reduced battery expenses, shorter travel times, and other benefits (Sadrani et al., 2023).

A case study on bus electrification in inner Stockholm, Sweden, provides valuable insights into the economic and operational implications of various charging strategies (Karlsson, 2016). The study evaluated three scenarios: (1) exclusive depot charging, (2) a combination of depot charging and end-station charging, and (3) charging at depots and at selected stations using fast chargers. The findings revealed that relying solely on depot charging would necessitate buses equipped with approximately 700 kWh battery capacity, resulting in costs 80–90 % higher than the alternative scenarios.

Mobile charging stations

Fixed charging stations, while offering convenient charging solutions, are characterized by substantial investment costs, low utilization rates, and inefficiencies arising from vehicles remaining parked even after achieving full charge (Zeng et al., 2019). To address these limitations, mobile charging stations (MCSs) have emerged as an alternative, providing charging services at times and locations convenient to users (Cui et al., 2018).

Mobile charging stations are defined as portable energy sources capable of traveling to electric vehicles parked at different locations to deliver the required charge. The charging process occurs while the vehicle is stationary and can be facilitated in diverse locations such as parking lots, highways, or other user-preferred areas. Neto et al. (2024) offer a comprehensive overview of MCSs, discussing their classification, battery technologies, converter topologies, and market solutions. Their findings emphasize the advantages of isolated DC/DC converters for ensuring safety, efficiency, and the ability to charge multiple vehicles simultaneously. The study also identifies cost-effectiveness as a strength of grid-connected MCSs, though their dependence on grid access limits operational flexibility. Moreover, large-scale deployment of MCSs encounters challenges, including high initial capital requirements, logistical intricacies, and sustainability concerns.

Fig. 6. Depot chargers for heavy vehicles (EVs, C., 2022).

A detailed review of advancements in mobile charging technologies is presented by Afshar et al. (2021). The study categorizes various MCS types and technologies while examining their architectures, advantages, challenges, and unresolved research questions. Technical reports and studies underline the critical role of MCSs within the EV charging market. However, significant gaps remain, such as optimizing coordination with other charging methods, assessing the impact of MCSs on EV market penetration, and developing strategic investment frameworks. These findings underscore the need for further research to realize the potential of MCSs in advancing sustainable and flexible EV charging solutions.

Truck mobile charging

Truck mobile charging stations consist of an electric or hybrid vehicle that can travel a certain distance to provide charging to multiple EVs. The energy requirements can be met either by an on-board battery pack or by directly connecting to the grid. These mobile stations can be employed for different purposes as shown in Fig. 7. A battery-less truck charger can be deployed to serve as a fixed charger for multiple vehicles in case of requirements for more charging outlets during high demand (Afshar et al., 2022). A battery integrated charger can provide charge at much more convenient locations, however, needs time to recharge its own battery pack, which limits its range and number of vehicles charged (Saboori et al., 2021). They are also deployed as battery swapping services and carry the battery packs to user's designated parking spots for swapping exhausted batteries for fully charged ones (Lambert, 2017).

Beyond EV charging, these systems have expanded applications. A novel vehicle-to-water (V2W) concept, proposed by Leijon and Lindahl (2021), envisions a truck mobile charger equipped with solar panels and a desalination unit to function as a multifunctional platform. This system provides transportation, freshwater production, and electricity supply, making it particularly beneficial for coastal regions affected by natural disasters or crises where access to freshwater and electricity is critical.

To address the increasing frequency of extreme disasters globally, a resilience enhancement scheme utilizing mobile charging stations is proposed by Shen et al. (2023). This approach leverages the spatial and temporal flexibility of truck-based MCS units to prevent large-scale outages. The proposed MCS sharing mechanism optimizes the driving routes and charging states of these units, enhancing the resilience of power distribution systems. Its effectiveness is validated using the IEEE 33-bus distribution test system, demonstrating the ability of mobile energy storage to mitigate disruptions and support efficient system recovery in disaster scenarios.

Mobile charging bots

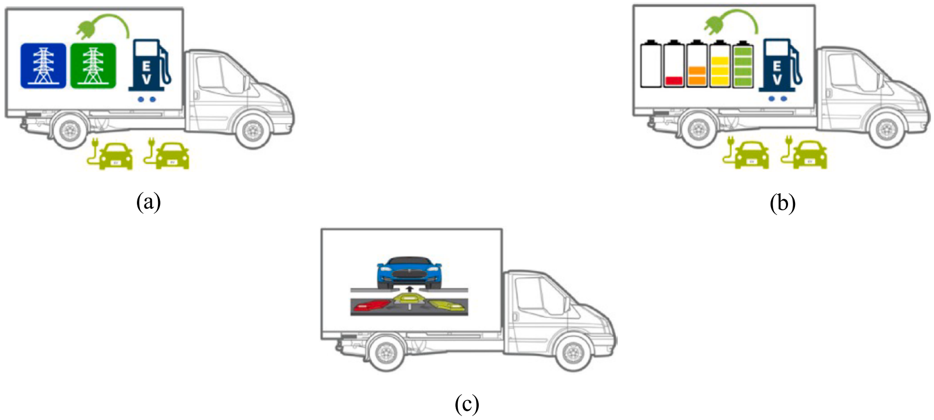
To charge vehicles in places with high density and short travel distances, which include parking lots of workplaces, autonomous charging bots are deployed to save costs on expensive infrastructure (Kong, 2019). They have lower mobility compared to truck charging and usually provide charge within the parking lot. They can either be deployed as autonomous robots that open and close charge inlets of EVs (Hirz et al., 2021; contact: The mobile charging robot – Presenting a vision; Tesla, 2015) as shown in Fig. 8 or an under-body charger that is deployed on the floor and charges through an opposite unit mounted on the under-body of vehicle (Flechl, n.d; Charging, 2023).

A case study conducted in Xiamen, China, demonstrated that mobile charging systems can be economically competitive compared to fixed charging stations, particularly when accounting for the value of time savings. The study found that mobile charging could save approximately 20 min per charging session (Zhang et al., 2020). Similarly, a comparative analysis focusing on workplace scenarios revealed that a small number of mobile charger bots can effectively meet the same demand as multiple fixed chargers. This efficiency is achieved by leveraging vehicles' idle time and the flexibility of mobile chargers, resulting in significant reductions in infrastructure costs (Khan et al., 2022).

Battery trailers

From the analysis of EV users' driving patterns, research reports that the typical EV user seldom travels long distances and that an EV with a small battery pack usually fulfills their daily requirements (Hooftman et al., 2018). However, when traveling long distances, a battery trailer can be towed or carried by the vehicle to extend its own stand-alone operation as shown in Fig. 9. A life-cycle impact study on EVs with battery packs of about 40 kWh found that the environmental impact can be significantly reduced by using an extended range only when needed (Hooftman et al., 2018). A battery bank trailer attached to an electric minibus taxi reduces recharge downtime by 4 % and increases the range by 120 % for the case study done in (Giliomee and Booysen, 2023).

Fig. 8. Mobile charging bots (Hirz et al., 2021).



(a)

(b)

(c)

Fig. 7. Truck mobile charging (a) battery-less truck charger (b) battery-integrated truck charger (c) battery swapping truck charger (Afshar et al., 2021).

Fig. 9. Battery trailer for range extension (Berman, 2020).

These trailers can also double as temporary charging stations for specific locations such as concerts and sporting events (Lambert, 2019).

Battery swapping stations

Battery swapping stations provide an alternative to traditional EV charging by allowing users to exchange depleted batteries for fully charged ones, thereby offering a rapid and convenient recharging process. Unlike truck-based services, these stations require users to visit a fixed location where the battery swap occurs. This model reduces the upfront costs of EV ownership by enabling users to rent batteries rather than purchase them outright. Despite initial commercial setbacks, battery swapping has gained renewed momentum, particularly in China, where substantial investments in new facilities are underway (Feng and Lu, 2021). The approach offers several advantages over fixed and mobile charging solutions, including reduced EV retail costs, shorter "recharge" times, lower grid impacts, and extended battery lifespans.

A detailed examination of automated battery swapping stations is presented by Adegbohun et al. (2019), which highlights Tesla's battery swapping initiatives as a case study. The study identifies key technical challenges, such as compatibility, scalability, and cost-effectiveness, that have hindered the widespread adoption of battery swapping. It further emphasizes the advancements necessary to make battery sharing networks viable for promoting EV adoption and supporting smart grid integration.

In a complementary effort, Marchesano et al. (2024) introduces a framework for optimizing battery swapping sta- tion operations, combining agent-based modeling, discrete event simulation, and linear programming. This framework demonstrates how operational efficiency, service quality, and battery lifecycle management can be enhanced, thereby increasing the sustainability and feasibility of battery swapping infrastructure.

A comparative analysis by Rafi et al. (2020) evaluates battery swapping against fast charging for electrifying underground haul trucks. The findings suggest that battery swapping with the largest feasible battery size (348 kWh) yields 2.8 % higher productivity compared to the most efficient fast-charging option (600 kW charge rate with a 228 kWh battery), though at a 65 % higher cost over a five-year period. For a 228 kWh battery pack, battery swapping achieves equivalent productivity to fast charging but incurs a 48 % higher cost. This growing body of literature underscores the potential of battery swapping in addressing key limitations of traditional EV charging methods. However, the economic and technical barriers identified highlight the need for further innovations and strategic investments to ensure the commercial viability of this promising solution.

Dynamic charging for EVs

Static charging methods offer high efficiency for EVs but requires the vehicle to remain stationary while a driver or other agent physically connects it to the charging station. However, advancements in AEV and driver-less technologies are expected to render such methods increasingly redundant. In autonomous systems, an on-board computer determines the route, schedules charging events, and navigates the vehicle to maintain sufficient charge, eliminating the need for human intervention (NHTSA, n.d). These developments also facilitate shared usage and ownership models, potentially reducing individual vehicle ownership and encouraging more efficient utilization of shared fleets (Vosooghi et al., 2020).

The absence of drivers to manually connect vehicles for charging presents a significant obstacle to traditional static charging systems, as noted by Yi and Smart (2021) and Leijon and Boström (2022). To address this challenge, mobile charging stations and autonomous charging bots have been developed as alternatives. These technologies were originally designed to replace slow chargers, leveraging vehicles' idle periods to reduce infrastructure costs (Das et al., 2020; Khan et al., 2022). However, in the emerging context of shared and autonomous vehicle economies, where vehicles are expected to have significantly reduced idle and parking times, these solutions become less practical. This shift necessitates the development of innovative charging strategies and comprehensive infrastructure planning to address the challenges posed by decreased parking durations and increased operational demands (Chen et al., 2016).

This review emphasizes dynamic charging as a promising solution to these challenges. Dynamic charging enables vehicles to recharge en-route without requiring driver assistance or stopping, providing a seamless integration of energy transfer into the operational flow of AEVs and shared fleets. For the purposes of this study, dynamic charging is defined as charging vehicles while they are in motion, achieved through various technologies. Notably, these dynamic charging systems can also be adapted for static charging of stationary vehicles with minimal modifications, offering a versatile approach to future transportation needs.

Dynamic charging is classified into three categories as shown in Fig. 4. Charging lanes provide charge through installed infrastructure on the roads, and can be categorized into conductive and wireless. Vehicle-to-Vehicle charging employs other vehicles to provide charge and is also classified as either conductive or wireless, as well as dynamic battery swapping, which allows battery swapping while in motion.

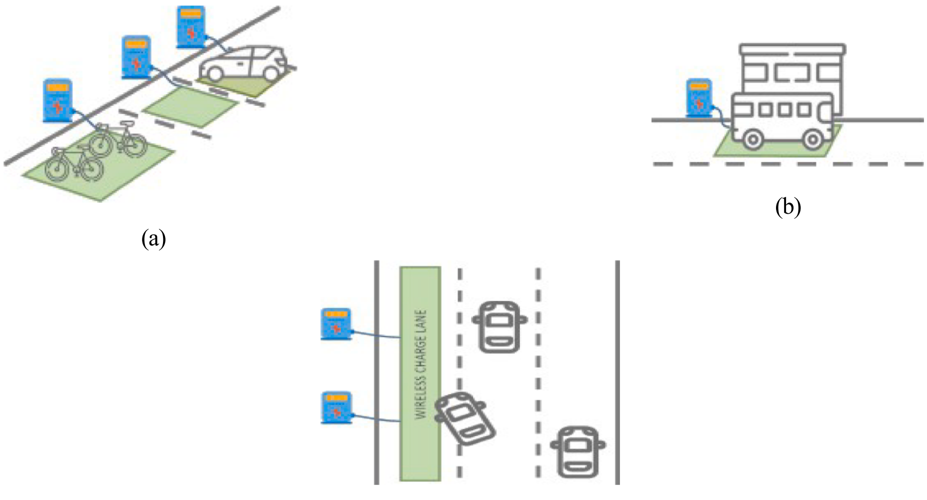
Charging lanes

Charging lanes, also known as electric road systems (ERS) in the literature, were developed to provide solutions to various issues related to EVs, such as high battery costs, short driving range, and long charging duration. They consist of charging methods that are deployed along a section of the road and can charge moving vehicles either by conductive or inductive means (Alaküla and Marquez-Fernandez, 2017). Various studies show that charging lanes may help in reducing required battery sizes by up-to 70 %, which can greatly reduce costs and weight of the EVs (Shoman et al., 2022; Rogstadius, 2023). In the following section, different technologies for implementing charging lanes are compared depending on location and type of energy transfer used for electrifying road segments.

Wireless transfer

Wireless transfer is defined as energy transfer achieved without any physical contact. The wireless charging technologies are categorized into three main categories depending on the mode of energy transfer, namely near-field charging (Niu et al., 2019; Sinha et al., 2019; Regensburger et al., 2018), medium-field charging (Vu et al., 2017; Qiu and Du, 2023) and far-field charging (Li et al., 2017), with near and medium field being the dominant ones and far-field still in development phase (Mohammed and Jung, 2021; Rabih et al., 2024). The wireless chargers are also categorized in terms of EV operation into one of the following: Stationary charging, where EVs are charged when parked as shown in Fig. 10a; Quasi-dynamic, where EVs are charged at low speeds either at intersections or at traffic lights as shown in Fig. 10b, and; Dynamic charging where EVs are charged in full motion (Jang, 2018) as shown in Fig. 10c.

Near-field charging relates to charging by means of either inductive,



(a)

(b)

(c)

Fig. 10. Wireless Charging for EVs (a) static (b) quasi-dynamic (c) dynamic (Triviño et al., 2021).

capacitive or magnetic resonant charging, where currently only magnetic resonant charging has achieved commercial implementation (Mohammed and Jung, 2021; Khalid et al., 2023). Although capacitive and inductive transfer are easier and cheaper to implement, they suffer from small air gap requirements (a few millimeters to a few centimeters) for efficient energy transfer, and require precise alignment (Mahesh et al., 2021).

The medium field charging uses mechanical force as the energy carrying medium and depends on the mechanical interaction of two synchronized permanent magnets (Siddique et al., 2019; Vu et al., 2017). They can transfer energy at a slightly higher range than near-field chargers and are currently only suitable for low power applications (Manivannan et al., 2023).

Far-field charging can achieve energy transfer from a range of few meters to several kilometers. They use electromagnetic radiation and can transfer energy through lasers (Zhang et al., 2018; Zhang et al., 2017), radio wave and micro-wave (Höhn et al., 2021; Halimi et al., 2022). Laser charging is currently under development to provide charging to drones. Recent research has shown capabilities to transfer 10 MW over 10 km, with an efficiency of 37 % and can potentially supply power to EVs and satellites. The main principle of laser charging is to convert energy to electromagnetic radiation using an emitter and then using a photovoltaic cell to convert this radiation back to electrical energy (Mohammed and Jung, 2021; Mahesh et al., 2021; Lee et al., 2020). The main barriers are low efficiency, constant communication between transmitter and emitter, and safety concerns for living beings if exposed to radiation.

Micro-wave transfer is achieved by using a magnetron to convert electrical energy to micro-wave for transfer and is converted back to electrical energy by the rectenna (Halimi et al., 2022) to charge EV batteries. It has the same limitations as laser charging and also requires a large antenna for high power transfer, which limits its usability for EV charging (Triviño et al., 2021).

Radio wave charging makes use of a rectenna (rectifying antenna) that employs a combination of high-frequency filter, a rectifier, and a low-frequency filter. Just as other far-field charging, it also suffers from low efficiency, constant charging connection requirements, and safety concerns for humans (Triviño et al., 2021; Mohammed and Jung, 2021). However, it is thus far the most cost-effective to be deployed and the first far-field charging to be commercialized with Wimo deploying radio wave chargers in collaboration with Tesla. The radio converter is mounted onto the charging station, which converts electrical energy to radio waves. The receiver is mounted on the vehicle, which then converts the radio wave back to electrical energy (WiMo, 2023).

Conductive transfer

The electric road transfer through conductive transfer can be achieved from three directions: (i) from top by using overhead wires, (ii) from the side by using a side-mounted rail, and; (iii) from the road surface by installing conductors on the road (Alaküla and Marquez-Fernandez, 2017; Karlsson and Alaküla, 2021). The transfer from the road can further be achieved through slots, embedded conductors or from the top of the road as shown in Fig. 11. A distinction is made for overhead conductive as it is only relevant for high vehicles such as trucks and buses (Domingues-Olavarría et al., 2018).

There are several advantages and disadvantages for the various locations of power conductors. Power conductors placed in slots made on the surface of the road as shown in Fig. 11a offers flexibility in energy supply to be AC, which lowers infrastructure costs, or DC, which lowers vehicle costs (Pei et al., 2024). Power conductors placed parallel to the road are presented in Fig. 11b (Elways, 2021) and utilizes knowledge from previous experience in railways and trams.

Power conductors can also be mounted a few centimeters above the road segment as shown in Fig. 11c. This method allows alternative opposite segments to be placed in line with some insulation (road) (road). This allows the segment length needed to be energized and charge the vehicle to be much smaller than previous solutions. This in turn allows for improved safety as only the segment beneath EVs are electrified (Domingues-Olavarría et al., 2018).

To minimize deployment costs and the need to modify existing roads, energy transfer from side railings have also been proposed in Fig. 11d (Ali et al., 2022, 2023). This system can charge both heavy and passenger vehicles, while also lowering installation and maintenance costs. This technology is currently in the testing phase, and requires further testing to ensure its reliability and safety (Tajima et al., 2017).

To charge heavy trucks and buses, overhead lines are deployed on highways and are currently being tested in Sweden (Fyhr et al., 2017). The energy transfer is achieved through pantograph connectors similar to trolley buses and trams. As the lines are energized even without any trucks charging, the lines have to be sufficiently high to avoid accidents from humans or animals as shown in Fig. 11e (Alaküla and Marquez-Fernandez, 2017). As this technology can only be used by heavy vehicles and not private vehicles, this solution is considered the least cost-effective method to implement charging lanes (Márquez-Fernández et al., 2021; Márquez-Fernández et al., 2017).

Compared to wireless charging lanes, conductive lanes have a higher technological maturity, and have an expected break-even period of 25–35 years. Compared to traditional roads, the carbon emissions are 167 to 220 % higher, but have the potential to reduce total emissions of

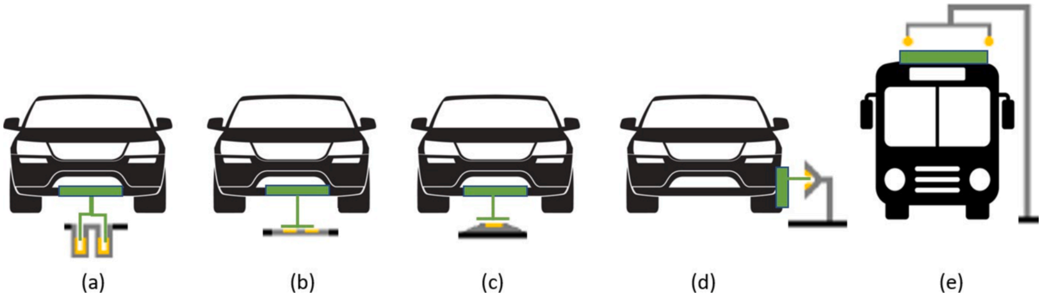


Fig. 11. Conductive road transfer (a) conductors placed in slots (b) conductors placed with the road segment (c) conductors placed above the road segment (d) conductors installed on guard rails (e) overhead charging (Márquez-Fernández et al., 2021).

the transportation sector when the use EVs instead of ICE vehicles are taken into consideration. These charging methods can also work in synergy with autonomous vehicles and other smart infrastructure to improve its effectiveness (Pei et al., 2024).

Vehicle-to-Vehicle transfer

To reduce the infrastructure and deployment costs of the charging lanes, a number of innovative solutions are being proposed in the literature. Vehicle-to-Vehicle (V2V) charging deals with deploying mobile vehicles to implement dynamic charging similar to charging lanes. It deals with a user vehicle requesting charge and a charger vehicle that travels alongside the user vehicle and provides charge either inductively or conductively. This allows dynamic energy transfer without the costly infrastructure requirements of charging lanes. In the following we categorize V2V charging in terms of their energy transfer as either wireless or conductive.

Wireless transfer

To minimize infrastructure modifications and allow for continuous operation of EVs, a wireless V2V solution is presented in (Nezamuddin et al., 2022). The system consists of a charger vehicle that is stationed on highways or charging stations. A user vehicle with low battery state of charge (SOC) can request the charge (Fig. 12a). The charger vehicle is then dispatched to the user vehicle location and moves along the route in a platoon with the user vehicle (Axelsson, 2016; Medawar et al., 2017; van Nunen et al., 2017) and provides the charge wirelessly as shown in Fig. 12b (Arya and Saxena, 2022) and then disengages and returns to station when the charging needs are met (Fig. 12c). The method employs a forward-facing powertrain and makes use of semi-autonomous vehicles as charger vehicles. The simulation analysis shows travel time savings of around 20 min compared to charging solutions with only static chargers (Nezamuddin et al., 2022).

A new structure for wireless V2V charging that enables the vehicles to charge from stationary chargers as well as other vehicles with wireless charging capabilities is proposed by Mou et al. (2018). The system enables charger sharing, wherein the first vehicle receives charging from a fixed charger, while simultaneously transferring energy wirelessly to a second vehicle, as illustrated in Fig. 13. The author suggests that this system can solve the issue of limited chargers by allowing multiple vehicles to charge from the same charging station (Mou et al., 2018). One major challenge with V2V transfer is lateral and angular misalignment of coils. A potential solution is proposed in (Mou et al., 2020) in the form of introducing a three-sided transmitter coil which also improves system power and efficiency.

Another method to provide V2V charging is presented by Kosmanos et al. (2018), where buses, trucks and other heavy vehicles are deployed as mobile charging stations as shown in Fig. 14. These mobile energy disseminators (MEDs) follow a specific route during the day and any vehicle requiring charge can follow the MED and get required energy via wireless transfer (Alaskar and Younis, 2024). A comparative study to assess the performance of this system found it to reduce travel distance as there is reduced routing to locate and travel to charging stations and as a result also reduce travel time by about four times when compared to a deployment scenario with only static chargers (Kosmanos et al., 2017; Alaskar and Younis, 2022). To utilize this service, the user needs to identify if there is an MED on its route, its availability and whether it has sufficient energy to provide charging (Kosmanos et al., 2018).

Another concept proposed is to charge buses using charging pods. The pods are stationed vertically to save space and are deployed when required. They can autonomously locate the bus, travel behind it to provide the charge wirelessly, and then return to the nearby available

Fig. 13. Charging from fixed chargers and sharing charger with other vehicles proposed in (Mou et al., 2018).

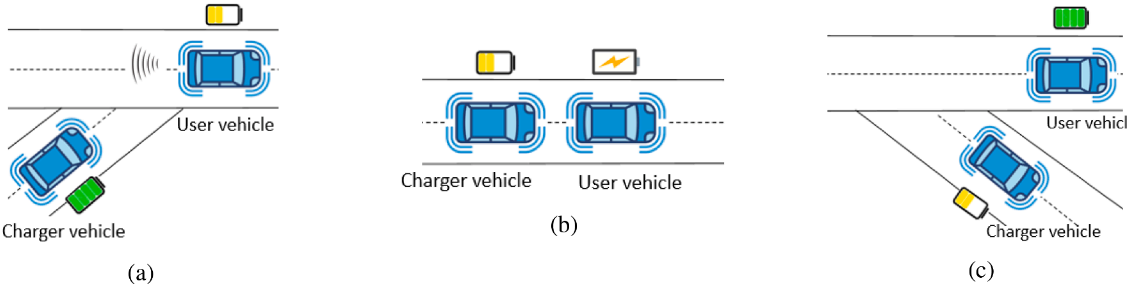


Fig. 12. V2V energy transfer (a) user requesting charge (b) charger vehicle providing the necessary energy (c) charger vehicle returning to the station (Nezamuddin et al., 2022).

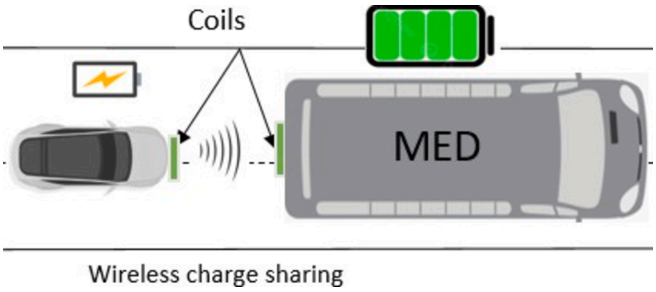


Fig. 14. Illustration of energy transfer by mobile energy disseminator (MED) (Kosmanos et al., 2018).

parking station (Frizziero et al., 2022).

Conductive transfer

Vehicle-to-vehicle wireless charging can provide convenient charging to EVs. However, they suffer from low power output and transfer efficiency. The wireless transfer techniques have efficiencies of about 60 % and require large coils, which are challenging to implement in vehicles (Pham et al., 2021). To circumvent this issue, conductive transfer between EVs while in motion is proposed by Chakraborty et al. (2022).

The study also proposes a two-battery system to minimize time spent charging, where one smaller battery is used for reducing charging time between vehicles and then transferring that charge to the bigger battery. The connection between vehicles can be achieved through a flexible wired connection, where each vehicle extends its arm and interconnects with each other as shown in Fig. 15a. The other method proposes the use of drones to make the connection where the drone lands on a charging pad on the vehicle to make the connection as shown in Fig. 15b (Chakraborty et al., 2022).

The feasibility of both solutions is analyzed using SUMO simulation and the results show a reduction in travel time and battery capacity requirements (Alvarez Lopez et al., 2018). The main drawbacks of this method are increased complexity, high level of communication, and coordination between AEVs and other nearby vehicles.

This charging method can also be deployed for modular vehicles, as they already have means for making a physical connection as shown in Fig. 16, and can potentially be used for sharing energy between different pods.

V2V charging presents a promising approach to reducing battery capacity requirements and enhancing the operational efficiency of electric vehicles (EVs) by facilitating on-route energy replenishment. For passenger vehicles, recent studies underscore the potential for substantial battery size reductions. For example, Yan et al. (2022) estimates that V2V charging could decrease battery capacity requirements by approximately 50 %. Similarly, Chakraborty et al. (2022) reports a 25 % reduction when a higher density of mobile charging units is deployed across the road network. These findings highlight the critical role of V2V charging in optimizing EV performance and reducing associated costs.

In addition to reducing battery sizes, V2V charging also minimizes travel time by eliminating the need for detours to charging stations. Studies have quantified these time savings, with Nezamuddin et al. (2022) reporting an average reduction of around 20 min, equivalent to a 20 % decrease in travel time. Similarly, Khan et al. (2024) observed a travel time reduction of approximately 4 % for passenger vehicles operating under continuous movement scenarios.

Dynamic battery swapping

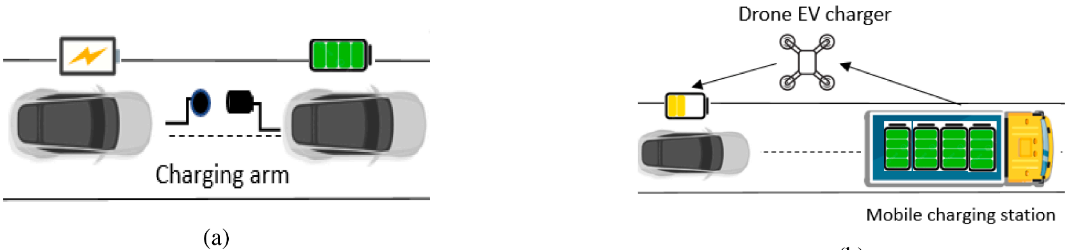
Battery swapping offers a fast and convenient way to replenish EVs by replacing depleted energy packs for fully charged ones. Although they were initially proposed as dedicated spots where vehicles can travel to exchange battery packs (static charging), recently, these solutions are being proposed for charging vehicles in motion (dynamic charging). A battery swapping vehicle that replaces a depleted battery while the vehicle is in motion is presented in Zhou et al.. The vehicle employs a holding and rotating mechanism to remove depleted batteries and install the charged ones.

An innovative internet-of-things framework called SAVIOR is proposed in Chakraborty et al. (2023), which employs combined use of mobile charging stations and drones to replenish EVs on the move. The drone can use the mobile station to pick up battery packs and then distribute to other nearby vehicles. The system is proposed to allow charging either by wired transfer or by battery swapping drones, where the depleted battery is exchanged for a charged one as shown in Fig. 17 (Chakraborty et al., 2023).

An automated battery replacement for city buses is presented in Masłowski et al. (2023), where the technology can exploit the cyclical and scheduled operations of buses to optimally manage batteries. As the schedule and demand of buses can be predicted, battery swapping can be deployed focusing only on heavily loaded buses, while the less loaded buses charge at depots, in order to save on investment costs. This can allow the electrification of whole bus fleets while minimizing charging infrastructure costs.

Opportunities and challenges of dynamic charging stations

With recent technological developments, the transportation sector is expected to undergo changes with vehicles becoming more connected and autonomous. These vehicles may be shared to some extent (Vosooghi et al., 2020). These developments will pose a challenge to charging infrastructure as shared, connected and autonomous vehicles will have different charging needs compared to conventional private vehicles. Such shared AEVs will have a higher utilization rate and less idle time for locating and queuing for charging stations, as extra travel time will lead to loss of revenue and customer satisfaction (Weiss et al., 2017; Loeb et al., 2018). Dynamic charging solutions emerge as a promising avenue to address these challenges, offering numerous benefits and opportunities. This section explores these prospects while integrating research gaps that require further investigation to facilitate the deployment of such solutions.

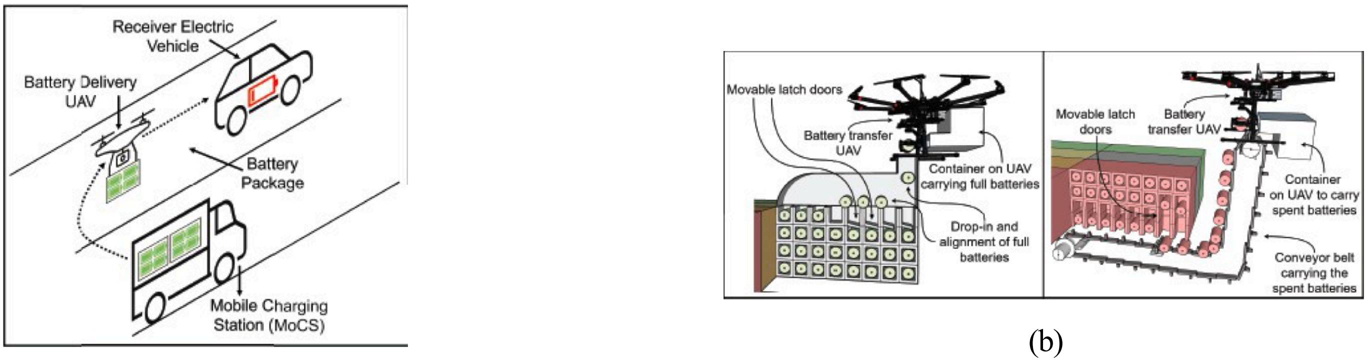


(a) (b)

Fig. 15. Illustration of peer-to-peer car charging (a) connection by robotic arms (b) connection by using drones to establish conductive charging from MOCS (Chakraborty et al., 2022).

(a) (b)

Fig. 16. Illustration of modular vehicles (a) modular pods (b) pods forming physical connection (Next, 2023).



(a) (b)

Fig. 17. Illustration of SAVIOR method (a) battery swapping drones travels to user vehicle (b) drone replacing the depleted batteries with fully charged ones (Chakraborty et al., 2023).

1. *Optimized routing and charging coordination:* Autonomous and connected vehicles can optimize routing and charging schedules through real-time communication with dynamic charging infrastructure. These systems allow vehicles to assess battery status, predict energy needs, and plan routes that pass through charging lanes or stations at the most opportune times (Hosseini and Yassine, 2022; Mahure et al., 2020; Mohamed et al., 2019; Giovannelli and Vicente, 2023). Future research should focus on developing algorithms and simulation models that consider factors such as traffic patterns, energy demand, and cost-effectiveness (Gao and Li, 2023; Sachan et al., 2020; Chen et al., 2017; Nguyen et al., 2024). Additionally, balancing the use of static and dynamic chargers to optimize vehicle routing and reduce queuing times warrants further investigation.
2. *Precise alignment for inductive charging:* One of the challenges of wireless charging is ensuring precise alignment between the charging infrastructure and the vehicle (Mou et al., 2018; Sagar et al., 2023). Autonomous vehicles equipped with advanced sensors and control systems can overcome this limitation by accurately aligning themselves with charging lanes, enabling efficient and safe energy transfer without human intervention. Future work should focus on developing common protocols to improve standardization and evaluating coil topologies to reduce alignment issues and enhance energy transfer efficiency (Sagar et al., 2023; Shanmugam et al., 2022; Patil et al., 2018; Niu et al., 2019).
3. *Platooning and charging:* Autonomous vehicle platooning, where vehicles travel closely together in a coordinated manner, can be combined with dynamic charging (Liu et al., 2019; Axelsson, 2016). Vehicles in a platoon can take turns to charge while others continue to move, thereby still maintaining a platoon and reducing the need for every vehicle to stop for charging simultaneously. This approach optimizes energy distribution and minimizes disruptions in traffic flow (Kabir et al., 2021). This can improve user experience as charging is automated, passengers can continue their journey without having to wait for locating or queuing at charging stations, and the autonomous vehicle can even notify passengers when the charging process has been completed (Zefreh et al., 2023). Further investigation is needed into the energy efficiency gains of integrating platooning with dynamic charging. Studies should explore how platooning configurations can reduce transportation energy requirements and operational costs (Triviño et al., 2021).
4. *Real-time data sharing:* AEVs equipped with real-time data sharing capabilities can streamline charging operations by communicating energy needs, anticipated charging times, and traffic conditions with infrastructure and other vehicles. (Aoki et al., 2022; Cho et al., 2020; James and Lam, 2017; Bathla et al., 2022). These features can also be extended to share information about their energy needs, upcoming charging requirements, traffic conditions and the expected queue at charging lanes (Li et al., 2018). Autonomous mobile charging units, including drones, can further enhance system flexibility by providing on-the-go charging services (Yan et al., 2022; Kosmanos et al., 2018; Qu et al., 2022). However, to achieve this, robust vehicle-to-infrastructure (V2I) communication protocols must be developed to enable seamless interaction between AEVs and charging systems (Wang et al., 2023; James and Lam, 2017; Vaidya and Mouftah, 2018). Moreover, cybersecurity measures to safeguard sensitive user and operational data are critical (Shanmugam et al., 2022; Wang et al., 2021).
5. *Safety and sustainability:* Autonomous vehicles are equipped with advanced collision avoidance systems, which can enhance safety during dynamic charging (Medawar et al., 2017; van Nunen et al., 2017). These systems can detect obstacles, pedestrians, or other vehicles in real-time and take evasive actions to prevent accidents during charging operations. Although, this makes dynamic charging feasible, there are safety and health issues related to electromagnetic radiation. Proper safety measures should be taken to avoid energizing the lane or vehicles when no vehicles are present. Research should address safety concerns related to electromagnetic radiation, alignment accuracy, and the impact of dynamic charging on vehicle, passengers and road infrastructure (Manivannan et al., 2023; Machura and Li, 2019). Future works can assess the life-cycle

environmental impact, including manufacturing, operation, and disposal, and explore ways to minimize the carbon footprint of these systems (Bi et al., 2018)

6. *Scalability and real-world implementation:* Scalable and cost-effective deployment of dynamic charging infrastructure is vital for widespread adoption. Real-world pilot projects can validate the performance of these systems in diverse scenarios, including public transportation and delivery services, while identifying operational challenges and strengths (Ali et al., 2022; Schwerdfeger et al., 2022). Based on pilot results, future work can provide insights into the legal and regulatory challenges associated with dynamic charging and propose policy recommendations to support its implementation (Plötz et al., 2024).
7. *Improved grid integration:* AEVs can adapt their charging behavior based on grid conditions and energy availability. Renewable energy sources can be prioritized during periods of abundance, with grid power utilized as needed to support sustainability objectives. Additionally, charging operations can be scheduled during times of lower energy costs, thereby contributing to grid load balancing(Rolufs et al., 2021; Pruckner and Eckhoff, 2020). The use of shared autonomous electric vehicles also may also improve V2G operations, contributing to load shifting and grid balancing without compromising passenger needs based on a case study in Tokyo (Iacobucci and Bruno, 2019; Dehkordi et al., 2022; Van Den Bergh et al., 2023). Future studies should assess the impact of dynamic charging on grid infrastructure, including load management during peak demand. Additionally, integrating vehicle-to-grid (V2G) operations with AEVs to support grid stability warrants further exploration (Deflorio and Castello, 2017; Koufakis et al., 2016; Qiu et al., 2021).
8. *Reduced battery capacities:* Dynamic charging offers the potential to reduce reliance on large battery capacities by enabling on-route charging. Unlike fast charging stations, which often diminish battery life due to high-power charging, dynamic charging mitigates this issue by facilitating frequent, shallow charging cycles. Studies, such as Jeong et al. (2019), reveal that frequent shallow charging through dynamic systems can enhance battery longevity compared to infrequent deep charging. However, this positive effect is conditional upon maintaining a sufficiently large battery size to balance charging efficiency and energy demands. Similar findings by Al-Saadi et al. (2022) highlight that increasing battery size can extend battery lifespan. Future research should aim to refine the trade-off between minimizing battery size and preserving battery life, particularly in the context of dynamic charging. This balance is critical for optimizing vehicle efficiency while ensuring economic and environmental sustainability.

The integration of autonomous technology with dynamic charging systems is a promising avenue for enhancing the viability and efficiency of future mobility solutions. It has the potential to reduce costs, increase convenience, and accelerate the adoption of electric and autonomous vehicles, ultimately leading to a more sustainable transportation ecosystem.

To realize the potential benefits provided by dynamic charging, optimal methods need to be considered to reduce investment costs and increase the utilization of these solutions. The choice between these dynamic charging methods depends on factors such as the specific application, budget constraints, infrastructure availability, and the desired balance between charging speed and flexibility. Different regions and use cases may favor one method over the others, or a combination of these methods may be employed to meet diverse charging needs (Leijon and Boström, 2022).

The potential pros and cons of various charging methods are presented in Table 2 based on findings presented in Chakraborty et al. (2022, 2023); Arya and Saxena (2022); Shoman et al. (2022); Nezamuddin et al. (2022); Villeneuve et al. (2020); Leijon and Boström (2022); Liao et al. (2024); Waseem et al. (2024); Zentani et al. (2024). As

Table 2

Potential pros and cons of various dynamic charging methods.

Charging Method	Pros	Cons
Wireless charging lane	- No Physical Contact: Wireless transfer eliminates the need for physical connections, making it convenient for EVs on the move. - Reduced Wear and Tear: Reduces mechanical wear on vehicles compared to conductive methods. - Suitable for Public Roads: Wireless charging lane can be implemented on public roads and highways, benefiting a wide range of users. - Potential for High Power: Some wireless ERS implementations can achieve high-power transfer, reducing charging time.	- Lower Efficiency: Wireless charging can be less energy efficient than conductive methods, leading to energy losses. - Alignment Challenges: Precise alignment between the charging infrastructure and EVs is crucial for efficient charging. It also requires constant communication between receiver and emitter and can be sensitive to disruptions. - Cost: The initial investment for wireless ERS infrastructure can be high. - Limited Adoption: Widespread adoption of wireless charging lanes may require standardization and vehicle modifications. - Health impacts: Several wireless charging methods have detrimental effects on living beings.
Conductive charging lane	- High Efficiency: Conductive charging lanes can offer higher charging efficiency compared to wireless methods. - High Charging Power: Conductive lanes can provide high-power charging, reducing charging time. - Suitable for Heavy Vehicles: Conductive lanes can deployed for heavy vehicles such as trucks and buses due to quick charging time and high energy transfer. - Proven Technology: Conductive charging has been in use for other transportation modes such as trams and trains.	- Infrastructure Costs: Installing and maintaining conductive charging lanes can be expensive due to increased wear and tear. - Compatibility Challenges: Vehicles require specific connectors and adaptations for conductive charging lanes. - Safety Concerns: Contact-based conductive charging can raise safety concerns related to electrical contacts. - Limited Flexibility: Routes and lanes with conductive charging are predetermined, reducing vehicle freedom.
Wireless Vehicle-to-Vehicle	- High Flexibility: Wireless V2V charging can be adapted to various routes and scenarios. - Cost-Effective: It is more cost-effective than building extensive infrastructure for charging compared to dedicated lanes and static chargers.	- Alignment Challenges: Precise alignment between charging vehicles is crucial for efficient wireless charging. - Lower Charging Rates: Wireless V2V charging has lower charging rates compared to conductive methods. - Additional Weight: Developing V2V infrastructure and retrofitting vehicles can involve upfront costs and increase weights of vehicles due to large coils. - Infrastructure Compatibility: Requires the deployment of charging vehicles with same compatible charger and the development of common charging infrastructure.
Conductive Vehicle-to-Vehicle	- High Flexibility: Wireless V2V charging can be adapted	- Alignment Challenges: Precise alignment between charging vehicles is crucial

(*continued on next page*)

Table 2 (*continued*)

Charging Method	Pros	Cons
	to various routes and scenarios. - Cost-Effective: It is more cost-effective than building extensive infrastructure for charging compared to dedicated lanes and static chargers.	for efficient wireless charging. - Lower Charging Rates: Wireless V2V charging has lower charging rates compared to conductive methods. - Additional Weight: Developing V2V infrastructure and retrofitting vehicles can involve upfront costs and increase weights of vehicles due to large coils. - Infrastructure Compatibility: Requires the deployment of charging vehicles with same compatible charger and the development of common charging infrastructure.
Conductive Vehicle-to-Vehicle	- High Charging Rates: Conductive V2V charging can provide high-power charging, reducing downtime. - Efficiency: Conductive methods are typically more efficient than wireless methods. - No Alignment Issues: Conductive connections do not require precise alignment. - Proven Technology: Conductive charging is a well-established technology	- Physical Contact: Conductive V2V charging relies on physical connections, which may wear over time. Moreover, they require improved communication to maintain the contact - Infrastructure Needs: Requires specific connectors and infrastructure on vehicles which may increase costs and weight of vehicles. - Complexity: Managing the connection process may require additional vehicle technology. - Infrastructure Investment: Requires the research and development of conductive charging infrastructure such as drones and charger arms.
Dynamic battery swapping	- Fast Charging: Battery swapping offers rapid charging by replacing depleted batteries with fully charged ones. - Suitable for Shared Fleets: Ideal for shared mobility services with high charging demand and less idle time. - Minimal Downtime: Swapping takes less time than traditional charging methods, reducing vehicle downtime. - Reduced Battery Degradation: Frequent swaps can extend the overall battery lifespan.	- Infrastructure Investment: Establishing a network of battery swapping bots/drones requires significant upfront investment. - Standardization Challenges: Swappable batteries must be standardized and compatible with various EV models. - Logistics and transportation: The logistics for handling and storing batteries can be complex. Moreover, the battery have to be designed to allow for easy swapping while moving. - Limited Range Extension: The range extension is limited by the availability of charged batteries at swapping stations and the capacity of the charging bot/drone.

many of these charging methods are still in development phase, many new challenges and advantages can only be identified when they are deployed and in operation. However, many studies have proposed preliminary estimates on the initial infrastructure deployment and expected maintenance costs. For charging lanes (wireless and conductive) the deployment costs for both directions and including electricity distributions are expected to be about 1.2–2.0 M EUR/km in an estimate made by the Swedish Transport Administration (Kristensson, 2023), 1.7 to 3.1 M EUR/Km according to the German Institute for Energy and Environmental Research (Kuhnel et al., 2018) and 0.4–2.7 M EUR/Km according to other studies (Limb et al., 2018; Taljegard et al., 2020; Bateman et al., 2018; Machura and Li, 2019). The annual maintenance and operation costs are expected to be around 0.01 M EUR/Km (Riksrevisionen, 2019).

The estimated costs for converting a bus to provide wireless charging are expected to be about 26,000 USD, while adding the same technology to a passenger vehicle is expected to cost around 1,500 USD (Kosmanos et al., 2018). The estimated costs for deploying charger vehicles are not yet available in the literature. However, as they provide the same service as mobile chargers, they may be expected to have similar costs of around 40,000 USD per charger vehicle (Zhang et al., 2020). The costs of conductive V2V transfer are expected to be the same as wireless V2V (Chakraborty et al., 2022), about 40,000 USD. However, as mentioned in SAVIOR system, the cost may be dependent on the energy demand based on the amount of vehicles using the segment of the road, which would decide the deployment of charger vehicles and drones (Chakraborty et al., 2023).

When considering dynamic battery swapping for implementation, it is important that vehicles are equipped with standardized batteries. Due to the lack of sufficient data on the costs of dynamic battery swapping, we instead assume the costs associated with stationary battery swapping, which are estimated at around 300,000 EUR (Masłowski et al., 2023).

Table 3 compares various state-of-the-art dynamic charging methods against fixed charging stations, which currently dominate the market. The comparison evaluates these methods based on factors such as costs, battery capacity reduction, flexibility, and their current development status based on findings presented in Chakraborty et al. (2022, 2023); Arya and Saxena (2022); Shoman et al. (2022); Nezamuddin et al. (2022); Villeneuve et al. (2020); Leijon and Boström (2022); Liao et al. (2024).

- Infrastructure costs: The financial requirements for charging infrastructure vary significantly across different charging solutions. Charging lanes represent the most capital-intensive option, with estimated costs ranging from 1.2 to 3.1 million EUR per kilometer. Conversely, V2V charging and fixed charging stations offer more cost-effective alternatives. The estimated cost of V2V charging is approximately $ 40,000 per vehicle, while fixed charging stations range from $ 40,000 to $ 60,000 per unit. These disparities in infrastructure costs highlight the importance of strategic planning in selecting suitable charging solutions tailored to specific operational needs.
- Battery capacity reduction: Dynamic charging methods provide substantial reductions in battery capacity requirements compared to traditional fixed charging systems. Charging lanes, for instance, can reduce battery size needs by up to 80 %, while V2V charging achieves reductions of up to 50 %. This decrease not only lowers vehicle costs but also enhances operational efficiency and sustainability. In

Table 3
Comparison of various state-of-the-art dynamic chargers.

Charging method	Infrastructure Costs	Battery capacity reduction	Flexibility	Current status
Fixed charging stations	High	–	Low	Mature
Charging lanes	Very high	60 % – 70 %	Low	Pilot
V2V charging	Moderate	25 % – 50 %	Very High	Development
Dynamic battery swapping	High	20 % – 30 %	High	Concept

contrast, reliance solely on fixed charging stations may necessitate larger battery capacities, potentially increasing vehicle costs by up to 80 % (Karlsson, 2016).

- Flexibility: Flexibility indicates how adaptable each method is to increased energy demands and technological advancements. V2V charging demonstrates the highest flexibility, making it particularly attractive for rapidly evolving mobility ecosystems. Dynamic battery swapping also shows high flexibility, allowing scalability across diverse use cases. However, charging lanes and fixed charging stations are less adaptable, requiring substantial infrastructural changes to accommodate new technologies.
- Development status: The development stage varies significantly across methods. Fixed charging stations are mature and widely implemented. Charging lanes are in the pilot phase, with several projects underway globally, including in Sweden. V2V charging is in the development phase, with promising prospects for commercialization. Dynamic battery swapping remains a conceptual approach, requiring extensive testing and development before real-world deployment.

From Table 3, charging lanes provide the highest reduction in battery capacities, making them ideal for applications prioritizing energy efficiency. However, their high costs and limited flexibility may restrict widespread adoption. Conversely, V2V charging emerges as a promising alternative, offering lower costs and substantial reductions in battery size requirements. Despite being in the developmental phase, its high flexibility makes it a strong candidate for future mobility solutions.

Dynamic battery swapping, while highly flexible, remains a conceptual solution. Its deployment may complement other charging methods, particularly in areas requiring scalable and modular infrastructure. Fixed charging stations, though mature, are less suitable for dynamic and autonomous vehicle ecosystems due to their low flexibility and higher associated battery capacity requirements.

From the analysis, it is evident that adopting hybrid strategies that combine complementary solutions could maximize effectiveness. For instance, stationary chargers and charging lanes can electrify primary routes, while V2V charging or dynamic battery swapping can cater to secondary roads and specialized applications. This integrated approach would ensure a balance between costs, energy efficiency, and scalability, tailoring solutions to specific regional and operational needs.

Conclusions and future research

This comprehensive review highlights state-of-the-art dynamic charging solutions and their potential integration with future mobility systems. A detailed classification of EV charging solutions is provided, focusing on three primary dynamic charging methods: charging lanes, vehicle-to-vehicle (V2V) charging, and dynamic battery swapping. Each method is critically analyzed, outlining its advantages, limitations, and the potential benefits of integration with autonomous electric vehicles (AEVs) and other emerging modes of transportation. This review serves as a foundation for understanding how dynamic charging can address the challenges of future transportation and contribute to a sustainable and efficient mobility ecosystem.

Each of these methods has distinct advantages and challenges regarding its potential role in the evolving landscape of AEVs and sustainable transportation. Charging lanes, also known as electric road systems (ERS), offer a promising solution to address the limitations of high battery capacity and charging time for AEVs. They enable AEVs to charge while in motion, reducing the need for large and expensive batteries. Wireless charging technologies, including near-field, medium-field, and far-field methods also provide flexibility in energy transfer modes. However, challenges such as alignment, efficiency, infrastructure costs, and safety must be overcome for these systems to become widespread.

V2V charging solutions present a flexible and cost-effective approach to extending the potential of charging lanes. They involve mobile charging vehicles that provide energy to AEVs while on the move. Wireless V2V charging, employing semi-autonomous charger vehicles, can reduce travel times compared to static chargers. Conductive V2V charging, with mechanisms such as flexible wired connections and drones, offers high-power transfer potential. However, ensuring alignment, common industry standards, and safety during the charging process remains critical for V2V solutions.

Dynamic battery swapping systems aim to replace depleted batteries with fully charged ones, allowing AEVs to continue their journeys without extended charging breaks. These systems are particularly valuable for high-utilization AEV fleets, such as buses and delivery vehicles. Effective management of battery swapping logistics, compatibility with various AEV models and modified battery packs to allow quick replacement are essential for their successful implementation. Dynamic charging solutions for AEVs hold significant promise for addressing range limitations, reducing downtime, and improving the sustainability of future mobility.

The potential choice between charging lanes, V2V charging, or dynamic battery swapping depends on factors such as vehicle type, operational requirements, infrastructure availability, and cost considerations. Moreover, wireless charging technologies, especially near-field and far-field methods, are advancing and have the potential to play a pivotal role in providing energy requirements for future transportation, especially urban air mobility. However, challenges related to alignment, as well as standards and safety issues during dynamic charging processes require further research and development to ensure seamless operation and user confidence.

Future research should focus on several critical areas to accelerate the adoption and scalability of these solutions. These include developing optimization models for infrastructure deployment, establishing industry standards for inter- operability, refining the trade-off between minimizing battery size and preserving battery life, particularly in the context of dynamic charging, and enhancing energy transfer efficiency while ensuring safety and sustainability. Additionally, integration with autonomous technologies, grid management strategies, and the development of user-centric designs are essential for maximizing the potential of dynamic charging systems.

By addressing these challenges and leveraging advancements in transportation technology, dynamic charging solutions can play a transformative role in creating a sustainable and efficient mobility ecosystem.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve readability and language. The authors also employed the following AI tools to find relevant literature studies: Semantic Scholar, Sci-space and Research Rabbit. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Mohd Aiman Khan: Writing – review & editing, Writing – original draft, Investigation, Data curation, Conceptualization. **Wilco Burghout:** Writing – review & editing, Supervision, Methodology. **Oded Cats:** Writing – review & editing, Supervision, Methodology. **Erik Jenelius:** Writing – review & editing, Supervision, Methodology. **Matej Cebecauer:** Writing – review & editing, Supervision, Methodology.

Declaration of competing interest

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Data availability

No data was used for the research described in the article.

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