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Electric Bus Charging Infrastructures: Technologies, Standards, and Configurations

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ABSTRACT Rapid growth in the electrification of bus fleets, driven by substantial environmental benefits, is facing challenges such as range anxiety, prolonged charging durations, and reduced flexibility compared to combustion engine buses. This study first conducts a comprehensive bibliometric analysis of diverse publications to identify key research trends in electric buses (E-buses). It then offers a thorough comparison of charging technologies, encompassing topologies, power flow capabilities, costs, grid impacts, and efficiency, along with an examination of existing standards, norms, and challenges. With a classification of nearly 150 references, the study aims to illuminate the strengths and weaknesses of each charging technology, providing a solid background for selecting optimal topologies and strategies for specific applications. Emphasizing the importance of a nuanced trade-off between the quantity and type of chargers and E-bus battery capacity in each scenario, the research goes beyond technical considerations to explore potential future trends in the field. The information gathered in this review is a helpful guide for policymakers, industry experts, and researchers dealing with the complexities of E-bus charging infrastructure.

INDEX TERMS Charging station, depot charging, electric bus, en route charging, B2X technologies, grid impact, in motion charging, standards.

I. INTRODUCTION

Transportation electrification holds significant promise as an effective approach to diversify transportation fuels and mitigate the adverse environmental impacts associated with fossil fuel-based transportation systems. Public transit, particularly buses, plays a pivotal role in urban mobility, with over 80% of passenger trips worldwide being made by buses. In such a condition, improving bus-based transit networks may significantly improve urban sustainability [1]. Electric buses (E-buses) hold a distinctive relevance within the realm of electric vehicles (EVs) when compared to other counterparts like private vehicles and taxis. Specifically designed for public transportation and mass transit systems, E-buses have the capacity to accommodate a significantly

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larger number of passengers, making them pivotal contributors to emissions reduction and traffic decongestion in densely populated urban areas. Their environmental impact surpasses that of private EVs and taxis, as each E-bus can replace numerous conventional vehicles, resulting in more substantial emission reductions per unit. However, it's crucial to acknowledge that E-buses face specific challenges, notably in the realm of charging infrastructure. Unlike private EVs, which can often be charged at homes or workplaces, E-buses require dedicated charging depots and infrastructure. This operational characteristic underscores the necessity for rapid and reliable charging solutions to minimize downtime. Furthermore, the impact of E-buses on local electrical grids warrants careful consideration, as their concentrated charging schedules and higher energy demands can strain existing infrastructure. Addressing these challenges, while also highlighting the unique benefits of E-buses, will be instrumental

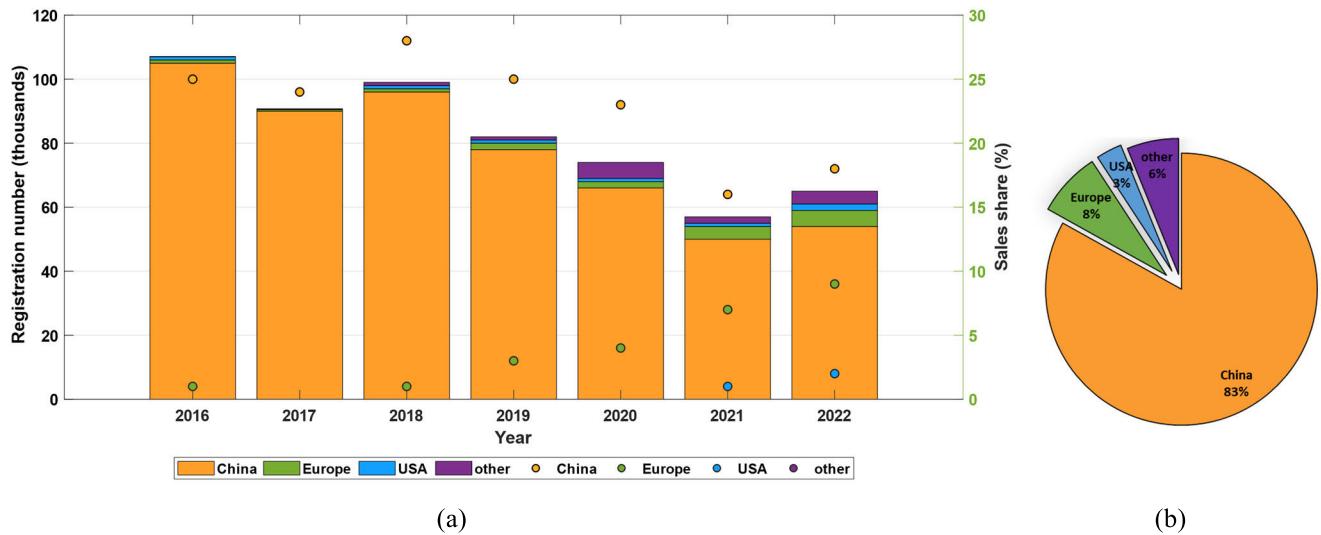


FIGURE 1. Annual E-bus registration and selling shares. (a) The number of E-bus and sales share around the world from 2016-2022*. (b) The number of E-bus registrations in 2022. * Bars represent the number of E-bus registrations while scatter points represent E-bus sales share.

in realizing their full potential within urban transportation systems. Meanwhile, the rise of multi-modal transportation systems has exerted a profound influence on the development of E-bus charging infrastructure. As cities increasingly adopt integrated networks comprising buses, metros, light rail, and other modes of transit, the demand for efficient charging solutions for E-buses has surged. This necessitates the implementation of strategically located charging stations at transportation hubs, transit interchanges, and key urban nodes. Moreover, a cohesive approach to infrastructure planning is crucial, ensuring seamless transitions between different modes of transportation while minimizing downtime for E-buses during recharging. By harmonizing charging infrastructure with the broader multi-modal framework, cities can achieve a more sustainable and resilient urban transportation system, meeting the diverse needs of passengers while significantly reducing environmental impact. It has been demonstrated that in comparison to diesel-powered buses, E-buses reduce carbon dioxide (CO₂) emissions by an average of 37.5% throughout the course of their operation lifetime [2]. Consequently, the globalization of the bus electrification process presents a chance to address major environmental issues. Recent advancements in long-range E-bus technology and the maturation of charging infrastructure have turned the vision of electrifying public transportation into a reality for cities across the globe [1], [3]. Remarkably, according to the International Energy Agency (IEA), sales of E-buses surged by 40% from 2021 to 2022, even amidst the relatively stable global bus industry as shown in Figure 1 for an illustration of the annual E-bus registration and sales trends from 2016 to 2022 [4]. For better clarity, Figure 1.b. provides a zoomed-in view of the annual E-bus registration, focusing specifically on the data for the last year.

E-buses currently come in three primary categories: battery, fuel cell, and hybrid. Among these, battery E-buses, often referred to as “all-electric” buses, have garnered the most attention and offer numerous advantages, including zero tailpipe emissions, reduced noise levels, greater maturity, and significantly longer lifespans due to minimal wear and tear [5], [6]. As such, this study primarily focuses on battery E-buses for their potential to expedite the transition away from fossil fuels in the transportation sector. In this study, although traditional trolleybuses draw power from overhead wires without on-board batteries, they are considered part of the battery E-bus category because they rely on continuous electricity from the grid, similar to battery E-buses.

While the environmental advantages of E-buses are evident, their widespread adoption hinges on overcoming key challenges, with charging infrastructure at the forefront. Various charging strategies have been devised to meet the charging needs of fleet buses, including plug-in, pantograph, battery swapping, wireless, and catenary systems. Plug-in charging is presently the most prevalent method. It involves using a cable connected to a charging station for recharging. Inductive or wireless charging, however, operates by transmitting power through an air gap to the vehicle. It offers potential advantages such as reduced anxiety over driving range. Battery swapping entails mechanically replacing discharged batteries with fully charged ones [7]. Pantograph charging is another widely used approach, particularly in high-power charging stations along the routes of E-buses. It facilitates automated contact between the bus and the charging infrastructure. Catenary charging, a long-established technology, employs overhead lines or catenaries for charging, primarily utilized in trolley buses [8].

Studies in [9], [10], and [11] conducted comparative studies between plug-in and wireless charging infrastructures.

In [9], the study compares plug-in and wireless charging for E-buses in terms of energy use and greenhouse gas emissions. The wireless system is found to be 0.3% more energy-efficient and emits 0.5% fewer greenhouse gases over its lifetime. Authors in [10] used a life cycle assessment to compare plug-in and wireless charging for E-buses. Despite higher initial costs for wireless chargers, the wireless system has the lowest life cycle cost and reduces carbon emissions due to lighter batteries. However, it must be noted that there is considerable uncertainty associated with this finding, with differences in life cycle costs being largely dependent on factors such as battery unit price, charging efficiency, and procurement, installation, and maintenance costs of chargers. According to [11], wireless charging allows a 46% reduction in battery size, lowering costs and energy consumption. It also enhances safety, aesthetics, and the potential for smarter road transportation. However, it's essential to note that these outcomes are specific to the case studies investigated in those papers. The bus service characteristics play a significant role in charging infrastructure performance, and these results may vary in different contexts. In addition, investigations into static and dynamic modes of wireless charging, which are perceived as solutions to range anxiety issues, have been documented in [12], [13], [14], and [15]. In [12], the focus is on companies, automakers, and research related to EV wireless charging. Reference [15] introduces an improved opportunistic wireless charging system for E-buses, combining stationary and dynamic wireless charging. Reference [14] addresses the deployment of dynamic wireless charging for E-buses, considering facility placement, battery size, and charging schedules. Reference [13] conducts a techno-economic assessment comparing wireless charging, wired charging, and conventional methods for airport shuttle buses. Economic analysis suggests that electrification is economically viable, with wireless charging allowing for smaller batteries and potential cost reduction.

Battery swapping technique have been explored in depth in [16], [17], and [18]. Reference [16] discusses the introduction of battery swapping stations, covering their infrastructure, methods, advantages compared to charging stations, and the significant challenges they present. In [17], an E-bus with a roof-mounted battery swapping system is presented, along with field test results from a pilot program, demonstrating its viability as a public transit option. Authors of [18] introduce in-depth battery swapping solutions and presents real-world demonstrations of battery swapping stations, offering a complete overview of transportation electrification powered by battery swapping. Both authors of [17] and [18] believe en route battery exchange system to become a leading choice in upcoming sustainable and environmentally friendly public transportation systems. Furthermore, pantograph charging, particularly its implementation in high-power charging stations along E-bus routes, has been comprehensively covered in studies like [19] and [20]. Reference [19] provides an explanation of various pantograph charging methods, their

standards, and communication methods. The authors argue that the existence of diverse pantograph charging modes presents a challenge for automotive OEMs and infrastructure producers, who must accommodate multiple variations. Meanwhile, in [20], the authors suggest an ultra-fast opportunity charging system based on a flywheel. This system is designed to mitigate the impact of peak power demand during en route charging of E-buses.

However, beyond the technical aspects, a myriad of economic, societal, and technological challenges must be overcome before E-buses can be widely adopted [21], [22], [23]. Reference [21] identifies obstacles to implementing E-buses in Canadian public transit, emphasizing the importance of political support, local operational data, standardization, and demonstration projects for encouraging electric powertrain adoption by service providers. The findings highlight that there is little desire from service providers to implement E-bus technology in a daily full-network operation. Although transit providers are supporting technological advancement, the huge financial burden hinders the implementation of E-buses in transit. Reference [22] discusses barriers (technological, financial, and institutional) and their impacts on the power grid, energy use, fleet operations, fire safety, and public willingness to pay. It summarizes lessons learned from real-world implementation. Authors of [23] address a fleet replacement problem, helping organizations create cost-effective plans for achieving their electrification goals. Factors considered include purchase costs, salvage revenues, operational expenses, charging infrastructure investments, and demand charges, along with various charging options. A major barrier in terms of finances is the expensive initial investment required for E-buses. Several articles, including [24] and [25], have conducted economic analyses of various E-bus charging stations. In [24], it is shown that transit system characteristics, such as service frequency, circulation length, and operating speed, significantly influence the cost competitiveness of charging infrastructure. For instance, they proved inductive charging lanes are cost-effective in systems with dense bus lines with high service frequency and low operating speed, while swapping stations, though facing battery compatibility challenges, prove more cost-effective than charging lanes and stations, especially in systems with high operating speed, moderate service frequency, and circulation length, making them promising for E-bus fleet operations. References [26] and [27] using the existing tramway DC grid infrastructures rather than installing new grid connection to cut down on initial construction costs. The issue of strategically locating charging stations has been investigated in some research. The right placement of different charging stations along with the best size for the E-bus fleet and batteries is another barrier that is discussed in [28], [29], and [30]. The main goals of these studies are to reduce overall fleet and infrastructure costs while maintaining service frequency and meeting the transit system's charging requirements. Reference [28] offers a method for assessing

feasibility and designing configurations for electric public bus fleets. It helps determine the right number of buses and battery capacities to meet scheduling needs with different charger sizes. The study suggests that bus operators with large fleets should group E-bus fleets by different battery capacities instead of choosing standardized buses. Additionally, midday in-depot charging is found to contribute more to the system peak than opportunity charging when many E-buses charge simultaneously. In [29], a mathematical model is introduced for a generic public transport system, and mixed-integer linear programming is used to find the optimal system design, including charging infrastructure placement (with en route and off-route charging), battery sizes, and charging schedules for all network routes. Authors of [30] optimize battery pack and charging infrastructure designs to minimize the total cost of owning an E-bus fleet. They select the best battery size, charging stations, and power based on specific conditions, such as schedules, vehicle traits, and environmental factors. Additionally, the widespread usage of E-buses in urban areas would have a very severe influence on the electricity network. To reduce them, the infrastructure needs to be improved and the charge of E-buses must be handled carefully. Several articles address the effects of various charging techniques on the grid. In [31], authors present findings from a Dutch pilot case involving daily fast and slow charging of E-buses in the same depot. Power quality measurements at this depot reveal harmonics and suprareactive emissions resulting from EV charging points. [32] introduces a fleet energy model for E-buses in an accelerated offline simulation. This model assesses fleet energy behaviour and charging loads across various scenarios, infrastructure types, and battery sizes, highlighting their effects on the electric utility grid. The authors of [33] and [34] created scheduling techniques that took volatility and uncertainty in energy usage and trip travel time into account as well. The authors of [35], [36], and [37] looked at the potential benefits that E-buses may have for the electrical grid in bus to grid (B2G) projects. Stationary battery storage systems in B2G can be used as a backup to the grid to satisfy peak demand, providing load shifting, arbitrage, and power quality.

Recognizing the dispersed nature of research in the E-bus domain, several research reviews have aimed to consolidate knowledge and address research gaps. These reviews have covered various aspects, such as the benefits and drawbacks of charging strategies, the evolution of E-bus technology, economic analyses, and the implications of E-bus deployment on the electricity network. Reference [1] offers a thorough literature review on the evolution of E-bus technology in order to determine the key topics, identify any research gaps, and offer guidance on how to approach certain issues and trends. Different E-bus powertrain layouts have been explored in [3], [22], and [23] concentrate on fundamental hurdles (technical, economical, and regulatory), implications of E-bus deployment on the electricity network, energy usage, and fleet operation. Authors of [38] performed qualitative

research with participants in E-bus projects to assess the benefits and drawbacks of various charging strategies and to identify the major issues that arose throughout the implementation and development of their projects. It highlights the need for a diverse mix of charging technologies, considering factors beyond economic considerations, and underscores the importance of early decision-making on charging locations and technologies for successful project continuation. Reference [39] assesses the technical and financial efficacy of E-buses under various circumstances of operation and computes the lifespan expenses for three distinct charging methods: overnight, opportunity, and end station charging. The main goal of the authors of [40] is to identify research gaps and suggest future research paths in the area of timetabling and vehicle scheduling, recharging planning, and location planning for fast-charging infrastructures and their effects on the grid. The authors of [41] conducted a survey of key components in E-buses, which include energy storage systems, powertrains, and electric motors. They also briefly explored trending research topics in the E-bus domain, such as power and energy management, range anxiety, developing charging strategies, and real-world trial projects. Additionally, they investigated future research opportunities and challenges, including modelling E-bus charging demands and assessing the impact of E-buses on power systems. In [42], work examined global advancements in E-buses and provided a summary of insights gained from their practical usage. They also delved into three approaches for addressing range limitations of these vehicles: slow battery charging supplemented by backup vehicles carrying fully charged batteries, battery swapping, and rapid opportunity charging during layover periods. In [43], a comprehensive examination is offered on the powertrain setups and charging technologies in E-buses, with a specific focus on power electronics systems. Additionally, an assessment is conducted on vehicle scheduling, optimizing charger placements, and strategies for managing the charging process. To establish cost-effective and comprehensive guidelines for planning charging infrastructure, the authors of [44] conducted a review of various methodological approaches in recent scientific literature. This review encompassed the entire charging infrastructure planning cycle, starting with target identification (which includes transport networks, modes, charging technologies, and potential sites), followed by data acquisition, and concluding with modelling, allocation, and sizing methodologies.

Table 1 provides a summary of review papers looking into E-bus charging stations, and it highlights the primary focal points of each paper.

Despite these reviews, there remains a need for a comprehensive study that synthesizes the progress in E-bus research, including charging technologies, barriers to adoption, and future trends. This study fills this gap by presenting a thorough examination of E-bus charging technologies to grasp the signs of progress in E-bus research, highlighting relevant works developed on E-bus charging technologies,

TABLE 1. Comparison between this study and the existing review literature on the E-bus charging infrastructures area.

Ref.	Bibliometric analysis	Components of E-buses		Power electronic converters	Modern charging technologies	Bus-to-everything (B2X) technologies	Standards and policies	Main challenges			Future trends
		Powertrain	Energy Storage system					Impact on grid	Range anxiety	Charging scheduling	
[1]	✓									✓	✓
[3]		✓	✓								
[22]								✓			
[23]											✓
[38]										✓	✓
[40]								✓		✓	
[41]			✓					✓	✓		✓
[42] ¹		✓	✓								✓
[43]		✓	✓					✓			✓
[44] ²				✓				✓		✓	✓
[45]					✓						
[46]					✓						
This study	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

comparing the present technologies, E-bus take-up barriers, future trends, among other topics. The work is organized as follows. A bibliometric study of the most recent research and studies in the topic of E-bus is presented in Section II. The various E-bus charging technologies available in industry are listed and discussed in the third section. Section IV provides a summary of the standards used in various E-bus charging stations. Section V compares the charging technologies and outlines their benefits and drawbacks. Section VI explains the difficulties and obstacles to the adoption of E-bus and, consequently, its charging stations, and the final paragraph of this section presents potential developments in charging technology. Finally, Section VII concludes the work by summarizing the key findings and emphasizing the importance of sustainable transportation through E-buses.

II. BIBLIOMETRIC ANALYSIS

A. KEYWORDS AND TREND ANALYSIS

A keyword survey is accomplished to map the evolution of E-bus technologies and manifest the basic research streams. Accordingly, the Scopus database is selected as the publication's primary source and data center taking advantage of Boolean search to get the most inclusive collection of articles. The search includes 743 documents in the time range of 2010- 2022 with extra limitations of language (English), article as source type, and research areas (engineering, energy, environmental analysis tool to realize and extract various key terms and streams. The extracted cluster map shown in Figure 2.a. revealed that the keywords can be grouped into four main clusters, indicating the different topics of research

in E-bus area. The circle dimension shows the number of times which selected keyword happened, and the distance and lines mean the relationship between each keyword in the group. Evaluating the keyword contents and the topics examined in each cluster, they can be classified and labelled as Charging Infrastructures, Sustainability, Energy Management, and Battery Technology. It is obvious from the extracted figure that, there are common relationships between each cluster and the strongest one is between the "Sustainability" and "Charging Infrastructures" clusters. These clusters are the main topics that will be discussed in this work. The words "charging", "costs", "fleet operation", "sustainable mobility", and "impacts" are realized as the most joint used keywords between these clusters reflecting the significance of the topic in the community. The time overlay based visualization map for this analysis is shown in Figure 2.b. Checking the area specified by the blue circle curve, one can find that the mentioned keywords together with most of other keywords related to clusters "charging infrastructures" and "sustainability" are trends which became more significant since 2018 and has been given great attention in recent years.

B. ANNUAL SCIENTIFIC PRODUCTION

Based on the publications found in analysis, the study on E-bus topic is not new and has been around for a long time. However, the research community has shown more focus on this issue in recent years.

To confirm this issue, the publications (all types of sources) collected in the analysis during the range of 2010-2022. There were a few research before 2010 where the contents are not completely in the line with the area of this work. Figure 3 illustrates the number of publications including journals,

¹It centers primarily on E-buses rather than E-bus charging technologies.

²This study is written for EVs in general, not E-buses specifically.

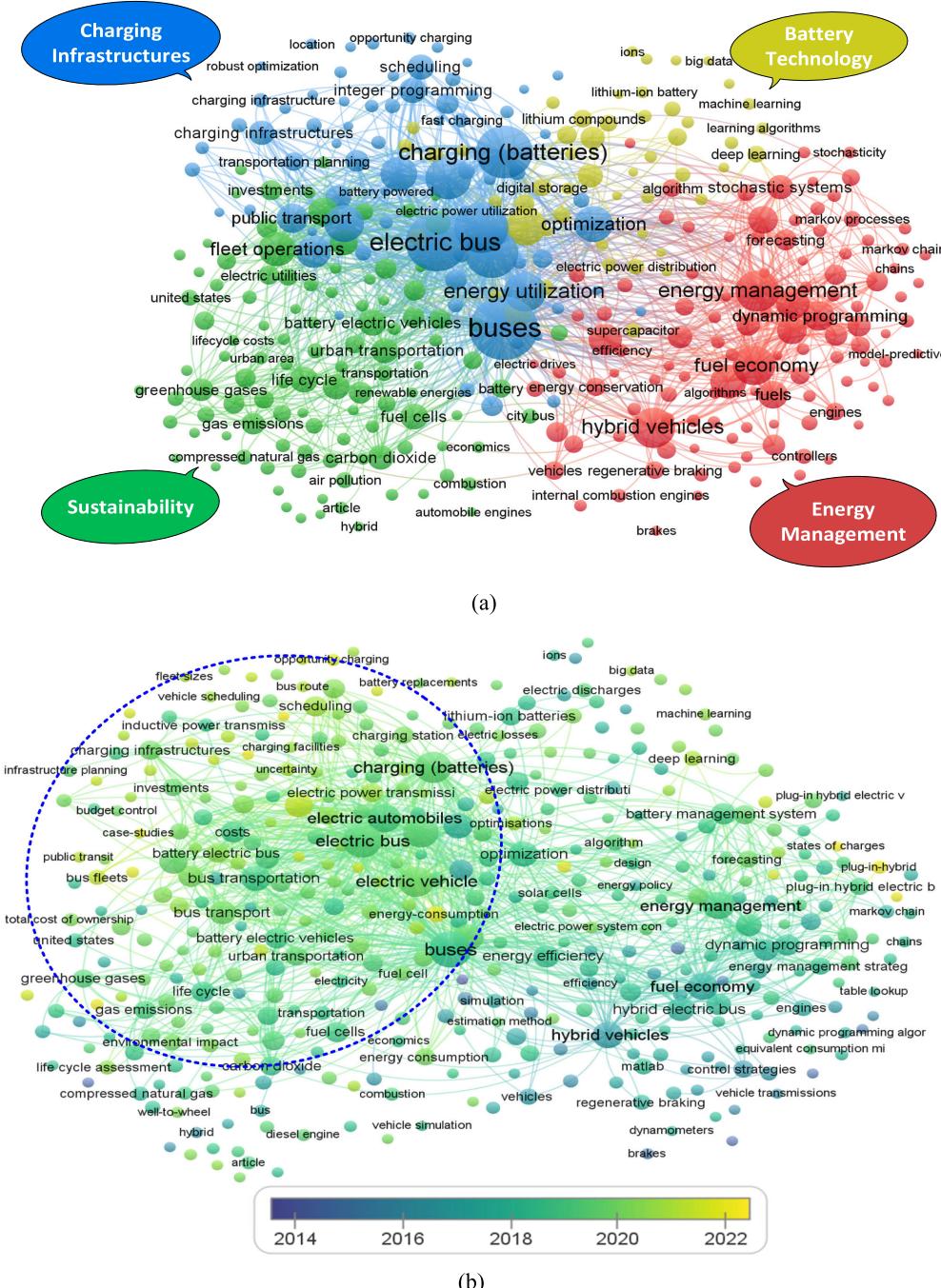


FIGURE 2. Extracted maps regarding bibliometric analysis of the keywords. a) network cluster map b) time overlay visualization map.

conferences, and book/chapter regarding E-bus topics by year. From 2010 to 2016, relatively few studies have been done in this regard discussing the technologies, feasibility, and economic point of view. However, since 2017 the annual publication rates have increased greatly for both journals and however, since 2017 the annual publication rates have increased greatly for both journals and conferences source

so almost 70% of the total publications are dedicated to 2017-2022. The bibliometric analysis confirms that the study on E-bus topic and each of the mentioned aspects and clusters is likely to spread more in the coming years.

According to the research stream and gap finding, the next section presents an overview of charging technologies and infrastructures dedicated to E-buses.

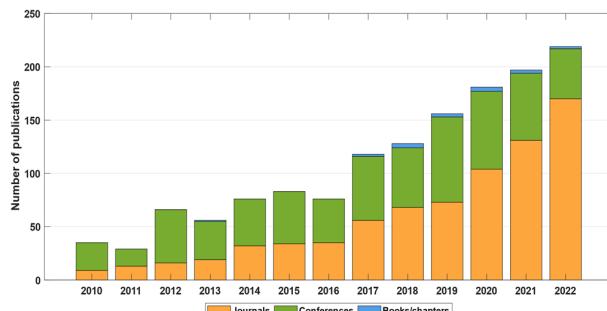


FIGURE 3. Annual scientific publication classification in subject of E-bus in the proposed analysis.

III. CHARGING TECHNOLOGIES AND INFRASTRUCTURES

The charging infrastructure is a critical component in the development of E-buses [47]. Today, a wide range of charging technologies are available worldwide. The charging technologies can be categorized based on charging power, connector type, or charging duration which are just a few of the several ways that charging technologies can be divided into categories. Depot charging, en route charging, and in motion charging are three simple categories that may be used to group different charging technologies according to where the charger is placed along the route that an E-bus takes.

- Depot charging refers to the charging that happens at the depot, usually overnight, and that is why sometimes it is called overnight charging. Depot charging systems are either AC or DC, and due to the fact that they have 5-8 hours to fully charge E-buses, they usually operate at comparatively low power (30 kW-150 kW) [48], [49].
- As the title suggests, en route charging takes place during the daytime when the E-bus stops shortly at the stations for passengers to get on or off the bus. The charging power is higher in this mode of charge as the charging time is so limited, between 150 kW and 600 kW, and the power is transferred in DC [48], [49], [50]. Due to high charging power, it just needs approximately six minutes to charge the E-bus [51].
- In motion charging i.e., charging during the journey, doesn't need that the E-bus stops to recharge. So, it is appropriate for demanding bus routes where it might be challenging to provide more stop duration, even at the end stops [20], [49]. The power range of in motion chargers is lower than 250 kW [52].

Each of the charging technologies named before can be subcategorized based on their working principle and charging connection type. Figure 4 presents a more detailed division of various charging options available based on their connection type. Each of these charging modes will be discussed in the section that follows.

A. PLUG-IN CHARGING

The most often utilized charging technique in depot charging is plug-in charging, also known as manual charging using a cable. It offers a wide range of charging power levels, making

it versatile for different bus models and battery capacities. Plug-in systems are easy to install, fitting well in existing depots. They are cost-effective and compatible with various E-buses. However, they have longer charging times compared to some fast-charging methods. Also, they rely on bus operators for consistent connection, which may occasionally lead to human error.

The industry and the EU Commission have decided to adopt the CCS/Combo2 standard and plug for this form of charging in Europe, whereas certain Japanese, Korean, and French E-buses utilize CHAdeMO, another standard for charging. However, BYD often uses its own chargers with specific Type 2 connectors called “Mennekes” [53]. The iconic illustration of plug-in chargers’ connectors can be seen in Figure 5. Detailed specifications of different connectors can be found in [54] and [55].

To prevent bus operation flow disruptions caused by hanging or floor-laying wires in depots, charging reels have been introduced as demonstrated in Figure 6. With the aid of these reels, the cable may be pulled close to the E-bus’s charging port and safe cable handling, adaptable positioning of E-buses, and highly ergonomic operator usage will be achieved [56], [57].

B. PANTOGRAPH CHARGING

In pantograph charging, an automatic connecting system (ACS) manages and controls a connecting device that is fixed to the conductive section of the E-bus (for example, on a pole, archway, bridge, or ceiling, etc.) [58]. In this mode of charging, the power normally varies from 150 to 600 kW. Pantograph connectors are available in a variety of configurations; roof mounted, inverted, horizontal, or under-body. Each of these technologies are illustrated in Figure 7. One extensively used configuration is roof mounted one due to its mechanical connection simplicity [44]. This method requires less physical space than plug-in charging, making it suitable for urban environments with space restrictions. However, its implementation entails significant infrastructure investment. Standardization efforts may be needed for compatibility between different pantograph systems and bus models. The overhead infrastructure’s visual impact should be carefully integrated into urban landscapes.

The flash chargers, which are a type of pantograph chargers and were initially presented by ABB TOSA charging system, require substantially less time to charge an E-bus with higher charging powers. E-bus uses a controlled moving arm to quickly attach to an overhead receptacle during the brief time it takes for passengers to enter and exit the bus. It represents a groundbreaking advancement in the realm of electric public transportation. Unlike conventional charging methods, flash charging enables rapid and high-powered recharging of E-buses during brief stops at designated stations along their routes. With charging durations as short as a few minutes or several seconds, flash charging minimizes operational disruptions and allows for continuous service, effectively eliminating concerns related to range limitations.

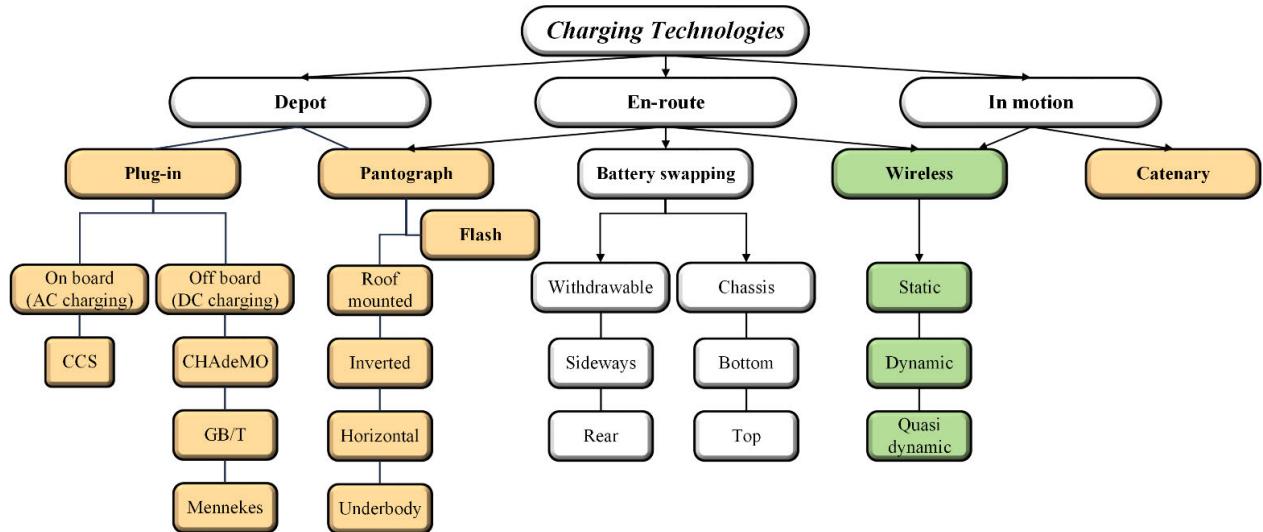


FIGURE 4. Current E-bus charging methods. The yellow boxes show conductive charging techniques, whereas the green ones show inductive charging methods.

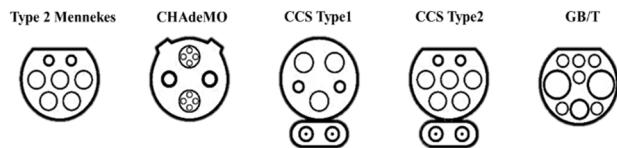


FIGURE 5. Different connectors of plug-in chargers used for E-buses.

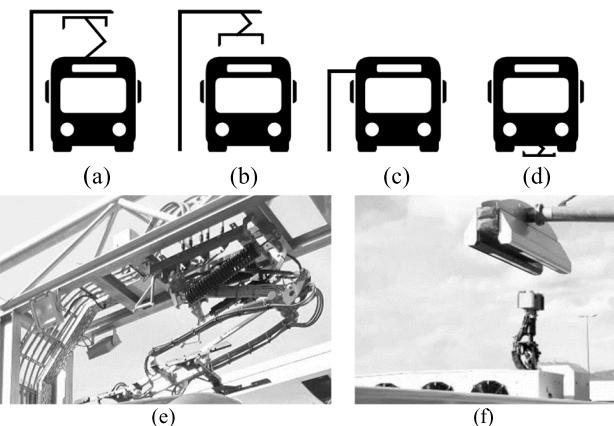


FIGURE 6. Charging reels for flexible charging cabling in depot charging.

Moreover, flash charging technology significantly reduces the need for large and costly on-board batteries, contributing to lighter, more energy-efficient E-buses. This innovation not only enhances the viability of E-buses for urban transit but also lays the foundation for a sustainable and environmentally friendly future in public transportation systems. The high-power flash charging technology charges the on-board batteries in several seconds [45]. The flash chargers at the terminals and along the routes in Geneva and Nantes provide 400 to 600 kW to maximize energy level recovery.

C. BATTERY SWAPPING

Another method of depot or en route charging that drastically cuts down on lengthy charging periods is swapping a depleted battery with a charged one [41], [59]. Swapping might take anything from 2.5 to 10 minutes [60]. A battery

swapping station's unused batteries can be utilized to assist the grid. In 2008, China implemented the battery swapping method for E-buses for the first time in a commercial context during the summer Olympics when they exchanged the batteries of 50 buses that were traveling on various pathways. Based on where the battery is located inside the bus, various swapping strategies are distinguished, as presented in Figure 8.

Nonetheless, swapping stations are now receiving less attention than other charging technologies. The fact that various manufacturers' designs for battery packs often differ from one another means that they cannot be interchanged. As a result, such a mismatch will make developing the battery swapping systems problematic. In addition, because batteries degrade with time, batteries with equal initial capacity may have varied energy storage capacity and, consequently, allow varying driving ranges.

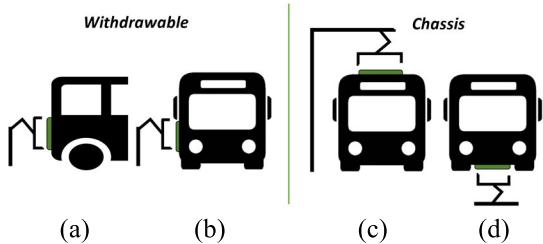


FIGURE 8. Different battery swapping modes; (a) rear (b) sideways (c) top (d) bottom.

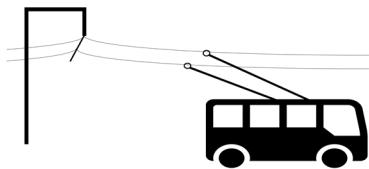


FIGURE 9. General structure of catenary charging for E-bus.

However, if swapping facilities are only intended for public transportation systems, the bus operator may simply handle the mentioned issues by unifying both its bus fleet and its batteries [24], [61].

D. CATENARY CHARGING

Catenary charging employs overhead wires to provide continuous, high-power charging for buses, allowing uninterrupted operation, especially on high-demand and long-distance routes. While proven and reliable, it requires substantial infrastructure investment for wire installation. Buses using this system are constrained to routes with existing overhead wire infrastructure, limiting their flexibility. Additionally, the visual impact of overhead wires requires careful urban integration. For many years, the transportation sector has used catenary or overhead charging for trolleybuses. These systems supply electricity to buses by using catenary lines along the whole path or at specified locations, Figure 9. The moving vehicle is connected to these lines by a power delivery equipment (pantograph or trolley) to provide electricity to its traction motor or to recharge its batteries. Recharging quite constantly and hence at reduced power levels is a benefit of using overhead power lines. Additionally, because it can function without a large energy storage system, passengers' room is increased, and vehicle weight is reduced. However, the overhead infrastructure can be expensive, and unattractive power wires may be required for most of the path [62].

E. WIRELESS CHARGING

Wireless charging for E-buses utilizes inductive or conductive systems, eliminating the need for physical connections. This streamlines the charging process, offering convenience and automation. Wireless charging relies on electromagnetic induction and employs two coils to transmit energy to an EV via magnetic coupling. Figure 10 shows how the primary coil is positioned on the road, while the secondary coil is positioned inside the E-bus [41], [63]. In 2009, Seoul Grand

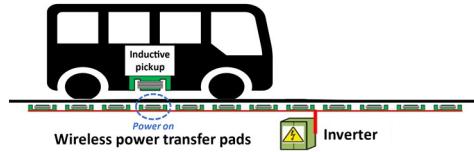


FIGURE 10. General structure of wireless charging for E-bus.

Park's trolley—the first commercial use of this technology—was unveiled [64]. Today's commercially available inductive charging systems are capable of providing up to 450 kW which is comparable with that of overhead and plug-in charging systems [65].

Wireless charging is the only charging option available today that doesn't require a conventional connection (but does require a standard coupling technology) and since there is no physical connection, it is possible to charge the vehicle even in motion [66], [67]. Recent advancements in wireless power transfer (WPT) technology and the need for smaller batteries on E-buses while being charged in motion have generated considerable interest in the development of wirelessly charged E-buses [34], [68], [69].

However, having no physical contact may result in poorer efficiency owing to misalignment of the power transferring coils, and efficiency can vary greatly depending on the distance between the coils on the road and the one on the E-bus and how well the vehicle is positioned over the inductive charger [70]. Concerns with electromagnetic interference are another issue that wireless power transfer technology is subject to [60]. Table 2 lists a number of chargers that are placed commercially across the world, along with their specifications. Advanced alignment technologies ensure efficient pad positioning. Wireless systems require less physical infrastructure, reducing visual impact and costs. While there may be some energy loss, ongoing advancements enhance overall efficiency. Initial investment for wireless infrastructure may be higher, and standardization efforts may be needed for compatibility. Despite considerations, wireless charging is an innovative, automated, and space-efficient solution for E-bus fleets.

Table 3 outlines specifications for various types of popular E-buses, detailing the vehicle type, battery capacity, and battery and connector type. The driving range of an E-bus is contingent upon its battery capacity, quantified in kWh. Consequently, contemporary battery E-buses (BEb) boast higher battery capacities, translating to driving distances ranging from 150 to 500 km on a single charge.

It's worth noting that plug-in hybrid E-buses (PHEbs) exhibit a relatively shorter driving range in electric mode compared to fuel cell E-buses (FCEb) and BEbs due to the lower size of onboard battery.

IV. TECHNICAL STANDARDS FOR E-BUS CHARGING STATIONS

To lower the expenses of the transition from traditional petroleum buses to E-buses, charging standardization, robust

TABLE 2. Examples of E-bus chargers' implementation around the world.

Charging type	Charger model	Producer	Power (kW)	Location	Comment	Ref.
Battery swapping	Depot	--	Jeju Energy New Industry	--	Jeju-do, Korea	The E-buses with swapping battery system are developed and produced by TGM. [71]
	Depot	QIS	Sun mobility	~ 40	Ahmedabad, India	Ashok Leyland has established Quick Interchange Stations across the city that within 2 min the battery can be swapped. [72]
Plug-in	Depot (CCS)	Rapid Modular chargers	Heliox	150	Glasgow, UK	Due to the fact that the bus fleet charges mostly at night, a charging system was created so that automobiles for business clients could well be charged throughout the day. [73]
	Depot (CCS)	C6EU	XCHARGE	120	Berlin, Germany	The facility has 30 charging stations, which can provide more than 3 MW of power altogether. [74], [75]
	Depot (CCS)	Flex	Heliox	150	Schenefeld, Germany	Suspended charging cables lower from the steel gantry via an automatic unwinding system so that both solo and articulated buses can charge without any problems. [76]
Pantograph	en route (flash)	TOSA	ABB	600	Geneva, Switzerland	Depending on the bus route, a flash-charging station is installed at every fourth or fifth stop and frequency and stopping times remain unchanged. With 600 kW charging power, it almost takes up to 20 s to charge the E-bus battery. [77], [78], [79]
	en route (flash)	SLS 102	Schunk	150, 500, 750, 1000	Koln, Germany/ Paris, France	With 1 MW charging power, it almost takes up to 30s to charge the E-bus. [80]
	depot (Roof-mounted)	Sicharge UC 100	Siemens	100	Leipzig, Germany	Siemens' infrastructure will be used to charge 21 VDL E-buses both at the depot and along the paths. [81]
	en route	OppCharge	ABB	450	Gothenburg, Sweden	A 5–7 minute stop would be sufficient to recharge an E-bus and it travels the route again. [82], [83]
	depot (Roof-mounted)	FAST DC chargers	Heliox	50	Groningen, Netherlands	In this project, a mix of opportunity and overnight charging has been employed. Three 300 kW chargers situated throughout the route and six overnight stations positioned in the depot. [84]
	en route (underbody)	SRS	Alstom	200	Malaga, spain	The power level of this prototype of SRS charging system is 200 kW. [85]
	in motion	eHighway	Siemens	--	Stockholm, Sweden	An overhead line system for trucks along a 2 km section of a motorway for a pilot project. [86]
Wireless	en route	PRIMOVE	Bombardier	200	Berlin, Germany	According to the Bombardier website, this is the first high power inductive charging station. [87]
	en route	--	Momentum Dynamics	200	Washington, USA	Bus charged 7–10 min every hour can maintaining 75% SOC up to 16 hours/day. [88]
	in motion	online EV (OLEV)	Korea Advanced Institute of Science and Technology	60	Gumi, South Korea	The 12 km route is equipped with OLEV chargers for E-buses. [89], [90]
	in motion	EV and roadway (EVR)	Utah State University	25	Utah, USA	The testing facility includes 0.25 mile of electrified track to charge vehicles. [91], [92]
Catenary	in motion	--	San Francisco Municipal Transportation Agency	--	San Francisco, USA	Trolley buses mainly operate on steep gradients and in demanding areas. The reliability of these trolleybuses is comparable to conventional buses. [8]
	in motion	--	e-BRT	--	Rimini, Italy	Italy has the largest number of cities with trolleybus systems in western Europe. [93]
	in motion	--	Stadtwerke Solingen	--	Solingen, Germany	Stadtwerke Solingen plans to make use of the existing trolleybus wires between Unionstraße and Bahnhof Mitte to supply trolley buses. [5]

TABLE 3. Specifications of commercial currently used E-buses.

Bus Model	Type	Battery size (kWh)	Battery type	Connector type & power range	Company /location Deployed
BYDK11M	BEb	578	LiFePO4	OppCharge <450 kW CCS1 <200 kW AC Charger Wireless charge <300 kW	China USA Europe
Proterra ZX5	BEb	492	LiFePO4	OppCharge <450 kW CCS <180 kW	USA
Lion's City 12 E	BEb	480	Lit-ion NMC	CCS <150 kW	Germany
Yutong E12	BEb	295	Lithium-ion	GB/T <300 kW	China
Solaris Urbino 12E	BEb	200	LiFePO4	OppCharge <450 kW CCS, CCS HPC <180 kW AC Charge	Poland
TOSA	BEb	88	Lithium-titanate	Flash Charging <600 kW	ABB Switzerland
Irizar ie	BEb	470	Lithium-ion	OppCharge <300 kW CCS2 <150 kW	Europe
Alexander Enviro400E R	PHEb	32	NMC	CCS <150 kW AC Charge <40kW	UK
Volvo 7900	PHEb	19	Lithium-ion	CCS <180 kW AC Charge <11kW	Poland, Europe
SLFA-180	PHEb	32	Lithium-ion	CCS2 <180 kW	Netherlands
Volvo B5LH	HEb	4.8	Lithium-ion	-	Poland, Europe
Xcelsior	FCEb	150	Lithium-ion	-	North America
Solaris Urbino12H	FCEb	30/60	Lithium-ion	-	Poland, Europe
Toyota FC	FCEb	253	NiMH	-	Japan

compliance testing, and ensuring the interoperability of diverse branded buses and charging facilities are crucial. The process of finalizing the standards of the E-bus charging stations is currently ongoing [47]. The absence of regulations for E-bus charging presents extra challenges for E-bus operators in terms of vehicle compatibility with different chargers. It usually locks E-bus operators onto a single bus or charger manufacturer, making it impossible to cooperate with other manufacturers in the future.

To remove these obstacles, standardization is essential, and cities would benefit from collaborating with national governments to promote the adoption of international standards [94]. The major focus of action in standardized development appears to be in the United States and Japan, with slower growth in the European Union [95]. The “International Organization for Standardization” (ISO) and the “International Electrotechnical Commission” (IEC), in particular the “IEC/TC 69 - Electric Road Vehicles and Electric Industrial Trucks” and the “ISO/TC 22/SC 37- Electrically propelled Vehicles,” are in charge of standardization at the international level for EVs. The European Committee for Electrotechnical Standardization (CENELEC) and the European Commission for Standardization (CEN) are the two European bodies, and “CENELEC 69X - Electrical systems for electric road vehicles” and “CEN TC 301 - Road Vehicles” respectively follow the work of ISO/TC 22/SC 37 and IEC/TC 69. The “Society of Automotive Engineers” (SAE) serves as the standard-setting body in the USA, whereas the “Japanese Electric Vehicle Association” (JEVA) does so in Japan. The Chinese national standards, commonly known as “Guobiao Standards” (GB), are also very important for electric

transportation [53]. Some of the main standards for E-buses and their charging stations are shown in Table 4.

V. MAIN CHALLENGES AND BARRIERS

E-buses’ widespread adoption is a crucial technique for reducing greenhouse gas emissions, environmental effects, and energy use. Meanwhile, there are significant obstacles preventing the widespread use of E-buses and restricting their potency for sustainability operation. These obstacles include: (1) the lack of convenient and accessible charging stations, which limits the range of E-buses and causes range anxiety; (2) the high upfront cost of E-buses and their charging systems, which is primarily due to the costly and huge onboard battery pack; and (3) the detrimental effects of high-power chargers on electricity grid [96], [97]. In the following sections each of the challenges are briefly discussed.

A. CHARGING SCHEDULING PROBLEM

Optimal charging scheduling is essential for minimizing range anxiety issue. For E-buses to operate effectively, charging infrastructure must be installed properly and charging events must follow an accurate timetable, especially those with smaller batteries which require to be charged more frequently [98]. The placement of chargers, as well as the quantity of chargers, are choices taken at the design stage. While at the operational level, the E-bus timetable must be optimised to guarantee prompt charging [97]. The possible effects, such as battery depletion, must be taken into account in such smart charging management, as well as the temperature, which affects aging [99].

The quantity of installed chargers is generally constrained, typically less than the size of the E-bus fleet, which results in a tight timeline because of the restricted space in stations and the high price of charging stations. In addition, even the best charging plans can be interrupted during real operations owing to the intrinsic unpredictability of bus journey timings. The most frequent uncertainty in energy consumption is caused by factors such as traffic conditions, climate, driving behaviour, travel speed, weight, and slope of the terrain, among others. They may cause charging plans to be disrupted, which could have several detrimental effects, including (1) charging at higher energy cost; (2) charging delays or refusals due to another bus occupying the charging station; (3) disruption of subsequent bus dispatches and crew schedules; and (4) excessive stress on the grid [97], [100].

Traditional mitigation strategies focus primarily on station-based measures including station bypassing or delaying buses at bus stops. While new methods are offered, such as a trade between holding time and speed [109]. Bus holding has the same impact as slowing down between bus stops and can be used at certain control point stops where a bus is stopped if it is too near to the one ahead of it [100]. A few research have also investigated partial charging in the E-buses charging scheduling challenge. Meanwhile, the underutilization of fast charging systems for E-buses poses a significant challenge in the broader adoption of electric public

TABLE 4. Standards for E-bus charging stations.

Charging type	Standard	Topic	Ref.
Plug-in	ISO 15118	Communication protocol for charging of heavy-duty vehicles as: Harbor Automated Guided Vehicles and Public transportation.	[101], [102], [103]
	ISO 17409	Specifications for plug-in charging modes 2, 3, 4, and reverse power transfer, Conditions for connecting to an isolated DC EV charging station in mode 4.	[104]
	SAE J1772	A standard supply equipment of conductive charging for PHEbs in North America, including operational criteria, functional and dimensional specifications for the vehicle intake and mating connector.	[105]
	SAE J2894	Test protocols for assessing Plug-In chargers, as well as their power quality requirements, Methods for assessing EV supply equipment (EVSE), charger, battery, and vehicle systems for energy efficiency, which is a part of power quality.	[106], [107]
	SAE J2953	Requirements and specifications by which a specific Plug-In EV (PEV) and EVSE pair to be interoperable.	[108], [109]
	SAE J3068	General physical, electrical, functional, testing, and performance criteria for conductive power transmission to a heavy-duty EV utilizing a Coupler capable of transmitting three-phase AC power, Mobile charging equipment like a service van.	[110]
	IEC 62196	General prerequisites for conductive charging of EVs, including plugs, socket-outlets, and vehicle connections and inlets.	[111], [112], [113]
	IEC 61851	Conditions for conductive EV connection to an AC or DC source (only applies to on-board charging units that have either undergone vehicle testing or component-level testing for the charging system).	[114], [115]
	DIN70121	Communication between the EVSE and the EV with regard to DC charging.	[116]
	GB/T 29318	EV off-board charger DC energy monitoring equipment for measuring the layout of installations, operational specifications, testing methods, and inspection regulations on the charge.	[117]
	GB/T 20234	EV conductive charging connector, device definitions, requirements, test methods and inspection rules.	[118]
	JEVS G101-G105	Fast charging systems, Fast charging stands, Communications protocol in fast chargers, and Connectors of fast charging systems.	[119], [120], [121], [122], [123]
	JEVS C601:2000	Plugs and receptacles for EV charging.	[124]
Pantograph	SAE J3105	Main physical, electrical, functional, testing, and performance criteria for conductive power transfer in pantograph charging (the focus is on vehicles that use ACS connections that can transmit DC power).	[125]
Wireless	SAE J1773	Minimal interface compatibility standards for inductively coupled charging of EVs in North America (Typically, electricity is transmitted at frequencies far higher than those of power lines).	[126]
	SAE J2836/6	Communication needs for the on-board charging system and the wireless EVSE (WEVSE) in support of WEVSE identification, charging operation, and its monitoring.	[127]
	SAE J2954	Minimum requirements for high power wireless charging of heavy-duty and off-road EVs and equipment applications, Interoperability, Electromagnetic compatibility, Minimum performance, Safety, Testing for WPT.	[128]
	IEC 61980	Equipment used for wirelessly transferring electric power from the supply network to EVs.	[129], [130], [131]
	JEVS G106-G109	General requirements, manual connection, and software interface of EV inductive charging systems.	[132], [133], [134], [135]
Battery swapping	IEC 62840	Safety requirements for battery swapping systems for EVs (it also applies to battery swap systems supplied from on-site storage systems, e.g., buffer batteries).	[136], [137], [138]

transportation. Despite the increasing integration of E-buses in urban transit fleets, fast charging stations designed for them often operate below their full potential. This can be attributed to various factors, including the uneven distribution of charging infrastructure, limited awareness among transit agencies, and the intermittent nature of bus routes. Additionally, with more E-buses equipped for overnight charging at depots, the reliance on public fast charging stations may decrease. As E-bus technology advances, addressing the underutilization of fast charging systems remains a pivotal focus area. This involves strategic placement, improved accessibility, and

comprehensive training for transit operators to optimize the benefits of fast charging technology for E-buses in urban transportation networks.

B. COST

In terms of investment capital, the choice of charging method strikes a compromise between the expenses of (1) installations (fixed cost), (2) batteries (semi-variable cost), and (3) maintenance and operation (variable cost), as shown in Figure 11. The greatest choice for the first factor, facility costs, is apparently depot charging. From the standpoint of

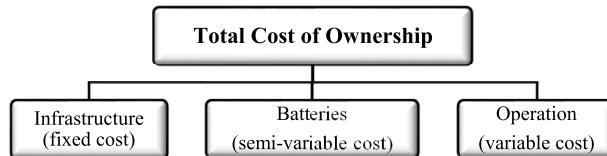


FIGURE 11. Constituents of total cost of ownership (TCO).

battery prices, however, en route and/or in motion charging methods are preferable options because they need buses with smaller batteries. Since drivers are not expected to spend more time for recharging E-buses and fewer replacement of buses is needed, the latter ones also result in cheaper operating expenses. The findings indicate that the reduction in fuel expenditures from the conversion to electricity might cover the expenses of building charge stations and purchasing new E-buses [38], [64]. Electricity prices, a major element in operating costs, have a significant role in the price of E-bus. Grid demand has been significantly impacted by the centralized charging of E-bus, and the utility enterprise has established the time-of-use (TOU) pricing system. The TOU rates are determined by time-dependent energy prices, which change based on the day and time of year [64], [97]. As a result, charging during peak hours, which is the case for en route and in motion charging, can cost more.

C. IMPACTS ON GRID

The integration of E-bus charging infrastructures brings about both positive and negative impacts on the electrical grid. Figure 12 provides a summary of the drawbacks of uncontrolled E-bus charging as well as the potential benefits in case of B2G.

1) POSITIVE IMPACTS

On the positive side, E-buses in B2G mode can offer ancillary services to the grid, enhancing stability, frequency regulation, and voltage support. Grid operators can also compensate transit agencies for their participation in B2G programs, creating new revenue streams. Furthermore, E-bus batteries, especially when coupled with bidirectional chargers, have the potential to supply both active and reactive power to the grid. This capability aids in maintaining grid stability and voltage regulation. With intelligent energy management systems, E-bus charging can be optimized to reduce peak demand charges, effectively lowering overall operational costs and minimizing stress on the grid during high-demand periods.

Strategic deployment of E-bus charging infrastructure, coupled with grid management solutions, can lead to a reduction in overall power losses and maintenance requirements. This enhances the efficiency of electrical networks. Additionally, properly managed E-bus charging can help mitigate issues related to power quality, ensuring a stable and reliable supply of electricity to the grid. The presence of E-bus chargers with bidirectional capabilities can contribute to grid stability by providing additional resources for frequency and

voltage regulation, especially during periods of high demand or fluctuations in renewable energy generation.

E-buses, when integrated into smart grid systems, can facilitate more efficient generation dispatch, enabling better integration of renewable energy sources (RES) into the grid. These positive impacts collectively highlight the potential for E-buses to not only revolutionize urban transit but also play a crucial role in enhancing the overall resilience and sustainability of electrical grids [139], [140], [141], [142], [143].

2) NEGATIVE IMPACTS

On the flip side, there are negative impacts to consider. The introduction of a significant number of E-buses to the grid can lead to substantial increases in load demand, potentially straining local distribution networks. For example, the electricity required to charge one BYD K9 E-bus overnight is similar to the typical energy usage of more than twenty North American homes.

Figure 13 shows the energy consumed by E-bus charging stations from 2015 to 2021 in GWh [64]. As a result, uncontrolled charging of E-buses may deplete the grid's reserve capacity, leaving less flexibility to address sudden spikes in demand or unforeseen contingencies. Rapid charging, especially in high-density transit environments, may result in voltage variations that can impact the stability of the local grid. The high demand associated with rapid charging can lead to increased power losses in distribution networks, potentially resulting in elevated temperatures and reduced equipment lifespan. Transformers, transmission lines, and switchgear protective devices experience a shortened lifespan as a result of excessive heat caused by overloading. The increased adoption of EV charging significantly impacts transformer performance as they are subjected to loads exceeding their recommended average capacity. Research findings indicate that the extreme overloading from E-bus chargers can result in insulation breakdown within the transformer. Components such as tap changers in substations may also experience increased wear due to the frequent switching associated with rapid charging, potentially necessitating more frequent maintenance and replacement.

Additionally, the integration of bidirectional and rapid chargers may introduce harmonics into the grid, potentially affecting power quality and leading to a lower power factor. The presence of non-linear power electronics in electric vehicle chargers is accountable for introducing current harmonics into the electrical grid. The heightened level of harmonics in the incoming line current directly impacts the power factor, subsequently raising the RMS value of the line current and causing degradation to various components of the grid, such as transformers [144].

Compared to en route and in motion charging methods, the grid effects of the depot charging methods are rather minimal. Three factors account for this: first, it is possible to benefit from the fact that the grid's base load is significantly lower at night. Second, the total power needed to charge the battery

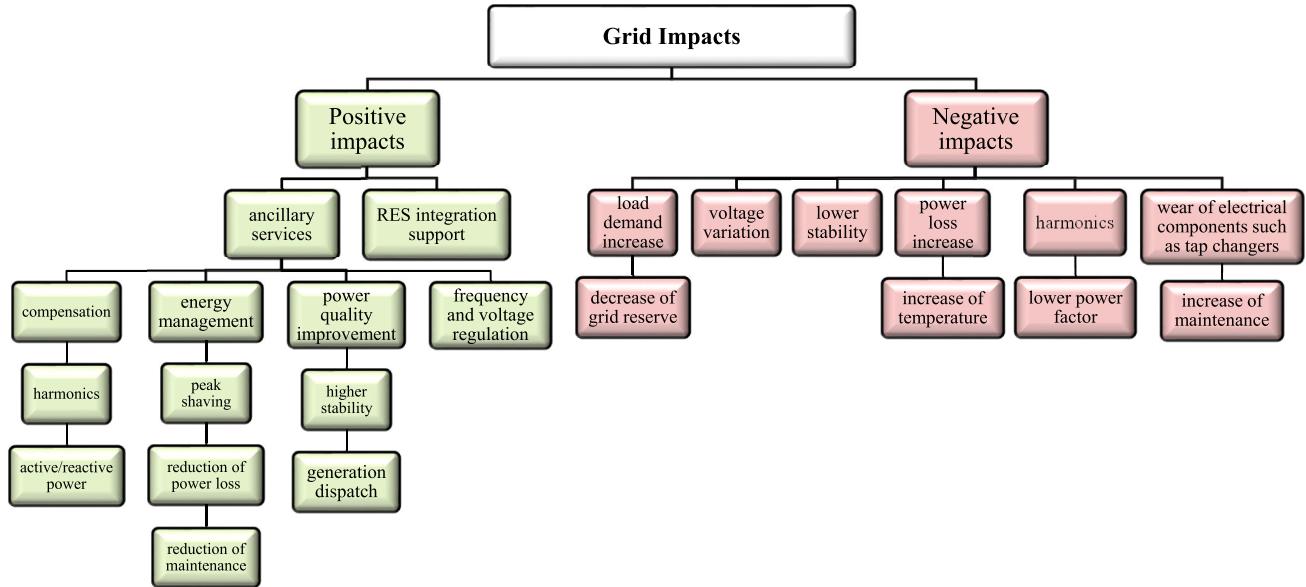


FIGURE 12. Positive and negative impacts of the introduction of E-bus chargers to current electricity grids.

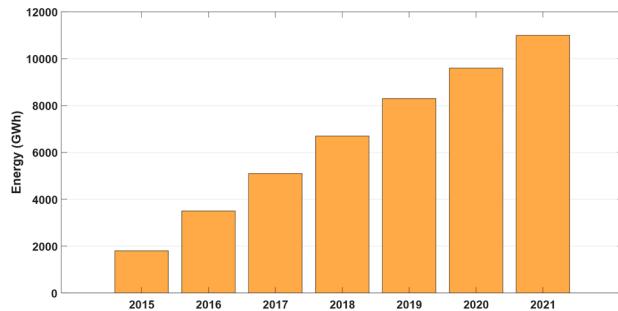


FIGURE 13. Energy (GWh) used to charge E-buses from 2015 to 2021 worldwide.

is lower when the batteries are charged continually compared to when there are interruptions. Thirdly, the depot is typically situated at a central MV node, which lowers losses and aids in line voltage stabilization [142].

In opportunity charging, the immediate peak demand may be significantly larger than the hourly average demand, particularly when multiple chargers spanning various bus routes are operating.

Consequently, the service transformer is usually five to six times larger than it is in depot charging. It has been proven that the total daily energy loss in the power grids with rapid charging systems has risen by about 30% compared to the case that no E-bus chargers are integrated [99], [145].

These negative impacts underscore the importance of careful planning, grid management strategies, and the adoption of advanced technologies to effectively mitigate potential challenges associated with the integration of E-buses into urban transportation networks. Balancing these considerations will be essential in realizing the full benefits of E-bus systems within urban environments. Aggregators play a pivotal role

in mitigating grid impacts associated with E-bus charging infrastructures. These intermediaries act as orchestrators, managing the flow of energy between the charging infrastructure, E-buses, and the grid. By leveraging real-time data and sophisticated algorithms, aggregators optimize the charging process to align with grid conditions, demand fluctuations, and the availability of RES. This dynamic management helps prevent spikes in demand that could strain the local grid, especially during peak periods. Furthermore, aggregators facilitate demand response strategies, allowing for controlled charging during off-peak hours or times when renewable energy generation is abundant. This not only minimizes the stress on the grid but also enhances the integration of renewable energy into the charging process, fostering a more sustainable and resilient urban transit system. Additionally, aggregators enable the monetization of grid services, creating potential revenue streams for transit operators and incentivizing efficient charging practices. As a result, the role of aggregators is indispensable in optimizing the grid impacts of E-bus charging infrastructures, ensuring a harmonious and sustainable integration within existing electrical networks.

VI. COMPARISON OF CHARGING TECHNOLOGIES

Each charging method has its own advantages and disadvantages. In this part, the depot, en route, and in motion charging methods will be evaluated in terms of the battery capacity needed for the E-bus, charging time, average mileage, and convenience of their use. In depot charging, there will be extended charging durations at night, but buses do not need to charge while operating, resulting in a lower impact on bus operation [24]. Due to the lengthy recharging delay for each E-bus, the amount of time it takes an E-bus to complete a circulation will undoubtedly rise if it wishes to be charged during its working hours. As a result, to ensure service

provision, the fleet management company must increase the size of its fleet or the battery size of E-buses. The energy needed by the bus operating on the most demanding working cycles defines the capacity of the battery. Typically, the huge capacity of batteries, as is the case with the depot charging technique, will greatly increase E-buses weights, leading in increased energy consumption and less space for passengers. According to research, a 10-kWh battery increase will result in a rise of 15 kg in E-bus mass, increasing energy consumption by 0.7–1.0 kWh/100 km [97].

The key benefit of the depot charging approach is that it serves as a straightforward replacement for petroleum public buses. The bus operator may utilize the same buses for different routes because the vehicles don't rely on the charger being accessible throughout the route [146], [147], [148]. Additionally, because the E-buses are charged overnight, during off-peak hours (with discounted power), the burden on the power grid is minimal and charging costs less [149]. Since it is using available grid capacity that isn't being used at night, it typically won't increase the grid's peak demand and won't necessitate grid upgrades. Furthermore, because the charging power is smaller, the grid connection can be simpler and the cost of the infrastructure supporting the charging system is lower.

The reverse of depot charging is true for in motion charging, where the battery size is the smallest, and since they do not face significant charging delays while in operation the weight of the battery pack and consequently the fleet size is decreased. This strategy not only saves money on battery purchases and maintenance, but it also results in reduced energy consumption and increased capacity in terms of number passengers onboard due to the reduction in battery weight and size. Almost importantly, this is the simplest charging option for the driver since they do not need to initiate the charging process at each station [146], [147], [148].

En route charge, or fast opportunity charging, allows for a considerable reduction in the size of the E-bus battery. Although this charging approach will result in shorter charging delays compared to depot charging, it will still require a bigger fleet than that in case of in motion charging. There is always a trade-off between the quantity of utilized chargers and the battery capacity. Installing fewer chargers at bus terminals for en route charging is made possible using large-capacity batteries, but the energy consumption of E-buses and the costs associated with batteries will rise. However, if bus companies choose for small-capacity batteries, extra chargers will be needed to be placed in strategic locations for en route charging to guarantee the E-bus system will function normally [97]. To account for all of these compromises, optimum design plans must be developed [24], [38]. In this charging mode, network connection can be difficult and charging equipment expenses might be considerable because the E-bus requires greater powers than depot charging.

As shown in Figure 14, shallow and frequent charging occurs multiple times throughout the day, often at short

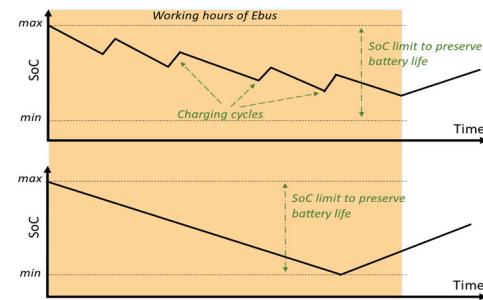


FIGURE 14. SOC variation in various charging modes: the upper one is shallow and frequent charging; the lower one is deep and infrequent charging.

intervals during layovers, whereas deep and infrequent charging takes place less frequently, typically once the bus returns to the depot or terminal for an extended stay. Regarding the duration of charging sessions, shallow and frequent charging involves relatively brief charging sessions, while deep and infrequent charging involves longer, more comprehensive charging sessions. In terms of location, shallow and frequent charging occurs along bus routes at strategically located charging stations, while deep and infrequent charging occurs at the depot or bus terminal, typically overnight. Finally, in relation to SOC levels, shallow and frequent charging maintains SOC at relatively high levels to support continuous operation throughout the day, while deep and infrequent charging allows for a more thorough recharging process, resulting in higher SOC levels.

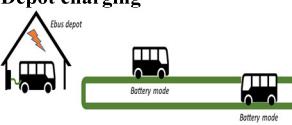
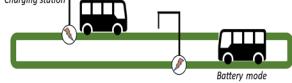
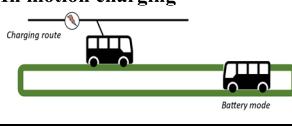
With in motion and en route charging, range concern is nearly eliminated, allowing E-buses to run for as far as required.

Nevertheless, on lengthy travels, it appears that in motion charging is preferable, as en route charging necessitates many stops for charging. Although these charging technologies appear to be promising, they nevertheless have a number of drawbacks.

The first is less flexibility in bus deployment since the chargers are placed at particular locations along the path, and if the bus wishes to take a different route, it can go out of power. Furthermore, charging typically occurs at high power levels (up to 500 kW) or at peak hours, and if energy storage is not employed to mitigate the effects on the electricity network, demand will increase, and energy costs are often higher. In Table 5, these three charging technologies, depot, en route, and in motion charging, are compared.

In Figure 15, a comprehensive radar map outlines the key attributes of various E-bus charging technologies, offering a nuanced evaluation of their suitability for urban transit systems. Flash charging stands out with its remarkable power output, facilitating rapid charging cycles. This high-power mode proves invaluable in time-sensitive operational environments, ensuring minimal downtime for E-buses. In contrast, plug-in charging, typically deployed at end stations or depots, operates at lower power levels, resulting in relatively extended charging durations. While slower, this mode is

TABLE 5. Main specifications of three charging modes; depot, en route, and in motion charging.

Charging method	Charging time	Power range (kW)	Fleet size	Electricity cost	Grid impact	Space need	Battery size	Dwell time
Depot charging 	4-8 hours	22-350	High	Low (charged at nights)	Low	High	High (~500-250 kWh Weight: ~5000-2500 kg Volume: ~2.5-1.25 m3)	High
En route charging 	20 sec-8 min	150-600	Average	High	Very high	Small	Low (~50 kWh Weight: ~ 500 kg Volume: ~0.25 m3)	Small (delay in some stations)
In motion charging 	While moving	up to 250	Small	High	Medium	Zero	Low (~30 kWh Weight: ~ 300 kg Volume: ~0.15 m3)	No extra delay

well-suited for overnight charging when buses are not in active service.

Conductive charging methods generally exhibit higher charging efficiencies compared to wireless alternatives. This characteristic underscores their effectiveness in energy transfer, contributing to reduced losses during charging processes.

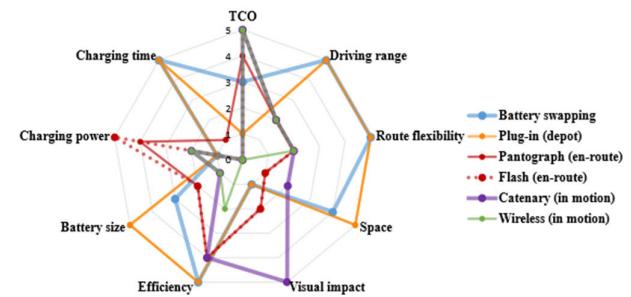
Dynamic wireless and catenary charging represents groundbreaking approaches where charging occurs while the E-bus is in motion, effectively translating to zero charging time within the operational schedule. These methods seamlessly integrate into routes without disrupting service, providing a unique advantage in maintaining continuous transit operations.

Considerations surrounding battery size and operational freedom are pivotal. Plug-in charging necessitates larger battery capacities to support E-bus operations throughout the day. In contrast, dynamic and en route charging, when strategically positioned along routes, alleviates the need for oversized batteries, granting operators greater flexibility in route planning and minimizing range-related concerns.

Plug-in and battery swapping charging methods offer extended driving ranges with a single charging event or battery exchange, catering to uninterrupted service over longer routes, a vital consideration for routes with limited access to charging infrastructure.

The total cost of ownership (TCO) closely correlates with charging power. As charging capacity escalates, so do associated maintenance and operation, and procurement expenses. This relationship underscores the need for careful cost-benefit analysis when selecting charging technologies.

In terms of initial investment, battery swapping incurs higher costs due to the acquisition of additional batteries for the exchange station. Meanwhile, catenary charging demands substantial infrastructure investment, as it requires

**FIGURE 15.** Comparison of main specifications of different charging modes.

the installation of overhead lines along the entire route. This not only affects budgetary considerations but also introduces visual elements that may alter the cityscape. This not only impacts budgetary considerations but also introduces visual elements that may alter the cityscape. Consideration of land requirements in charging station installations is essential. Plug-in and battery swapping stations generally necessitate more space compared to other en route and in motion charging options, influencing land usage considerations.

VII. B2X TECHNOLOGIES AND INTEGRATION OF RENEWABLE ENERGY SOURCES

Charging technologies and infrastructures for E-buses should encompass the integration of Bus-to-everything (B2X) technologies too. Despite the fact that Vehicle-to-everything (V2X) concept has been extensively studied and is widely acknowledged for electric vehicles such as cars, it is comparatively less explored for E-buses. While, E-buses, with their prolonged idle periods throughout the day, present an opportunity to function as high-capacity stationary energy storage system, capable of storing renewable energy from

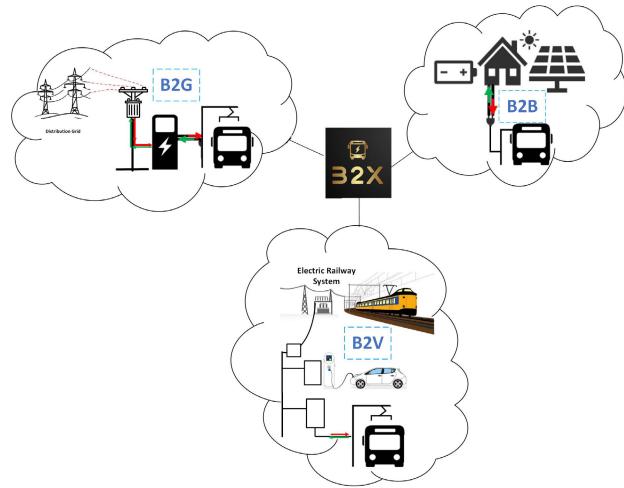


FIGURE 16. B2X technologies including bus-to-grid (B2G), bus-to-building (B2B) and bus-to-vehicle (B2V).

local RESs or capturing braking energy from light railway networks like trams and metros [150], [151]. These E-buses can then serve various purposes as shown in Fig. 16 such as supporting the grid (B2G), supplying energy directly to residential or commercial buildings (B2B), or facilitating charging for other EVs with higher priority (B2V).

Given the distinct characteristics of E-buses compared to small cars, such as larger battery capacities, they may be better suited for delivering B2X services.

A. B2G

The integration of E-bus chargers into the electricity grid (B2G) offers a means to enhance grid capacity and stability [149]. This approach assists network operators in managing grid flexibility, reducing peak demand, and mitigating system degradation and losses due to overload. Recent studies have explored the potential of E-bus fleets to serve as mobile energy storage units during emergency situations. By integrating E-buses into emergency power supply systems, a coordinated restoration approach can be established, encompassing network reconfiguration and load optimization. Research [152] reveals the feasibility of deploying E-buses for emergency power supply in urban settings, akin to traditional diesel generators, as demonstrated in a study focused on the metropolis of Hamburg. B2G technology empowers E-buses to function as portable batteries, aiding in the stabilization of the electric grid. This category of Distributed Energy Resources (DERs) is crucial for the advancement of the grid infrastructure. As the integration of variable RES increases, grid fluctuations become more pronounced. ESSs, including batteries within E-buses and other EVs, assume a vital role in mitigating the intermittency inherent in resources like wind and solar power [35]. Moreover, utilities can mitigate emissions by utilizing E-buses as DERs during periods of peak energy demand, thereby avoiding the need to activate conventional fossil fuel resources for short durations.

Notably, the “Bus2Grid” project launched in London in 2018 is a significant initiative where 28 E-buses are actively involved in interacting with the energy system, aimed at developing a comprehensive strategy for the mass deployment of B2G technology capable of returning over 1 MW of power to the grid [153].

During the summers of 2021 and 2022, Highland Electric Fleets and BorgWarner employed B2G technology to release over 10 MWh of energy to the Massachusetts grid across 158 hours. This marked the inaugural utilization of battery storage from electric school buses in a commercial B2G initiative within the United States [154].

B. B2B/B2H

Bus-to-building (B2B) or Bus-to-home (B2H) technologies can represent innovative approaches where E-buses can serve as integral components in supplying power to homes or buildings. Similar to Vehicle-to-Home (V2H) or Vehicle-to-Building (V2B) concepts, these systems enable E-buses to act as mobile energy storage units, capable of storing excess energy and redistributing it when needed. By leveraging the large battery capacities of E-buses, surplus energy generated during off-peak hours or through regenerative braking can be stored and utilized during peak demand periods or power outages. This not only optimizes energy usage but also enhances the resilience of local energy systems. Additionally, B2H and B2B technologies contribute to reducing carbon emissions by promoting the integration of RESs and minimizing reliance on conventional grid infrastructure.

In 2012, in Japan, Toyota Motor Corporation unveiled a power supply system designed to utilize electricity generated within an FCEb for supplying power to various devices, including household electrical appliances [155].

C. B2V

Bus-to-vehicle (B2V) technologies can represent an innovative extension of the Vehicle-to-Vehicle (V2V) concept, wherein E-buses can actively support other EVs. Much like V2V communication, B2V systems enable E-buses to share their surplus energy with other EVs, thus extending their driving range and enhancing overall efficiency or facilitating charging for other EVs with higher priority. This exchange of energy can occur dynamically, allowing EVs to top up their batteries while on the move or parked at designated charging stations. Meanwhile, capturing regenerative braking energy from light railway networks like trams and metros [149]. The real integration of E-bus opportunity charging stations with DC railway systems is realized in Milan, Italy, as shown in Fig. 17 [26]. In this integration, both systems are connected in a DC hub S1/S2, shown in Fig. 17.b, enabling bidirectional power flow.

D. INTEGRATION OF RESs AND ENERGY MANAGEMENT SYSTEMS

The integration of EVs with pre-existing RESs poses a transformative impact on the utility grid. This transition from

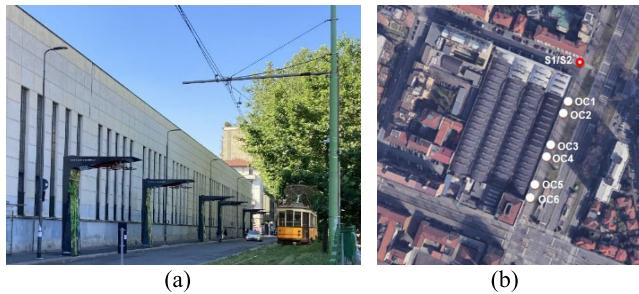


FIGURE 17. Integration of opportunity charging E-Bus station with DC Tramway line in Viale Zara, Milan.

fossil fuels to diverse RES forms is still in its infancy, yet it holds the shared objective of advancing green energy adoption and fostering sustainable mobility. While there is a vast array of RESs available, including biomass, geothermal, and tidal energy, the focus of such an integration is on solar, wind, and hydropower for EV charging stems. By harnessing the power of RESs, such as solar or wind energy, in conjunction with innovative charging technologies, cities can substantially reduce their reliance on conventional power grids. This not only enhances the environmental footprint of E-bus fleets but also fosters greater energy independence and resilience. Moreover, exploring these integration scenarios opens avenues for research and development, aiming to create more efficient and harmonized systems for the future of public transportation.

The deployment of EVs in conjunction with rooftop photovoltaic (PV) systems, especially in the case of E-bus charging fleets, can introduce a dual-layered effect on grid dynamics. Firstly, by leveraging rooftop PVs to charge E-buses, there's a direct reduction in grid reliance during peak demand periods, potentially alleviating strain on traditional energy infrastructure. Additionally, the integration of E-bus charging fleets with rooftop PVs enhances grid resilience by decentralizing energy production and distribution. This decentralized approach reduces transmission losses and enhances energy security, particularly during grid outages or emergencies. However, challenges such as energy management and load balancing [35], [156], and infrastructure upgrades must be addressed to maximize the benefits of this integration while ensuring grid stability. Overall, the integration of solar power with E-bus fleets represents a significant advancement in sustainable transportation infrastructure, such as those in Brisbane, Australia, and Montgomery County, Maryland, USA. In Brisbane, Transdev, a prominent public transport operator, is pioneering the use of a “green mobility megawall” comprising 250 solar modules and 10 Tesla Powerwall units to charge two new E-buses [157].

Meanwhile, Montgomery County, Maryland, has taken bold strides towards greener transportation with the deployment of the largest electric school bus fleet in the United States, comprising 86 buses. Notably, the county has also established the Brookville Smart Energy Bus Depot, a cutting-edge facility powered by solar energy and equipped

with a microgrid energy storage system. This integrated system, boasting 4.14 megawatts of charging capacity, effectively powers 70 E-buses – half of Brookville's bus fleet – while ensuring resilience through a 3 MW/4.3 MWh CPS-i ESSs. This energy storage solution enables uninterrupted operational capacity for the depot, even during grid outages, underscoring the reliability and sustainability of solar-powered E-bus charging infrastructure [158].

VIII. FUTURE TRENDS

The transition towards electric mobility is currently in progress, driven by declining costs of battery-powered vehicles and breakthroughs in range and efficiency. However, this development is not without its challenges and opportunities for further research. The majority of these research endeavors are focused on overcoming barriers to the widespread adoption of E-buses. This study identifies several key areas for potential research:

Global standardization of regulations and protocols is imperative to enhance the market acceptance of E-buses and their charging infrastructures. A unified approach to standards and regulations on a global scale is necessary to drive widespread adoption.

With the extensive deployment of E-buses, cybersecurity concerns have emerged as a critical issue requiring attention [148]. The integrity of information transfers, communication systems, and firmware/software components within the E-bus infrastructure are all identified as potential vulnerabilities.

To bolster grid stability and resilience without the need for costly new conventional infrastructure, dynamic approaches are anticipated. These may involve situating power production systems or stationary energy storage systems in proximity to charging facilities, as well as integrating RESs. Integrating existing infrastructure, such as railway and subway supply systems in a DC hub with E-bus charging fleets, is also gaining popularity as an alternative to costly new investments.

Energy management and optimization systems have garnered significant interest due to their potential impact on power networks. The primary goals of defining an energy management system for E-bus charging stations are to optimize charging efficiency, balance energy demand, integrate with RESs, reduce costs, ensure grid stability, enhance user convenience, and manage fleets effectively. However, the implementation of effective energy management systems faces several challenges [159]. Battery degradation is a significant concern, as frequent charging and discharging cycles can lead to decreased battery capacity and lifespan. Moreover, ensuring compatibility and interoperability between different charging infrastructure components and E-bus fleets presents technical hurdles.

Addressing issues such as E-bus fleet energy demand forecasting and managing uncertainties in charging plans are other topics of interest in energy management definition. Additionally, the concept of the energy internet, enabling a



FIGURE 18. E-bus alternative charging system.

fully autonomous power network through advanced energy management solutions, is gaining traction.

Implementing smart charging strategies for E-buses holds the potential to significantly enhance the integration of renewables [160]. This integration holds significant promise for the advancement of sustainable urban transit systems. While E-buses hold promise for bolstering resilient energy infrastructure and countering the effects of extreme events, addressing challenges related to infrastructure upgrades and system optimization is crucial to maximizing their effectiveness. For instance, [161] highlights the need for infrastructure upgrades, specifically inverters and protection infrastructure, to manage inrush currents and ensure the successful black starting of the microgrid's prime power generator. These challenges underscore the need for further research and investment to ensure the seamless integration of E-buses into emergency power supply systems, ultimately enhancing the resilience of energy infrastructure in the face of extreme events.

According to the study carried out, E-buses face significant challenges in its relationship with charging resources, primarily due to limitations in battery capacity, extended charging durations, and inadequate charging infrastructure. It is demonstrated that enhancing energy density and offering en route charging options could potentially mitigate these drawbacks. However, the feasibility and effectiveness of these proposed solutions are not completely confirmed since the task of increasing battery density has a considerable technical challenge. Therefore, alternative solutions can be considered in the form of the following technologies.

Currently, there is active installation and exploration of prototypes for in-motion inductive charging systems and flash charging [148]. These technologies hold great promise due to their potential to alleviate range anxiety and their user-friendly nature, suggesting increased utilization in future public transportation systems. Mobile charging vehicle (MCV) is another concept which utilize bidirectional chargers to distribute energy across a local grid to E-buses through a dedicated aggregator. Inspired by modular bus architecture, MCVs are wired for energy transfer and can connect to the target E-bus. This innovative technology transforms traditional fixed bus charging stations into active ones, as MCVs accompany E-buses on scheduled trips, providing energy replenishment during the journey. This eliminates the need for fixed charging locations, enabling on-the-go charging. Additionally, MCVs can offer services at night to support more intensive schedules [162].

V2V wireless charging is another promising development expected to gain traction allowing buses for in motion charging. This technology enables buses to wirelessly transfer energy between vehicles, providing a dynamic and adaptable approach to maintaining charge levels as shown in Figure 18. By utilizing the power of V2V charging, E-buses can extend their operational range and minimize downtime, further bolstering the viability of electric transit. Incorporating the latest advancements in E-bus charging technologies, we explore the potential of V2V wireless charging. With the establishment of a safe distance for energy transmission, dynamic wireless V2V charging becomes feasible. This system ensures a constant influx of energy into the network, eliminating any concerns of mileage anxiety for E-buses on the road. As an E-bus nears the conclusion of its timetabled journey, it redistributes surplus energy across the road network, reserving a small portion for its return to the depot. However, the integration of energy flow adds a layer of complexity to system operations. Challenges include safety regulations and maintaining effective power transfer under dynamic high-power requirements. Due to the variability in the relative positions of the vehicles involved in the charging process, efficiency concerns arise. Depending on these positions, the efficiency of energy transfer may vary significantly, potentially adding to the carbon footprint of the whole process. According to [161], V2V wireless transmission may become more viable when power efficiency reaches approximately 45%. Therefore, while V2V wireless charging holds promise, it's essential to conduct thorough assessments to mitigate the efficiency concerns.

The future of E-bus charging is likely to witness advancements in Portable charging devices (PCDs). These compact and flexible systems can be deployed quickly to provide temporary charging support and extra battery capacity, making them invaluable in emergency situations or for buses operating in areas with limited charging infrastructure. It serves to further reduce reliance on obtaining energy from other vehicles. It can be likened to a reserve battery equipped with ample energy to sustain an E-buses for a complete scheduled journey. Consequently, major interchange stations function as central battery banks within this system. E-buses with charging requirements arrive at these stations and connect to one or more portable charging. Once connected, they are subsequently replaced with fully charged units from the next en route battery banks once their own energy is depleted. Critical considerations encompass the weight, efficiency of energy transfer, ownership expenses, and operational lifespan of portable charging. To prevent adding undue strain on the E-buses, as shown in Figure 18 it might be designed in the form of a trailer, moving alongside the E-bus rather than being affixed directly to its structure [162].

IX. CONCLUSION

A survey of E-bus charging technologies was done in this work. A bibliometric analysis and review, main characteristics of each E-bus charging technology, available standards

for charging stations, challenges and barriers to uptake of E-buses, a comparison of each charging category, and probable future developments of E-bus market were thoroughly assessed in this work.

First, depot, en route, and in motion charging modes are introduced and reviewed. These three charging modes are then further subcategorized to plug-in, pantograph, wireless, battery swapping, and catenary charging. Each charging technology has its own pros and cons and can be implemented in different fleet systems with different characteristics. In depot charging, there will be extended charging durations at night, but buses do not need to charge while operating and in order to ensure service frequency, the bus company must increase the size of its fleet or the battery of E-buses. The reverse of depot charging is true for in motion charging, where the battery size is the smallest, and since they do not face significant charging delays while in operation. Additionally, en route charging and fast opportunity charging facilitate a reduction in the size of the battery for E-buses. Although this charging approach will result in shorter charging delays compared to depot charging, it will still require a bigger fleet than that in case of in motion charging. There should be a trade-off between the quantity of utilized chargers and the battery capacity. To capture all of these trade-offs, the establishment of optimal design plans is necessary.

This review also provides an overview of the different challenges involved in making the full transition from combustion engine buses to E-buses. These issues include: 1) charging schedules to prevent any disruptions in service provision of the fleet of E-buses; 2) the price of E-buses, which is directly correlated with battery capacity and established charging network, 3) adverse effect of uncontrolled charging on the electricity network. Given the high power needed for recharging E-bus fleets, uncontrolled charging can have a serious effect on the grid. This problem can be resolved by adding stationary energy storage or production systems near the charging stations, and integration of RESs to the grid. In addition to the technical aspect, this study also covered some non-technical topics related to the standards and regulations for E-bus charging stations and potential future trends.

While providing a comprehensive overview of E-bus charging technologies, it's important to acknowledge potential limitations. Emerging technologies and niche applications may exist beyond our scope, warranting further exploration. Additionally, the effectiveness of each charging mode depends on specific operational contexts and fleet characteristics. Tailored recommendations may be necessary for different transit agencies. Addressing challenges in transitioning to E-buses, such as charging schedules and grid impact, requires context-specific solutions, which future studies can explore.

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