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Review

An Investigation into the Viability of Battery Technologies for Electric Buses in the UK

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Abstract: This study explores the feasibility of integrating battery technology into electric buses, addressing the imperative to reduce carbon emissions within the transport sector. A comprehensive review and analysis of diverse literature sources establish the present and prospective landscape of battery electric buses within the public transportation domain. Existing battery technology and infrastructure constraints hinder the comprehensive deployment of electric buses across all routes currently served by internal combustion engine counterparts. However, forward-looking insights indicate a promising trajectory with the potential for substantial advancements in battery technology coupled with significant investments in charging infrastructure. Such developments hold promise for electric buses to fulfill a considerable portion of a nation's public transit requirements. Significant findings emphasize that electric buses showcase considerably lower emissions than fossil-fuel-driven counterparts, especially when operated with zero-carbon electricity sources, thereby significantly mitigating the perils of climate change.

Keywords: batteries; electric bus; public transport; electric vehicles; Li-ion battery

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1. Introduction

Integrating advanced technological solutions into everyday life is becoming increasingly crucial amid the escalating threat of climate change. In 2019, transportation accounted for 27% of greenhouse gas emissions in the United Kingdom (UK) [1], signifying the most significant share among sectors. Addressing the urgent need to mitigate climate change requires a pivotal shift toward electrifying transportation [2]. While privately owned electric vehicles (EVs) are gradually supplanting traditional fossil fuel vehicles [3], one area that needs to reach the same level in this electrification endeavor is the realm of buses. Currently, public buses in the UK contribute 4.3 million tons of CO_2 [4]. Fossil-fuel-powered buses, especially in urban environments, are major sources of NO_x emissions. They are known for their association with respiratory disorders and other health complications [5], particularly affecting vulnerable demographics like children. As urban populations surge [6], the demand for public transport escalates, particularly considering the declining convenience of privately owned vehicles in urban settings [7]. As we can see from the discussion above, addressing these challenges necessitates an urgent mitigation of direct emissions and pollutants from transportation.

One way to reduce these emissions and pollutants is to electrify public transport. This transition has already succeeded in underground and overground railway systems within cities. However, buses have specific issues to overcome—for example, range limitations and charging times. Despite these challenges, electrifying buses have significant promise for eliminating direct pollutants, as mentioned earlier. Buses are ideal for electrification; they follow predictable routes, can be regularly interchanged with other units, carry consistent loads, and enjoy priority lanes and roads in the UK. These factors delineate a distinct use case for buses that would allow for the seamless integration of electrification. Moreover, buses can transport many passengers daily, minimizing emissions per passenger compared to privately owned vehicles [8].

This paper explores the viability of electrifying buses without fundamentally hindering their operational efficiency. It will analyze various contemporary battery materials [9] and technologies [10] to examine the potential implementation of modern-day battery technology in buses [11]. Additionally, forthcoming technologies will be reviewed to assess the veracity of claims made by companies regarding battery densities, capacities, charge times, and their feasibility for implementation based on a comprehensive cost–benefit analysis. Furthermore, various approaches and technologies will be explored to gauge the problem comprehensively and reach a holistic conclusion that yields the most efficient solution. Beyond addressing technological hurdles, cost is one of this sector's foremost issues [12]. This paper will also attempt to compare and contrast solutions, seeking alternative methods to circumvent this issue by devising novel solutions and leveraging existing technologies.

2. Literature Review

2.1. Batteries

Batteries are utilized across almost every industry as a convenient way to supply energy [13]. Operating on the fundamental principle of converting chemical energy into electrical energy on demand [14], batteries consist of four essential components: the anode, cathode, electrolyte, and separator [15]. The chemical reactions within a battery lead to the accumulation of electrons on the anode, thus creating a potential difference. Upon completing the circuit, electrons find a path to the anode, generating a current [14]. Batteries are categorized as primary (single-use, requiring disposal after depletion) and secondary (rechargeable, allowing for multiple usage cycles) [16,17].

The heart of any battery lies in its active materials, which dictate its efficiency and performance [18]. Cathode active materials (CAMs) and anode active materials (AAMs) are responsible for the efficiency, reliability, costs, cycle, calendar life, and size of batteries. Together, these materials account for 60–70% of total cell costs with today's raw material prices [19]. Recent advancements have led to a surge in research focusing on developing and optimizing active materials such as lithium (Li)-ion, sodium (Na)-ion, and others [18]. Understanding the nuances of these materials is pivotal for achieving higher energy density, longer cycle life, and improved overall battery performance [20].

The electrochemical reactions within a battery are responsible for its functionality [14]. Understanding the complexity and multifaceted nature of these reactions within a battery is crucial for predicting its behavior and degradation [21]. Sophisticated battery management systems (BMSs) are essential for optimizing the safety and performance of battery systems. Breakthrough technologies are being developed to address fast charging [22], material optimization [23], and recycling issues [24]. Innovative solutions ranging from novel electrolyte formulations to advanced thermal management techniques are being explored, showcasing the dynamism of contemporary battery research.

Moreover, researchers are striving to improve battery performance, safety, and durability with minimal environmental impact [23]. Key research areas involve the advanced characterization of cell components like electrodes and electrolytes to improve overall battery design [25], conducting fundamental studies on ion storage [26] and modifying surface or coating properties [27]. Also, data-driven approaches have been proposed for the rational design of battery materials based on resource and performance considerations [28,29].

This paper will focus on secondary batteries, particularly Li-ion batteries, which are more appropriate for transport and comprise most of the battery and automotive market. Without delving extensively into Li-ion battery research, this paper will discuss key considerations such as material choices, cost benefits, and performance analysis, aligning with electric bus battery technologies in the UK.

2.2. Public Bus Use Case

To comprehend the implementation of electrification in local public buses, understanding the current design prerequisites and operational demands of these buses is essential. Notably, during the 2019/2020 fiscal year, the average distance covered by a bus on a London route was around 130 miles [30]. Therefore, any electric powertrain introduced should match or improve this range.

The existing UK bus fleet encompasses various engines, predominantly diesel engines from manufacturers like Volvo and Daimler [31]. However, for this analysis, we will focus on the Cummins diesel powertrain, particularly the ISB6.7 Euro6 Cummins engine, a significant component of the local TFL bus fleet [32]. These engines offer power ranging from 164 to 239 kW (220 to 320 HP) and torque between 900 to 1200 Nm (664 to 885 lb-ft), varying based on their application. Furthermore, the Cummins diesel powertrain can carry a payload of 1800–3300 kg [33], necessitating any proposed to adhere to these performance criteria.

A critical aspect of the design of any public infrastructure is cost. Currently, the cost of internal combustion engine (ICE) buses is around GBP 250,000, with specific configurations reaching up to GBP 500,000 [34]. Bus operating expenses currently range between 419 and 449 pence per vehicle mile [30]. Therefore, any prospective electric system must compete with or surpass current pricing structures. Expenditure in the public sector undergoes stringent scrutiny compared to the private sector, requiring substantial incentives to sway councils and private bus operators from proven, existing technologies toward newer, untested ones. Consequently, proposed electric solutions should promise tangible short- or long-term savings—ideally both.

3. Cost Analysis

For the analysis, we will primarily compare two buses currently in use across cities in the UK: the Mercedes-Benz Citario and the Yutong TCe12. These models are extensively utilized throughout the UK and exhibit notable comparability.

3.1. Purchase Cost

Economic feasibility is the primary determinant for the viability of electrified bus transport. This factor fundamentally influences the adoption of new technology by both private companies and local governments. Notably, significant discrepancies exist between the components constituting ICE and electric drivelines [35]. Understanding these disparities is pivotal, as they engender distinct operational behaviors and functionalities in vehicles, which will be elaborated upon later. Moreover, these differences give rise to varying benefits and drawbacks. Comparatively, the cost of purchasing a brand-new electric bus significantly surpasses that of a traditional ICE bus. For instance, a single-decker Yutong Tce12 electric bus costs GBP 295,000, positioning it approximately GBP 100,000 higher than its diesel-powered equivalent [36].

3.2. Fuel Cost

Electric vehicles are often presented as having lower operating costs than ICE vehicles [37]. However, it is important to note that this price is susceptible to market factors, as illustrated in Figure 1, which showcases the prices of red diesel and crude oil in red and blue colors, respectively. It also demonstrates how fuel prices, though correlated with fluctuations in the crude oil price, can exhibit relative stability over long periods, with price increments aligning with inflation rates [38]. Typically, traditional ICU buses consume approximately 24 L of fuel per 100 km, traveling at an average speed of 60 km/h [39]. This means a diesel bus will consume an average of 150 L of fuel (assuming three round trips on an average route within a 9–10 h shift) with current wholesale diesel prices (131.88 pence per liter), which costs GBP 197.82 per bus per shift for fuel alone [40].

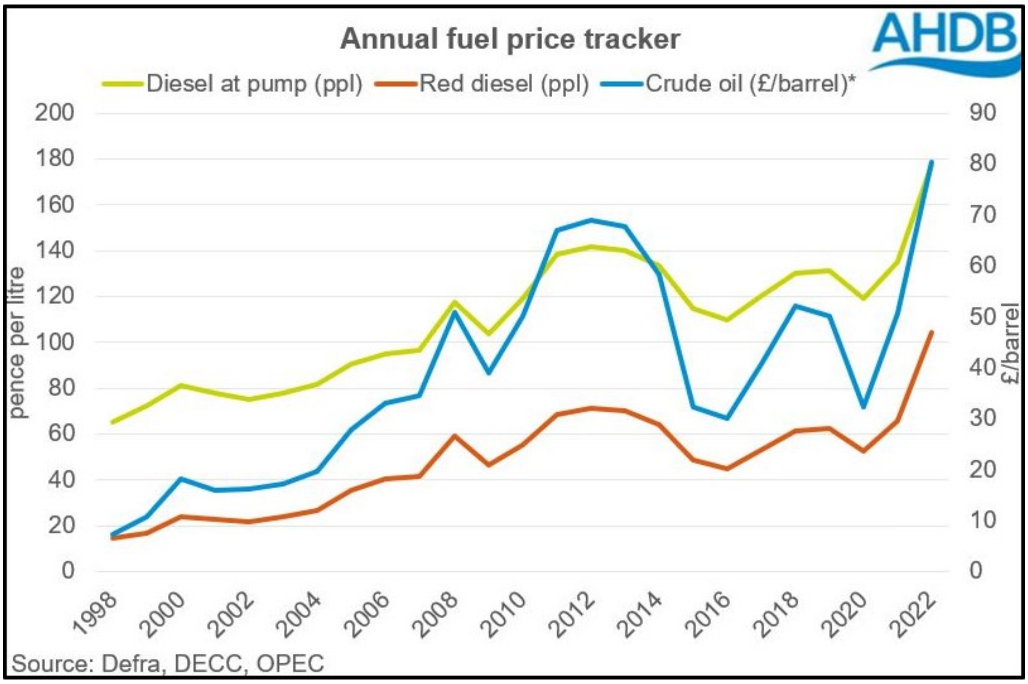

Figure 1. Wholesale fuel prices over time. Reproduced with permission from [41].

One advantage of using fossil fuels lies in the government's capability to temporarily reduce or completely alleviate any fuel duty imposed on wholesale fuel sales [42]. This measure aims to ensure public transport's affordability during crises, especially when the fuel cost per liter significantly surpasses historical averages due to shortages and supply chain disruptions. Before this increase (using prices from January 2019, 96.85 pence [40]), the daily cost per shift would have been GBP 145.89 per bus. This results in the saving of GBP 51.93, translating to substantial savings when extended across an entire fleet of buses.

Figure 2 shows the relative stability of electricity prices over the past decade, except for the last two years, during which they more than doubled rapidly. This substantial increase has significantly impacted the operational costs of running a fleet of electrified buses. To cover the same distance as an equivalent diesel bus at current prices (28 pence per kWh [43]) along a 130-mile route, making 3 round trips within 9–10 h, the estimated cost would be around GBP 236.33. This cost far exceeds the current expense for the same trip using diesel. Before the steep increase in electricity costs per kWh, the journey would have cost GBP 165.42, using 2019 prices [43]. This shows the vast range of possible operational costs that could harm bus operators. It is important to note that the quoted content for the Yutong TCe12 is 370 km, which might necessitate a mid-journey charge, impacting route planning and driver shift schedules.

Comparing the two costs, it is evident that, using both 2019 and current figures, running diesel buses is considerably cheaper in terms of fuel cost. In the 'normal' scenario, operating an ICU bus per shift is GBP 19.53, which is less expensive. Scaling this up to an entire fleet of buses (around 400 buses for a mid-sized city) results in an increased cost of GBP 7812 per day, totaling over GBP 2.85 million annually. Unless government subsidies or a significant increase in inexpensive electricity occurs, bus operators will likely continue using ICU buses due to these financial incentives.

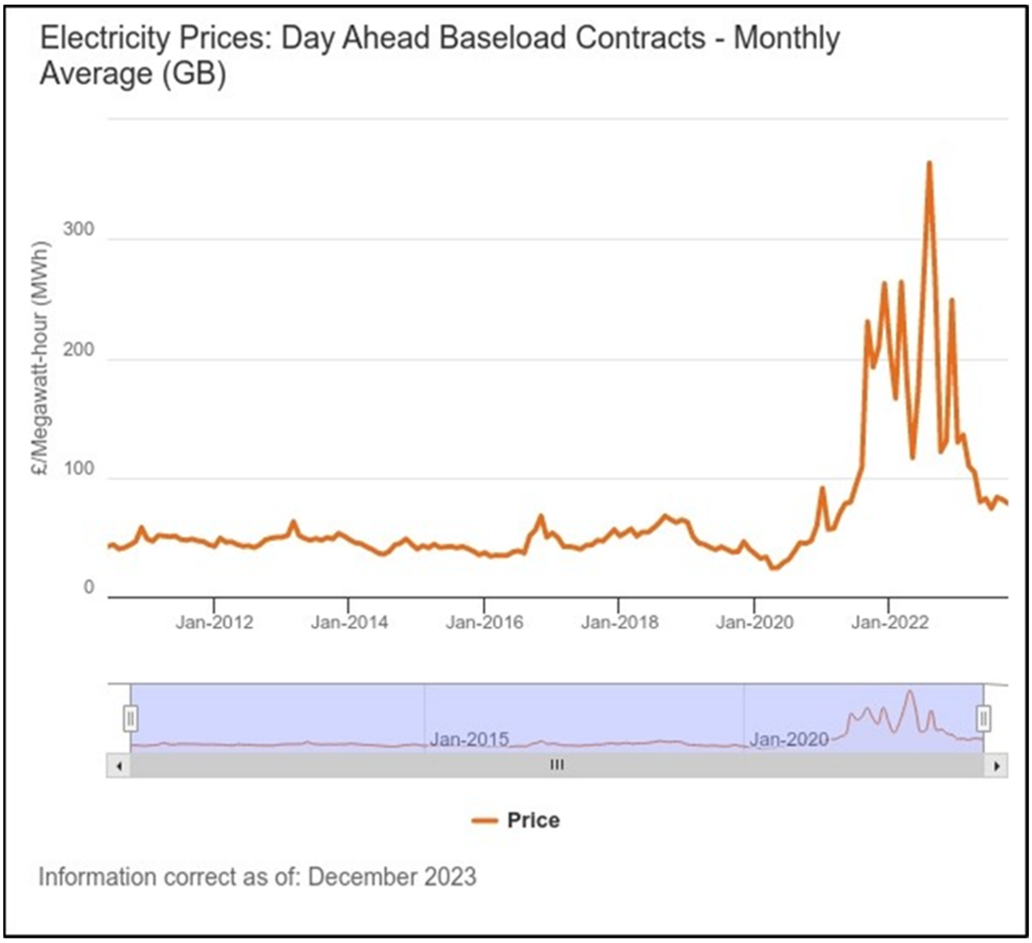

Figure 2. Electricity prices, monthly average. Reproduced with permission from [44].

3.3. Maintenance Costs

Maintenance adds a significant cost to bus operators. Only maintenance costs associated with the drivetrain will be considered for this part of the analysis. For comparative purposes, labor costs have been assumed to be USD 50 (GBP 42) per hour, acknowledging their considerable variability based on the service provider [45].

In the case of a traditional diesel bus, maintenance primarily involves oil, oil filters, air filter replacements, and considerations for any fuel system maintenance costs [46]. The average price of these parts comes to USD 3273.25 (GBP 2753.75), involving an average labor time of 42.75 h [45]. These calculations are based on an assumed distance of approximately 100,000 miles driven over 24 months, costing USD 0.54 per mile, as detailed in Table 1 [45].

Table 1. Analysis of four similar bus maintenance costs. Reproduced with permission from [45].

Bus Number	Miles Driven	Labor Hours	Part Costs	Total Cost (USD/mile)
		Diesel Group		
2203	105,499	892	USD 11,965	USD 0.54
2204	106,788	835	USD 14,254	USD 0.52
2205	110,133	965	USD 14,178	USD 0.57
2206	105,981	852	USD 13,555	USD 0.53
Totals	428,401	3544	USD 53,951	USD 0.54

The maintenance for an electric powertrain is notably more straightforward owing to the reduced number of parts, fostering the potential for increased reliability through enhanced robustness in each component [47]. However, one form of maintenance that must be considered is the replacement of the battery, which degrades and reduces capacity over time. The frequency of these replacements depends on many variables, such as the manufacturer of the battery, the charge and discharge cycles, the composition of the battery's materials, etc. Li-ion batteries, subject to extensive real-world usage, can take between 2000–4000 charging cycles, depending on how often DC fast charging is used [48]. This equates to approximately 5 to 10 years before requiring replacement, as illustrated in Figure 3.

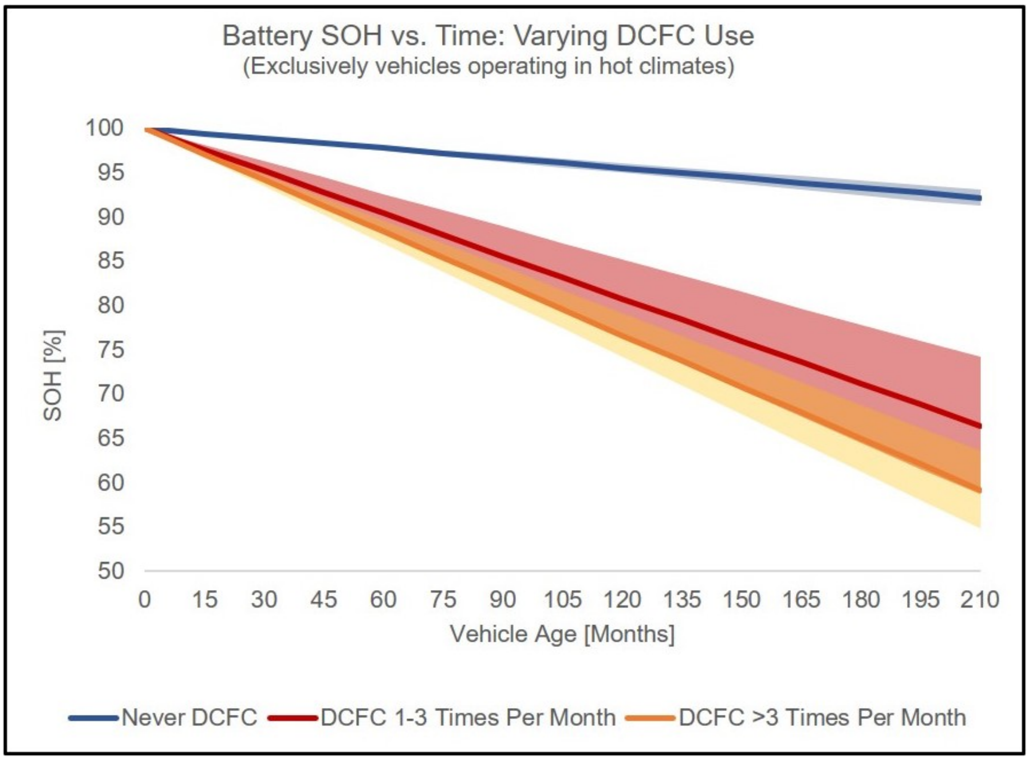

Figure 3. Lithium-ion battery degradation. Reproduced with permission from [49,50].

The Yutong TCe12 has a projected battery life of 6 years, requiring a replacement cost of USD 195,900 [51]. This replacement cost equals a per-mile equivalent of USD 0.653, assuming a similar mileage to the diesel bus. This estimation only considers the inevitable degradation of the batteries and does not include any possible failures of other driveline components, such as the motors.

Figure 3 also highlights the fact that battery degradation can accelerate significantly when utilizing DC fast charging, a common practice in electrified bus networks. Therefore, fast charging a bus multiple times a day is a popular strategy to maintain operational bus services, given the limited range of a battery electric bus [52]. However, this practice can substantially impact the lifetime of battery packs, leading to operator costs.

The cost of replacing Li-ion batteries, predominantly used in all EVs today, is predicted to decrease over time [53].

Figure 4 shows the declining trend in battery price per kWh. This indicates a substantial future decrease in the cost of battery replacements, suggesting that if an electrified bus network is established, the expense of replacing batteries in 6–10 years will witness nearly a 50% reduction. This can also have cascading effects on purchasing electric buses in the near future, making them far more cost-effective. Furthermore, early adopters of the technology will drive down prices, thereby increasing overall demand and further reducing costs.

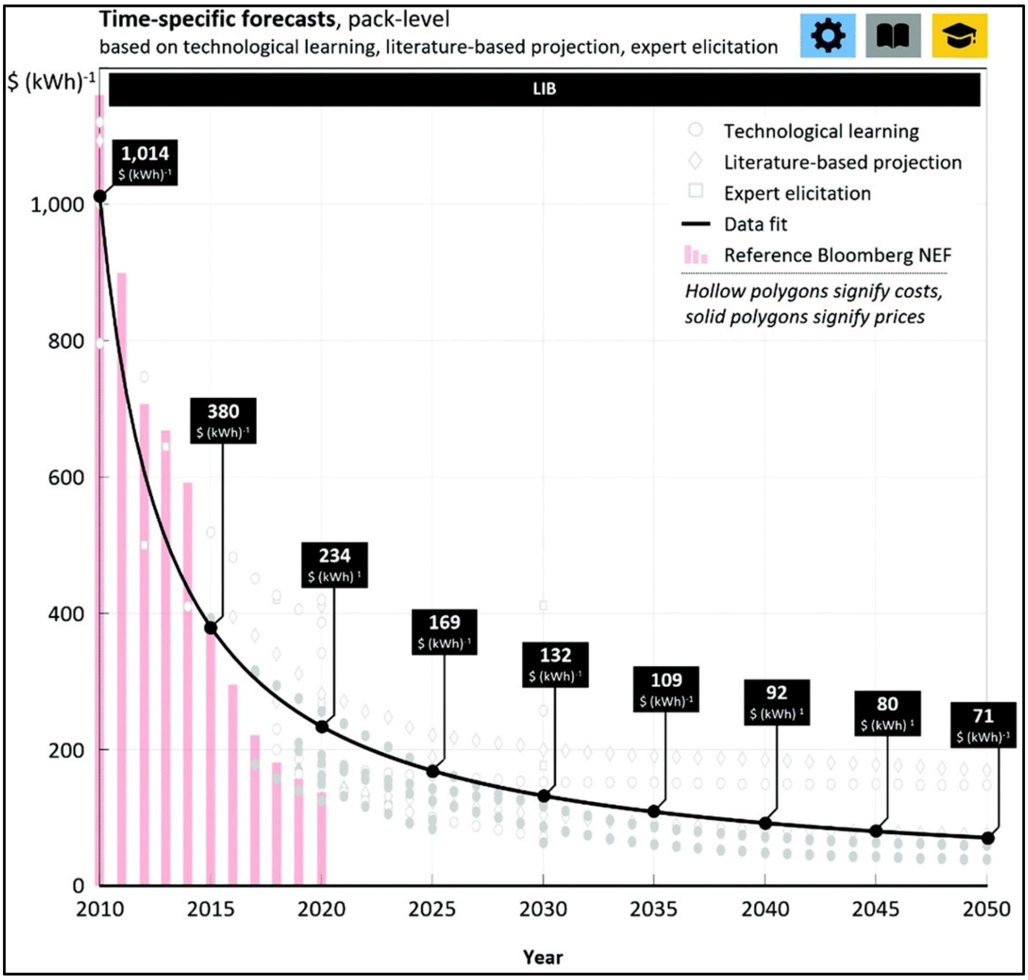

Figure 4. Prediction of battery prices over time [53]. Copyright 2021, *Energy & Environmental Science*.

Although battery prices per kWh are forecasted to decrease, recent global events highlight the EV industry's sensitivity to global raw material prices [54]. Lithium is an essential material in the production of batteries for EVs. This means that any scarcity in the raw material can devastate battery prices, potentially rendering a battery electric transport network economically unfeasible [55].

Figure 5 illustrates how the volatility in material cost can dissuade bus operators from choosing battery electric buses when upgrading their fleet. In addition to lithium prices, it is evident that the other materials required to make batteries are also subject to similar market fluctuations.

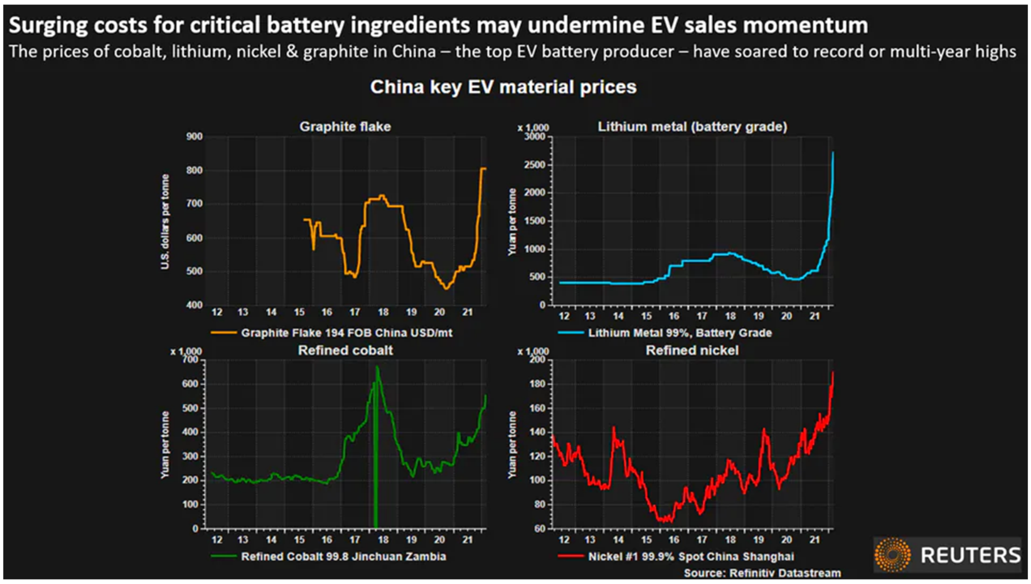

Figure 5. Battery raw material price over time. Reproduced with permission from [56].

3.4. Infrastructure Costs

Another significant cost of adopting battery electric buses is the infrastructure required to keep a fleet operational. Charging infrastructure must be retrofitted into bus depots and potentially along routes to support an electrified bus fleet [57]. Three types of charging infrastructure can keep a fleet running: pantograph, plug-in, and ground-based charging (as in Figure 6) [58].

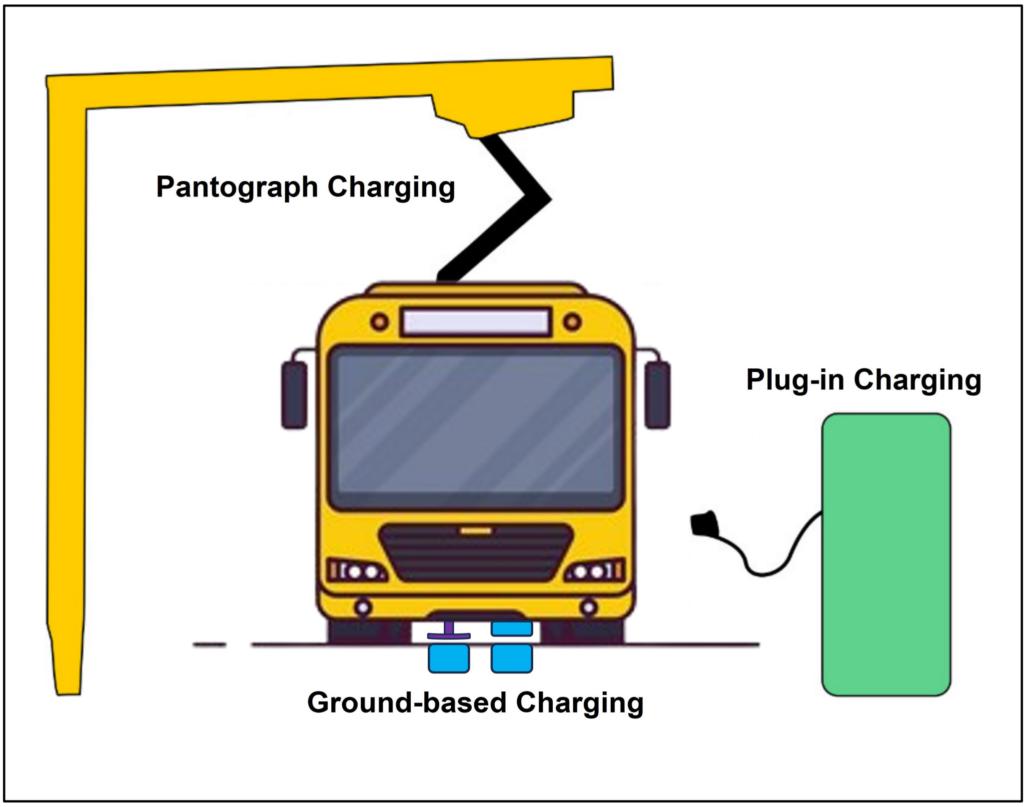

Figure 6. Illustration showing the three primary forms of charging.

The most common form of charging is plug-in charging, which involves manually plugging a physical charger into the bus. However, this method can pose challenges for large-scale fleets. Despite this, plug-in charging offers relative affordability and minimal road and foot traffic disruption. Furthermore, using a standardized charging plug, commissioned by the European Union (EU) [59], promotes interoperability among bus manufacturers and operators. Meanwhile, DC fast charging can significantly boost charging speeds, which proves beneficial for daytime charging. As previously discussed, it can substantially diminish battery pack longevity, necessitating earlier replacements. To mitigate this issue, one approach involves integrating DC fast charging as a supplementary method to overnight 'slow' charging, enabling mid-route battery recharging for an extended range. However, this can still have detrimental effects on battery longevity, depending on use. The primary advantage of plug-in charging lies in its widespread usage and established technology. This paves the way for rapid advancements in innovation, aligning with the automotive industry's improvements in plug-in charging for personal EVs. The costs associated with installing a plug-in fast charger for a single bus can range between USD 123,750 and USD 303,300 [60].

Pantograph charging achieves automated contact between the bus and the charging infrastructure [61]. These chargers come in two variants. The first variant involves roof-mounted 'pantograph up' style connections, where the driver activates a switch inside the bus to raise the pantograph, initiating charging. The second type is the pole-mounted 'pantograph down' configuration. These operate conversely, establishing a connection to overhead poles, typically through Wi-Fi, and remotely triggering the pantograph to lower. Figure 7 illustrates both configurations and outlines the respective advantages of each.

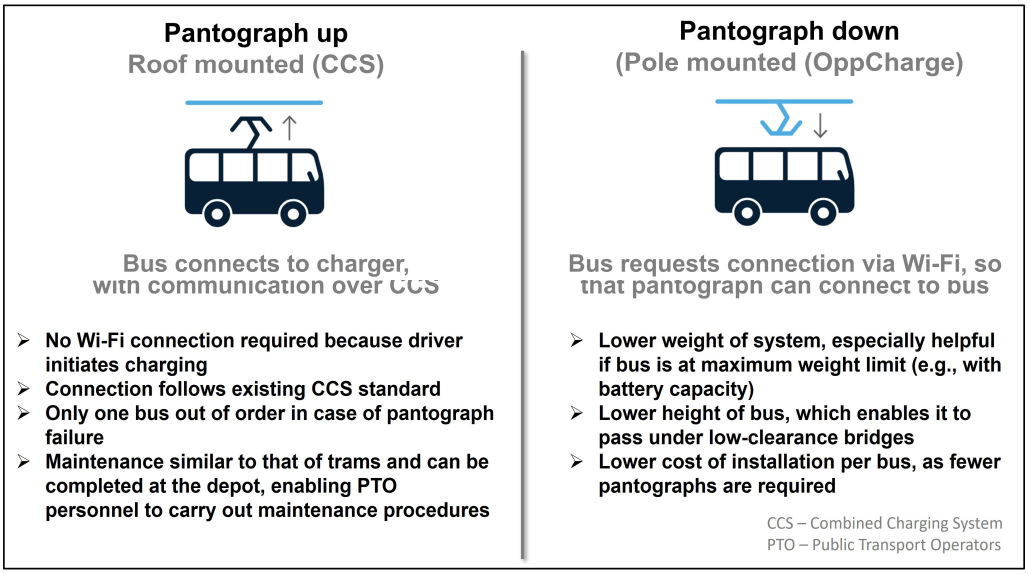

Figure 7. Figure illustrating the benefits of each pantograph system. Adapted from [62].

The advantage of employing a pantograph-style charger lies in its automated process, allowing charging contacts to be connected with a simple button press or even in an automated fashion. This renders pantograph chargers suitable for on-route charging or large-scale depot charging. Additionally, overhead cables strategically installed along routes enable trolleybus-like operation, facilitating extended range without service interruption [63]. Pantograph charging also offers faster charge times than plug-in charging, owing to its capacity for higher power transfer [64].

As discussed earlier, the cost of installing this charger type can vary significantly due to different implementation methods. Depot pantograph chargers, for instance, may range between USD 67,000 and USD 160,000 per charger, exclusive of installation costs [65]. On-route charger expenses vary due to land and permission costs associated with public land installation, estimated as high as USD 571,420 per bus [63]. However, these chargers can service multiple buses throughout the day. The primary advantage of pantograph chargers lies in their ability to swiftly and autonomously provide rapid charging.

Ground-based chargers function similarly to pantograph chargers, where a 'shoe' extends from beneath a bus to establish contact with a conductive device embedded in the road, transferring power to the batteries [66]. These systems enable even faster charging rates, with power outputs reaching 200 kW. Additionally, the overall system is more compact and less intrusive to foot traffic, as it eliminates the need for overhead poles and masts, allowing most infrastructure components to be concealed underground or integrated within bus stops. Moreover, ground-based charging systems are safer than overhead pantograph systems, as the exposed charging pads are entirely covered during the charging process.

Although ground-based chargers represent emerging technology, and practical pricing data are not available, their cost is assumed to align with pantograph charging to remain competitive in pricing.

Each charging method optimally serves specific scenarios. For instance, plug-in chargers suit slower overnight depot charging, ensuring battery longevity. Overhead pantograph-style chargers are ideal for charging while the vehicle is in motion and suitable for routes with infrequent stops. Ground-based charging suits placements at each stop, allowing fast charging to extend the battery range until the next stop.

A study by the Department of Civil and Environmental Engineering at Utah State University [67] outlines a potential charging strategy using a mathematical model for an ideal bus route layout. This strategy proposes the placement of 'Quasi-dynamic wireless chargers' at bus stops and traffic lights.

City planners and bus operators must meticulously assess all charging options and strategize effectively for a transition to an electrified bus network, maximizing the advantages of these systems. By doing so, they can reduce costs and enhance services beyond the current offerings.

4. Emissions Analysis

The key advantage of employing an electric drivetrain is the complete elimination of tailpipe pollutants. The shift to EVs aims to reduce harmful emissions, particularly in urban areas. However, it is noteworthy that these vehicles still contribute to greenhouse gas emissions, given that a substantial portion of global electricity generation relies on processes that emit greenhouse gases [68]. The most effective approach to reducing emissions associated with driving EVs involves completely decarbonizing the electric grid system. Projections indicate that the National Grid in the UK aims to achieve 'net zero' emissions by 2050 [69]. Therefore, an electrified transport network will become an indisputable solution regarding usage emissions in the long term.

In the short term, an anticipated reduction in the carbon intensity of electricity by more than 30% by 2030 is expected [70]. This anticipated improvement allows for the emissions of an electrified transport network to decrease without requiring modifications to the vehicles themselves, making them an ideal and consistent option for bus operators. This concept is evident in Figure 8, illustrating that 'fuel cycle' emissions can significantly vary depending on the country's electricity mix. Countries heavily reliant on nuclear power [71] and renewable energy [72] sources, like France or Norway, demonstrate minimal to no fuel cycle emissions [70]. By contrast, countries like Germany, which heavily utilize oil and gas in their electricity generation mix, showcase higher fuel cycle emissions [73].

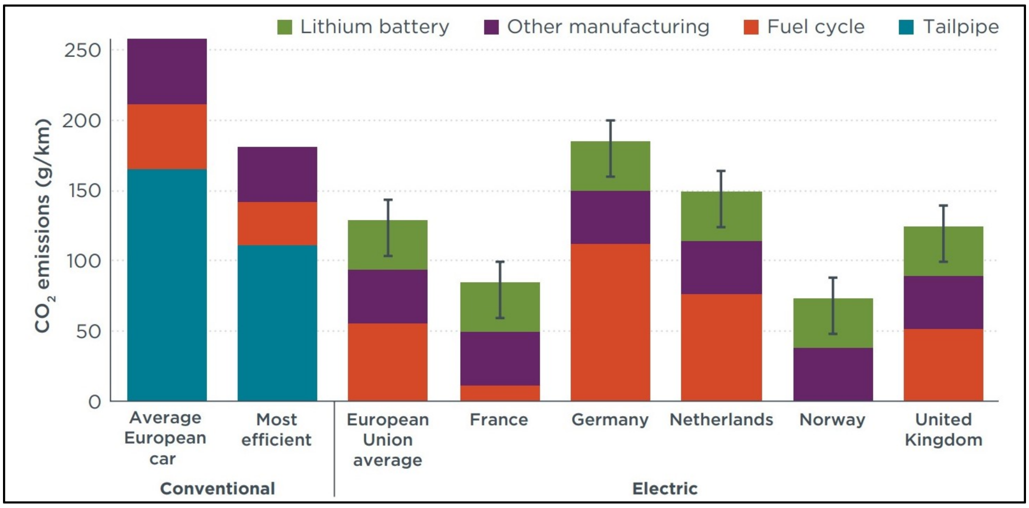

Figure 8. Life-cycle impact of vehicle activities. Reproduced with permission from [70].

Figure 8 exemplifies how electric grid systems must be decarbonized to maximize the benefits of an electrified transport network, including a fully electrified bus fleet.

An area that demands scrutiny involves the emissions linked to battery production and end-of-life disposal. One significant factor impacting these emissions is the manufacturing location. Several factors influence the CO_2 output, ranging from logistics transporting raw materials to implemented mining strategies. Specific reports indicate a potential increase of 'up to 74% more CO_2' in factories powered by fossil fuels [74]. Consequently, governments must rigorously scrutinize manufacturers before granting import and operational licenses if governments aim to curtail carbon emissions.

An area where an electric driveline surpasses an ICE driveline is in efficiency. The electric motor boasts an efficiency range of around 70–90%, contingent on the load [75]. In comparison, an equivalent ICE motor operates at an efficiency of roughly 20–25% [76]. However, when considering overall efficiency, which factors in electricity production sources, the efficiency may decrease to 13–31% [77]. This number can rise to 40–70% if renewable sources are utilized.

Nevertheless, Figure 9 depicts significantly lower CO_2 emissions from electric buses in the US, where the electricity mix resembles most Western nations. Immediate reductions in carbon emissions are feasible in cities such as Lahore and Delhi, which suffer from exceptional levels of air pollution [78]. This illustrates how the overall efficiency of an electric vehicle can outperform an equivalent fossil-fuel-powered vehicle.

According to a study by the University of Bangalore [79], each vehicle could save 25 tons of CO_2 emissions annually, assuming a daily travel distance of 170 km. These emissions can be further reduced with the adoption of renewable energy sources. Eliminating tailpipe emissions also eradicates NO_x emissions, a pollutant unique to internal combustion engines, particularly diesel engines, prevalent in most large vehicles today [80]. This reduction is vital in curbing the health risks associated with NO_x, especially in urban areas where these emissions pose significant health hazards, especially for vulnerable groups like children and older adults.

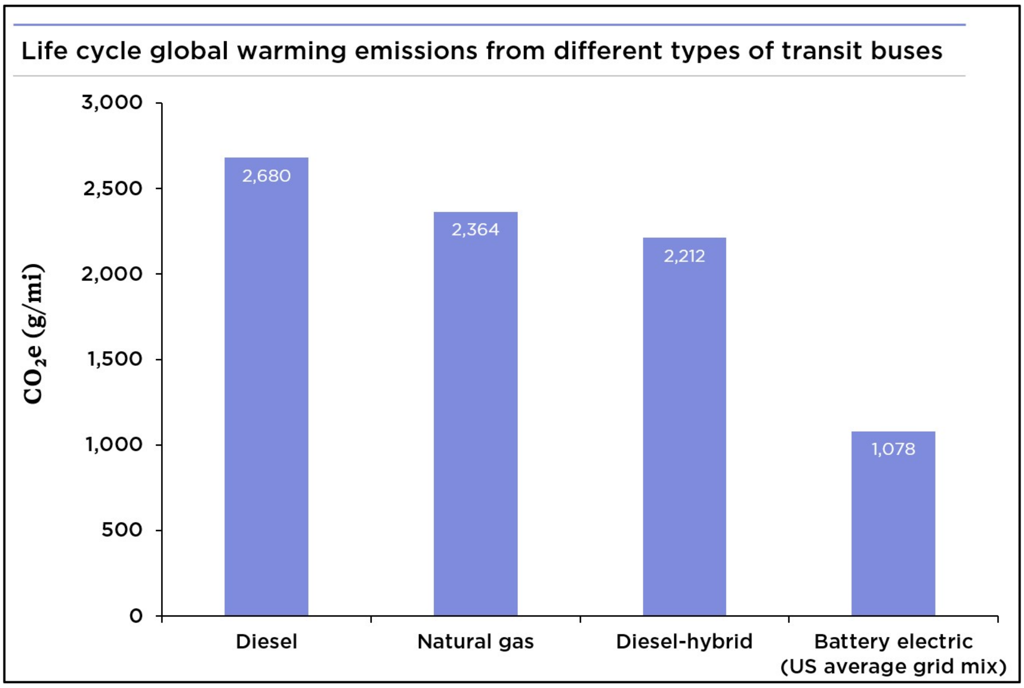

Figure 9. CO_2 emissions from buses. Reproduced with permission from [81].

In emissions analysis of battery electric vehicles, a crucial yet often overlooked aspect is end-of-life battery recycling emissions [82]. As mentioned, assessing these emissions becomes critical since electric buses require a new battery pack every six years. The prevailing methods used for recycling electric vehicle batteries include pyrometallurgy and hydrometallurgy [83].

Pyrometallurgy involves subjecting the entire battery to extreme temperatures of up to 1000 °C, generating alloys, matte, and slag, which can then be processed into usable elements. This process is predominately used to recycle and extract Cu, Co, and Ni [69]. While this method offers high process efficiency, good compatibility for the Kroll process, and continuous operation [70], it fails to recover lithium effectively, the primary element in EV batteries, resulting in wastage. Moreover, with battery manufacturers reducing cobalt usage, this method is gradually becoming obsolete [69].

Hydrometallurgy, utilizing various solvents to extract pure substances, can be environmentally friendly with high efficiency [84]. However, its drawbacks include high cost, substantial chemical consumption, poor working environments, and time consumption, rendering large-scale recycling impractical [85].

Recycling batteries post-degradation is pivotal for sustainability and emission reduction [86]. Yet, current methods are financially and ecologically impractical, rendering them unviable options for reducing overall emissions [87].

5. Performance Analysis

The Cardiff Council presently operates a fleet of 36 Yutong TCe12 buses [88]. A direct ICE competitor to this model is the Mercedes Citario. A comparative analysis between these two vehicles reveals the following figures.

Referring to Table 2, we observe both vehicles' power and torque specifications. While they exhibit similar power figures, the Yutong bus nearly doubles the torque of its counterpart. This higher torque allows for lower throttle settings, potentially increasing the range. Notably, there is substantial disparity in the maximum capacity between the two buses, with the diesel bus outperforming the electric bus by 50%.

Table 2. Comparison of the two typical buses used in the UK [89,90].

Feature	Mercedes	Yutong
Engine/Motor	Mercedes-Benz OM 936	Yutong Drive motor system YTM280-CV4-H
Transmission	Voith automatic transmission, 4-speed	N/A
Power [kW]	220	215 continuous, 350 peak
Torque [Nm]	1200	3200
Maximum Permissible Gross Vehicle Mass [kg]	19,000	18,000
Range [km]		300–350
CO_2 Emissions [g/km]	915	80
NO_x Emissions [g/km]	0.41	0
Maximum capacity	105	70

5.1. Passenger Comfort

An advantage of an electric powertrain is its near-instantaneous torque delivery at any wheel speed. It eliminates the need for a gearbox and ensures continuous power application when the throttle is engaged. This results in a smoother experience for passengers, avoiding the jolts associated with gear changes, which can contribute to travel sickness and related symptoms [91].

Another benefit of an electric drivetrain is noise reduction. Electric buses produce minimal to no noise when stationary, maintaining ambient noise levels [92]. They operate around 5 dB to 7 dB in motion, quieter than their fossil-fuel-powered counterparts [93]. This is particularly advantageous in cities where noise pollution concerns local governments [94].

Passenger polls consistently show a preference for electric buses over diesel or biogas-powered buses across various categories, including emissions and noise [95]. An intriguing statistic from the survey is that most passengers would recommend trying an electric bus to others, which could significantly support government initiatives to encourage greater public transport use. Furthermore, most drivers preferred the drivability of electric buses, with some even considering them superior to other bus types [95]. Driver complaints primarily revolved around bus software and easily rectifiable issues. Rear visibility concerns were also raised, though these appear specific to certain models rather than inherent drivetrain issues.

5.2. Range

The average distance urban transport buses cover daily is approximately 130 miles [30], but this can extend to 240 miles on specific routes. Therefore, an equivalent electric bus must offer a similar range capacity.

In South Wales, the current fleet of electric buses comprises the Yutong TCe12. The company quotes an official range of 300–350 km [90], yet customer experience in real-world conditions suggests a range closer to 140 miles, providing a potential distance of 180 miles [96]. This discrepancy requires further investigation and testing of the bus's Li-ion battery pack to validate these claims. It is evident that electric buses cannot cover all existing bus routes with current technology and require further enhancements to replace diesel buses entirely. Alternatively, as discussed earlier, substantial investment in charging infrastructure could enable bus operators to charge buses strategically at different intervals along their routes.

5.3. Alternative Battery Technologies

This paper primarily concentrates on Li-ion batteries, widely employed in the automotive industry. Despite this focus, various other battery materials have been developed and researched for potential use in electric vehicles, each possessing distinct characteristics that could be applied in an electric bus context.

Table 3 exhibits the distinct characteristics of several popular battery materials [97]. Lead acid batteries are known for their cost-effectiveness, simple manufacturing process, high overcharge tolerance, and discharge rates. However, they suffer from low energy density, limited deep discharge cycles, potential thermal runaway, and environmental damage due to their electrolyte media [98].

Table 3. Comparison of different battery materials [97].

Specification	Lead Acid	Nickel-Cadmium (NiCd)	Nickel-Metal Hydride (NiMH)	Li-Ion		
				$LiCoO_2$	$LiMn_2O_4$	$LiFePO_4$
Specific energy (Wh/kg)	30–50	45–80	60–120	150–250	100–150	90–120
Internal resistance	Very low	Very low	Low	Moderate	Low	Very low
Life cycles (80% DoD)	200–300	1000	300–500	500–1000	500–1000	500–1000
Overcharge tolerance	High	Moderate	Low	Low		
Self-discharge per month	5%	20%	30%	<5%		
Discharge temp. (°C)	−20 to 50	−20 to 65		−20 to 60		
Maintenance	3–6 months topping charge	Full discharge every 90 days		Maintenance free		
Safety	Thermally stable	Thermally stable, fuse protection		Protection circuit mandatory		
Toxicity	Very high	Very high	Low	Low		
Cost	Low	Moderate		High		

Nickel–cadmium (NiCd) batteries offer rapid charging, excellent low-temperature performance, and this group's lowest cost per cycle. Yet, they face drawbacks, including relatively low energy density and the 'memory effect' issue [99].

Nickel–metal hydride (NiMH) is often seen as an alternative to NiCd, offering 30–40% higher capacity and the potential for increased energy densities. However, its drawback lies in the low number of deep cycles, which limits its automotive application [100].

Experimental materials like Na-$NiCl_2$ batteries have shown superior theoretical performance compared to their Li-ion counterparts [101], reaching energy densities of up to 350 Wh/kg [102]. Nevertheless, safety concerns and potential battery degradation hinder their immediate implementation, necessitating further data for conclusive assessment.

However, due to their exceptional characteristics, Li-ion batteries have emerged as the optimal choice for electric buses. With high energy density ranging from 150–250 Wh/kg, they outperform lead acid, NiCd, and NiMH alternatives, providing more energy storage for extended travel ranges. Li-ion batteries exhibit low internal resistance, ensuring efficient energy conversion, and offer a longer cycle life of 500–1000 cycles, surpassing their counterparts. Nevertheless, these other emerging battery technologies showcase promising advancements, signaling possible alternatives to traditional Li-ion batteries.

5.4. Other Considerations

One advantage of maintaining a fossil-fuel-powered transport network is the government's capacity to access stored oil reserves, particularly during wartime if necessary. This serves to bolster a nation's transport system security when required.

However, should a complete transition from the current bus fleet to an all-electric battery fleet occur nationwide, substantial considerations concerning the power grid must be addressed. It will necessitate power regulation at the charger level and the integration of 3-phase fast charging connections into a high-voltage network. This demands collaboration with national grid organizations to facilitate seamless integration. Due to these infrastructural requirements, implementing electrification plans could pose significant challenges for local councils and governments.

6. Conclusions

6.1. Electric Bus Viability

The concept of an electric bus fleet is still in its early adoption phase, with a few local councils and private companies integrating them as an addition rather than a replacement to their existing fleets. A significant commitment from national governments is imperative for battery electric buses to become viable. This involves strategic investments of substantial public funds for infrastructure development and the transition process. Decisions need to be made regarding the type of infrastructure—whether it requires depot charging, on-route charging, or a combination of both. Investment in technology, both for infrastructure and buses, is crucial to drive innovation and widen the applicability of electric buses. Advancements in the field are necessary for mass adoption since a complete transition is not yet feasible with current technology.

Electric buses have the potential to curtail carbon emissions in major cities, even on a small scale, contributing to reducing the overall carbon footprint of a city's transport network. This reduction can foster further technological advancements in the electric bus domain.

6.2. Recommendations for Future Research

This research could be enhanced in several ways, including long-term testing of newly developed battery materials to broaden the paper's scope. Additionally, a comprehensive cost–benefit analysis of various charging infrastructures would provide more precise recommendations. Conducting an extensive, long-term study on the impact of rapid charging on the batteries used in the Yutong TCe12 would be instrumental for determining the real-world longevity of the drivetrain. Furthermore, this study did not analyze alternative fuels for internal combustion; therefore, a meta-analysis of alternative fossil fuels and their implications for the public transport system would be highly beneficial.

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