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Impact of Different Charging Methods on Electric Bus Battery Size and Grid Demand

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Abstract

This paper presents an agent-based model (ABM) that estimates battery size and electricity grid demand for bus charging infrastructure. The ABM considers four charging methods: overnight charging (ONC), end-line charging (ELC), occasionally fast charging (OFC), and wireless charging (WLC). The model accurately captures the energy consumption and charge load of battery electric buses (BEBs) by incorporating GPS coordinates, average speed, and temperature profiles. A case study is conducted on a bus route in Cardiff, UK, to showcase the functionality of the ABM. The results of simulations demonstrate significant reductions in electric bus battery sizes for different charging methods. For example, end-line charging reduces battery size by 235 kWh per bus compared to overnight charging. Occasionally fast charging and wireless charging achieve even lower capacities of 86 kWh and 69 kWh, respectively, however, these charging methods lead to higher and more fluctuating grid loads, resulting in a poor load factor. In summary, this ABM provides a practical tool for infrastructure planners. The case study illustrates its effectiveness in optimizing battery size and evaluating grid demand for BEB charging infrastructure. The findings provide critical directions for both bus operator shifting towards electrification of their fleets and city planners responsible for the deployment of related charging infrastructure.

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Keywords: Battery electric buses; battery capacity; multi-agent modelling, battery charging

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1. Introduction

To achieve decarbonisation of the transport sector, a structural change from private to public transport is necessary. In 2019, buses were responsible for 3.1 MtCO2e emissions in the UK (Department for Transport, 2021). To reduce these emissions, various climate-neutral drive systems for buses have been proposed, such as buses powered by hydrogen or biofuels (Miles & Potter, 2014). However, these two technologies cannot be implemented on a large scale in the foreseeable future for example due to a lack of hydrogen charging stations and low efficiency of hydrogen generation (Kolodziejski et al., 2022; Li & Taghizadeh-Hesary, 2022). As a result, BEBs are currently the most promising solution towards transport decarbonisation. Yet, three main challenges remain:

- The range of BEBs is dependent on battery capacity with current market-available chemistries having smaller available range than fossil fuelled busses (Basma et al., 2021).
- The upfront capital expenditure (CapEx) of purchasing BEB's is higher than for conventional buses due to the price and size of the batteries (Rodrigues & Seixas, 2022).
- The transition to BEBs requires significant investment in upgrading the charging and grid infrastructure (Basma et al., 2021).

A potential solution to address these issues would be to utilize different charging methods (e.g. occasional wireless or fast, end-of-line, overnight) in order to reduce battery size and manage network demand (Basma et al., 2021). However, before bus operators decide regarding the adoption of one of the charging methods, a technical comparison is necessary. Therefore, in this paper, an ABM which was developed in AnyLogic is proposed that processes travel and weather data and simulates energy consumption and battery demands for four different charging methods: end-line charging, overnight charging, occasionally fast charging, and stationary wireless charging. It further computes the net load curves and allows conclusions to be drawn about the optimal charging method for specific circumstances. Consequently, this ABM provides a comprehensive tool for urban planners to find the best charging methods regarding the local conditions.

To the best of the authors' knowledge, this is the first ABM that evaluates geographic data of buses at given times, then projects them onto different charging methods, and as a result calculates the required battery size and the network load.

2. Charging Methods

There are mainly four charging methods proposed in the literature: overnight charging, end-line charging, occasionally fast charging, and wireless charging (Basma, Mansour, et al., 2022; He et al., 2019). Overnight charging represents the most common charging method for BEBs (Rogge et al., 2018). Central charging stations are installed to charge electric buses during the night (Borlaug et al., 2021; Rogge et al., 2018). The battery must be fully charged until the next morning to ensure uninterrupted service throughout the day (Basma, Mansour, et al., 2022). This approach is favoured by many bus operators, as it allows the charging process to be carried out on company grounds and therefore installation is rather simple (Basma et al., 2021). Typical charging stations for overnight charging provide a power output of 60 kW and are thus capable of fully charging large batteries overnight (He et al., 2019; Houbbadi et al., 2019).

End-line charging functions are similarly to overnight charging, with charging taking place at the terminal station. However, the charging process is initiated also at the end of each trip, not just at night (Basma, Haddad, et al., 2022). The bus charges at the terminal station until it is scheduled to operate again (Basma, Mansour, et al., 2022). For instance, if a bus travels along a certain route four times, it can be fully charged between each cycle, thus significantly reducing battery capacity requirements and capital costs (Basma, Haddad, et al., 2022; Basma, Mansour, et al., 2022; Houbbadi et al., 2019).

Occasionally fast charging and wireless charging distinguish themselves from the aforementioned charging methods by featuring charging stations installed along the route. Due to their high charging rates, fewer charging stations and shorter charging times are required for occasionally fast charging (He et al., 2019; Joos et al., 2010). The position and number of charging stations can be adjusted to the circumstances, i.e., overall length of the route and climatic conditions. Charging stations with power outputs between 120 kW and 360 kW are recommended for occasionally fast charging (He et al., 2019; Joos et al., 2010). However, ultra-fast and rapid chargers with power outputs that exceed this range are being developed (Dik et al., 2022).

Wireless charging is unique in its ability to automatically start and stop the charging process without the need for manual intervention. There are two types of wireless charging: dynamic and static. In dynamic charging, the bus charges on the move, whereas in static charging, charging coils are only installed at bus stops.

Efficiency losses between the charger and the power grid are an inherent issue in electric vehicle charging, independent of the charging method employed (Al-Ogaili et al., 2021; Gautam et al., 2012). Wireless chargers, in particular, exhibit significantly lower efficiencies of approximately 73% (Yin et al., 2022), in comparison to cable-bound charging stations, which boast much higher efficiencies of around 93% (Gautam et al., 2012).

3. Model Design

The main objective of the developed ABM is to determine the ideal battery size for electric buses by considering different charging methods and assessing their impact on the power grid. The added value of this analysis is that it takes into account individual bus schedules and environmental conditions.

The BEB charging methods were implemented in the AnyLogic programming environment. The reason for using AnyLogic is that it is an established platform for transport and logistics simulations. AnyLogic provides a geographic information system (GIS) map feature in which the movement of 'agents' (buses) can be implemented. Additionally, AnyLogic is a multi-method modelling software including both 'discrete event' and 'system dynamics' modelling tools.

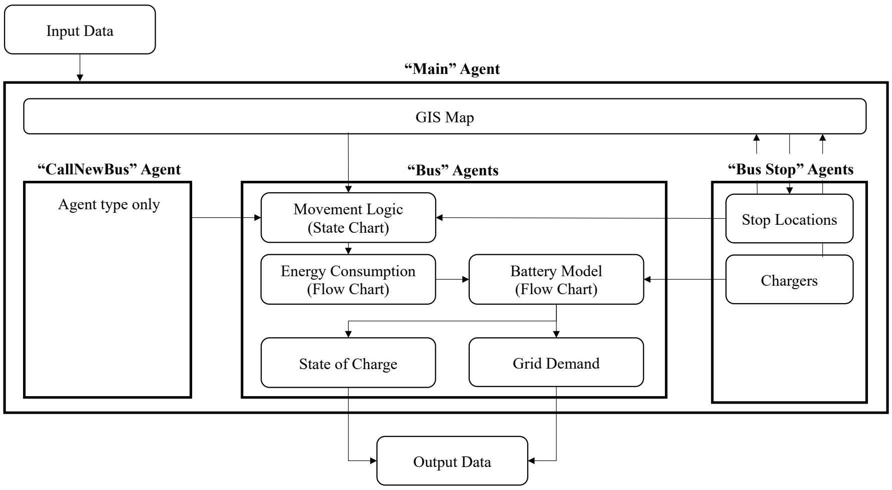

Fig. 1 Structure of the AnyLogic model including four agents that interact with each other.

Furthermore, by designing an agent type, the simulation can be implemented for a whole fleet of buses. Thus, the model is scalable and can be adopted to a variety of bus lines in different environments, with varying operational and environmental conditions.

The structure of the developed ABM is illustrated in Figure 1. 'Bus stop' agents are positioned on the GIS map using input files containing GPS coordinates of the bus stops. These stops serve as destinations for the buses, influencing their direction of movement. The 'bus agents' constitute the most important component of the model, as they simulate the BEB movement and energy consumption at the current average speed and ambient temperatures. At the outset, a population of 'bus agents' is implemented at the terminal station for each charging method. The bus agents of the different populations drive the route simultaneously but exhibit distinct charging behaviors. For example, for overnight charging, a population of agents is implemented that only charges during the night, whereas for end-line charging, the corresponding bus agent population charges at the end of the route. The buses' movement is defined as a state chart diagram and is controlled by approaching the next bus stop agent. Upon reaching a 'bus stop' agent, a 'bus agent' halts for 60 seconds before resuming its journey. The bus speed is calculated as an average value based on the distance between two stops and the duration of the journey, which varies depending on the time of day and the day of week. The data required to calculate the average speed between two stops is extracted from the input file. The bus battery is represented by a ‘flow chart’ diagram, which includes a charging current, a storage tank representing the bus battery, and a discharging current. The charging currents are determined by the charging method outlined in Table 1. The discharging currents are based on a separate flow chart that model energy consumption, considering the current temperature and speed, following a model proposed by Basma et al. (2020).

Table 1. Specifications of different charging methods for BEB service.

Charging Method	ELC	WLC	OFC	ONC
Charger Type	Cable-bound	Wireless/ Cable-bound	Cable-bound	Cable-bound
Location	At the terminal station	Wireless chargers at every bus stop Cable-bound chargers at terminal station	At five defined stations, equally distanced and at the terminal station	At the depot
Charging Time	Day	Day	Day	Night
Charging Duration	Terminal station: until bus departs	Terminal station: until bus departs Charger (stop): 1 min	Terminal station: until bus departs Charger (stop): 2 min	Depot: until bus departs
Charging Power	60 kW	Terminal station: 60 kW Stops: 25 kW	Terminal station: 60 kW Stops: 120 kW	60 kW
Charger Efficiency	93%	Terminal station: 93% Stops: 73%	93%	93%

The ABM assumes a simplified linear charging curve. This simplification is justified by considering that the subsequent battery re-dimensioning process assumes charging up to a maximum state of charge (SOC) of 80%. Only above an SOC of 80% the charging curve deviate significantly from a straight line (Basma et al., 2021; He et al., 2019; Mohamed et al., 2017).

Bus coordinates are frequently synchronized with the terminal station. If they match, the bus waits until it receives a signal indicating its scheduled departure. At that point, a non-visual agent called ‘CallNewBus’ is created by the ‘main agent’, solely facilitating communication between the main agent and the bus agents.

The model generates output including the current battery capacity, total energy consumption, and the grid load profile. The simulation steps are limited to minute-level temporal resolution.

4. Case Study Cardiff City

To demonstrate the functionality of the ABM, a case study was conducted for Bus Line 1 in Cardiff, known as the City Circle Line. This bus line consists of a total of 17 main stops, spanning approximately 27 km, with an average travel time of 1 hour and 53 minutes per route. The service operates six days a week. Departure times of the buses and GPS coordinates of the bus stops are provided by Cardiff Bus.

In the AnyLogic ABM, it is assumed that the service is carried out by three buses, each equipped with a battery capacity of 350 kWh. Additionally, weather temperature data for year 2021 in Cardiff is used as an input obtained from WeatherSpark and the average temperature values are used for each thirty-minute interval.

The ABM generates the level of charge and charge flow into each bus agents’ battery as output parameters at one-minute intervals.

5. Results and Discussion

This section presents the analysis of energy levels in the battery model of the bus agent and the corresponding grid demand. First, the energy consumption per discharge cycle is assessed and different battery sizes based on the energy consumption are proposed. Subsequently, the impact of extreme weather events on battery sizing is examined. Finally, an assessment of the grid demand is carried out and the relevant load factors are computed.

5.1. Energy Consumption

The primary factor in battery re-dimensioning is the energy consumption or the utilized capacity interval of the battery. In this study, the required capacity $C^{m}_{req,i}$ is defined as the difference in kilowatt-hours between the fully charged battery $C^{m}_{max,i}$ and the minimum charge level of the battery $C^{m}_{min,i}$ (Eq. 1). The index $m \in \{ELC, ONC, WLC, OFC\}$ refers to the charging method, while the index i corresponds to the discharge cycle, which signifies the time interval between two fully charged states.

$$C^{m}_{req,i} = C^{m}_{max,i} - C^{m}_{min,i} \tag{1}$$

Figure 2 illustrates the fluctuation in required capacity per discharge cycles for a period of 365 days. Notably, $C^{ONC}_{req,i}$ demonstrates the highest values, ranging from 180 kWh to 250 kWh. In contrast, the consumed capacity per discharge cycle for occasionally fast charging reaches a maximum of 53 kWh and frequently drops below 30 kWh. While both $C^{WLC}_{req,i}$ and $C^{ELC}_{req,i}$ surpass $C^{OFC}_{req,i}$, they remain considerably lower than $C^{ONC}_{req,i}$.

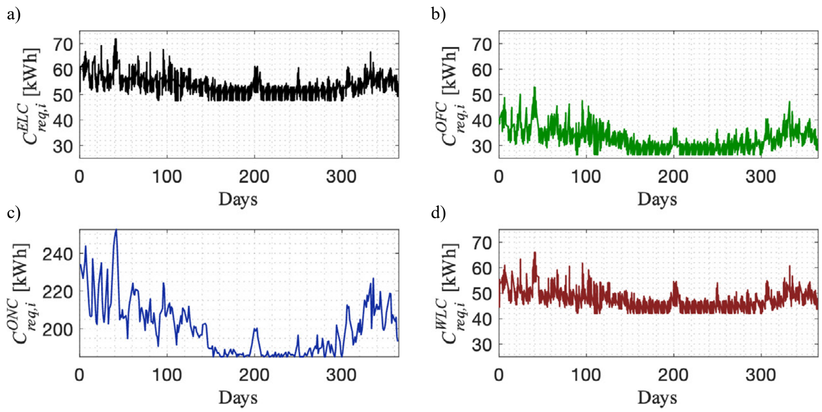

Fig. 2 Required capacity per discharge cycle for a) end-line, b) occasionally fast, c) overnight and d) wireless charging.

The graph reveals significant variations in energy demand throughout the year, with peak requirements occurring during winter and the lowest levels observed in summer. This pattern is primarily attributed to the increased heating demand during winter and the relatively moderate temperatures with reduced heating, ventilation, and air conditioning (HVAC) consumption during summer.

The subsequent analysis focuses on determining the battery dimensioning based on the maximum $C^{m}_{req,i}$ and explores the influence of rare energy-intensive events on battery size. This investigation allows for a reflection on potential battery over-dimensioning and the optimization of battery capacity accordingly.

5.2. Battery Dimensioning

Ensuring safe operation and maximizing battery life are critical factors in the design of BEBs. Full charging of BEB batteries generates heat and can pose safety risks (Leising et al., 2001), while complete discharging leads to battery degradation and reduces the overall service life (Doerffel & Sharkh, 2006). Thus, it is recommended to maintain the SOC of BEB batteries between 10% and 80% (Basma, Mansour, et al., 2022). To comply with this recommendation, the battery capacity should be at least 30% larger than the operating capacity range of the battery. In this study, the operational capacity range, denoted as $C_{req,max}^{m}$, is defined as the maximum difference in kWh between the battery charge levels. Based on this, the battery capacity $C_{Battery}^{m}$ of BEBs is dimensioned as follows:

$$C_{Battery}^{m} = C_{req,max}^{m} \cdot (1 + 0.3) \tag{2}$$

Table 2 provides an overview of the battery sizes of the BEBs for the different charging methods, which were calculated using Equation 2 and $C_{req,max}^{m}$, obtained from Figure 2.

Table 2. Maximum required capacity and battery capacity for four different charging methods.

Charging Method	ELC	ONC	WLC	OFC
$\boldsymbol{C_{req,max}}$ **(kWh)**	71.90	252.51	65.99	52.99
$\boldsymbol{C_{Battery}}$ **(kWh)**	93.47	328.26	85.78	68.89

Overall, overnight charging exhibits the largest required battery capacity by a significant margin, reaching 328.26kWh, which is 145 kWh greater than for end-line charging. In comparison, wireless charging and occasionally fast charging demonstrate the lowest required capacities, with 85.78 kWh and 68.89 kWh, respectively.

5.3. Impact of extreme ambient temperatures

From the results of Figure 2, the highest peaks in energy demand deviate significantly from the average capacity required per discharge cycle. To provide an overview of the effectiveness of battery sizing based on maximum energy consumption, Figure 3 presents a quantitative representation of the relationship between the coverage of cycles and the corresponding battery capacity. The red lines in Figure 3 indicate the capacities required to cover 95% and 100% of the discharge cycles.

From Figure 3, the curve diagram demonstrates a significant flattening trend at higher battery capacities. This indicates that as the capacity per kilowatt-hour (kWh) increases, the additional number of trips that can be covered diminishes. This phenomenon is primarily attributed to infrequent but energy-intensive trips that occur during cold temperatures, resulting in a higher energy consumption by HVAC system.

To specifically address the most energy-intensive 5% of trips, an average of 16% more battery capacity is required compared to the capacity needed to cover 95% of trips.

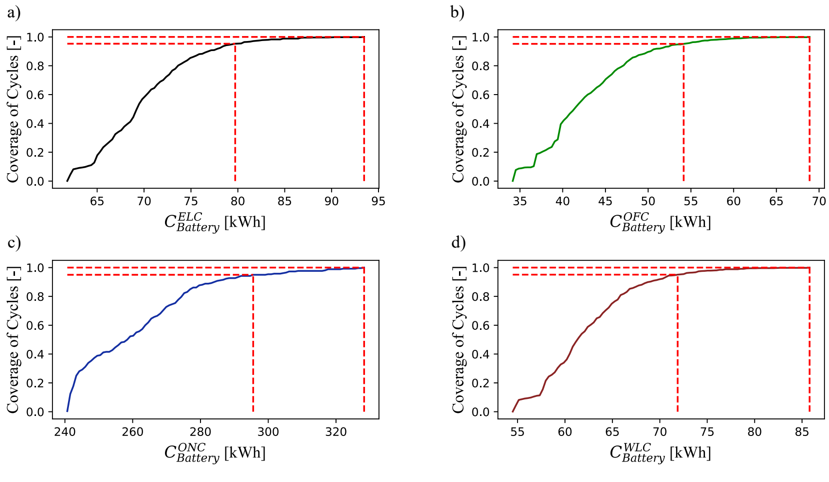

Fig. 3 Proportion of trips covered by each battery capacity for a) end-line, b) occasionally fast, c) overnight and d) wireless charging.

5.4. Grid Demand

Figure 4 presents the electric power requirements from the grid for charging the bus fleet of the Cardiff 'City Circle Line' bus route. The data was derived by summing the charging currents into the batteries, considering the transmission losses between the grid and the battery electric buses (BEBs).

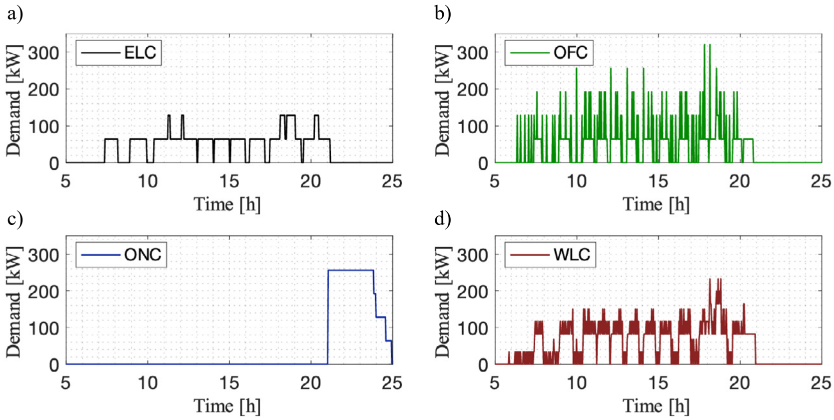

Fig. 4 Grid demand for a) end-line, b) occasionally fast, c) overnight and d) wireless charging.

Wireless charging, end-line charging, and occasionally fast charging exhibit a similar grid load curve structure, while overnight charging deviates significantly from this pattern. Among the three methods, loads vary to different extents throughout the day. End-line charging demonstrates a relatively consistent load profile, while occasionally fast charging experiences the highest fluctuations, with load peaks exceeding 300 kW for the four considered buses. In contrast, overnight charging follows an inverse pattern, with no bus charging during the day but instead scheduled for night-time charging. Nevertheless, overnight charging still exhibits a high peak load exceeding 250 kW. To further quantify the results, the load factor for each charging method will be assessed in the next section.

5.5. Load Factor

To assess the load on the grid, the load factor is introduced, which classifies the homogeneity of a network load. It is defined as the ratio of the average charging demand to the maximum load within a defined period of time (Dahl & Nygaard, 1966). The load factor can also be understood as a metric for the utilisation of the charging station's power transformer and the efficiency of electrical energy use (Mohamed et al., 2017).

Table 3 illustrates the load factors associated with different charging methods. End-line charging stands out with the highest load factor, indicating a close alignment between the average grid load and the maximum load. This suggests that end-line charging maintains a relatively stable power profile throughout the day, minimizing deviations in power demand. Wireless charging exhibits the second highest load factor, reaching 0.22. This implies a relatively consistent power distribution, although not as pronounced as end-line charging. On the other hand, overnight charging, and occasionally fast charging exhibit low load factors, indicating periods of high demand and low utilisation rate.

Table 3. Load factors for four different charging methods.

Charging Method	ELC	WLC	ONC	OFC
Load Factor	0.32	0.22	0.16	0.13

6. Conclusion and Outlook

This research paper introduced an ABM implemented in AnyLogic to evaluate different charging methods for BEBs in terms of battery size and grid load. The ABM considers driving patterns as well as temperature profiles and provides a practical tool for infrastructure planners and bus operators. The ABM was applied to a case study on 'Bus Line 1' (the 'City Circle Line') in Cardiff. The case study revealed that the current battery sizes used in electric buses might be larger than necessary, thus presenting an opportunity for cost and material savings through optimized charging methods.

Among the analysed charging methods for the City Circle Line, overnight charging resulted in the largest battery capacities. However, overnight charging has the advantage of not requiring charging during peak hours reducing the impact on the power grid. End-line charging emerged as a favourable option, demonstrating the highest load factor and the potential to mitigate the impact on the grid. Occasionally fast charging exhibited the smallest battery sizes but displayed a low load factor, leading to uneven pulsating grid loads. Wireless charging, while slightly increasing battery capacities compared to occasionally fast charging, also presented lower load factors.

A notable finding from the case study is that all charging methods faced challenges from rare weather events significantly affecting battery size requirements. Approximately 16% battery oversizing was necessary to meet energy needs for the most energy-intensive 5% of the trips. However, occasionally fast charging and wireless charging show potential in mitigating these challenges by relying on extended charging durations rather than larger battery capacities, making them more resilient to extreme temperatures.

The ABM proposed in this paper and the results of the case study serve as a basis for future research, in particular for investigating the economic impact of different charging methods. The up-front costs in this context encompass the investments in charging infrastructure and buses, considering their battery sizes. Meanwhile, the operating costs are significantly influenced by the dynamic grid load profiles and the resulting demand charges.

Nevertheless, it is essential to acknowledge limitations within the model. The ABM relies on well-justified theoretical data, namely departure times derived from Cardiff Bus schedules as well as energy consumption models from former research works. However, this approach falls short in considering potential deviations in travel times that may arise during actual bus operations, which can differ from the planned schedules. Additionally, the model assumes fixed destination times and a constant passenger volume, constraining its ability to fully capture the complexity and dynamics of real-world discharge patterns. To address these limitations and enhance the ABM's accuracy in capturing real-world intricacies, it is recommended to gather data on bus driving patterns and passenger volumes for the modelled region. By seamlessly integrating such data into the model, it can be adeptly tailored to the prevailing traffic conditions. Moreover, conducting a comparative analysis between the modelling results and the actual collected consumption data can offer valuable insights and potential refinements for the model's further development.

In conclusion, the ABM presented in this research paper serves as a valuable tool for bus companies, enabling them to estimate the appropriate battery size for each bus line and assess the corresponding impact on the power grid, a factor of interest for Distribution Network Operators. The case study conducted on 'Bus Line 1' in Cardiff showcases the advantages of specific charging methods while effectively addressing the challenges associated with rare weather events. Overall, this research contributes significantly to the field of sustainable transportation planning by facilitating the efficient utilization of battery electric buses.

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