EVALUATION OF DIFFERENT ENERGY STORAGE SYSTEMS FOR ELECTRIC BUS OPERATION

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ABSTRACT

Operational trials of battery electric buses (BEBs) have begun on different scales around the world, and lithium-ion (Li-ion) batteries are usually selected as their power source. In this study, different Li-ion-based energy storage systems were evaluated for electric bus operation. Technical visits were conducted to study the features and performance of BEBs in different cities. Lithium iron phosphate (LFP), lithium nickel manganese cobalt oxide (NMC), and lithium titanate (LTO) were found to be the most common types of Li-ion batteries adopted for BEBs. The characteristics of these three types of Li-ion batteries are reviewed together with their charging and operation modes. LFP was found to have the highest energy consumption, and LTO had the lowest. The evaluation results show that LTO with the opportunity charging mode is the best choice of energy storage systems for BEBs, particularly in densely populated Asian cities.

Keywords: Electric bus, energy storage system, lithium-ion battery

1. INTRODUCTION

Global greenhouse gas (GHG) emissions by road transport accounted for 75% of the total GHG emissions from transport in 2014, and road transport was the major source of air pollutants in urban cities (IEA, 2016). To enable sustainable and low GHG development as outlined in the Paris Agreement, electrification of public transit is a possible measure. Policies, such as tax exemption and initiative, have been announced by governments all over the world to promote the use of electric vehicles (EVs). Compared to the booming market of private EVs, the number of electric buses (e-buses) in commercial operation is increasing much more slowly.

A bus service is characterized by long working hours, high mileage, and heavy loads; therefore, the vehicles' power source must be reliable in terms of power and capacity. The electrification of buses must overcome certain technological barriers to promote the use of e-buses. Various e-buses with different power sources, including lithium-ion (Li-ion) batteries and supercapacitors, have been developed to study the feasibility of e-buses in real-life operations.

In recent years, the operational trials of Li-ion battery electric buses (BEBs) have begun on different scales around the world. Li-ion batteries are defined by their characteristics of high specific energy, high efficiency, and long life (Burke and Miller, 2011; Scrosati and Garche, 2010), which make Li-ion batteries a distinguished option as an energy storage system for BEBs. The market share of Li-ion batteries in the e-bus sector has grown substantially because they have enormous potential to fully satisfy the requirement of energy storage for the commercial operation of BEBs.

Many major cities, particularly in mainland China and Europe, are considering the electrification of public transport by road. In fact, since 2011, China has aggressively worked on a very strong support program to encourage the use and manufacture of e-buses and e-minibuses. Major cities such as Beijing, Shanghai, Guangzhou, and Shenzhen have fixed schedules to phase out all conventional buses within the next decade. India has a program titled Faster Adoption and Manufacturing of Hybrid and Electric Vehicles (FAME). South Korea and Japan have launched e-bus trial programs. The European community launched the Zero Emission Urban Bus System (ZeEUS) program. Many European countries, including the UK, Germany, Belgium, France, and Switzerland, have initiated their own e-bus programs. Some programs, particularly those in London and Shenzhen, have been more successful than the others because of the very strong financial, technical, and institutional support they have received from governments and relevant stakeholders.

In this study, technical visits to major cities in China and Europe were conducted to evaluate the energy storage systems and the corresponding operation modes of BEBs. An energy storage system on a BEB is considered to be a combination of the energy storage material, the charging mode, and the corresponding components, such as safety precautions. Lithium iron phosphate (LFP), lithium nickel manganese cobalt (NMC), and lithium titanate (LTO) are the most common types of Li-ion–based energy storage systems adopted for BEBs. These three types of Li-ion batteries have different properties, and different charging modes in terms of the power level are required to suit these properties. In this study, we aim to evaluate different Li-ion-based energy storage systems of BEBs in real-life operations. The performance of each energy storage system is presented and evaluated on the basis of the practical experience gathered from the technical visits.

The rest of the paper is organized as follows. The characteristics of the Li-ion batteries and charging modes are presented in Section 2. The operation modes for BEBs are discussed and evaluated in Section 3. Section 4 reviews the experience of the implementation of an e-bus program in China and Europe. Finally, conclusions are presented along with recommendations for further study in Section 5.

2. LI-ION BATTERY AND CHARGING MODE FOR BEBS

2.1 Li-Ion Battery

Various Li-ion batteries are commercially available for the energy storage for BEBs. The selection of the appropriate type and size of battery is important to ensure that BEBs deliver their best performance along the service routes. The prevailing battery types and characteristics are summarized in Table 1 (Buchmann, 2017). This information is compiled from the manufacturers' specifications and independent test laboratories as well as crowdsourcing from Battery University (http://batteryuniversity.com/); it was updated with the information obtained from operators and manufacturers during the technical visits conducted as part of this study.

Table 1. Characteristics of Three Li-Ion Batteries

Battery	**LFP**	**NMC**	**LTO**
Specific Energy (Capacity)	90–120 Wh/kg	150–220 Wh/kg	70–80 Wh/kg
Typical C-rate	1C	0.7–4C* Charge current above 1C may shorten battery life	1C typical; 6C* maximum
Cycle Life	1,000–2,000 (related to depth of discharge and temperature)	1000–10,000* (related to depth of discharge and temperature)	5,000*–20,000*
Thermal Runaway	270°C; very safe battery even when fully charged	210°C typical; high charge may promote thermal runaway	Safest Li-ion battery

*This information was updated with the results from the technical visits.

LTO and LFP are the safest batteries with minimum thermal runaway. Charging at the acceptable current and voltage can prevent thermal runaway and maintain cycle life. LTO has the least specific energy and the highest cycle use but is the most expensive type of battery. LFP is the most popular because of its low cost, and its specific energy is approximately 50% higher than that of LTO; however, its cycle use is considerably less. The cycle use of NMC is a few times longer than that of LFP but still shorter than that of LTO.

2.2 Energy Consumption of Li-Ion Battery in Real-Life Operations

The average energy consumption in terms of kilowatt-hour per kilometer (kWh/km) of the three common types of Li-ion batteries is listed in Table 2. The measurement unit reflects the energy consumed per unit distance by BEBs.

These energy consumption data have been collected from various commercially operating BEBs in different operating environments in China and Europe. The average energy consumption of the LFP, NMC, and LTO BEBs is 1.37, 1.2, and 1.1 kWh/km, respectively. The average battery capacity of the LFP, NMC, and LTO BEBs is 322.4, 124.5, and 70.2 kWh, respectively. Among the three types of Li-ion-based energy systems, the LFP BEBs have the highest average energy consumption and battery capacity, whereas the LTO BEBs have the lowest values.

Table 2. Average Energy Consumption of the LFP, NMC, and LTO BEBs

Battery Type	Average Energy Consumption (kWh/km)	Average Battery Capacity (kWh)	Recharging Time (min)
LFP	1.37	322.4	30–480
NMC	1.2	124.5	10–60
LTO	1.1	70.2	8–15

The significantly higher battery capacity of the LFP BEBs indicates that a certain amount of energy is consumed to bear the weight of the battery packs during movement. This higher battery capacity results in higher energy consumption per unit distance. An extra precaution is commonly used for NMC BEBs. The NMC battery packs are often immersed in thermic fluid oil to prevent thermal runaway, which leads to additional weight on the NMC BEBs. A balance of battery capacity and extra precautions must be considered in BEB design to achieve the best energy consumption per unit distance. LTO BEBs have the lowest battery capacity. The relatively low weight of the LTO BEBs provides the advantage of relatively low energy consumption per unit distance.

The recharging time of the LFP BEBs, shown in Table 2, is significantly longer than those of the NMC and LTO BEBs. The recharging time basically depends on the charging C-rates of batteries, but it can be influenced by the charging power. Higher charging power leads to shorter recharging time. The recharging time of the LFP ranges from 30 to 480 min in a real-world operation, that of the NMC ranges from 10 to 60 min, and that of the LTO ranges from 8 to 15 min. Note that the charging power is not constant during the entire recharging process. The charging power is set to gradually decrease from the last 30% of the total battery capacity to maintain the battery life cycle. The recharging time of the LTO is significantly shorter than that of the other two battery types and is comparable to the refueling time of traditional buses.

2.3 Charging Mode

There are three major charging modes: ultrafast, fast, and slow charging. The charging rate of the ultrafast, fast, and slow charging mode is more than 6C, 1C, and less than 0.5C, resulting in a charging time of 10 to 15 min, 0.5 to 2 h, and 4 to 8 h, respectively. This difference in C-rate is caused by the battery characteristics and the charging power input. These charging modes are usually selected on the basis of operational needs.

With these characteristics, one ultrafast charging point can serve many buses, whereas one slow charging point may serve only one bus. However, a major disadvantage of ultrafast charging is that the battery requires more frequent charging in the daytime, which may affect the power supply, particularly during peak hours in a city. The slow charging battery will place a relatively heavy weight on the bus and thus reduce its energy efficiency per passenger carried.

3. OPERATION MODE FOR BEBS

The differences in properties between the energy storage systems characterize unique operation modes for BEBs. The two main BEB operation modes are overnight charging and opportunity charging. Overnight charging implies that BEBs are only recharged during “out of service” time, and opportunity charging means that BEBs are recharged during service time whenever possible. As shown in Table 1, LFP has the lowest charging C-rate among the three types of Li-ion batteries. A higher battery capacity is thus required for an LFP BEB to achieve a reasonable driving distance. The high specific energy and minimum thermal runaway of LFP result in a practical possibility of higher battery capacity. These properties favor the use of the overnight charging mode for LFP BEBs. The charging C-rates of NMC and LTO are higher than the charging C-rate of LFP, which implies that the charging time of NMC and LTO can be considerably shorter than that of LFP. Therefore, the opportunity charging mode is favored for them. The specific energy of NMC is the highest; this finding indicates the potential of achieving higher battery capacity for NMC BEBs. However, thermal runaway is a definite problem of NMC. It limits the number of battery cells that can be installed in a BEB because of the requirement of the additional safety precautions. The lowest specific energy of LTO indicates that LTO BEBs with a high battery capacity are not energy efficient. This implies that high battery capacity is not necessary for LTO BEBs.

The two operation modes are suitable for various needs. Opportunity charging provides more flexibility in bus management, whereas overnight charging favors long-distance bus routes with a stable schedule. A high-power charger for ultrafast charging, similar to that at conventional gas stations, can serve many BEBs, whereas a low-power charger for slow charging can only serve one BEB during overnight charging. We found from the technical visits that each high-power charger at an ultrafast charging station can serve 6 to 10 BEBs. The utilization rate of a charger in the opportunity charging mode is considerably higher than that in the overnight charging mode.

The capital costs of the two modes are different in terms of space and the cost of the charger. The cost of an ultrafast charging point is higher than that of a slow charging point. However, the number of ultrafast charging points that need to be installed is considerably smaller than the number of slow charging points. The cost and availability of space is crucial in e-bus implementation.

The features of the opportunity charging mode are more suitable for the downtown areas of a city. Further, the flexibility of bus management in the case of the opportunity charging mode is high for a reasonable coverage of the ultrafast charging station. The space required for charger installation is relatively less than that required in the overnight charging mode, which is a crucial factor particularly in densely populated Asian cities.

4. EXPERIENCE IN CHINA AND EUROPE

Table 3 shows the information of BEBs and their corresponding charging facilities in some major cities of China and Europe. All the three common types of Li-ion-based energy storage systems can be found in both China and Europe. Because the adoption of an operation mode is limited by the battery characteristics, no variation is observed in the combination of a Li-ion–based energy storage system and the operation mode.

Table 3. BEBs and Charging Facilities in Some Major Cities of China and Europe

BEB Information		**BEB**	**Charging Facility**
Location	Shenzhen, China		
Battery Type	LFP		
Battery Capacity (kWh)	324		
Charging Mode	Slow Charging		
Operation Mode	Overnight Charging		
Location	Beijing, China		
Battery Type	NMC		
Battery Capacity (kWh)	129		
Charging Mode	Ultrafast Charging		
Operation Mode	Opportunity Charging		
Location	Chongqing, China		
Battery Type	LTO		
Battery Capacity (kWh)	77.8		
Charging Mode	Ultrafast Charging		
Operation Mode	Opportunity Charging		
Location	London, UK		
Battery Type	LFP		
Battery Capacity (kWh)	324		
Charging Mode	Slow Charging		
Operation Mode	Overnight Charging		
Location	Munster, Germany		
Battery Type	LTO		
Battery Capacity (kWh)	62.6		
Charging Mode	Ultrafast		
Operation Mode	Opportunity Charging		

4.1 Successful Examples

Some cities have been more successful than others in running either trial e-bus programs or full implementation of an e-bus operation. Owing to the high upfront costs (e-bus and charging facilities), all governments must subsidize the upfront costs, and some governments must subsidize even the running costs to launch the trial programs. Among the cities visited as part of the technical visits of this study, Shenzhen, Chongqing, and London were found to be the more successful examples of e-bus programs.

4.1.1 Shenzhen

Shenzhen government has taken full responsibility of implementing the e-bus program. It intends to phase out all conventional buses (over 10,000 in total) by 2017. Apart from the subsidy from the central government, Shenzhen government injects RMB 500 million every year to support the development of the e-bus program, including e-bus purchases, operation, and installation of the charging infrastructure. The maximum subsidy for an e-bus purchase from the central government is RMB 500,000 per vehicle, and Shenzhen government matches this subsidy to reach a total of RMB 1 million per vehicle. That is, the government pays the bus operator around RMB 1 million to buy an e-bus. Shenzhen government further subsidizes the operator RMB 450,000 per vehicle if the e-bus covers more than 60,000 km per year. The electricity price is also controlled at a level below RMB 1 per kWh. As of March 2016, more than 3,000 e-buses were in operation in Shenzhen.

The local manufacturer, BYD, fully cooperates with the Shenzhen government in producing e-buses to meet the need of the bus operators. Because BYD also provides the charging infrastructure, the defects of a bus or the charging are fixed on the spot, thereby reducing the downtime to the minimum. BYD e-buses run on the slow-charging LFP battery. Shenzhen government is now building 13 multistory bus depots for charging e-buses. The target is to have one charging port per e-bus; a total of 26 such depot buildings will be built by 2020. The government also plans to develop an e-bus charging network along major routes, targeting to have one e-bus charging point per 5 km^2.

With the abovementioned support, the Shenzhen East Bus operator, one of the two largest local operators, is happy with the e-bus program, although there were some teething problems, such as defects in the battery and other mechanical faults that required 20% more e-buses in the fleet to provide the same service level as that of the conventional buses. The workload on vehicle maintenance has been reduced, and the drivers are happy with the e-buses.

4.1.2 Chongqing

In Chongqing, the main driving force of the e-bus program is the battery and vehicle manufacturer. The government grants land only for the charging station installation. The battery/vehicle manufacturers and the charging service provider work closely with the bus operator to ensure the smooth implementation of the e-bus program.

Currently, compressed natural gas (CNG) buses form a majority of the bus fleet in Chongqing. Although, in April 2016, only 46 e-buses were in operation in Chongqing, 31 of these e-buses had been running since 2011 and the battery degradation was only around 6%. Thus, we inferred that the e-buses performed better than the conventional buses.

The charging infrastructure is tendered out to TELD, one of the biggest charging service providers in China. The Central government only subsidizes slow-charging e-buses at the time because slow-charging buses require charging overnight and do not compete for power in the daytime. The battery and the vehicle manufacturers have been very attentive to the rectification of any discrepancies found. The bus operator and the drivers are happy with the performance of the e-buses even though no subsidy is received from the government.

4.1.3 London

The e-bus program was initiated by Transport for London (TfL), a corporation under the city government. The bus fleet of London consists of around 9000 vehicles running on approximately 700 routes. TfL tenders the bus operation out in groups of routes to private operators. Currently, 1700 of these buses are hybrid (diesel–electric) buses. The main incentive of electrifying buses is the implementation of Ultra Low Emission Zones (ULEZ) in London, whereby all single-decker buses will be zero-emission buses and double-decker buses will be Euro VI hybrid by 2019.

To meet with the challenge of low/zero emission and optimize the business opportunity, a partnership group called Low Carbon Vehicle Partnership (LowCVP) was established in the UK in 2003 to accelerate a sustainable shift to low-carbon vehicles and fuels and create opportunities for UK businesses. Almost 200 organizations are engaged, and the Bus Working Group has more than 50 active members (Weston, 2016).

At the end of 2016, 73 pure e-buses were in service in London. E-bus suppliers include BYD, BYD/ADL, Optare, and Irizar. Fifty-one BYD single-decker e-buses are currently in service on light duty routes (4 to 5 hours of service a day). Five BYD double-decked e-buses are on trial runs. The Southern Electric Energy, the largest energy supplier in the UK, in collaboration with the UK Power, develops the charging infrastructure for e-buses. The e-bus manufacturers and the charging facility service providers are required to be attentive to the e-bus trials.

4.2 Major Barriers

Technology, operation, and finance are the three major barriers to commercial electric vehicles. The performance of energy storage in terms of power and energy capacity, which were the largest technological barriers, is greatly enhanced by the more mature Li-ion battery technology (Burke and Miller, 2011; Scrosati and Garche, 2010). Power and energy capacity improvement in turn enhanced the feasibility of commercial electric vehicle operation. However, the energy efficiency still varies considerably depending on the driving cycle and the bus configuration (Lajunen, 2014).

The core operational limitation of commercial electric vehicles is flexibility in operation. This flexibility is significantly limited by the vehicle features. Specific commercial electric vehicle models for different routes are required to maximize performance and cost efficiency (Lajunen, 2014 and Pihlatie et al., 2014). As specific models may only be energy/cost-effective for a specific route, the flexibility in scheduling and operation is decreased as compared to that in the case of diesel vehicles. BEBs, in particular, have been questioned in terms of operational flexibility because of the influence of the charging time on the schedule (Miles and Potter, 2014). Miles and Potter (2014) estimated that all e-buses provide similar performance to diesel buses on the basis of range extension by 5 min of refueling/recharging, except overnight BEBs. Further, BEB opportunity charging is considered to have less impact on operation than overnight BEB charging because it can be achieved by various charging infrastructure options including charging spots, pantograph charging, and inductive charging (Mahmoud et al., 2016). Although only minor modification to the current infrastructure is needed for BEB opportunity charging, the considerable number and distribution of charging points required is a barrier to its implementation (Kakuhama et al., 2011).

5. CONCLUSIONS

Based on the information collected from the technical visits to some major cities in China and Europe, different energy storage systems have been evaluated for e-bus operation. We found that LFP is the most common type of Li-ion battery used in China, while the market shares of NMC and LTO are increasing.

The battery capacity of LTO enables LTO BEBs to maintain a better balance between the driving distance and energy efficiency because of the low energy consumption. BEBs with LTO can be applied with ultrafast charging, and thus, the opportunity charging mode is applicable to LTO BEBs. The opportunity charging mode is particularly suitable for densely populated cities as less space is required for the installation of the charging facilities. The experiences of other cities show that BEBs with LFP are also available in many cities with a high population density. However, their operation, which includes the number of vehicles needed and the bus frequency, needs to be optimized.

Further study will be carried out to design an e-bus system for a selected area considering the energy consumption of the energy storage systems. The bus routes, frequency, and battery charging schedule for e-bus operation will be examined in a case study.

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7. REFERENCES

Buchmann, I. (2017) BU-205: Types of Lithium-Ion. Battery University. Retrieved from http://batteryuniversity.com/learn/article/types_of_lithium_ion

Burke, A. and Miller, M. (2011) The power capability of ultracapacitors and lithium batteries for electric and hybrid vehicle applications. *Journal of Power Sources*, 196(1), 514-522.

IEA (2016) Global EV Outlook 2016 - Beyond One Million Electric Cars. Paris, France.

Kakuhama, Y., Kato, J., Fukuizumi, Y., Watabe, M., Fujinaga, T. and Tada, T. (2011) Next-generation public transportation: electric bus infrastructure project. *Mitsubishi Heavy Industries Technical Review*, 48(1), 1-4.

Lajunen, A. (2014) Energy consumption and cost-benefit analysis of hybrid and electric city buses. *Transportation Research Part C: Emerging Technologies*, 38, 1-15.

Mahmoud, M., Garnett, R., Ferguson, M. and Kanaroglou, P. (2016) Electric buses: A review of alternative powertrains. *Renewable and Sustainable Energy Reviews*, 62, 673-684.

Miles, J. and Potter, S. (2014) Developing a viable electric bus service: The Milton Keynes demonstration project. *Research in Transportation Economics*, 48, 357-363.

Pihlatie, M., Kukkonen, S., Halmeaho, T., Karvonen, V. and Nylund, N.O. (2014) Fully electric city buses - The viable option. *Proceedings of the 2014 IEEE International Electric Vehicle Conference (IEVC)*, Florence, Italy.

Scrosati, B. and Garche, J. (2010) Lithium batteries: Status, prospects and future. *Journal of Power Sources*, 195(9), 2419-2430.

Weston, M. (2016) Supporting reduction in pollution. Presented in the Motor Vehicle/Vessel Emissions Control Workshop 2016, Hong Kong.