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Redesigning European Public Transport: Impact of New Battery Technologies in the Design of Electric Bus Fleets

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Abstract

At the COP21, 195 countries adopted the first-ever universal, legally binding global climate deal showing universal concern for global warming. Worldwide, carbon dioxide emissions from fuel combustion rose by 49% between 1990 and 2011. Moreover, urban mobility is set to double by 2025. Public transport consumes 3.4 times less energy per passenger kilometer than automobiles. Therefore, an increase in the share of public transport and a technological shift are key to meet EU 2050 objective to decarbonize the transport sector. In a Well-to-Wheels perspective, electric vehicles emit less nitrogen dioxide and fine particulate matter than internal combustion engine vehicles. Thus, promotion of electric buses in public transit fleets is highly valued. Multiple factors must be considered to achieve both objectives of low cost and energy efficiency. Electric bus performance depends on driving distance, road orography… recharging infrastructure depends on number/length of bus stops, electric grid characteristics and electric tariffs. On-board batteries must adapt to demanding cycling profiles that can severely impact their performance and lifespan. New battery technologies allow for improved electric buses design and recharging strategies. However, technical information about the relationship between battery technologies and electric bus performance is limited. In this paper, strengths and weaknesses of different batteries and charging technologies are presented when used in battery electric buses projects implemented in European. Lessons learned may help to redesign European public transport.

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Keywords: Electric Buses (EBs); LFP batteries; LTO batteries; fast-charging; regenerative braking

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1. Introduction

Transport accounts for nearly a quarter of Europe's greenhouse gases (GHG) emissions, and CO2 emissions from the sector are predicted to increase by 120% on 2000 levels by 2050 (OECD/ITF, 2008). In 23 out of 28 European Union (EU) Member States air quality standards are still exceeded (European Commission 2016). Consequently, one in three people living in Europeans cities today suffer air quality that is illegal under EU air quality standards, and almost all the population living in European cities are exposed to levels of air pollutants considered damaging to health by the World Health Organization’s more severe guidelines (EEA 2016). Transport is the main cause of air pollution in cities. (European Commission. 2017).

Nitrogen dioxide (NO2) and fine particulate matter (PM) are the two main air pollutants from road transport; they are associated with adverse cardiovascular, respiratory, morbidity and other effects on mortality and health (Schucht 2015). 15-30% of all new cases of asthma in children could be caused by living near busy roads. Moreover, some 15-30% of chronic obstructive pulmonary and coronary heart diseases in adults older than 65 years are related to air pollution.

In a Well-to-Wheels perspective, electric vehicles (EVs) emit 20 times less NOx and four times less PM than internal combustion engine (ICE) cars (Mobi. 2017). One study looking at 20 European cities estimates that Sulphur content reduction of fossil transport fuels as a result of compliance with EU legislation has prevented 2,200 premature deaths from ambient SO2 emissions, which accounts for savings worth €192 million (Hooftman 2016).

Public transport in European urban areas accounts for 21% of the total number of motorized trips but it is only responsible for roughly 10% of transport related GHG emissions. This is because public transport consumes 3.4 times less energy per passenger kilometer than automobiles, and this ratio is even more favorable under increasingly congested driving conditions. Electric Buses (EB) have also higher energy efficiency benefits than conventional diesel and hybrid diesel counterparts (Li 2013) (Ji 2011).

Therefore, promotion of EBs in public transit fleets is highly valued in local governments as a crucial asset in clean air action plans. An electric public mobility system must take into account a wide range of factors to achieve both objectives of cost and energy efficiency. On the one hand, electric bus performance depends on driving distance (urban/suburban/designated use), road orography, climate etc. On the other hand, the charging infrastructure depends on number and length of bus stops, peak hours of consumption, electric grid characteristics and electric tariffs. Other key aspects as capital cost, infrastructure investments, maintenance and operational costs must be also considered. The combination of these factors demands specific energy storage systems on-board the electric buses, and also at key locations to reduce the impact of recharging on the electric grid. Mainly, the on-board battery must be carefully selected because the demanding cycling profiles required in e-mobility applications can severely impact battery performance and lifetime, impacting negatively in costs. In last years, new battery technologies have been developed, contributing to improve electric buses design and opening the door to new recharging strategies. However, technical information about the relationship between battery technologies and electric bus performance is limited. Regardless the increasing number of battery electric bus projects, the lack of information also affects other areas. For example, the available literature about recharging infrastructures and their implementation costs is scarce, particularly for novel applications such as long-distance catenary or inductive equipment. That is why greater research is needed to estimate future technology possibilities and costs (Eelco 2013).

In this paper, strengths and weaknesses of different battery and charging technologies are presented in relation to this use in battery electric buses. Moreover, several projects implemented in European cities are analyzed. The main objective is to show how the use of new technologies can improve the design of electric bus fleets, helping in this way to redesign public transport.

1.1. Battery Technologies

To design an optimized EB public transport fleet it is of foremost importance to select the adequate energy storage technology for each operational context. Battery parameters (size, service-life and so on) depend strongly on working conditions but, at the same time, they impact directly in overall cost and performance of electric buses. The specific characteristics of the cities define diverse types of cycling for the bus batteries since each city locates the charging points at different positions, the orography marks the level of regenerative braking and so on. The type of cycling profile has a direct impact in battery performance and lifetime: the current (C-rate) of operation conditions, the depth of discharging, the application of fast-charging and/or regenerative braking can affect battery power capability and battery service life. Therefore, it is necessary to analyze battery behavior under specific e-mobility requirements prior selecting the most suitable technology for each application.

Li-ion batteries have an outstanding combination of high energy and power density, making it the preferred technology for hybrid and full electric vehicles (Nitta 2015) (Tarascon 2001). However, there is a wide variety of Li-ion technologies, each of them adequate for different applications.

$LiCoO_2$ (LCO) was the first technology to use layered transition metal oxide cathodes. LCO is a very interesting material because of its relatively high theoretical specific capacity of 274 mAh g^{-1}, high theoretical volumetric capacity of 1363 mAh cm^{-3}, high voltage (3.6 V/cell), good cycling performance and low self-discharge (Pasquier 2003).

The limitations of this technology are low thermal stability, poor response under stress working conditions (high charging or discharging rates) and high cost. For these reasons, this is the most widely used technology in portable applications, where battery volume and weight are the most critical parameters. However, it is not adequate for electric mobility applications.

Three types of Li-ion batteries (LFP, NMC and LTO) show promise in the application for EB due to the strengths of long life span, high specific power and/or specific energy, and high thermal and safety performance.

- $LiFePO_4$ (LFP) is a commonly used technology in EB because of its competitive characteristics: high cycling-life, good power parameters, high thermal stability and competitive price. The major weakness of LFP technology is lower voltage (3.2 V/cell) and lower specific energy (90–120Wh/kg) than other Li-ion technologies, resulting in bigger and heavier batteries what is not ideal in automotion. Moreover, LFP technology has slower charging rate and higher self-discharge (this can cause balancing issues with aging and thus shorter lifespan of the battery pack) than other Li-ion technologies. For example, LFP batteries are the choice of BYD, Nova bus or Volvo buses.

- $LiNiMnCoO_2$ (NMC) shows promise in their use in EBs as this technology has a better specific energy and longer operating life compared to many other lithium ion approaches. The increased specific energy (150–220Wh/kg) can either contribute to a longer driving range or to a lighter and smaller battery pack and therefore lighter buses. However, LFP technology is safer than NMC technology, which is vital considering the large batteries of electric buses. In the case of an accident, massive amounts of toxic, flammable leakage could be produced. Furthermore, NMC technology contains cobalt and thus it is usually more expensive than LFP technology. For example, NMC batteries are used by Proterra buses.

- $Li_4Ti_5O_{12}$ (LTO) technology has excellent thermal stability and it can be charged/discharged at very high current rates without affecting its cycling-life. LTO anode can last for tens of thousands of cycles in comparison of only 2000 in a regular Li-ion battery giving this electrode a distinct advantage over most other anode materials. In this way, ultra-fast charge is possible substantially reducing the necessary charging time, and regenerative braking can be applied without problems increasing the bus efficiency. Besides, LTO technology has outstanding cold temperature performance (Doughty 2012) making them ideal for cold starts up. Regarding main disadvantages, this technology has reduced cell voltage (2.40V/cell) and lower theoretical capacity parameters (175 mAh g^{-1} & 600 mAhcm^{-3}) than other Li-ion technologies, resulting in bigger and heavier battery packs. Moreover, it is an expensive technology due to the high price of Ti (Zaghib 2011). For example, LTO batteries are used by Proterra and Vectia buses.

Along with technical characteristics, economic feasibility is the other key feature to select a specific battery technology. Average price of lithium ion batteries in December 2017 was 209 $/kWh, with a 79% drop since 2010 (Curry 2017). Moreover, prices are set to fall below $100/kWh by 2025 (BNEF) foreseeing the cost parity between internal combustion engines and electric vehicles for the latter half of the 2020s.This changing context made necessary to reevaluate previous conclusions and scenarios; for example, the reduction of battery price will have impact on long range technology. Currently, the more widely used technologies in battery electric buses are LFP and LTO. LFP technology shows high cycling life, high power capability, flat voltage profile, high reliability and safety, low toxicity and large availability of materials. However, LFP is a sensitive technology to aggressive cycling profiles, showing in this case diminished battery performance and lifetime. LTO technology has lower cell voltage; so, more cells are needed in the battery pack leading to bigger and more expensive batteries. However, LTO technology accepts very high charging and discharging current peaks allowing the application of stressing cycling profiles; the application of ultra-fast charging and regenerative braking reduce battery size and costs but the charger infrastructure is more complex and require specific power grid characteristics. Although LFP technology is still cheaper than LTO, the price drop of the latter makes it profitable to invest in its superior technical characteristics. Currently, China dominates the electric bus and battery market, with 97% of e-buses and 75% of their batteries produced there. China manufacturers prefer LFP batteries while NMC and LTO batteries are largely made elsewhere. NMC batteries are a good competitor to LFP batteries due to their higher energy density and if they safety keep on increasing they could be a good alternative to LFP and shift the market outside China.

1.1. Charging technologies for battery electric buses

In general, range has been the key barrier for urban electric mobility. The improvement of the EB battery performance and the design of new recharging strategies have greatly reduce the “Range Anxiety”, proving that EB fleets are an effective mobility solution for daily travel activities. However, this objective is only possible selecting the fitting battery for the application and coupling it with the optimal recharging infrastructure.

There is no definitive charging solution for EBs because they have different energy requirements depending on use (urban, suburban,…), number and length of the bus stops, orography driven, climate and so on. Other key aspects are the available time per stop on route and the recovery time at end-line stops, the infrastructure of the power grid and the electric tariffs.

The charging strategy must be selected having mainly account of the available charging time and the ability of the battery to accept fast-charging. The charger technology mainly depends on selected strategy, the possibility of place the required hardware on-board and the characteristics of power grid.

1.1.1. Charging Strategies for Battery Electric Buses

Slow charging: This type of charging applies to buses with large battery packs (over 300 kWh) and charges up to a maximum of 50 kW, recharging the buses in around 6 hours. Slow charging allows for flexible routing (for example, in the case of road works) or changing routes due to travel demands (school buses and so on) (Li 2014). However, charging during the operation is not possible, reducing the availability time of the bus and the possibility of long routes. Bigger batteries can solve this problem but adding extra weight to the vehicle and thereby reducing bus energy efficiency and increasing costs.

Fast/opportunity charging: Buses using fast/opportunity charging use smaller batteries that can be charged at higher power than those using slow charging, about 50 to 200 kW for inductive charging and up to 500 kW for conductive charging. These buses have a smaller free range but shorter charging times and therefore higher availability (they can be charged several times during operation) (Rogge 2015). Smaller batteries allow for lighter buses and higher energy efficiency but the limited available time per stop on-route may not be enough to sufficiently recharge the batteries. It must be pointed out that fast charging is only possible in some battery technologies, reducing battery service life if it is not applied following technical instructions of battery manufacturers. Moreover, fast charging requires higher hardware inversion costs and puts higher stress to the electric grid (high power demand in short periods of time).

Regenerative braking: In regenerative braking, the loss of kinetic energy from braking is stored and later fed back to provide power to the electric motor. However, regenerative braking produces more aggressive battery degradation (reduction of battery cycle life and battery power) than fast charging because the mix of charging/discharging peaks is a very demanding battery cycling profile. The cycling profile is determined by the orography, traffic conditions, driving style and also on the average bus speed (Choi 2015). Using regenerative braking only in a certain range of SoC soften its impact on the battery, allowing for a second life of the battery. (Ansean 2016) (Ansean 2013).

Combination of slow charging with opportunity charging: These buses use slow charging at the end of the route and fast charging on-route. A correct dimensioning of the batteries and the usage requirements ensures the highest energy efficiency and the less stress for the electric grid. However, this combination implies higher hardware inversion costs.

In motion charging/hybrid trolley: In Motion Charging (IMC) is a system which consists of battery buses with small batteries (<50 kWh) that are charged through overhead wires on selected sections of a route, which the vehicles connect to with poles. Standing still charging power is maximized at 100 kW due to heat restrictions of socket connecting the poles of the bus to the overhead wires. Charging whilst driving is less stressful for the electric grid because it is done at lower power, and also due to fewer kilometers of overhead wire the infrastructure is cheaper than for a traditional trolley system. The small batteries allow for light and energy efficient buses.

Physical change of batteries: In this case, the batteries are switched when depleted and replaced with charged ones at battery switching stations. Moreover, the charging is scheduled. Therefore, it is the faster system and the less stressful for the power grid, minimizing also the electricity cost. However, it is only economically viable in some cases due to the added cost of the standby batteries and labor price.

1.1.2. Charger Technologies for Battery Electric Buses

There are different types of charger technologies attending to the charging strategy, and also having account of the necessary hardware that must be placed on-board and/or at the bus stops. Inductive charging uses a charging device installed in the ground. The inductive system does not need any urban remodeling that leaves a visual impact on the city and ensures efficiency, sustainability, security and versatility of the system. Technically, the inductive charging system has a performance of 85-90 percent, lower than contact load, but does not require EBs to stop completely if they are completely discharged. The inductive charging system is safer because it only works when a bus is present at the charging station. By contrast, the conductive charging is usually done with a pantograph mounted either on the bus or on a pole it is cheaper to install and has been widely tested.

- Off-board top-down pantograph: The top-down pantograph is a fast-charging system that can be mounted on a mast or roof of a bus stop. Pantographs charge the bus batteries sufficiently to arrive to the next charging point, being all the connection and charging process fully automatic. This offboard charging solution can be used with multiple bus types and different conditions of power grid. Although this technology mainly uses high power direct current (DC) charging posts catenary charging for heavy duty vehicles (HDVs), it is already being demonstrated in small scale applications such as the Siemens eHighway projects in California (Riddett 2015) and Germany (Siemens 2017a).

- On-board bottom-up pantograph: The bottom-up pantograph is a better option when the charger must be integrated into existing power networks. In this case, the entire charging equipment is installed on the bus, including the pantograph that contacts the overhead line. This is a cost-efficient system, and it usually chargers DC from the overhead line allowing for fast charging.

- Charging via connector (Plug-ins): In this case, a DC charger post is controlled by an operator. Charging begins automatically when the system is connected to the bus and the user has been identified. The user monitors the state of battery charge and he can manually stop the charging process at convenience. This system uses high power DC charging posts allowing for flexible positioning and guaranteeing maximum efficiency. The system can be designed both for slow or fast charging but it is usually used at the end of the lines for night charging and therefore slow charging is favored as the charging impact to the grid is diminished.

1.2. Examples of battery electric buses projects

Battery electric buses account for a small share of the bus market in the European Union. However, European cities increasingly see electric buses as a way to decarbonize and reduce local air pollution. Municipalities as Paris and Amsterdam have set goals to switch to zero-emission buses in the coming years. Moreover, cities like Madrid, Amiens, Geneva, Manchester, Valladolid and Paris are shifting toward electric drivetrains from ones that use diesel or natural gas.

1.2.1. Geneva (Sweden)

This demonstrator is one of the earliest examples in Europe, being in service since 2013, between Geneva airport and Palexpo (ABB 2013). It comprises one articulated bus (manufactured by HESS), one 400 kW Flash charging station at Palexpo and one 200 kW terminal station at Geneva Airport. This Flash charging electric bus system was deployed for the first time on a large capacity electric 18.7 meter bus, carrying up to 135 passengers.

The bus is charged directly at designated stops with a 600-kilowatt 15-second energy boost while the passengers enter and leave the bus. A further 4 to 5 minute charge at the end of the bus line enables a full recharge of the batteries.

1.2.2. Stockholm (Sweden)

In 2015, Stockholm was the first European capital to have an electric highway. The highway uses a system of catenaries designed by Siemens and Scania, which electrified a two-kilometer stretch on the E16 motorway. It has two 150 kW chargers that are used by hybrid trucks. Stockholm project had several replications like the installation in 2015 of two 300 kW chargers in Gothemburg, 60 kW DC charger at Stuttgart’s airport and two twin charges installed at Geneva’s airport.

1.2.3. Madrid (Spain)

Since 2011 both the Municipal Transport Company of Madrid (EMT 2017) and several intercity companies have massively incorporated hybrid vehicles into their fleet (EMT 2017 b). This solution allows lower implementation costs, by not requiring a specific recharging infrastructure. Madrid has several bus models with this technology such as: Tata Hispano Area, MAN Lion's City, Iveco Urbanway and Castrosua Tempus. In 2017, a pilot project was launched in Madrid on one bus line with 42 stops, the first full electric induction line. The system uses 8 minutes chargers in the headers of the itineraries while the full recharge is carried out at night in the hours that the itinerary is not active. It is planned that by the year 2020 there will be 88 electric buses in operation in Madrid.

1.2.4. Manchester / London (United Kingdom)

The bus loading system was installed in the Shudehill transport interchange and was operational for eight weeks in 2017. This charging system is called OppCharg and it was developed by ABB as part of the range of ABB AbilityTM digital solutions that include connection to the cloud. This connection makes it possible to manage and analyze remote diagnostics, guaranteeing an efficient and reliable infrastructure for bus users. The bus used is a Volvo 7900e and the 76 kWh battery is charged directly via pantograph at designated stops with a 3 to 6 minutes energy boost, allowing the bus to run 24/7. Following the Manchester trial, the vehicle was used at a demonstration at London’s Heathrow Airport for a period of eight weeks. This involved transporting airport staff and customers to and from the car parks and terminals.

1.2.5. Amiens (France)

Amiens granted the biggest European contract in 2017, forty-three 18-metre articulated buses supplied by the Irizar Spanish manufacturer. (HYE 2017a) The model is Irizar ie Tram (Irizar 2018) (HYE 2017b) and it has a nominal power of 235 kW with a 90-150kWh capacity depending on the number of batteries. The fleet is handled with opportunity charging, the recharging time of the buses is approximately 5 minutes and the maximum recharging power is 500 kW.

1.2.6. Valladolid (Spain)

Valladolid (Movilidad 2017) commissioned in 2017 five hybrid buses supplied by Vectia that operate in full electric mode in the city center, more than four kilometers of an area declared zero emissions. The bus has 45 kWh LTO batteries, and the vehicle itself is the responsible for charging the batteries through regenerative braking in the electric operation mode. This battery can also be recharged from the electric grid by 5 ultrafast chargers enabled at the ends of bus line. The chargers have 150 kVA, scalable up to 300kVA. The project is also testing inverted pantographs chargers on route (the pantograph is not mounted onto a bus roof, but rather is integrated into the existing infrastructure, e.g. in the roadway mast of the holding station, bus station or depot). Partial recharges are done in 4 minutes.

1.2.7. Paris (France)

In 2016, one bus line was fully fitted with electric buses. In 2018, Ile-de-France Mobilités and RATP are launching a tender to buy 1 thousand 12-meter electric buses in order to equip two bus lines and test partial battery charging in terminuses (RATP 2018). The first "series" deliveries of electric buses from this tender should be made at the end of 2020. For recharging infrastructure, the economy of scale of a large project will be exploited, selecting the company a night-time slow charging to minimize the impact on power grid. Thus, the fundamental requirement of these vehicles is that they must be able to offer a wide autonomy during the day. The RATP fleet, comprising 4,700 buses, already has 800 hybrid vehicles, 140 bio-GNV and 74 electric buses.

1.2.8. Frankfurt and Darmstadt (Germany)

In 2018 (Siemens (2017b), an electric line for electric trucks will be built in a 10 kilometer stretch of the German A5 motorway, between the Frankfurt airport and the city of Darmstadt. This system aims to generate a zone of neutral emissions along the 10 kilometers covered by the installation of the catenaries. The project uses Siemens technology (Siemens 2017c). The trucks will use hybrid propulsion, that is, the vehicles will be able to operate without contact with the catenary. They would be propelled by the electricity stored in their batteries or by natural gas or other fuels. This prevents service interruptions due to lack of load.

2. Conclusions

This article highlights the recent and future developments of clean public bus transport in Europe and its relation with the market introduction of new Li-ion battery technologies. Even though EB fleets are still at a nascent stage in terms of public implementation, several European projects are testing different battery technologies and charging scenarios. In general, EB fleets have proven operational flexibility comparable to ICE buses, zero local emissions with a pathway to zero emissions when the batteries are supplied from renewable energies, and satisfaction for end users (drivers & passengers). Moreover, it is previewed that battery capacity will increase whilst costs decrease, improving electric bus performance and reducing costs.

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