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Electric Bus: A Critical Overview on the Dawn of Its Widespread Uptake

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Dedicated to Professor Giampiero Maracchi for all he has done to promote sustainable development in Italy and across the world

The battery powered electric bus is the first electric vehicle whose market share in the world's leading industrial economy has surpassed the 80%. Within the next decade (2019–2026), the authors argue, electric buses powered by Li-ion batteries and hydrogen fuel cells will become ubiquitous across the world, displacing bus and coaches powered by fossil fuels burned in the internal combustion engine. Critically reviewing the economic, health, and environmental benefits of the electric bus, this essay offers an updated outlook in a key area of the global energy transition.

1. Introduction

To keep pace with natural wealth and global population growth identified be the model combining the competing dynamics of oil price, economic growth, and oil extraction costs, oil companies by 2025 should make globally available an extra output of >32 million oil barrels per day (adding to current consumption rate of roughly 90 million barrels per day).[1]

Hence, to avoid facing the undesirable consequences of conflicting oil availability and population and wealth growth, mankind urgently needs to replace energy obtained by burning oil in internal combustion engine (ICE) and in thermoelectric power plants with renewable electricity obtained by sun, wind, and water.[1]

Dramatic recent progress in power generation from renewable energy sources at country level in China, Germany, Italy, Spain, India, USA, and several other industrialized countries is increasingly accompanied by widespread adoption of electric vehicles (EVs) powered by electricity stored Li-ion batteries or obtained by hydrogen and air's oxygen reaction at the electrodes of fuel cell (FC) electric vehicles.[2]

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The replacement of the diesel-fueled bus with the electric bus is already providing tangible energy and economic benefits. By early 2018, out of world's 3 million buses some 385 000 were already electric buses, though practically all of them (99%) running in China.[3]

The amount of diesel fuel displaced depends on the amount of km run every day. According to estimates for the average electric bus,[3] about 500 barrels of diesel fuel per day are displaced by 1000 battery electric buses. Taking into account the number of electric buses on roads in 2017,[3] this translates into displacement of around 177 000 barrels a day of diesel fuel only in that year.

Another key energy aspect of the concomitant widespread adoption of renewable energy sources for power generation, particularly solar photovoltaics (PV), and EVs for mobility is the synergistic and beneficial effect on the electricity price. In brief, the significant reduction in electricity costs due the impact of PV generation on the power day ahead market is synergistically magnified by a growing electricity demand.[4]

Public transit on electric buses makes travel more comfortable, due to dramatically lower noise and vibration levels, whereas the lack of harmful air pollutants improves the quality of polluted urban air. Maintenance costs decrease due to the drastic reduction in complexity of the electric drivetrain compared to the ICE powertrain. As it happens for all today's battery electric vehicles, when the vehicle is in braking mode the electric motor acts as a generator and the recovered energy is stored in the batteries extending their capacity.

Despite these benefits and perhaps due to dramatic growth in one country only, a number of myths surround both battery and fuel cell electric buses. These include poor mileage (energy autonomy), prohibitive upfront cost, poor performance in steep terrain and with cold weather, lack of articulated electric buses, short duration of battery, and reliability of fuel cells, technically unfeasible rise in electricity demand when entire bus fleets are electrified, and overly expensive cost of the charging or hydrogen refueling infrastructure.

Drawing from successful and successful case studied from across the world, this study offers a critical overview of the electric bus technology. We provide a wider perspective which includes economic, environmental, health, and societal aspects.

Besides being of direct interest to policy makers and managers at public transit and bus industry companies, the conclusions will inform new educational initiatives aimed at energy, mobility, and sustainability professionals.

2. Technology and Economic Aspects

The key technology enabling the widespread uptake of the electric bus is the Li-ion battery. Not only were electric buses powered by the obsolete lead-acid battery largely unsuccessful but also first generation hydrogen fuel cell buses deployed In London in 2000 achieved limited bus availability (55%) even though bus availability increased year after year with ever new fuel cell power modules, and then with the introduction of new fuel cell power modules combined with Li-ion batteries in 2008, up to 85% availability in 2017.[5]

Li-ion batteries today are installed in all electric fuel cell buses to provide maximum torque to accelerate from idle in the frequent stop-and-go running mode typical of the city bus. Furthermore, the durable Li-ion battery enables the regenerative braking technology further enhancing the significant autonomy of new generation FC electric buses running on hydrogen.

Along with reduced noise and smoother ride for improved passenger riding experience, hydrogen FC buses offer unprecedented route flexibility, with no need for *en-route* recharging, having 450 km range between refueling with refueling typically taking 7–10 min.

In August 2017 the FC electric buses powered by fuel cells made in Canada achieved a new durability record with more than 25 000 h of service through London's streets with no significant maintenance to the fuel cell stack,[6] equivalent to operating a bus on a 14 h daily schedule, 5 d per week for 6.9 years.[6]

In brief, hydrogen FC buses are ideal to electrify the most difficult routes that cannot be electrified with battery electric buses. Indeed, market analysts were recently reporting how almost suddenly the number of hydrogen fuel cell buses produced in China went from 0 in August 2017 to close to 200 the subsequent December.[7] The figure is still negligible, compared to sheer number of battery electric buses adopted in China during the same period, but points to forthcoming rapid changes on which we return below.

In the following we summarize achievements and economic aspects of the two main technologies powering the electric bus.

Having decreased from about \$400–600 kWh^{-1} in 2016 to \$250 kWh^{-1} in 2018,[8] the price of lithium-ion batteries is the main cost faced by battery electric bus manufacturers. Price of any goods, including Li-ion batteries, is always higher than its production cost, at times also much higher. This single aspect offers a unique competitive advantage to companies able to self-produce the batteries: from the single Li-ion cells to the assembled battery package.

The unit price paid by the state-owned intermediary company for transforming the whole fleet of 16 359 buses of Shenzhen with 12 m bus, equipped with lithium iron phosphate (LFP, **Figure 1**) safe and long lasting batteries providing 250 km autonomy prior to recharge, was 1.8 million yuan (slightly less than \$260 000).[9]

In detail, state-owned Potevio receives the yearly financial subsidies both from the central government and the Shenzhen municipality (400 000 yuan from Shenzhen city and 100 000 yuan from the central government for each vehicle that it runs).

Figure 1. Shenzhen hosts the world's largest electric bus fleet. Reproduced under the terms of the CC BY-SA 3.0 license.[60] Copyright 2012, The Artist.

With a bank loan based on the subsidies above, the company purchased the electric buses, assuming ownership and maintenance of their batteries, and built the charging infrastructure providing also the charging service by buying the electricity on the market.[10]

Potevio then leases for 8 years the EV bodies and batteries to the Shenzhen Bus Group in order to recover the costs sustained (**Figure 2**). Furthermore, it built 40 000 charging facilities open also to private electric passenger cars to enhance revenues. This largely reduced the financial pressure on the Shenzhen Bus Group in purchasing the electric buses and made the transition possible.

Savings are even higher in Europe where the cost of diesel fuel is considerably higher than in China. In Italy's city of Novara, for example, in only 111 d of service of three electric buses, similar to those running through Shenzhen's roads between January 1 and May 16, 2018 (excluding Sunday), the public transport company saved 26.546 L of diesel fuel.[11] In 300 d of service in 1 year, the company will save 71 746 L of fuel.

Assuming conservatively that the company in 2018 paid diesel fuel at 1.25 € L^{-1} rate (after a tender, in Italy indeed the average diesel fuel price exceed €1.5 L^{-1} in 2018), these figures translate into around €90 000 of diesel fuel expense.

Purchase of diesel fuel is now replaced by purchase of 527.4 kWh of electricity per day[11] which, assuming a €0.11 kWh^{-1} price, translates into close to €17 400 to buy the 158 220 kWh amount of electricity to meet the yearly energy needs of the electrified route.

The cost of the kWh, furthermore, can be easily reduced by installing a large PV array on the roof of the company's depot, as it happens in the near city of Turin or in Turkey's Izmir with their fleet of some 20 battery electric buses.

Along with the energy cost reduction, there is a significant reduction maintenance costs, when compared to ICE vehicles, due to the highly efficient electric motor and dramatic reduction in the number of moving parts.

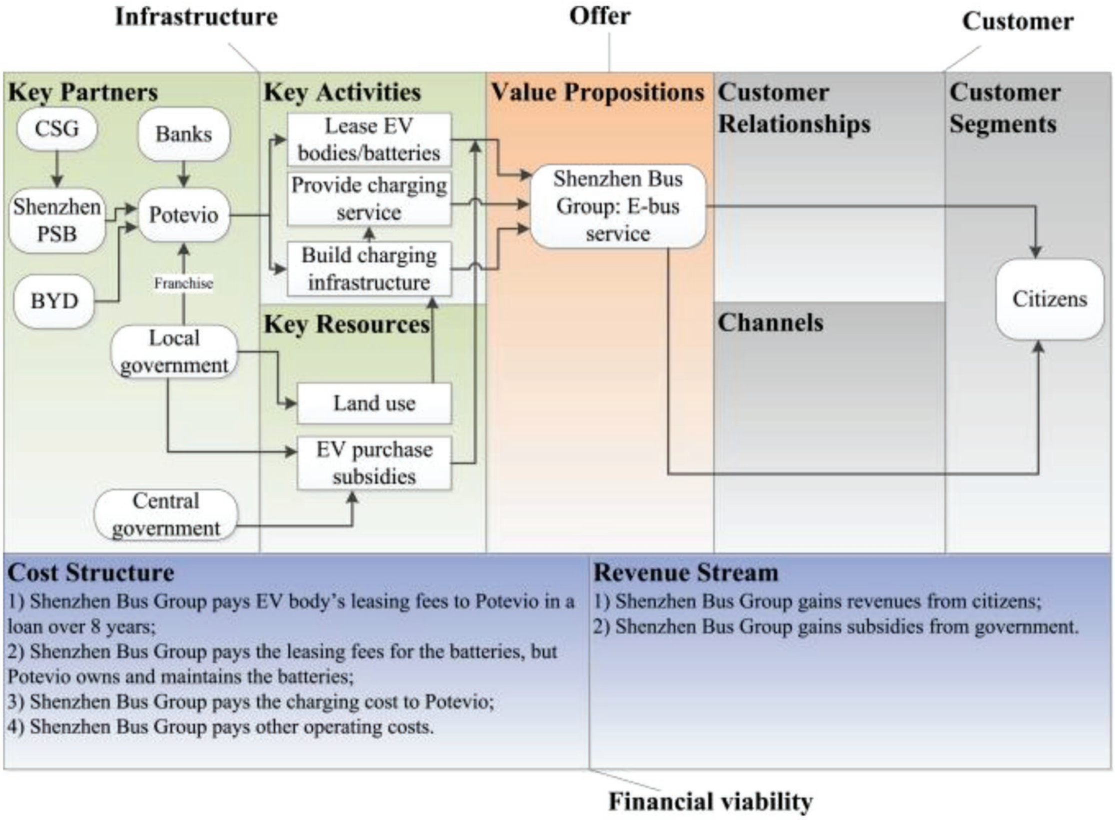

Figure 2. The innovative business model with which state-owned Potevio acted as intermediary actor between the electric bus manufacturer and the Shenzhen Bus Group. Reproduced with permission.[10] Copyright 2016, Elsevier.

In Denmark's municipality of Roskilde replacing the 20 buses serving all of its bus lines with battery electric vehicle since April 2019, for example, the cost picture was further improved with the 10 year warranty included with the electric buses, compared to the 6 year warranty on the current fleet of diesel buses.[12]

Following a tender for procurement published in late 2015, each 12 m electric bus running through Novara's roads was paid by the Piedmont Region, along with the charging infrastructure and a 10 year full service, around €526 000.

However, to understand the rate of the lithium battery price decrease it is revealing that one of the two Russian suppliers lately selected to provide Moscow's state-owned transit companies with 100 e-bus, announced in November 2017 that its electric bus equipped with Li-titanate oxide (LTO) batteries manufactured in Russia would cost 20–30 million RUB (275 000/412 000 EUR).[13]

Here, following extensive tests of battery electric buses manufactured in China, Russia, Finland, and Belarus carried out in the streets of Moscow since August 2016, public transport company Mosgortrans in mid 2018 awarded to two Russian automotive manufacturers the first contracts to supply the city with 100 electric buses each.[14] The mandatory condition of the contract for the delivery of electric buses was the localization of the manufacture process on the territory of Russia.

In detail, each contract worth 6.35 billion RUB (about 87 million EUR) consisted in the supply of 100 buses (200 in total), 31 ultrafast charging stations (62 in total), and 15 years of maintenance services according to which the e-bus supplier is responsible for the quality and reliable operation of the buses as well as of the charging stations for 15 years subsequent to delivery.[14]

Showing maturity of the technology, furthermore, the electric bus purchased will need to resist the harsh Russian winter conditions. Indeed, contrary to what happened with an electric bus costed 560 000 EUR to the city of Trier which in winter 2018 was forced to return to garage due to low temperatures,[15] no such problem was encountered with those running around the same days through the streets of much colder Russia's capital Moscow equipped with the right Li-ion batteries.[16]

Each bus is powered by LTO batteries in which LTO nanocrystals replace the graphite in the anode of the typical Li-Ion battery, affording excellent low-temperature performance (up to 80% of its full capacity at a −30 °C) and quick charging times (the new generation electric bus comes with ultrafast, small, and automated electric bus charging station taking 6–20 min to recharge the LTO battery pack, affording 100 km autonomy with rigid temperatures).

Likewise to the LFP battery, also the LTO lithium battery is designed for >20 000 cycles of full charge/discharge, equating to more than 15 years of consecutive operation.

The other 12 m long electric bus instead uses LFP batteries (produced in Russia) retaining a discharge capacity of about

Figure 3. The first e-buses running in Moscow since September 2018, decorated with the bright pattern that distinguishes them among other buses as a new mode of transport. Reproduced under the terms of the CC-BY licence.[61] Copyright 2019, Denis Grishkin.

≈67% even at -40 °C.[17] The bus ran 13 500 km in Moscow between February and June 2017 with an average daily mileage of 110 km on a single charge, with either the heating system on during winter or the air conditioning working during spring and summer.

The first electric bus with a capacity of 85 passengers (with 30 seats) entered service on route 73 on early September 2018, when the suppliers had to supply the first 15 electric buses, even though some vehicles did not arrive in time. By January 2019 the city operated 45 electric buses on five routes on which the new e-buses (**Figure 3**) had carried already over one million passengers.[18]

The electric buses are low-floor vehicles lacking level difference, being equipped with universal serial bus (USB) mobile phone and laptop chargers, climate control, cameras, satellite navigation systems, and video screen with route information for passengers.

An unified mask design featuring expressive light emitting diodes as daytime headlights used "to promote the positive image of city transport as the reliable partner for traveling around Moscow"[14] communicates the efforts made by the company to achieve a quality-driven transition to electromobility.

Currently, the State-owned Moscow transit agency Mosgortrans operates more than 6500 buses. A procurement for another 100 electric buses was held on December 2018. Overall the city in 2018, 2019, and 2020 is purchasing every year 300 electric buses (life cycle contract 15 years).[14] From 2021 on, aimed at cutting harmful polluting emissions and improve service, the city will be procuring only electric buses.[14]

A myth still surrounding electric buses is that they would not allow mass scale transportation, being limited to 8–12 m long vehicles. Following 6 months of real life testing of two articulated 18 m e-buses started in Oslo on December 2017 to check their performance during Norway's cold winter directly across one of the country's heaviest duty routes (routes 31 and 31E carrying approximately 50 000 daily travelers), the city's transport operator ordered 42 units of the same 18 m e-bus.[19] Scheduled for delivery in 2019, the new e-buses will replace a current fleet of diesel vehicles.

Fast charging with pantograph (opportunity charging, hence the OppCharge trade name of the technology) at certain bus stops or at terminals enables to provide the extra charge required to complete service up to 16 h d^{-1}. Dynamic wireless charging,[20] furthermore, allows bus drivers to charging their buses while in motion, which greatly reduces battery size and operational capability of e-buses, with charging lanes enabled by currently available inductive wireless charging technology being cost competitive for most of the existing bus rapid transit corridors.[21]

Finally, another unsubstantiated fear is that full electrification of city's bus fleets would not be possible due to insufficient power available from the electric grid. The case of Shenzhen, a 12.5 million inhabitant city whose electric bus fleet of 16 359 buses is about three times larger than the entire 5700 units fleet of New York, immediately dispels this myth.

As briefly summarized by Jobson, chief electric vehicle engineer at a large car and bus manufacturer based in Sweden:

"The average city in Europe is quite small, with around 150 000 inhabitants. They have overcapacity in the electric grid in most places. The overall energy use has been going down for the last 10 years, with a few exceptions. If the full bus fleet is electrified, there is no case where we have increased the energy use by more than 5%. If we move to the total electric vehicle fleet, it might increase by 25%. Sometimes you need to adjust the grid or build a new substation, but normally as a whole, the average city has good adaptabililty."[22]

In late 2016, the first bus depot in Europe converted from diesel to electric has been London's Waterloo Garage. It was enough to install two substations and two transformers (from 11 000 to 400 V) in the space-constrained garage (no room for expansion) along with two distribution boards and 43 charging units (39 rated at 40 kW and 4 rated at 80 kW) to complete the transition to electric mobility for both routes (five buses are operated from another depot).[23]

Operated 16 h a day on routes 507 and 521, the 51 electric buses have recorded availability above 98%, with 99.2% monthly average since launch.[23] Charging takes place overnight when electricity in the UK is cheaper, absorbing a maximum of 2.2 MW of power. No problems were encountered in around 2 years of service despite large electricity consumers nearby.

Hydrogen fuel cell buses are electric buses, with the same electric drivetrain as battery electric buses, with battery-fuel cell hybrid configuration and a *common* platform for maintenance as they *share* over 90% of the same components as battery electric buses.

The technology is proven with over 12 million km in commercial service through challenging climates and road conditions, and more than 15 years on the road in different environments, with recorded bus availability above 85%. Maintenance is simple and preferably preventive consisting in a series of simple check activities on filters, coolant conductivity, calibration of sensors, and ventilation fans to be carried out every 8000 km by a trained transit operator technician.[5]

Hydrogen refilling rapidly takes place in 7–10 min at the hydrogen refilling station conveniently and safely installed at transit depot as it happens with diesel fuel refilling.

The price for a basic 12 m FC electric bus around €650 000 as of early 2018 was about twice higher than that of a battery electric bus, but it was more than 75% lower than the price of the first FC buses commercialized on small scale in the mid 1990s. According to a leading industry's practitioner, with volume purchases over 100 buses per year, the price could reach €650 000 beyond 2020.[5]

Similarly to what happened with battery EV, with the market entry of China's companies in hydrogen fuel cell EV the decrease in cost and prices might be even quicker. Only in 2018 the country invested $12.4 billion in national and local subsidies, by providing up to $30 000 subsidy per FC vehicle locally produced, reaching the annual target of 5000 fuel cell vehicles 2 years earlier than planned.[24]

Indeed on October 2018 the city of Datong, in northern Shanxi province, invested 1 billion CNY (around $157 million) ordering to an FC bus company based in its Economic Development Zone the delivery of the first 300 fuel cell buses. It is also instructive that the bus fuel cell maker is a firm which used to make conventional lead-acid batteries, but now develops Li-ion batteries and hydrogen fuel cells.[25]

Cost and performance data validated by bus operators in Europe and in North America recently led market analysts to conclude that FC buses could compete with battery electric buses,[26] particularly for the most difficult routes (long range, and heavy duty vehicles) where they can replace diesel buses in a 1:1 replacement with any schedule.

Closing the solar energy cycle, hydrogen will be obtained by water electrolysis using clean electricity from renewable energy sources.[27] In other words, compressed H_2 needed to power the bus will no longer be shipped from distant petrochemical plants as it happens for the hydrogen FC bus fleet operating in London, where hydrogen manufactured in the Netherlands via methane steam reforming is shipped across the English Channel as liquid H_2 and then trucked to the transit bus maintenance facility (as of July 2015, over 96 tones of hydrogen supplied for more than 5600 fillings).[28]

The water-to-hydrogen electrolysis technology can be easily scaled, and today's manufacturers of "turn-key" hydrogen refilling station, which includes the water electrolyzer, hydrogen compressor, and dispenser, are able to cost-effectively increase the capacity of the refilling station from 10 to 100 buses by upgrading the compression and storage equipment and adding dispensers.

As shown in Sweden Mariestad's hydrogen refueling station (HRS) powered by solar power only (**Figure 4**), a properly designed HRS powered by PV and wind energy could generate enough hydrogen for FC bus operations. Operated by a regional energy and utility company, the HRS will go completely green and off-grid by March 2019 with hydrogen produced on-site by water electrolysis using electricity from adjacent PV and wind parks feeding a containerized alkaline electrolyzer designed to run dynamically with fluctuating supply of power from PV installations and wind turbines.[29]

Access to low cost renewable electricity is therefore critical to achieving affordable solar hydrogen from water only, which is already achievable in countries and regions such as Italy, Denmark, Sweden, Norway, Germany, Portugal, Costa Rica, Brazil, and Quebec where a large share of electricity in the grid is obtained from truly renewable energy sources (sun, wind, and water).

According to multiple analyses, a hydrogen fuel price of €5–6 kg^{-1} is widely accepted as the target for the industry, as this is the level which allows parity with diesel costs for today's buses.[5] Hydrogen at several California's hydrogen car refilling stations already sells at <$10 kg^{-1}.

Alongside with new electric engine powered by electricity, the new energy technologies on electric buses drive redesign and

Figure 4. Funded by the European Union within the project hydrogen mobility europe (H2ME) and cofunded by fuel cells and hydrogen joint undertaking (FCH JU), the hydrogen refueling station in Mariestad, Sweden, generates H_2 from water using electricity from the PV park adjacent to it. On November 2018 the first containerized electrolyzer was delivered to the hydrogen filling station. Reproduced with permission.[62] Copyright 2018, Nilsson Energy.

improvement of all bus aspects and components, including the electric motor. For example, the latest generation of hydrogen FC buses manufactured by a company in Belgium incorporates a permanent magnet motor controlled by advanced electronics to minimize noise and further reduce maintenance even compared to other electric engines.[30]

Electric buses are no longer be constructed in steel, but either in light aluminum or in composite material. For instance, all the buses made by China's largest electric bus manufacturers use an aluminum space frame, aluminum wheels, and fasteners. As a result, the weight of the bus body was reduced by over 1.2 tones (namely by over 40%) in comparison to the original steel model.[31]

The combined weight savings improved the overall range of the electric bus by more than 10%, extending it to 290 km (180 miles; and since then further improved).

Aluminum wheels for electric buses are not only lighter compared to steel wheels but also offer better heat dissipation prolonging the tire and brake life. The aluminum external surface, furthermore, after the "Glanzeloxierens" surface treatment process enables the wheel to withstand thousands of km and washes without cracking, peeling or corrode.

Similarly, the battery electric buses of a U.S.-based manufacturer use lightweight carbon-fiber-reinforced composite material for the whole bus frame. As a result, the buses are even lighter than those made of aluminum and can travel steep roads without autonomy problems.

The composite structure utilizes a combination of reinforcement materials including fiberglass and carbon fiber that, beyond reduced weight, offer improved strength and crash resistance since the composite can absorb much more energy in a crash, and at much faster rates than metal.

In further detail, the structure is manufactured in layers.[32] A gel-coat layer is first inserted in the mold a to produce the smooth exterior. Dry fabrics are then subsequently arranged (triaxial fiberglass reinforcements; unidirectional carbon fiber; carbon fiber; and quadriaxial fiberglass material) in the mold. The resulting layered structure is eventually added with vinyl ester resin system and cured at room temperature.

The new electric powertrain is driving innovation even in tire industry. With the unique ability of the electric motor to deliver the full torque immediately, the electric bus accelerates much more quickly than the ICE bus, requiring faster tire response to speed as well as enhanced protection from contact to curbstones. Hence, a leading South Korean manufacturer recently launched a tire specifically designed for urban electric buses featuring very low rolling resistance, high grip, increased load capacity, and reinforced sidewall to protect the tire from damage following contact with curbstones.[33]

3. Environmental and Health Impact

The main responsible for air pollution in cities is, invariably, the combustion of fossil fuels (coal, diesel, gasoline, and natural gas) mainly in internal combustion engines (road traffic) but also in heating systems to heat buildings in the cold season. Combustion of fossil fuels also takes place at industrial plants and at thermoelectric power units. Road traffic of ICE-powered vehicles is responsible for a large fraction of the overall release of harmful fine and ultrafine particulate matter with aerodynamic diameter less than 10 µm (PM_{10}) and 2.5 µm ($PM_{2.5}$), NO_x, VOC (volatile organic compounds), black carbon, ozone, and CO air pollutants.

In London, for instance, a thorough analysis of air polluting emissions shows that whereas in 2008 road transport contributed 46% of PM_{10} and 49% of $PM_{2.5}$, the percentage values had respectively increased to 50% and 54% in 2013.[25] Furthermore, practically no decrease in road traffic contribution was noted for nitrogen oxides (NO_x) emissions (51% in 2008 and 50% in 2013).[34] Where concentrations are highest and limits exceeded, most NO_x emissions are from transport. In the same city, poor air quality is known to cause respiratory and cardiovascular conditions and is linked to around 9400 premature deaths a year.

It may also surprise to learn from real-world testing in the roads of Spain's Barcelona, that traveling in diesel-fueled bus exposes commuters to the highest concentration of harmful aerosol inhalable particles ($>5.0 \times 10^4$ cm^{-3} of particles 10–300 nm in size), with extreme transient peaks at busy traffic crossings accompanied by peaks in Black Carbon and CO.[35] In brief, diesel buses are an especially potent pollutant source.[36]

Recent real-world results for electric buses tested in Macau, China indicate that a 12 m battery electric bus significantly reduces the well-to-wheel emissions of NO_x and VOC air pollutants under all operating conditions (by 60–80% in comparison to "Euro IV" diesel bus), and by 40% for $PM_{2.5}$ under congested traffic conditions.[37]

Under the latter conditions, typical of urban bus cycles, the instantaneous power profile of the electric engine provides a significant advantage in saving energy compared to both ICE and hybrid buses, which adds to the their superior energy efficiency from tank to wheel.

When traffic conditions become increasingly congested (lower average speed), the energy consumption increases for both 10 and 12 m battery electric buses (**Figure 5**).[37] However, whereas consumption under half load conditions (and air conditioning off) increases by 32% for the 12 m electric bus and 27% for the 10 m electric bus when average speeds are reduced

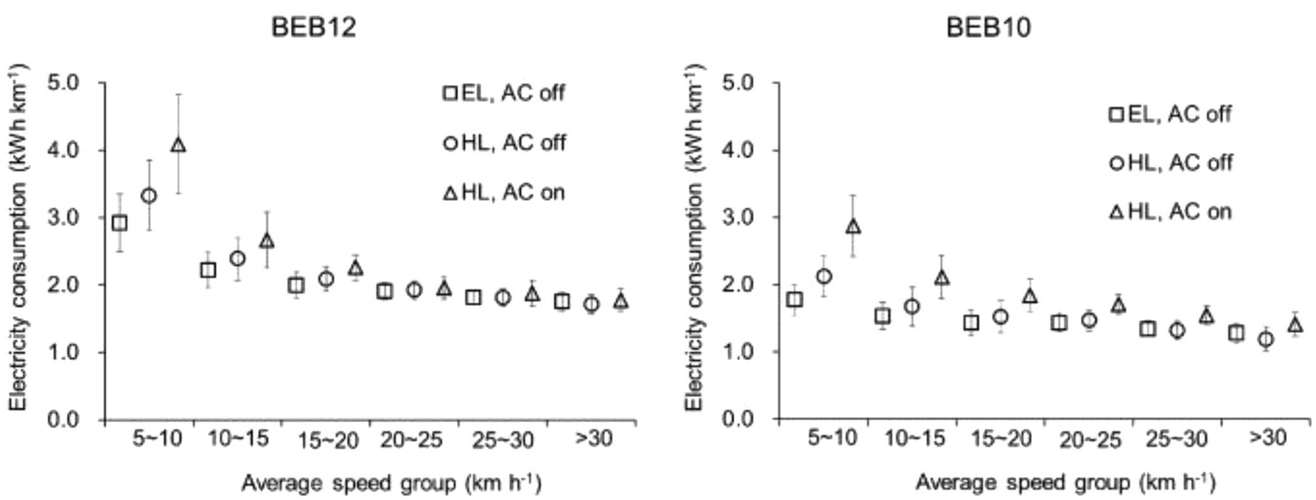

Figure 5. Distance specific electricity consumption of two battery electric bus (BEB, 12 and 10 m long) under various traffic and vehicle usage conditions traveling in Macau at half load (HL, 40–45% of maximum loading capacity) or empty load (EL). AC is air conditioning. Electricity consumption is estimated using second-by-second current and voltage data recorded by the on-board diagnostic. Reproduced with permission.[37] Copyright 2018, Elsevier.

from 25–30 to 10–15 km h^{-1}, energy consumption for both diesel bus and hybrid diesel bus increases by over 60%.[37]

During transit, an electric bus does not emit any gaseous pollutants. Gaseous emissions, if any, take place elsewhere by generating the electricity needed to power the bus. Hence, they heavily depend on the power mix of the country and region where the electric buses are deployed. Emissions will be vanishingly low in Costa-Rica,[38] where practically all power originates from hydroelectric and wind power, or in Quebec, where close to 100% energy originates from hydroelectric dams.

If the same electric buses traveling across Macau are deployed in Beijing streets, where most electricity originates from coal-fired power stations, the well-to-wheel emissions of $PM_{2.5}$ would be greater than the diesel counterparts.[37] This calls once again for the need for concomitant deployment of electric vehicles along with increase in renewable power generation.[4]

In countries such as Germany, Italy, Norway, Spain, Denmark, Brazil, and Portugal where the amount of power generated via renewable energy sources approaches or even exceeds 50% (close to 100% in Norway, Costa-Rica, Quebec, Brazil, and Portugal), the deployment of electric buses is and will be particularly advantageous.

Another key health advantage of the electric bus is that it helps to significantly reduce noise in the urban environment. In idle mode, an electric bus is so quiet it is almost impossible to measure its noise.

Compared to a state of the art hybrid (diesel-electric) bus certified at a noise level 5–7 dBA below the demanding Sweden's legal requirement, a battery electric bus manufactured by the same company at the typical city bus speed emits a noise that, perceived at 7.5 m from the bus, is 7 dBA lower than that of the diesel-electric bus (almost half perceived noise level when leaving the bus stop; with even larger noise reduction indoors).[39]

This single outcome contributes to make public transport with the electric bus highly attractive to *new* passengers, thereby reducing traffic and pollution from private cars.

In addition, replacement of ICE with electric buses dramatically increases the value and the attractiveness of urban areas served by electric buses formerly plagued by the noise produced by the city traffic and by diesel-fueled buses. Only in the EU countries about 125 million people are exposed to unhealthy noise levels.

The latter indeed, in most cases are not the low noise diesel-electric buses, but older and much noisier diesel-only buses whose continuous stop-and-go operating mode greatly affects the quality of life in urban neighborhoods across the world.

An independent study carried out in 2013 for the Swedish Transport Administration, conservatively established that diesel-fueled buses contribute >37% to the overall socioeconomic costs of road noise.[40] The replacement of the conventional bus fleet with a fleet of e-buses would save 90% of said cost.

4. Outlook and Perspective

Commenting in 2017 the repeatedly inaccurate forecasts concerning photovoltaic energy growth published every year since 1979 by the International Energy Agency (IEA), Shahan emphasized how "obsessively pessimistic forecasts mislead the public, mislead investors, mislead businesses, and mislead policymakers."[41]

Similarly, the current market estimates projecting poor annual growth (2–3%) of the electric bus market over the next decade, might end likewise to what happened to PV energy, projected by the IEA in 2010 to reach 180 GW of installed capacity by 2024 while the target was met in January 2015.[42]

Writing at the end of 2018 a practitioner of Europe's bus industry was noting that:

"Although much lower than 5 years ago, latest estimates suggest an EV bus in Europe still costs somewhere between €470 000–520 000..., far higher than an ICE counterpart. Unsurprisingly, this means that without additional funding to offset high initial purchasing costs and bring the Total Cost of Ownership closer to parity with ICE vehicles, non-ICE buses are currently unaffordable."[43]

A recent study comparing different bus options based on their total lifecycle costs (including vehicle and infrastructure, fuel, maintenance, infrastructure, and air pollution damages) shows that battery electric buses are already competitive with liquid natural gas, compressed natural gas, and hybrid diesel buses.[44]

In particular, the study found that if 80% of the upfront capital costs of new bus purchase were covered (as it typically happens with public transit agencies receiving capital funding from city and central governments) both rapid- and slow-charging battery electric buses were already largely competitive.

The fundamental reason for which public transit agencies beyond China were facing electric bus prices "somewhere between €470 000 and 520 000" is the absence of the lithium ion battery industry in their countries. One of the two Russia-based bus and car manufacturers currently supplying to Moscow with 100 out of the first 200 electrobuses, claimed in November 2017 to be able to profitably sell an advanced 12 m battery electric buses with battery and electric engine at €275 000.[13]

A glance to the battery electric bus market share in Europe Middle East and Africa in 2018 (**Table 1**) is enough to notice the absence of most Europe's main conventional bus manufacturers.[7]

In EU countries, the electric bus market first went from roughly 400 buses sold in 2016 to 1031 in 2017 (+158%) and is expected to double again in 2018 as the number of buses ordered during the first *half* of the year almost exceeds the overall number for all of 2017.[45]

Table 1. Europe, Middle East, and Africa electric bus market share in 2018 (buses above 6 tones, not including trolleybuses). Adapted with permission.[7] Copyright 2018, Elsevier.

Manufacturer	Country	Market share [%]
BYD (and ADL)	China (and UK)	29
VDL Bus and Coach	Belgium	24
Solaris	Poland	17
Irizar	Spain	9
Volvo	Sweden	8
Other	–	13

It is also instructive to learn that in China, regardless an overall Chinese bus market decreasing by 13.5% in the first nine months of 2018, the market for electric buses increased by over 20% to a total of 55 658 e-buses sold.[46]

In September 2018, the country's largest e-bus manufacturer had already achieved a total sales volume of 90 000 electric buses,[47] whereas it is also revealing to learn that the 50 000th e-bus produced on January 2019 by China's second largest e-bus manufacturer was being exported to Spain, with the company recording a clientele already spanning across 300 cities around the world.[48]

Such market growth rates are distinctly far from the 2–3% annual growth rate forecasted by several market research firms. Accordingly, one bus manufacturer based in Spain thanks to a 75 million EUR investment inaugurated on May 2018 the first plant entirely dedicated to manufacturing electric buses (1000 vehicle per year capacity) in the Spain's town of Aduna.[49]

The world's lithium battery industrial capacity was 28 GWh in 2016 and increased to 220 GWh in 2018,[50] with China holding over 60% of the world's output. Currently, there are 52 lithium-ion battery large factories under construction or announced, with capacity projected to reach over 1100 GWh by 2028.[50]

Similarly, large electric utilities already hit in revenues and profits by the unforeseen dramatic growth of wind and solar PV power[51] are finally deploying EV charging poles at accelerated pace in their home countries where the production of battery and hydrogen electric vehicles has remained a niche, regardless of announcements and presentation of prototypes.

Add to this the impact of government mandate on the adoption of e-bus to combat air pollution with, for example, California requiring that all new buses be carbon-free by 2029; Moscow purchasing electric buses only since 2021; or Shanghai, with 24 million inhabitants the world's most populous city, replacing all traditional vehicles in its public transport system including over 17 000 buses (9368 of which, 55% of the entire city fleet, already electric by early 2019) to be completed in 2020, 2 years ahead of schedule.[52]

Finally, a still widespread concern among potential producer of EVs regards the feasibility to use lithium as key component of Li-ion batteries in the long term.

A comparison of Li-ion batteries with lithium manganese oxide and lithium iron phosphate cathodes shows that the resource availability issue in this case is not originated from the lithium itself but from manganese ore.[53] Alongside with Narins we remind that access to lithium is limited more by logistical issues (cost-effective access) and quality than actual availability, with the world's largest (or second largest, with over 9 million lithium tones) known lithium reserves (in Bolivia) not yet exploited.[54]

Similarly today's FC vehicles use approximately the same amount of platinum present in the catalytic converters of diesel-fueled cars.[2]

After prolonged use in EVs, batteries can be used to store and make available electricity to small and large buildings in true second-life solutions,[55] as it happens for example at Amsterdam's football stadium where a 3 MW/2.8 MWh energy storage system partly using former electric car batteries now provides valued backup power and useful services to the grid.[56]

Furthermore, the higher price of lithium, manganese (and cobalt) due to dramatically increased demand from the battery industry today makes recycling economically profitable,[57] with several new recycling plants having lately started operation in Asia, Europe, and North America.

Under these practical circumstances, with production costs rapidly decreasing driven by dramatic growth in production and in light of the economic, health and environmental benefits brought to cities briefly addressed in this study, the destiny of internal combustion engine urban bus is clear: in the course of the next decade (2019–2028) it will be the first ICE vehicle to go out of production.

Following previous studies in which we identified the need and suitable ways to reshape education of energy managers,[58] particularly in the field of solar energy,[59] the outcomes of this study will be useful also to inform new educational initiatives aimed to provide undergraduate students and energy and mobility professionals with updated critical knowledge in the key emerging technology area of electric vehicles, and of electric buses in particular.

Conflict of Interest

The authors declare no conflict of interest.

Keywords

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