

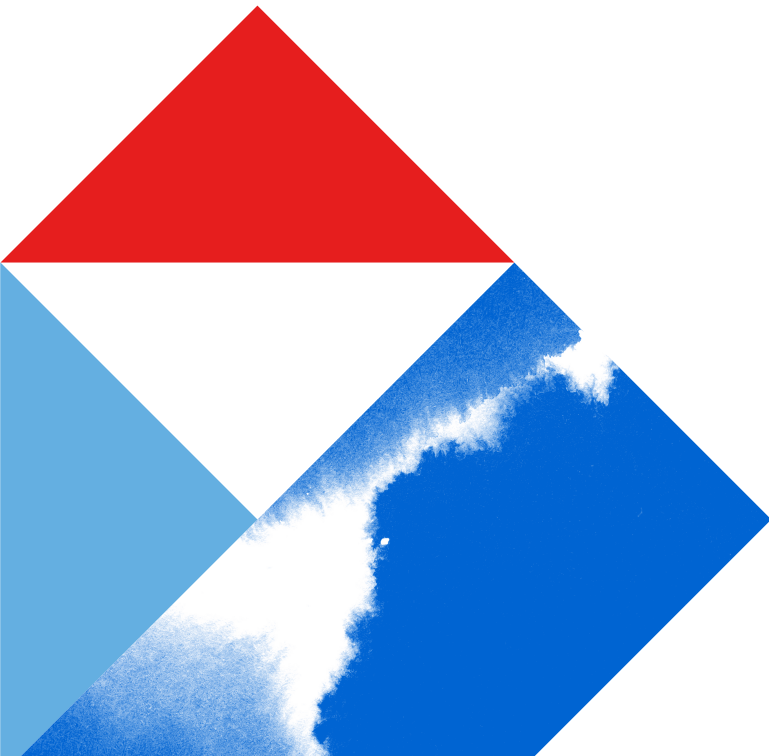
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Battery requirements for emission-free buses

Advantages of LTO batteries for special bus types



The market for local emission-free buses is growing at a rapid pace. According to a study by Chatrou CME Solutions¹, 42% of buses registered for the first time in Europe in 2023 had emission-free drivelines. This means growth of +53% compared to the previous year and almost triple the level in three years. In 2023 a total of 6,147 battery electric buses (battery electric vehicle, BEV) were newly registered. The number of new buses with fuel cells (FC) doubled to 207.

This development is being partly driven by the EU CVD Directive² (EU-2019/1161), which sets minimum targets for the procurement of low- and zero-emission passenger cars, commercial vehicles and buses used in public transport services. By the end of 2025, at least 24-45% of new buses throughout the EU must be “clean” and by 2030 the figure is 65% for some countries. The result is rapid growth in the market for emission-free buses. 42% of all city buses registered for the first time in Europe in 2023 were already emission-free, 53% more than the previous year.

A high energy density enables overnight charging of battery electric buses at the depot

The typical ranges of battery-powered buses these days are in the order of 300km, with battery capacities of up to 600kWh. This means that most daily rounds within urban areas can be completed with a single charge. BEV buses, which are only charged overnight at the depot, are therefore in widespread use now.

This has been made possible by the development of lithium-ion batteries with very high energy densities. At the level of the battery pack, NMC batteries with more than 175Wh/kg and LFP batteries with over 125Wh/kg are now possible these days. However, these high energy densities are always coupled with a limited charging power and service life. It generally takes 3 to 5 hours to recharge the battery. In order to prevent excessive ageing and maintain the range of the battery at a reasonably constant level, however, the effective usable capacity is often limited to around 60%. Therefore in actual operation the gain in terms of energy and range is limited to a considerable extent. Even allowing for this limitation, the service life is limited by calendar ageing. In most cases the battery needs replacing at least once during the typical operating life of a bus. This major influence on the total costs over the life cycle of the bus (total cost of ownership, TCO) is often not taken into consideration.

Limitations for quick charging and service life

These limitations are largely due to the properties of the graphite anodes. The low reduction potential of the graphite anodes requires the generation of a protective layer, the so-called solid electrolyte interphase (SEI), to provide a passivation layer on the electrode surface and inhibit the progressive decomposition of the electrolyte. This SEI protective layer grows over time, depending on temperature and state of charge, which leads to the ageing of the battery cell. It loses capacity and its internal resistance increases.

In addition to calendar ageing, the service life of the battery is also limited through its operation. The volume of the graphite anode changes by up to 15% during charging and discharging. This regular expansion and contraction causes small cracks in the SEI protective layer, which further accelerates the growth and ageing of the cell.

Notes

¹ Chatrou CME Solutions: <https://www.sustainable-bus.com/news/electric-bus-market-2023-registrations-man-solaris-yutong-wrightbus/>

² CVD Directive EU-2019/1161: <https://eur-lex.europa.eu/legal-content/DE/TXT/?uri=CELEX:32019L1161>

There is yet another important factor in cyclical ageing as well. As a consequence of the low electrochemical potential of the graphite anode, there is a risk that rather than being intercalated in the graphite when the cell is charged, the lithium ions are deposited in the form of metallic lithium on the surface instead. This is referred to as lithium plating. It also causes a reduction in capacity and increase in the internal resistance of the cell. The likelihood of lithium plating increases the faster the cell is charged. It is particularly likely when the battery is already highly charged (high state of charge) or if it is charged at very low temperatures. On the one hand, therefore, the use of graphite anodes enables a very high energy density, but on the other hand its properties mean that there are limitations in terms of the charging speed and service life of the battery.

Alternatives to depot charging

In addition to BEV buses, which are charged overnight at the depot, there are a range of alternatives for emission-free buses. Over long distances and for rounds which exceed the range of the available batteries, e-buses are recharged during daily operation. This is generally undertaken at bus stops at the end of a route or at the junctions where several routes meet and is referred to as opportunity charging (OC). This opportunity charging needs to be far more rapid than charging overnight at the depot of course. The battery needs to be charged up again within just a few minutes with very high charging power. Opportunity charging is also often used for buses which are in operation more or less round the clock. In this case, there is simply no time for hours of charging overnight, or the number of buses would need to be increased in order to compensate for these times.

Furthermore, charging large fleets simultaneously overnight is quite a challenge in many cases. The depots need an expensive grid connection with very high peak power to be able to do this. Opportunity charging means that the power can be spread over numerous locations and times. A further advantage for OC buses is that more frequent recharging means the batteries have a significantly lower capacity, saving space and weight. A special type of OC bus is used at airports. These buses never have to travel far for each trip. A very small battery can be used here instead, one which is regularly recharged again during the stops at the terminal.

For long distances, fuel cell buses are increasingly used. This is also the case for buses which are not used just for a single route only but are intended to be used on a flexible basis. The longer range and faster refuelling of FC buses is an advantage here. There are already over 500 of these buses on the roads in Europe. The electric power train of FC buses is very similar to that of battery-powered buses. The energy is stored in the form of hydrogen which is then converted into electricity in the fuel cell. However, FC buses still require a battery between the fuel cell and the motor to compensate for power fluctuations and absorb the energy recovered during braking.

A third alternative is trolleybuses. The high level of capital expenditure required for the installation of the overhead wires is a frequent obstacle. Trolleybuses are generally more efficient than BEV buses in operation, making them often cheaper as a result. In addition, they offer advantages in winter too, when the power of the battery is reduced in cold temperatures. Trolleybuses also have a battery on board so that they can also run in areas without overhead wires. This can be the case, for example, where there are roadworks, diversions, junctions or in historic city centres. The larger the proportion of the route on which the bus has to operate without overhead wires, the larger the battery needs to be.

Battery requirements and advantages of LTO

What all the alternatives, namely OC and FC buses and trolleybuses, have in common are the requirements relating to the battery. They are very different from those relating to depot-charged BEV buses. In all cases the range, and hence the energy density, is not the key issue. Instead, what is most important is that the battery can be recharged very often and very quickly despite having a lower capacity. It is therefore not primarily a question of storing the energy, but using it efficiently.

This is why LTO batteries are often used in these buses. Unlike NMC and LFP batteries, graphite is not used as the active material for the anode, but lithium titanate oxide (LTO) instead. LTO has a spinel crystalline structure, the volume of which does not change during charging and discharging. LTO batteries therefore have much higher cycle stability and can be charged and discharged between 20 to 40 times more frequently. Moreover, the LTO anode requires practically no SEI protective layer. This means that there is no SEI growth and much lower calendar ageing due to the decomposition of the electrolyte. LTO batteries can achieve much longer service lives of 15, 20 or more years.

A third major difference compared to graphite is that the electrochemical potential of LTO is significantly higher than that of metallic lithium. There is therefore no risk of the dreaded lithium plating occurring during charging, even if the battery is charged up very quickly. Depending on cooling, LTO cells can be charged up to 20C, which means that 80% of their capacity can be charged in just 3 minutes.

LTO battery cells have an energy density of approx. 100Wh/kg, which is well below that of NMC or LFP. For OC and FC buses and trolleybuses, however, it is the rapid chargeability, higher cycle stability and longer service life that are more important. These properties of LTO are what make it possible to minimise the size, weight and total costs of the battery and at the same time avoid the need to replace the battery during the service life of the bus.

Another key advantage of LTO is their inherent safety mechanisms. With graphite, dendrites can form on the anode surface over time. The more the lifespan progresses, the greater the risk that these needle-like structures can generate an internal short-circuit between the electrodes, which could lead to a dangerous thermal runaway in the cell. Since there is no plating of metallic lithium when LTO cells are charged, there is also no such risk of a short-circuit due to dendrites. Should a short-circuit nevertheless occur for other external reasons, the cell discharges very slowly due to the material properties of the LTO. This prevents the cell from heating up quickly and prevents the risk of thermal runaway. For these reasons LTO batteries are extremely safe and are the preferred option for use in safety-critical applications such as public transport.

In Europe there are already over 3,000 buses on the roads, some of them for over ten years now, with LTO batteries from Toshiba. Most of them are OC buses and trolleybuses. There has not been a single safety-related incident during this time and not one of the batteries has had to be replaced due to age yet.

Examples from practice

Due to the challenging topographic situation and cold winters, Zürich lightTram® 19 uses buses with overhead wires from Hess AG. On line 83, the diesel buses used to date are replaced by nine light trams, thereby saving over 200,000 litres of diesel and around 540 tons of CO2 each year. Other cities with trolleybuses from Hess include, for example, Lyon, Neuchatel, St Gallen, Bern. To cover sections of routes without overhead wires, smooth out power peaks and recuperate braking energy, Hess uses batteries with Toshiba SCiB™ LTO cells in the buses. This enables the buses to be driven 30 km without overhead wires.

Solaris has secured over 500 orders for its fuel cell city buses, establishing itself as the leading European manufacturer in this segment. Over 180 of these FC buses are already operational across a dozen European cities. The Urbino 18 hydrogen bus offers a range of 600 km (according to SORT2 tests) and can be refuelled in 20 minutes. To ensure optimal fuel cell efficiency, Solaris uses a high-performance lithium-ion battery from Impact Clean Power Technology. This battery effectively addresses start-stop issues of the fuel cell, features a regenerative braking function and improves drive dynamics. Impact relies on SCiB™ cells from Toshiba for the battery, ensuring service life of more than 10 years despite the high energy throughput, high current levels and low capacity of only 60kWh.



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