PRIMER: BATTERY ELECTRIC VEHICLE (BEV) BUSES

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January 2023

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A Primer: Batteries for Electric Buses

Preface

This Primer complements A Primer: Hydrogen as a Fuel for Public Transport,[1] published November 2022. By 2040s it is widely forecast that Battery Electric Vehicles (BEV) buses – the terms BEVs and EVs are interchangeable – will make up at least 70% of global bus fleets and will be the fastest growing segment of road transport. Driving the argument for BEV buses have been two separate issues. At the commercial level, the cost of batteries, which account for anything up to 40% of vehicle cost, has fallen close to the point where BEVs become price competitive with vehicles driven by internal combustion engines (ICE) using petroleum, diesel or some form of liquified natural gas.

At the environmental level, the imperative is to reduce tailpipe and kerbside emissions of the Green House Gas (GHG) CO2 (carbon dioxide) and very fine particulate matter. This is known by its measure as PM2.5 and consists of such particles as nitrogen oxide (NOx), carbon monoxide (CO), and sulphur dioxide (SO2). These are especially dangerous as they penetrate the lungs and can enter the blood stream. Beside the costs of premature deaths and days off due to sicknesses, the rise in GHGs on its own has become an existential threat to the entire planet. However, switching to BEVs – buses, cars, trucks, trains, ships, aircraft, etc. – may only reduce the dangers at one end of the transport supply chain by increasing them at the other where electricity generation is a major source of GHGs. The race is now on to replace carbon fuels such as coal, oil and natural gas with 'green' renewable sources of energy such as solar power, wind power, hydro-power, biomass, etc. But the existential question is will renewables be sufficiently sustainable commercially to offset carbon fuels.

This concern is creating a reversion to nuclear reactors which are carbon-free but produce indestructible radioactive waste instead. Although a science laboratory has finally created a net-positive output of energy simulating nuclear fusion from which there is no radioactive waste, it is not forecast to become commercially viable any time before the COP (Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change) target of net-zero emissions by 2050. Unless there is a marked reduction in the demand for electricity, such as a wholesale shift away from private to public transport, net-zero emissions by 2050 seem like a bridge too far. Although the policy choices are of the utmost importance, they are not the subject of this Primer.

This Primer focuses rather upon the technological and economic trade-offs involved in the operational and transport policy choices surrounding the transition to BEV bus fleets. The focus is upon single and double-decker buses although passing reference is made to mini/maxi buses and trams. Other forms of public road transport such as taxis and tricycles are not addressed, but two addendum have been added on e-ferries and e-taxis. The *Primer on Hydrogen as a Fuel for Public Transport* recognised that hydrogen fuel cells might be more appropriate for vehicles that required rapid refuelling such as taxis, but fast recharging battery technologies may yet change the options.

The Primer reviews the most recent developments in BEV battery designs, the supply, demand and fluctuating prices of the minerals that enter their production, their price and competitiveness over their lifecycle with diesel alternatives, the economics of BEV buses and the operational challenges of

[1] John Ure (November 2022) A Primer: Hydrogen as a Fuel for Public Transport https://accesspartnership.com/a-primer-hydrogen-fuel-for-public-transport/ and https://www.wcbc.online/publications

battery recharging infrastructures, including the sustainability of the battery-swapping business model, and the equally daunting challenges of battery recycling, and finally the trade-off between reduced kerbside emissions and the rising demands for electricity generation which can be carbon-intensive. The golden rule for e-bus development, from battery types to bus types and route operations to infrastructure choices is repeated throughout the literature… there is no golden rule; unsurprisingly for a nascent sector, everything from manufacturing and battery standards to bus designs varies across markets. As such, and as with the *Primer on Hydrogen as a Fuel for Public Transport*, this Primer only claims to review the already published evidence.

This primer is a contribution to a research application project (RAP-2) on decarbonising public transport as part of the Data Trust 2.0 project being planned by the HK PolyU.[2] It is entirely based upon secondary sources and does not claim to add new insights but to explain existing ones. It may be reproduced in full or in part by third parties subject to acknowledgment being given of the sources.

Thanks to my colleagues Dr Jenny Wan and Terry Graham in help in formatting and proofreading the draft, and to Andrew Pickford for his insights, and to Eliz Sham for her contribution to the country studies.

[2] Dr John Ure is director of the Fair Tech Institute of Access Partnership. He authored a paper *Decarbonising public Transport in Hong Kong* as chapter 4 in the final report of Data Trust 1.0 in October 2021 – see https://datahub.hku.hk/articles/report/Intermodal_Transport_Data-Sharing_Programme_Final_Report/17040194.

Primer: Batteries for e-vehicle buses (BEV buses)

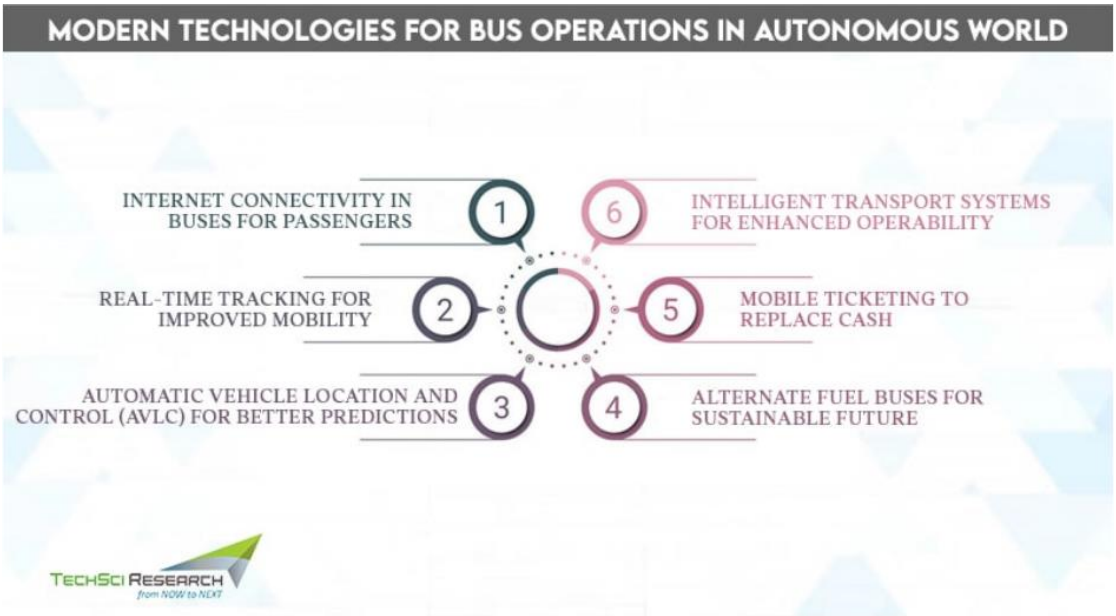
> The difference between an internal combustion engine (ICE) and a BEV is that the former requires a spanner, the latter a computer.

Part 1: Batteries for E-Vehicle (BEV) Buses – Chemistry and Costs

Batteries to power an engine are of an entirely different order from other vehicle batteries. All modern motorised vehicles are packed full of electronics, some to provide power steering, some to control functions such as emergency breaking, air conditioning, remote monitoring, prediction and diagnosis of faults, and so forth. Supporting this is connectivity to the Internet. This is the age of Intelligent Transport Systems (ITS), including driverless or autonomous vehicles. But engine batteries are different.

Although many buses have become Battery-driven Electric Vehicles (BEVs), for the most part public service buses remain emissions-producing during a period of transition from diesel internal combustion engines or the use of Liquefied Petroleum Gas (LPG), in Spain for example,[3] or Liquified Natural Gas (LNG), in India, for example,[4] or Compressed Natural Gas (CNG) Buses in the USA for example[5] – of the three CNG is relatively less polluting, but they differ in their energy densities, so for long distance trucks for example LNG is often the preferred option.[6] Figure 1 offers a summary of the role of electronics in an ITS.[7]

Figure 1



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[3] Auto-Gas.Net (2021) *First bus powered 100% by LPG under development in Spain* https://auto-gas.net/mediaroom/first-bus-powered-100-by-lpg-under-development-in-spain/

[4] The Indian Express (June 2021) *Kerala rolls out its first LNG-powered bus service* https://indianexpress.com/article/india/kerala/kerala-first-lng-powered-bus-service-ksrtc-7368963/

[5] Via (2020) *Compressed Natural Gas (CNG) Buses* https://www.viainfo.net/cng/

[6] Universal Technical Institute (January 2020) *CNG vs. LPG vs. LNG Fuel: Understanding the Differences* https://www.uti.edu/blog/diesel/cng-lpg-lng-fuel

[7] TechSciResearch (March 2022) *Modern Technologies for Bus Operations in Autonomous World* https://www.techsciresearch.com/blog/modern-technologies-for-bus-operations-in-autonomous-world/298.html

An historian of the battery might trace its conceptual origins back 2,000 years to the Parthians who used a jar full of vinegar as an electrolyte, an iron rod and a copper cylinder, but the reproduction and general use of electricity is a modern invention dating from the 1800s, with the first creation of a 'voltaic cell' for static or battery electricity attributed to Alexandro Volte.[8] A Wikipedia list of battery types lists 33 non-rechargeable or primary batteries, over 30 secondary or rechargeable types, and 24 "batteries by application", including the electrical-vehicle battery.[9]

Battery Capacity

The capacity of a battery is measured in amp-hours (Ah) and the following formula can be used to determine how long before it needs recharging:

Amp Hours (Ah) / Amps (A) = Hours (H)

For example, if an electric car (e.g., a Tesla) has a 350 Volt lithium-ion battery that has a capacity of 230 Amp hours it can deliver 230 Amperes of electric current to charge a 350-Volt device for one hour. A rule of thumb is that the higher the Ah the longer it will retain its energy.[10] But overheating is always a danger due to variations in temperature, alternator and recharging problems, sudden extra heavy usage such as acceleration up steep inclines, short circuits, malfunction of the cooling system, etc.[11] For this reason a properly installed vehicle battery comes with a Battery Thermal Management System (BTMS) to help regulate the battery temperature, and batteries for vehicles will usually come with their own Battery Monitoring System (BMS) to give warning.

Battery Pack for Double Decker Bus[12]	**Battery Pack for Single Decker Bus**[13]
	

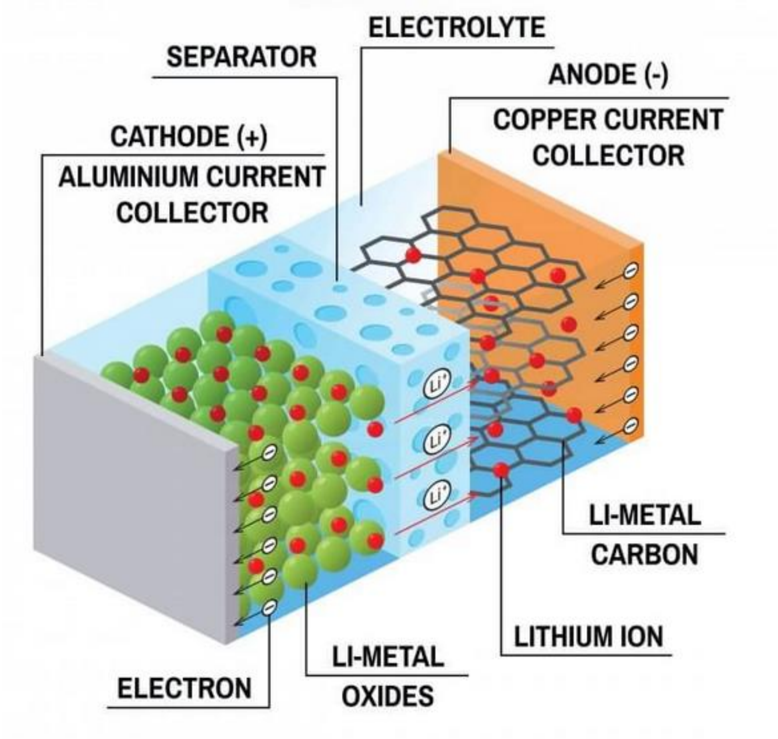
The components of a complete 'battery pack' for installation are its packaging and mounting structures, an electrical or electronic control system and a series of connected battery cells each

[8] Battery University (February 2022) *BU-101: When Was the Battery Invented?* https://batteryuniversity.com/article/bu-101-when-was-the-battery-invented
[9] Wikipedia (August 2022) *List of battery types* https://en.wikipedia.org/wiki/List_of_battery_types
[10] WebstaurantStore (2022)*Types of Batteries* https://www.webstaurantstore.com/guide/923/batteries-buying-guide.html
[11] Repair Smith *Why Is My Car Battery Overheating? (9 Reasons + Solutions)* https://www.repairsmith.com/blog/car-battery-overheating/
[12] Progreen (2017) Pure electric bus battery pack http://www.progreensgroup.com/en/product/html/?83.html
[13] TUMA (July 2019) *How to store lithium-ion battery cell pack in electric* bus? https://www.heavydutyslide.com/en/news/How+to+store+lithium+ion+battery+cell+pack+in+electric+bus%3F

containing an anode and a cathode, together with an electrolyte solution and a separator between them.

Figure 2

Lithium-Ion Battery Charge/Discharge



Source: Battery diagram royalty-free images[14]

Figure 2 illustrates a Lithium-Ion (Li-ion) battery with a current running from an anode through the electrolyte to a cathode as described later in this Primer. Note: an ion is a positive electrically charged atom or 'cation', an 'anion' is a negatively charged atom. The anode and cathode store the lithium with a separator between them. The electrolyte carries positively charged lithium ions from the anode to the cathode through the separator when discharging a current of electricity to the vehicle, and vice versa when the battery is being charged.

BEV Battery Energy Ratios

Batteries for powering vehicles are known as 'deep cycle batteries' – they can be discharged to a lower depth and have a higher charge cycle[15] – as opposed to batteries for ignition and lighting. They are identified by their **specific density** which is measured according to two ratios:

- **Specific energy or energy density** – is *how much energy* the battery can store with respect to its mass (a power-to-weight ratio, e.g. how far can it drive a vehicle), also known as the **gravimetric energy density** and typically expressed in Watt-hours/kilogram (Wh/kg)

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[14] Battery diagram royalty-free images https://www.shutterstock.com/image-illustration/liion-battery-diagram-rechargeable-which-lithium-791697073

[15] Science Direct (2016) *Charge Cycle* https://www.sciencedirect.com/topics/engineering/charge-cycle

- **Specific power or power density** – is *how much power*-to-volume ratio to minimise the space they occupy in the vehicle (a power to mass ratio, e.g. how fast can it drive the vehicle), also known as **volumetric energy** density, measured as Watt-output/kg or Wo/kg.

Box 1

Electrical power definitions and ratios: 1 Watt = 1 Volt x 1 Amp

- **Volt** - is a unit of electric *potential*, also known as electromotive *force*, and represents "the potential difference between two points of a conducting wire carrying a constant current of 1 ampere, when the power dissipated between these points is equal to 1 watt."
- **Amp** - short for ampere, is a unit of electrical *current* measuring the electromagnetic force between electrical conductors carrying electric current.
- **Watt** - is a measure of *power* where one watt (W) is the rate at which work is done when one ampere (A) of current flows through an electrical potential difference of one volt (V).

Source: About Mechanics[16]

Other important measures are:

- **State of Charge (SOC)**[17] – the percentage of a battery's energy that has been used up; different batteries react in different ways according to their chemical composition and structure: in some cases regularly running a battery down towards a zero charge can extend its lifetime, in other cases keeping the state of charge above 50% extends its lifetime.
- **State of Health (SOH)** – how long the battery can remain in a state of charge compared with its default under warranty.
- **Stress Levels**[18] – a stress level generally follows the default and warranty conditions, such as 'End of Life after 8 years', where level 1.0 means according to the default, and 2.0 would mean twice the recommend stress level and possibly reducing the lifetime of the battery by half.
- **Calendric (or calendar) ageing and Cyclic ageing**[19] – when the battery is not in use it ages by time, and this is overlayed by cyclical ageing when in use; influencing factors include temperature, SOC, charging/discharging current, and mechanical factors exacerbated by vibrations and pressure.
- **Charge Cycle –** how often a battery can be recharged from zero to 100% where recharging from 50% to 100% counts as ½ cycle.[20] Batteries for e-Buses are steadily lengthening the distances they can travel without a recharge, say to 300-400 kilometres depending upon the terrain and temperatures.
- **Deep cycle batteries** – batteries that can be discharged to lower levels/percentages with a high charge cycle; these include e-Bus lithium-ion and LiFePO4 batteries.[21]
- **C-Rate** – is the rate or time it takes to charge the battery; batteries in general use DC (direct current), but where AC (alternating current) is used it fuels a converter inside the vehicle where

[16] About Mechanics (October 2022) *What is the Difference Between an Amp, Volt, and Watt?* https://www.aboutmechanics.com/what-is-the-difference-between-an-amp-volt-and-watt.htm
[17] EV SmartCharge (Queensland) *Insights Issue 3. Battery State of Charge (SOC) and State of Health (SOH)* https://www.google.com/search?client=firefox-b-d&q=battery+state+of+health+vs+state+of+charge
[18] Sustainable Bus (#7) *Stress level: what hurts? [The Battery Cycle #7]* https://www.sustainable-bus.com/components/stresslevel-battery-factors-explained/
[19] Sustainable Bus (#7) *Stress level: what hurts? [The Battery Cycle #7]* https://www.sustainable-bus.com/components/stresslevel-battery-factors-explained/
[20] Batteries Plus Blog (November 2021) *How Do Battery Charging Cycles Work?* https://www.batteriesplus.com/blog/power/battery-discharge-cycle
[21] Tycorun Energy (2023) *Benefits of deep cycle electric bus battery and the FAQ guide* https://www.takomabattery.com/benefits-of-deep-cycle-electric-bus-battery-and-the-faq-guide/

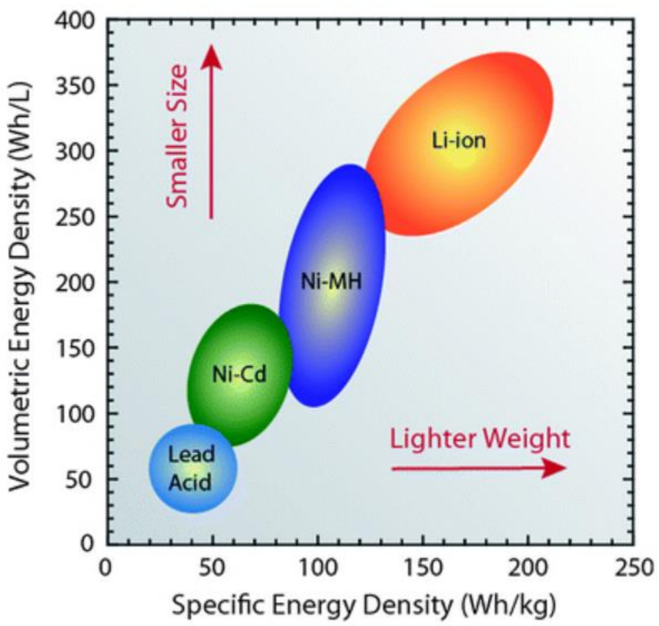
the "onboard charger" is really a converter into DC, whereas a converter in an DC charger transforms the voltage which runs straight to the vehicle's battery. DC is therefore typically used directly for recharging for cars with batteries of 40kW or above, and for buses anywhere from 128kW for mini-buses upwards of 548kW or more for double-deckers.[22]

Box 2

AC vs DC
AC – the direction of current alternates in a cyclical fashion, and is widely used in national electricity grids, for buildings, etc., being cheaper to produce and to transport. **DC** – unidirectional and widely used in batteries and devices using batteries See *What are the Advantages of DC over AC?* [23]

Figure 3 [24] shows gravimetric density (specific energy) and volumetric density (energy density) of four common vehicle battery types: **Li-ion** (lithium-ion), **Ni-MH** (nickel metal hydride), **Ni-Cd** (nickel-cadmium), and **Lead Acid**. But it should be noted that different chemical compounds and battery constructions will give different sets of results, and these will be reflected in different assessments by different vendors.

Figure 3



Source: epectec

[22] AFEEE (January 2021) *Electric Buses: Where and How to Charge Them?* https://aeee.in/electric-buses-where-and-how-to-charge-them/
[23] Linquip Tech News (February 2021) *What are the Advantages of DC over AC?* https://www.linquip.com/blog/advantages-of-dc-over-ac/
[24] Epectec (2022) *Battery Cell Comparison* https://www.epectec.com/batteries/cell-comparison.html

Box 3

Rechargeable Battery Types for Vehicles[25]

- **Lithium-ion/Lithium-polymer:** Lithium-ion (Li-ion) batteries were first demonstrated in 1979 – see Box below – and originally developed for consumer electronics such as laptop computers; they have high specific energy density (often cited 150/265 W-hr/kg) and lifespans of 5-10 years ideal for EVs. Early challenges included sensitivity to heat and easy to ignite causing fires (combustibility). Recent variants are many, mostly developed to create more stable, less combustible and longer-lasting battery types, but sometimes at the expense of their specific densities. Another factor is the source of the 'rare earth minerals' that can be used and the substitution of more readily available alternatives, such as phosphates.
    - **Ion** – a single or combination of atoms or molecules consisting of electrons and protons where, purely by convention, an electron is considered negative, equal and opposite to a positively charged proton. An ion may have a positive charge, an **'anion'** with fewer electrons than protons, or a negative charge, a '**cation'** with more electrons than protons. Anion and cations are attracted together to form ionic compounds.
    - **Variant ionic compounds** – in chemistry ion-compounds, knowns as 'spinels', refer to any class of crystallized minerals consisting of **anions** (graphite is the most widely used) and **cations**, that is ion compounds including aluminium, cobalt, chromium, iron, magnesium, manganese, nickel, phosphate, silicon, titanium, vanadium and zinc.
    - **Most widely used** – due in part to the availability of the minerals: lithium nickel cobalt magnesium oxide (NCM), lithium cobalt oxide (LCO), lithium iron phosphate (LFP or LiFePO4) especially in China, lithium manganese oxide (LMO), lithium nickel cobalt aluminium oxide (NCA) all mostly with graphite as the anion.
    - **Li-Titanate Oxide (LTO)** – military-grade robust, very low energy density and costly.
- **Flooded Lead-acid:** low-cost and found in older ICE vehicles used for ignition, but in an EV they need to be used as deep cycle batteries; lower specific energy 30-50 W-hr/kg than petroleum is compensated in an EV by a lighter drive-train. The battery efficiency is 70-75% at best, and the liquid electrolyte – sometimes replaced by gel – needs attention not to drop below 50% of volume; the lifecycle is much shorter than that of the vehicle itself; non-carbon emissions of hydrogen, oxygen and sulphur.
- **Zinc-air:** high energy density but the corrosion of the zinc limits them mostly to primary usage rather than rechargeable usage.
- **AGM:** stands for "absorbed glass mat" in which fibreglass covers thin strips of zinc to add greater power density over flooded lead-acid and they last longer, but they are more expensive and lack the depth of discharge and lifecycle of lithium batteries.[26]
- **Nickel-cadmium/Nickel-metal hydride:** low-cost and found in older EVs such as Allison hybrids prior to 2013;[27] a lower efficiency than flooded lead-acid batteries at around 60-70%, but higher specific energy at 30-80 w-h/kg and longer lifecycles but there are recharging issues.
- **Sodium-nickel chloride ('zebra'):** uses molten sodium chloroaluminate and has a specific energy of 120 W-h/kg but a low specific power of <300 W/kg; it is non-toxic but needs heating which wastes energy; it has been used in van-type road transport passenger/goods vehicles capable of holding up to 8 (US) or 9 (EU) persons plus the driver. A *Nikkei Asia* study in 2022

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[25] Wikipedia (October 2022) *Electric Vehicle Batteries* https://en.wikipedia.org/wiki/Electric_vehicle_battery

[26] CrownBattery (January 2022) *AGM vs Flooded Batteries - What You Need to Know* https://www.crownbattery.com/news/agm-vs-flooded-batteries-what-you-need-to-know

[27] Green Car Congress (2013) *EnerDel introduces Li-ion pack for upgrading Allison NiMH-based hybrid buses* https://www.greencarcongress.com/2013/05/enerdel-20130507.html

reveals the world leader in steady-state patents is Toyota (1,331) followed by Panasonic (445) underscoring the R&D role of laboratories of vehicle manufacturers.[28]

- **Iron-based:** are more stable and safer than lithium-ion and do not rely upon expensive minerals for cathodes and anodes, but require a physical pump to move the electrolyte[29] and are therefore bulky and mainly used for storage, but can be used in shipping.
- **Solid State:** scaling up from mobile phone use to an EV level poses major R&D hurdles; the liquid electrolyser is replaced by a more solid substance, such as 35 microns thick lithium tin foil with "the consistency of wet tissue paper"[30] which has a tendency to grow dendrites during usage leading to short-circuits – but non-inflammatory – or a ceramic or plastic polymer which easily crack, or silicon which adds weight and reduces the energy density of the battery; scaling up conventional Li-ions gives rise to only 80%-90% usable cells, and in R&D solid state batteries have an even lower rate and also are less efficient in cold weather; but they are faster charging, if using lithium foil they could increase energy efficiency, and they require fewer finite mineral resources; forecasts by vendors such as QuantumScape and Solid Power and car manufacturers such as Toyota, BMW, Ford, Toyota, Volkswagen suggest prototypes for BEVs could become available by 2024-25.[31] China's BYD forecasts solid state batteries soon to reach a gravimetric-energy density of 350-450 Wh/kg.[32]

See *Critical Minerals in Electric Vehicle Batteries*[33]

Battery Costs and Battery Research

In its report on *Critical Minerals in Electric Vehicle Batteries*, the US Congressional Research Service[34] writes as follows:

> "Various EV battery research efforts are underway that could alter the mineral requirements of future EVs. Efforts generally aim to lower the costs of EV batteries, extend the range of EVs (by increasing battery energy and power densities), and reduce charging time, all while ensuring safe operation of the battery. EV battery research often overlaps with chemical energy storage generally, whose focus may not be on EVs. Some research focuses on improving cathode or anode production processes, which could lower the production costs of some types of battery relative to others, potentially impacting mineral demands. Additional research focuses on enhancing secondary supply (i.e. recycling) of critical minerals for EV batteries …"

The focus here is upon reducing the costs of batteries, although other factors such as battery safety are also important. Key market considerations include, first, battery costs need to come down – it is

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[28] HT Auto (July 2022) *This automaker is a global steady state battery patent leader: Study* https://auto.hindustantimes.com/auto/news/this-automaker-is-a-global-solid-state-battery-patent-leader-study-41657785754562.html and by subscription https://asia.nikkei.com/Business/Technology/Toyota-secures-huge-lead-in-solid-state-battery-patents

[29] Nicolas Yensen and Peter B. Allen (2019) *Open source all-iron battery for renewable energy storage* HardwareX V.6, October 2019 https://www.sciencedirect.com/science/article/pii/S2468067219300318

[30] Wired (June 2022) *The Next Challenge for Solid-State Batteries? Making Lots of Them* https://www.wired.com/story/the-next-challenge-for-solid-state-batteries-making-lots-of-them/

[31] Capital One (October 2022) *What is a Solid-State Car Battery?* https://www.capitalone.com/cars/learn/finding-the-right-car/what-is-a-solidstate-car-battery/1823

[32] GIZ (January 2022) *E-Bus Development in China: From Fleet Electrification to Refined Management* https://transition-china.org/mobilityposts/e-bus-development-in-china-from-fleet-electrification-to-refined-management/

[33] Congressional Research Service (August 2022) Critical Minerals in Electric Vehicle Batteries https://www.google.com/search?client=firefox-b-d&q=Critical+minerals+in+Electric+Vehicle+Batter

[34] Congressional Research Service (August 2022) Critical Minerals in Electric Vehicle Batteries https://www.google.com/search?client=firefox-b-d&q=Critical+minerals+in+Electric+Vehicle+Batter

estimated that up to 40% of the cost of a BEV is in the battery[35] and around 60% of battery costs are the costs of the minerals used[36] – which is something that scale of production will achieve. But in addition finding cheaper and more accessible minerals for the functioning of batteries is important, especially so during a period of sharply rising prices and market turbulence as supply chains are disrupted by regional and even global conflicts, shutdowns due to pandemics, and trade wars that undermine the flow of global investments into battery production activities. This point is additionally important as conventional wisdom holds it typically takes ten years to bring an investment into full scale production. For these reasons, car manufacturers are increasingly investing in early-stage mining operations.[37]

Second, the supply of BEVs, which is in the hands of the private market, will react to demand which in turn is subject to multiple forces, including inducements by governments for bus operators and the operators of other vehicles to 'go electric' as a way to combat Green House Gases (GHG) or exhaust pipe emissions. The withdrawal of subsidies where governments are feeling a financial squeeze – for example, the UK government will withdraw zero-excise payments on electric vehicles by 2025[38] and apply road taxes for other vehicles in 2023[39] – will reduce demand unless fully compensated by cheaper batteries to run the vehicles, or by batteries that have an improved performance in terms of distances before recharging is required, and the speed of recharging and lifecycles before replacement is required.

Third, much depends upon the recharging infrastructure and what support governments can give. In the case of buses, this support will be partly financial, partly regulatory such as allowing recharging stations in bus depots or along intermediate bus stops, or allocating scarce urban land to such facilities, but also whether battery-business models arise such as the replacement and pick-up of spent batteries at depots by specialist enterprises.

A fourth consideration is the thermal safety of batteries. For example, 140,000 Chevrolet Bolt vehicle batteries belonging to General Motors were recalled in 2021 due to battery fires, at a cost of USD2 billion, of which over half linked to LG Energy as the supplier.[40] In 2015 one of the first electric buses to be trialled in Hong Kong caught fire due to an overheated battery.[41] Although iron-based batteries are thermally more stable and cheaper, they are too bulky and heavy for most forms of transport except for shipping, and currently 95% of them are made in China.

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[35] Financial Times (7th December 2022) 'China's battery makers' clout raises fears in European motor industry' https://www.ft.com/content/d407772c-4a76-4e59-9bb0-998b3f22383b

[36] Financial Times (11th September 2022) 'Electric vehicles will have to wait for solid-state battery 'game-changer'' https://www.ft.com/content/8409972a-6fa4-4cde-b0c3-cc96f3a10891

[37] Financial Times (15th November 2022) *Carmakers shift gear on attitude to miners* https://digital.olivesoftware.com/olive/odn/ftasia/default.aspx

[38] HM Revenue and Customs (November 2022) *Introduction of Vehicle Excise Duty for zero emission cars, vans and motorcycles from 2025* https://www.gov.uk/government/publications/introduction-of-vehicle-excise-duty-for-zero-emission-cars-vans-and-motorcycles-from-2025/introduction-of-vehicle-excise-duty-for-zero-emission-cars-vans-and-motorcycles-from-2025

[39] Yahoo!finance (November 2022) 'Jeremy Hunt's new 'Tesla tax' to add hundreds of pounds to electric vehicle running costs' https://sg.finance.yahoo.com/news/jeremy-hunt-tesla-tax-add-130026753.html

[40] Industry Week (October 2021) *LG to Reimburse GM $1.9 Billion Over Chevy Bolt Recall* https://www.industryweek.com/operations/safety/article/21178108/lg-to-reimburse-gm-19-billion-over-chevy-bolt-recall

[41] Keller-Liang, Rosalind (2018) *Benefit-Cost Analyses of Introducing Electric and Natural Gas Buses in Hong Kong*. Master's thesis, Harvard Extension School https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwigyImJi5T8AhXu5HMBHVntCdkQFnoECBgQAQ&url=https%3A%2F%2Fdash.harvard.edu%2Fhandle%2F1%2F37365367&usg=AOvVaw1pg6Yaj8_Fal1w_Wq1gXtl

Box 4

BEVs and zones as a means of reducing GHGs – the case of TfL

Clearly, the long-term drivers of EVs will be mainly government regulations requiring ICEs and hybrids to be replaced by BEVs, and falling relative lifecycle costs of BEVs. But there is a parallel view which sees the main advantage of shifting to BEV buses less in them being battery-driven *per se* and more in attracting passengers off private cars into BEV buses. This is the view for example of the CEO of Bravo Bus in Hong Kong who argues that if only 5% of car users could be shifted to public transport this would have more impact than converting all buses to BEVs.[42] For this to be true, it will require highly proactive regulatory authorities, and possibly central government tax authorities, to discourage private car ownership. London, for example, like other UK cities is discoursing car usage with congestion charges.

London has also introduced a tax on petrol and diesel cars entering the city in what is an expanded Ultra-Low Emission Zone (ULEZ) together with a subsidy on scrapping such cars. The main pollutants measured by Transport for London (TfL) were Nitrogen Dioxide (N02) that arises directly from tailpipe emissions, and fine particulate matter (PM2.5). Road transport is the largest single source of fine particulate matter in London, accounting for around 30% of emissions, including sources such as breaking and tyre wear-and-tear – which one report suggests is even more polluting than emissions[43] – but also "over half of London's concentrations of PM2.5 come from regional, and often transboundary sources outside of London. PM2.5 concentrations from these sources are also heavily influenced by meteorological conditions, causing more variation between different years."[44] Measuring the effectiveness of the ULEZ is therefore complex because while nitrogen dioxide (NO2) was clearly down during April-July 2022, P2.5 was slightly higher. One reason would be the post-COVID recovery of motor vehicles, which is why PM2.5 from breaking and tyres increased even as tailpipe emissions fell. The trends however are clear: governments are increasingly likely to add congestion and carbon charges to passenger car usage, and to incentivise the switch to BEVs. If that switch happens then roadside emissions could really fall, and consequently the demand for bus batteries will grow.

Battery Mineral Sourcing and Manufacturing – China and Beyond

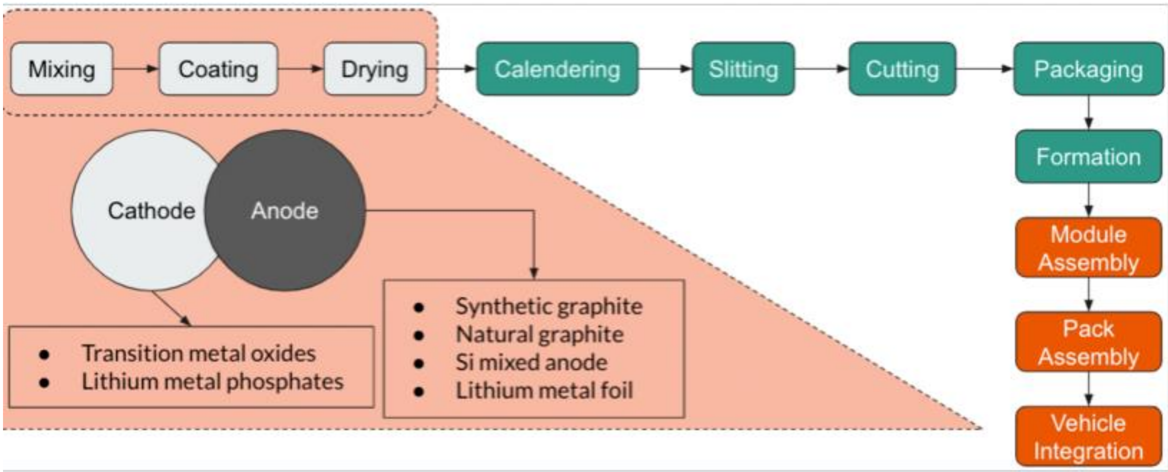
Figure 4 shows the various complex stages involved in battery manufacture, from the choice of minerals for the cathode and anode and electrolyser, to their preparation and assembly as cells into battery packs and their insertion into the vehicle.

[42] Interview with Adam Leishman, 16th November 2022.

[43] The Guardian (June 2022) *Car tyres produce vastly more particle pollution than exhausts, tests show* https://www.theguardian.com/environment/2022/jun/03/car-tyres-produce-more-particle-pollution-than-exhausts-tests-show

[44] Mayor of London (July 2022) *Expanded Ultra Low Emission Zone – Six Month Report Including Low Emission Zone – One Year Report* https://www.london.gov.uk/sites/default/files/expanded_ultra_low_emission_zone_six_month_report.pdf

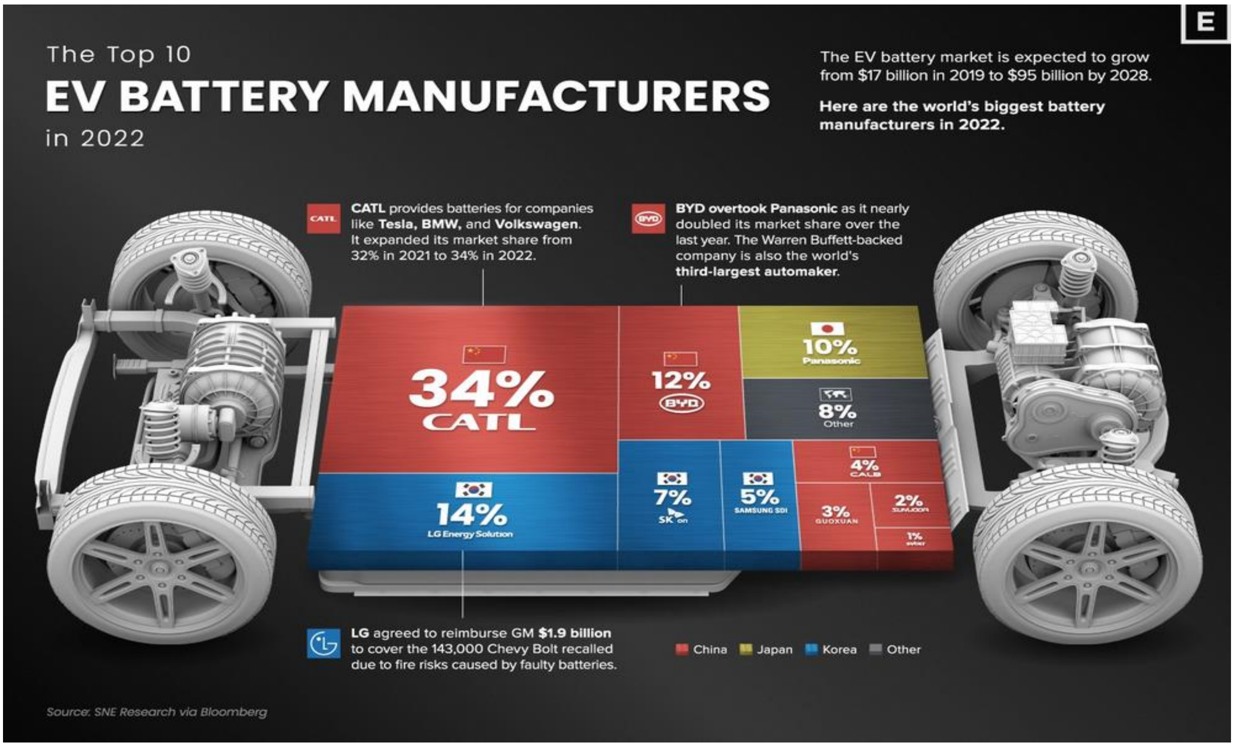
Figure 4
From Manufacturing to Delivery of EV batteries



Source: Wikipedia[45]

As of 2022-23 Chinese manufacturers dominate world production of batteries, as Figure 5 from E-Vehicle.com illustrates.[46] Although, five of the top companies in 2022 were non-Chinese compared with only three in 2021 – two from Japan and three from S. Korea,[47] by January 2023 the top two Chinese producers reached a combined market share of 50%.[48]

Figure 5



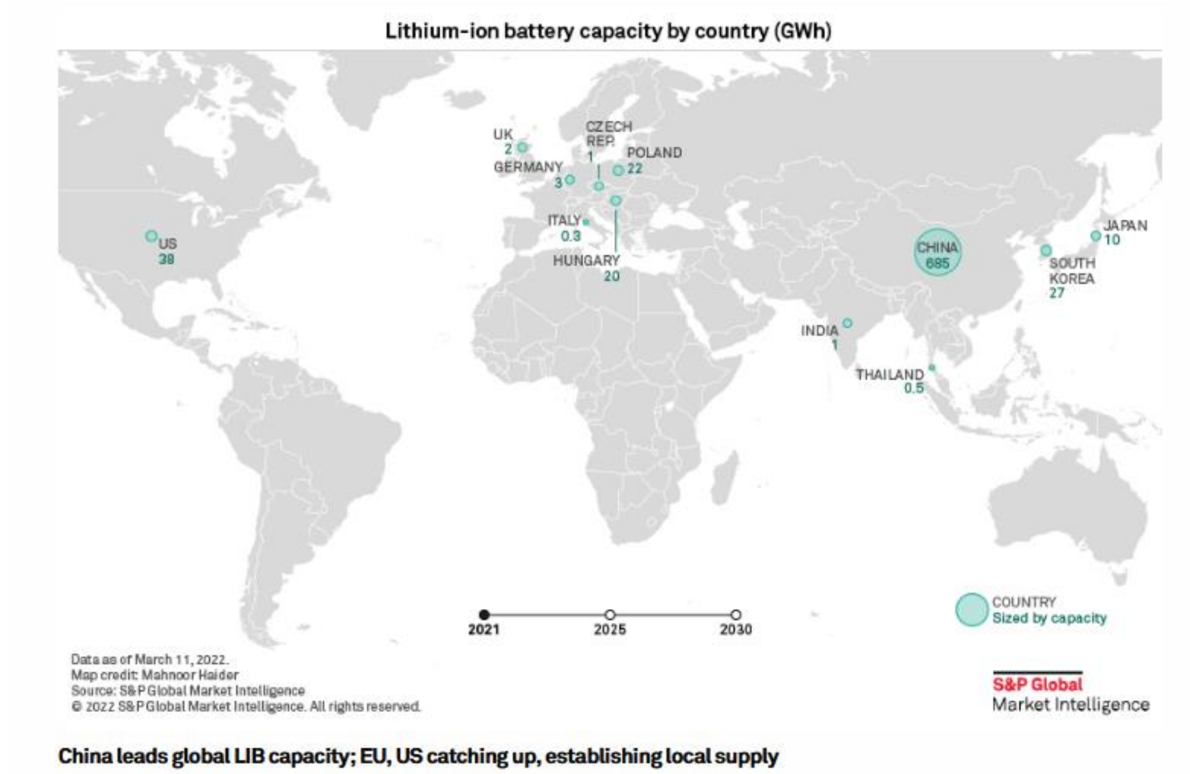
Source: E-Vehicle.com

[45] Wikipedia (December 2022) *Electric Vehicle Battery* https://en.wikipedia.org/wiki/Electric_vehicle_battery
[46] E-Vehicle.com (October 2022) *Top 10 EV Battery Manufacturers in World by Market Share* https://e-vehicleinfo.com/global/ev-battery-manufacturers-in-world-by-market-share/
[47] Tycorun Energy (November 2021) *Top 10 power battery companies in the world in 2021* https://www.takomabattery.com/top-10-power-battery-companies-in-the-world-in-2021/
[48] Financial Times (5th January 2023) *Chinese battery manufacturers extend their dominance over global supply*

As with semi-conductors, so with batteries, the manufacturing rivalry between the US and China seems likely to impact upon the future location of battery-making capacity as Japanese and South Korean companies plan to move investment to the US as highlighted by the Financial Times,[49] following a report from Goldman Sachs.

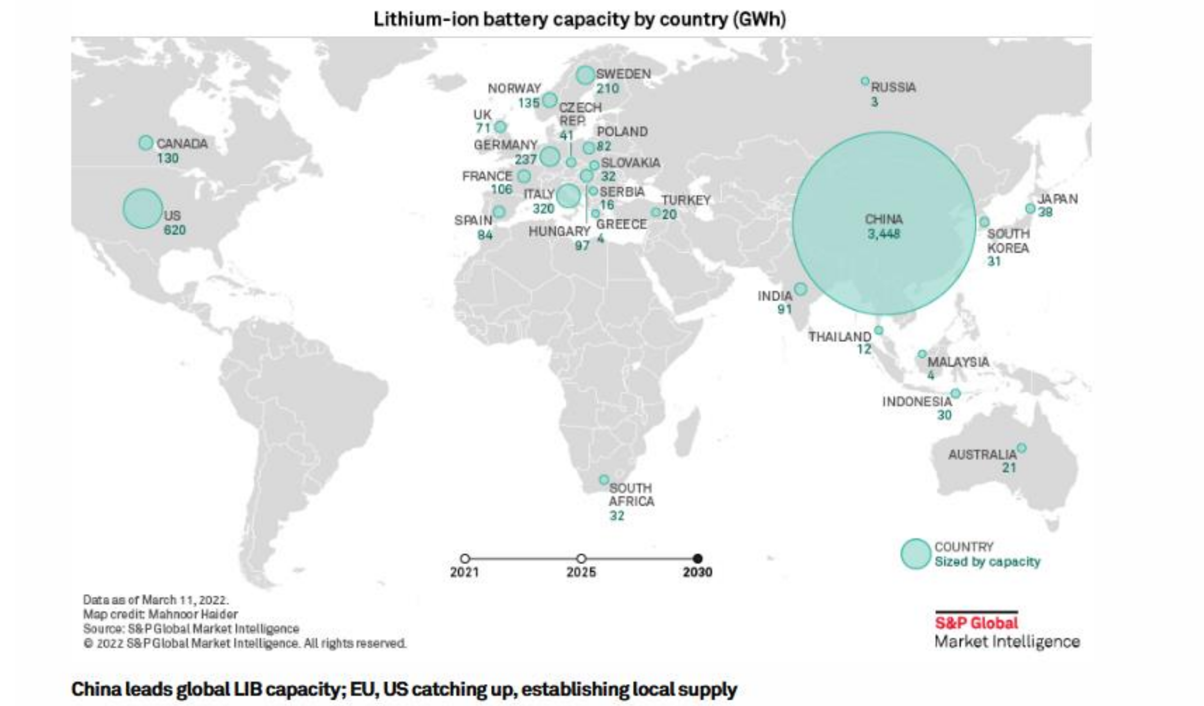
> "[T]he investment bank's analysts believe a stark pivot to protectionism in Washington and Brussels, combined with an unprecedented spending spree by non-Chinese companies, have the potential to extricate the west from its reliance on Beijing over the next seven years. To obtain a self-sufficient supply chain, countries competing with China would need to spend $78.2bn for batteries, $60.4bn in components and $13.5bn in mining of lithium, nickel and cobalt, as well as $12.1bn in refining of those materials, the report calculated. The bank's analysts believe demand for finished batteries could be met without China within the next three to five years, largely thanks to big investments in the US by South Korean conglomerates LG and SK, who have been attracted by massive subsidies from US taxpayers. LG Chem said on Tuesday it would invest more than $3bn to build a battery cathode factory in Tennessee, the biggest of its kind in the US. Goldman forecasts that the market share of the Korean battery makers in the US will soar to around 55 per cent in three years, from 11 per cent in 2021. The passage of the Inflation Reduction Act in August means huge tax benefits and other subsidies for localising battery supply chains and fuelling the uptake of EVs. Goldman expects the 'average eligible EV in the US' will receive more than $10,000 in benefits from the IRA."

Figure 6a - 2010



[49] Financial Times (22nd November 2022) *West could end reliance on Chinese batteries by 2030, says Goldman Sachs* https://www.ft.com/content/458ebaf3-c1ee-499c-b7f3-2e5d7f1bb6df

Figure 6b - 2030



Figures 6a and 6b illustrate the lithium-ion battery production capacity globally for 2010 and the projected capacity for 2030.[50] An estimate by the CEO of Piedmont Lithium of a proposed mine and refinery in North Carolina and of a refinery in Tennessee comes to USD1 billion and USD600 million respectively; he concludes that it makes sense for battery companies and auto companies to co-invest. The obvious problem is that they have opposing price interests,[51] yet for car manufacturers it may be the only way to guarantee supply. It does raise the prospect of mining conglomerates taking shares in their customers' business as a hedge.

Battery Minerals Prices, Supply and Demand

Many of the minerals used in the manufacture of batteries are either in short supply globally, often due to interrupted supply chains rather than a lack of minerals in the ground, or their mining presents environmental issues. Following the mining of minerals, such as lithium, which is found in geothermal brine deposits, clay or in hard rock as a lithium aluminium inosilicate, otherwise known as spodumene, there needs to be processing and refining. Australia has the largest known reserves of raw material lithium, over half the global supply, but for processing and refining it all goes to China. Chile, Argentina and Brazil are the next most plentiful suppliers, followed by China and North America (mostly Nevada) – see S&P forecast Figure 7.[52] A new trade agreement in December 2022 between the EU and Chile will provide greater access to Chile's lithium.[53]

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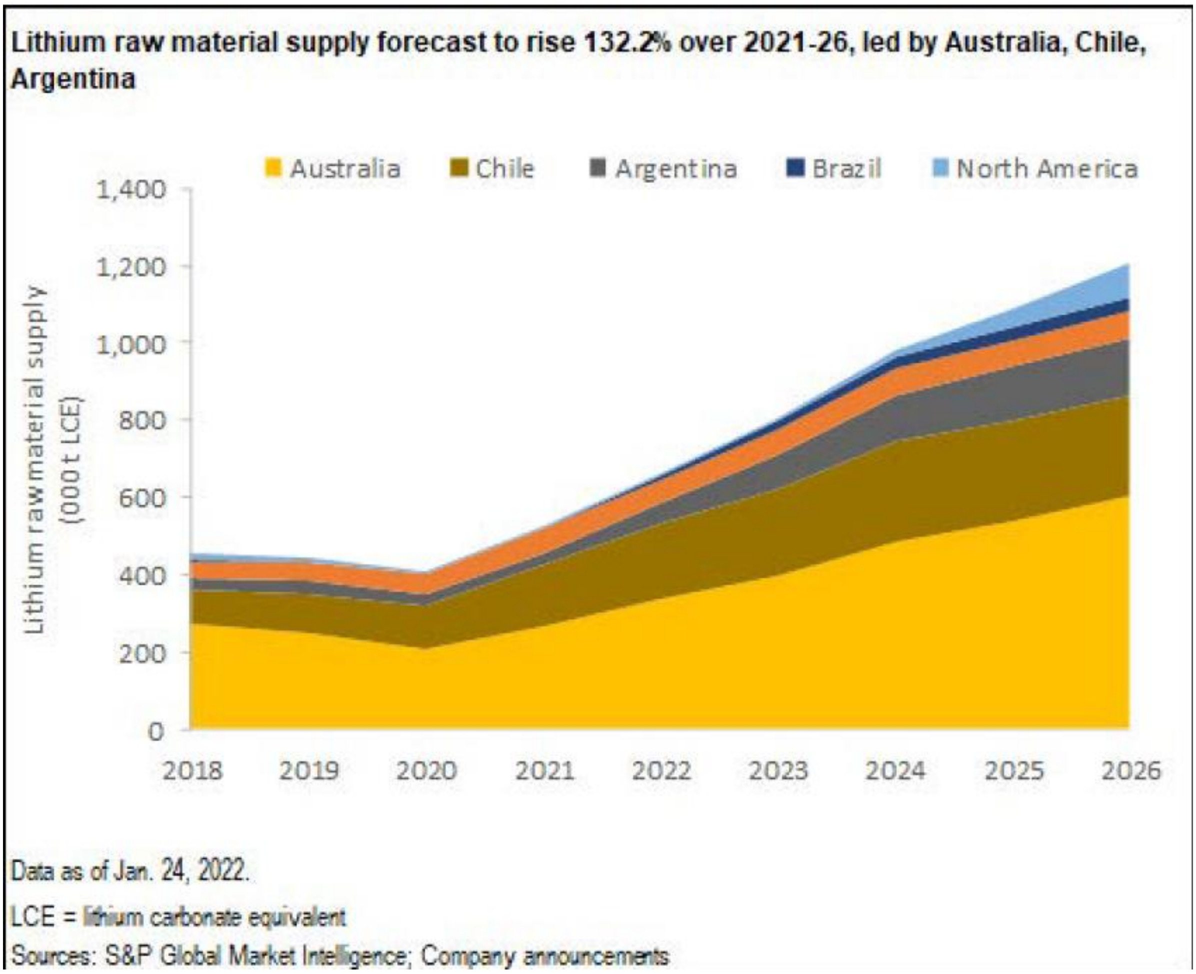
[50] S&P Global (April 2022) *Investment in lithium-ion batteries could deliver 5.9 TWh capacity by 2030* https://www.spglobal.com/marketintelligence/en/news-insights/research/investment-in-lithium-ion-batteries-could-deliver-5-point-9-twh-capacity-by-2030

[51] Financial Times (15th November 2022) 'Carmakers shift gear on attitude to miners/' https://digital.olivesoftware.com/olive/odn/ftasia/default.aspx

[52] Green Biz (June 2022) *Lithium Deficit Threatens EV Sales and Energy Transition* https://www.greenbiz.com/whitepaper/lithium-deficit-threatens-ev-sales-and-energy-transition

[53] European Commission (December 2022) *The EU-Chile agreement explained* https://policy.trade.ec.europa.eu/eu-trade-relationships-country-and-region/countries-and-regions/chile/eu-chile-agreement/agreement-explained_en

Figure 7

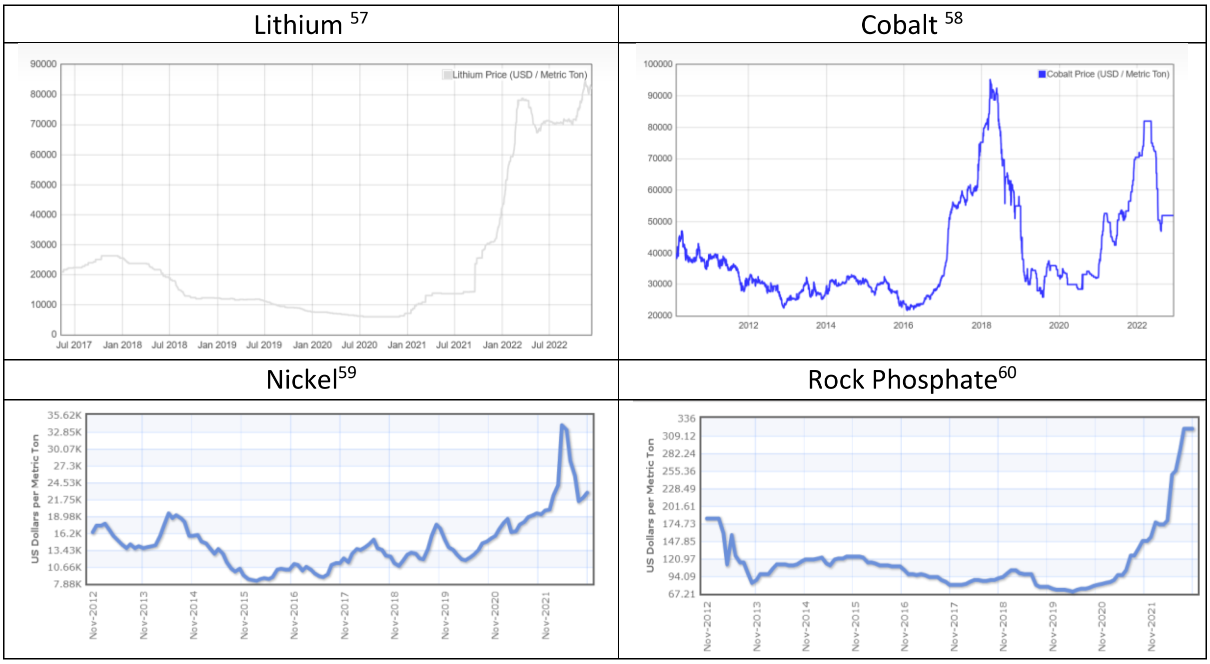


Cobalt – More than 70 percent of the world's cobalt is produced in the Democratic Republic of the Congo (DRC), and 15% to 30% of the Congolese cobalt is produced by artisanal and small-scale mining (ASM).[54]
Nickel – The world's nickel resources are currently estimated at almost 300 million tons. Australia, Indonesia, South Africa, Russia and Canada account for more than 50% of the global nickel resources.[55]
Manganese – not rare, the main producers are China, South Africa and Australia.[56]

At least temporarily, price volatility of minerals has replaced steady price declines over the past decade as shown in the charts, see Figure 8.

[54] Council on Foreign Relations (October 2020) *Why Cobalt Mining in the DRC Needs Urgent Attention* https://www.cfr.org/blog/why-cobalt-mining-drc-needs-urgent-attention
[55] Nickel Institute (2022) *About Nickel* https://nickelinstitute.org/en/about-nickel-and-its-applications/
[56] Royal Society for Chemistry (2022) *Manganese* https://www.rsc.org/periodic-table/element/25/manganese

Figure 8



Demand

Rising costs due to supply chain disruptions may outlast the disruptions unless further innovations in battery manufacturing and production at global scale outweigh them, but an incessant increase in demand may be difficult to meet. The anticipated supply shortfall for minerals for battery production is shown in Figure 9 from the IEA, comparing the sustainable demand scenario with a stated policy scenario.[61] The anticipated demand arising from BEVs is the main driver; for example, the IEA estimates a shortfall of 1 million metric tons of graphite by 2040 with 75% of demand coming from BEVs. Because graphite needs to be of a certain quality, China is currently the primary source.[62]

These existing and projected shortages could be eased if R&D comes up with new battery designs that rely less upon scarce minerals, one of which will be solid-state batteries for BEVs but the hurdles to be cleared remain high – see Box 3. Further, battery scientists and engineers are not the principal inventors in materials science, innovation there rather comes from academic research labs – see Box 5 below. Figure 10 from Statista[63] shows transport sector as the main driver of demand for batteries.

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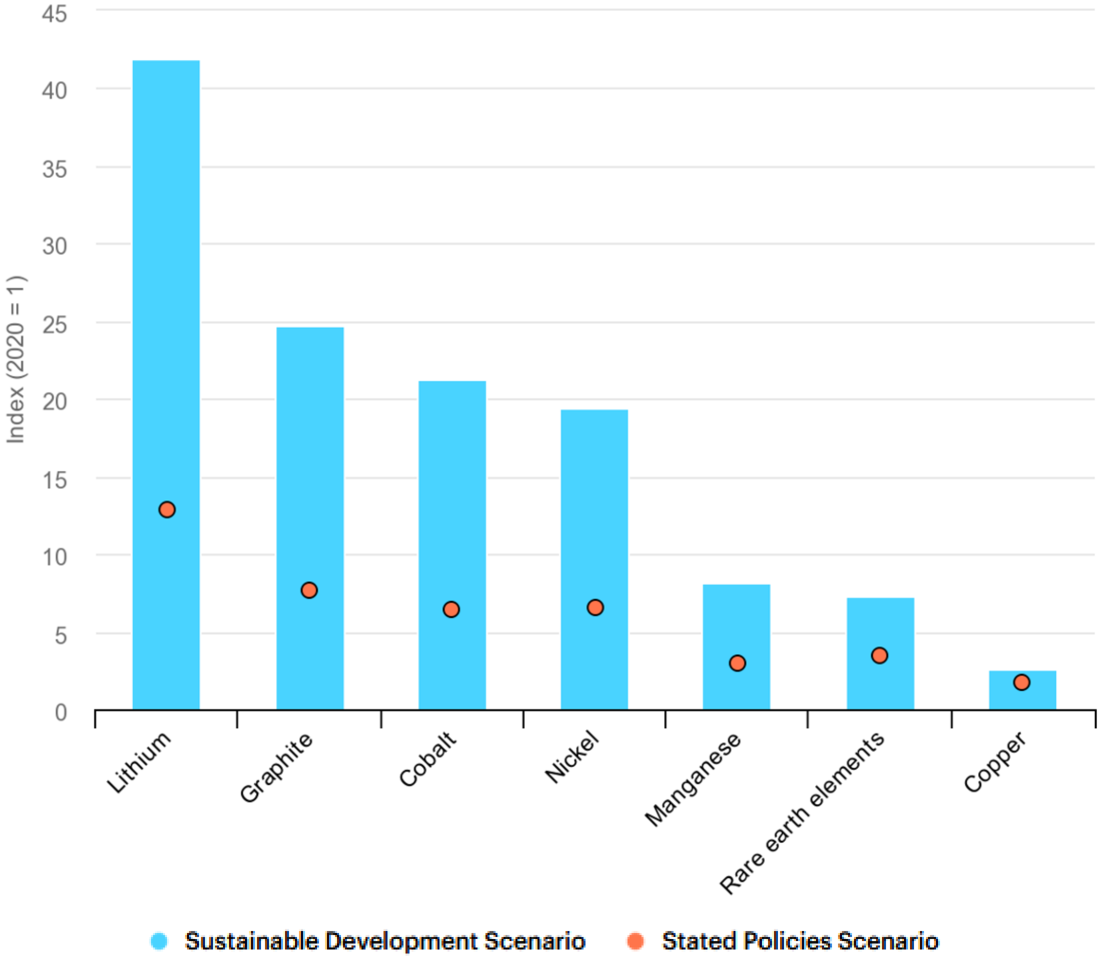
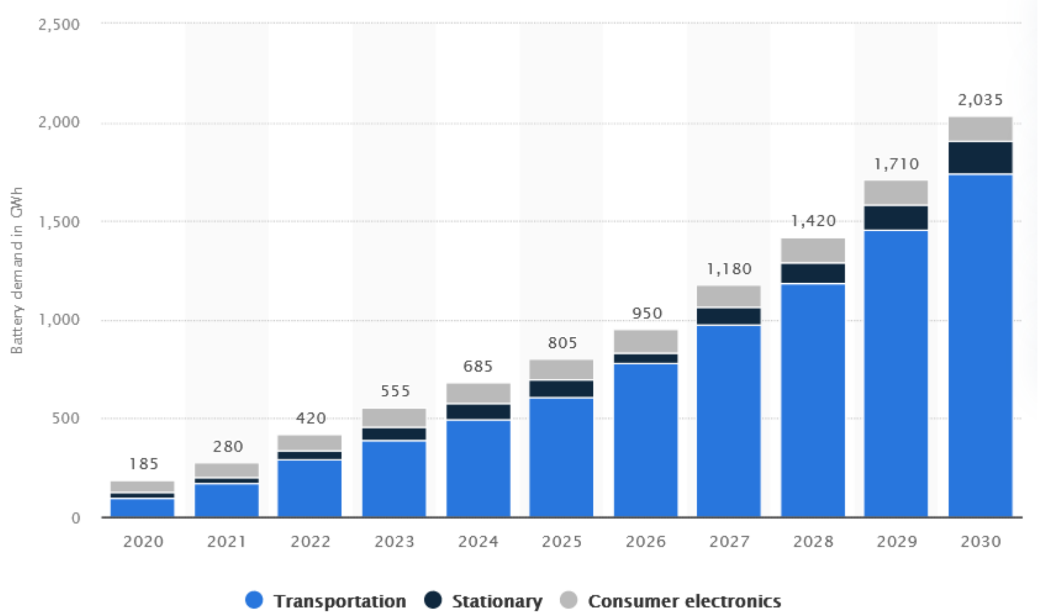
[57] Daily Metal Prices (visited 9th December 2022) https://www.dailymetalprice.com/metalpricecharts.php?c=co&u=lb&d=0
[58] Daily Metal Prices (visited 9th December 2022) https://www.dailymetalprice.com/metalpricecharts.php?c=co&u=lb&d=0
[59] Index Mundi (visited 11th December 2022) https://www.indexmundi.com/commodities/?commodity=nickel&months=120
[60] Index Mundi (Visited 11th December 2022) https://www.indexmundi.com/commodities/?commodity=rock-phosphate&months=120#google_vignette
[61] IEA (May 2021) *The Role of Critical Minerals in Clean Energy Transitions* https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions
[62] S&P(January 2022) *Threat of graphite supply shortage looms over electric vehicle rollout* https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/threat-of-graphite-supply-shortage-looms-over-electric-vehicle-rollout-68335809
[63] Statista (2022) *Projected global battery demand from 2020 to 2030* https://www.statista.com/statistics/1103218/global-battery-demand-forecast/

Figure 9
IEA Estimates Mineral Demand from Two Scenarios



Source: IEA

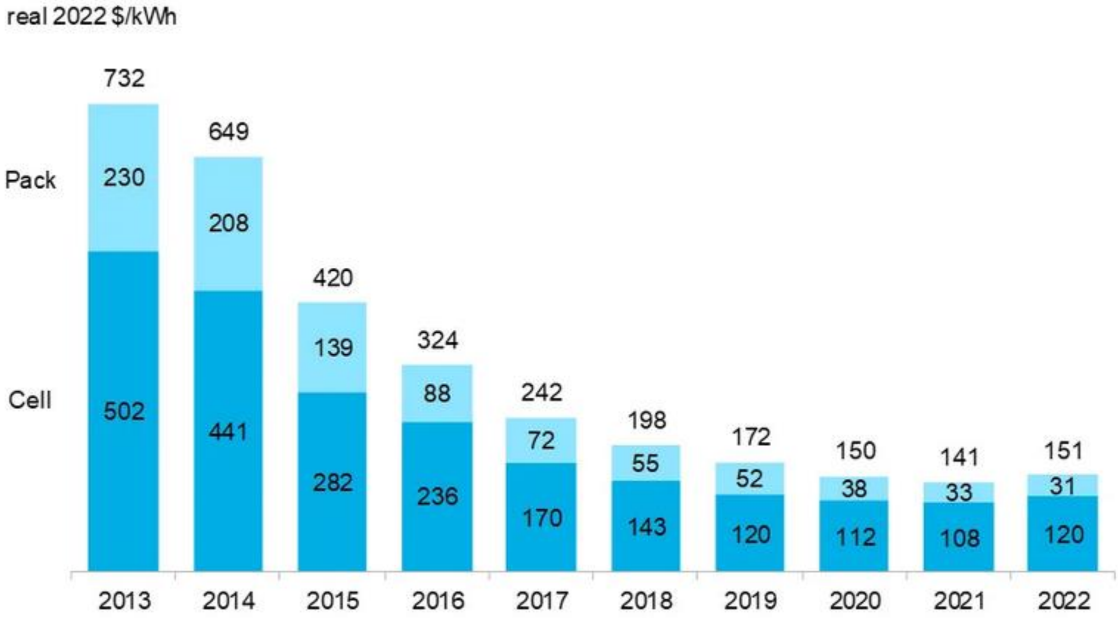
Figure 10
Projected global battery demand from 2020 to 2030, by application (in gigawatt hours)



Battery Cell and Pack Prices

As Figure 11 from Paultan.org[64] shows, in 2022 Lithium-ion battery pack prices went up for the first time since 2010 due to the rising cost of raw materials and battery components.

Figure 11
Volume-weighted average lithium-ion battery pack and cell price split, 2013-2022



Source: Paultan.org citing BloombergNEF; in real 2022 dollars, weighted average survey values include 178 data points covering passenger cars, buses, commercial vehicles and stationary storage

Pack Prices – as Paultan.org points out, there are regional variations in the price of Lithium-ion battery packs, with prices in the USA and Europe typically 24% and 33% higher than in China where production costs are lower at USD127 per kWh. China's shift towards cheaper lithium iron phosphate (LFP) batteries – they do not use either cobalt or nickel which are in short supply in China[65] – partly explains the difference. Basically, outside of China, 88% of EVs use Korean and Japanese-made Li-ion batteries containing nickel, and 95% of batteries inside China use iron phosphate. Tesla's China's factory is also switching to the cheaper LFP.[66] Due to these differences and the supply chain disruptions, vehicle manufactures have started hedging their bets against a more uncertain future by investing directly in mining operations.

Cell prices – specifically reflect the costs of minerals. The war in the Ukraine, the disruption to global supply chains and to investments as a consequence of the outbreak of the COVID-pandemic, and the post-2019 inflationary macro-economic disruptions reversed what had been a fairly steady fall in the average weighted price of minerals used in battery pack production – traditionally Lithium-ion consisting of Lithium, Cobalt and Nickel – from USD732 per kWh in 2013 as shown in Figure 8 above to USD141 per kWh in 2021 and then up to USD151 per kWh in 2022. Battery packs make up around 40% of the cost of a BEV and the cost of minerals make up around 60% of battery costs – see above – and the car industry regards USD100 per kWh as the price point where battery-driven vehicles

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[64] Paultan.org (9th December 2022) *Lithium-ion battery pack prices increased for the first time since 2010 – could make EVs more expensive* https://paultan.org/2022/12/09/lithium-ion-battery-pack-prices-went-up-for-the-first-time-since-2010/
[65] CNEVPost (September 2022) *BYD chairman believes LFP batteries right choice for China* https://cnevpost.com/2022/09/23/byd-chairman-believes-lfp-batteries-right-choice-for-china/
[66] Financial Times (23 February 2022) *Tesla switch to iron based batteries risks over-reliance upon China*

become price competitive with ICE vehicles – a 60 kWh battery will serve a family-sized car – a price previously anticipated being reached in 2024 but now pushed back to 2026.[67]

Daimler Trucks suggests an even lower price point closer to USD60 kWh to compete with diesel engines for large trucks. If the internal materials of a combustion engine for a truck average around €25,000 (USD26,500) and if the truck needs to travel 400 kWh at USD60 kWh the costs comes to USD24,000 for battery cells. Anything higher and a battery subsidy will be required to shift to BEVs.[68] A crucial variable is the price of petrol or diesel. Should it rise substantially then the costs of running a non-EV vehicle would outstrip the price differential between ICE vehicles and BEVs, as had happened across most of Europe by December 2022.[69] If the price differential were sustained then the total cost of ownership (TCO) would favour BEVs. A complicating factor is the cost of recharging a BEV which varies widely between public and private recharging systems and across countries.

Box 5

The Long Story of Lithium-ion Discovery

The first solid-state electrolyte was discovered by Michael Faraday in the 1830s, but "pioneering work on the lithium battery began in 1912… [and] it wasn't until the 1970s when the first non-rechargeable lithium batteries became commercially accessible. During the oil crisis of the 1970s, an English chemist named Stanley Whittingham began working on the concept of a new battery that was able to recharge on its own in a timely manner. He hoped that this could lead to fossil fuel-free energy in the future. Whittingham attempted to use lithium metal and titanium disulphide as the electrodes, however this caused the batteries to short circuit and catch fire, raising safety concerns about the experiment. In the 1980s, John Goodenough decided to experiment using lithium cobalt oxide as the cathode, doubling the energy potential. This led Akira Yoshino to experiment with using a carbonaceous material, petroleum coke, which led to the finding that the battery was significantly safer without lithium metal. This was the beginning of lithium-ion battery development." All three were awarded the Noble Prize for Chemistry in 2019.

Based upon *A Brief History of Lithium-Ion Battery Development*[70]

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[67] AutoNews Europe (June 2022) *Metals costs could slow race for cheaper electric cars, researchers say* https://europe.autonews.com/automakers/metals-costs-could-slow-race-cheaper-electric-cars-researchers-say
[68] NPP (March 2022) *Daimler Truck CEO says cost of electric trucks will "forever be higher"* https://www.newpowerprogress.com/news/daimler-truck-ceo-says-cost-of-electric-trucks-will-forever-be-higher-/8019370.article
[69] Financial Times (12th December 2022) *Cost of owning EVs slips below petrol and diesel* https://digital.olivesoftware.com/olive/odn/ftasia/default.aspx
[70] Hidden (February 2022) *A Brief History of Lithium Ion Battery Development* https://www.hidenanalytical.com/blog/lithium-ion-battery-development/

Part 2: Economics of Electric Buses

According to the IEA, globally, transport in general accounts for around a quarter of carbon dioxide emissions, the nearly 75% of those emissions.[71] The electrification of public transport is therefore seen as an urgent issue. By 2022, Shenzhen (China) had the world's first and largest *fully* electric bus and taxi fleets, with its urban transit fleet of 16,359 buses 100% electrified.[72] The World Economic Forum (WEF) reckons 98% of the world's municipal e-buses are in China.[73] Another report in 2022 estimates that in 2017 there were 385,000 electric buses globally, and 99% of them were in China, and China was adding to its total by roughly 9,500 every five weeks.[74]

E-buses come in different shapes and sizes, from elongated trams to typically 12 - 18 metre buses. Volvo, for example, manufactures both 12 and 18 metres with standard width (2.5m) and heights (3.3m) – see Figure 12. BYD's 12 metre e-bus uses a 310 kWh LiFePO4 battery.[75]

For heavier double-decker buses, for air-conditioned buses or buses needing substantial heating, and for buses covering long and perhaps uphill routes, larger battery packs are required, to be offset by high passenger numbers (pay loads) assuming the bus runs at nearly full capacity.

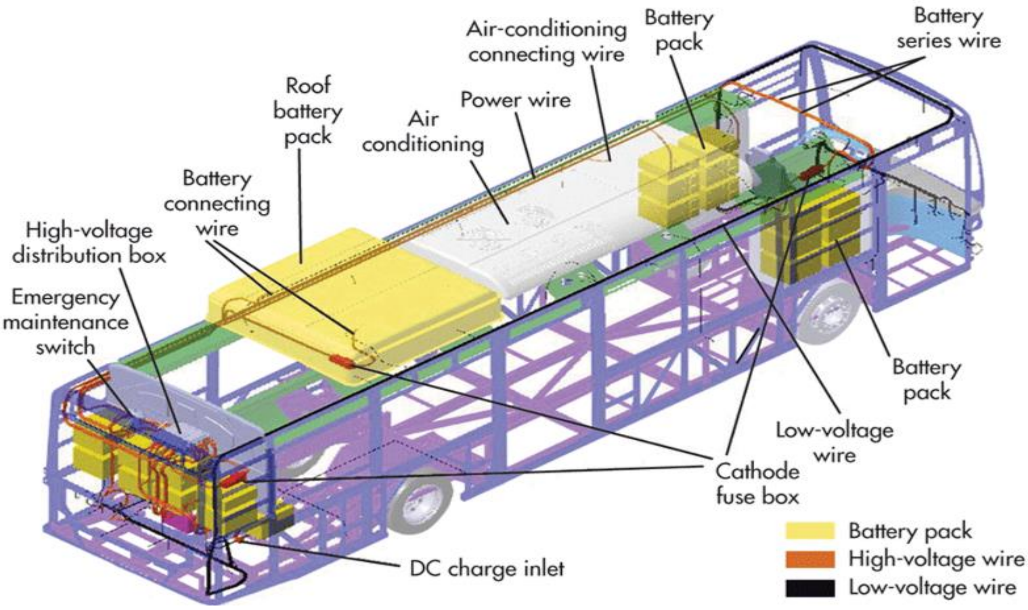
Figure 12
Volvo 7900 Electric Buses with Plug-in and Pantograph recharging

Source: Volvo[76]

Figure 13 shows a typical single-decker e-bus design complete with battery packs for driving the bus and operating its electronic devices, such as air conditioning and headlights. The development of light weight 'universal' chassis for e-buses[77] somewhat compensates for the weight of the battery packs, but the space taken up reduces the passenger pay loads. Recharging the batteries on the roof of the bus can be done using a pantograph that descends from a gantry at the bus terminus or other facility *en route* used for recharging. Otherwise overnight plug-recharging takes place. On-route will likely be fast recharging, although it may shorten the life of the battery. An alternative business model is battery swapping which may take only minutes.

[71] IEA (2022) *Global EV Outlook 2022* https://www.iea.org/topics/transport
[72] Energy Watch (January 2022) *Lessons from Cities with the World's Largest E-Bus Fleets* https://www.energywatch.com.my/blog/2022/01/14/lessons-from-cities-with-the-worlds-largest-e-bus-fleets/
[73] WEF (March 2021) *What's really driving the trend in e-vehicles? Your local electrical bus* https://www.weforum.org/agenda/2021/03/municipal-buses-lead-electrification-effort
[74] Autonomy (November 2022) *Conquering the World: the Success of Chinese Electric Buses* https://www.autonomy.paris/conquering-the-world-the-success-of-chinese-e-buses/
[75] LanTransportGuru.Net (July 2022) *BYD K9 (Gemilang)* https://www.google.com/search?client=firefox-b-d&q=BYD+e-bus+battery+and+lkength
[76] A.B. Volvo (2022) *Specifications Volvo 7900* Electric https://www.volvobuses.com/en/city-and-intercity/buses/volvo-7900-electric/specifications.html
[77] FMI (2022) *Bus Chassis Market: Introduction* https://www.futuremarketinsights.com/reports/bus-chassis-market

Figure 13: A BEV bus



Source: Parveen Kumar[78]

Box 6

Financial, Economic and Political Models for Public Transport

Public Transport Access Levels (PTAL) models as developed by Transport *for* London (TfL)[79] can be used to measure the supply and demand for buses and other forms of public transport at different locations, along different routes and times of day to produce rational models of bus distribution and availability, but as a public good, public transport is often required to gravitate away from financial models towards economic and even political models to serve local communities to their fullest satisfaction. In such cases, public transport economic models may include subsidies or investment incentives, land discounts for depots, terminals and other facilities, or in some cases cross-subsidy from their investments in commercial buildings. In Hong Kong for example, the metro (MTR) owns and operates several commercial properties (offices, shopping malls, residential apartments) that provide the revenues to subsidise train fares.

Batteries for Buses

As shown below, for heavy vehicles such as truck and buses, two types of Lithium batteries are in contention, Li-ion (NCM) and LFP (LiFePO4) with the use of less combustible, cheaper and more environmentally friendly cathode components such as iron phosphate.[80] Graphite in the anode is the heaviest component which includes a silicon mix. A silicon compound may replace graphite as ways are found to maintain its stability during the charging process,[81] given silicon gain in gravimetric capacity.[82]

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[78] Parveen Kumar (2016) *Electric Vehicle & Sustainable Cities - World Resources Institute (WRI)* https://www.researchgate.net/figure/Schematic-of-an-electric-bus-showing-battery-and-electrical-layout_fig7_33666670

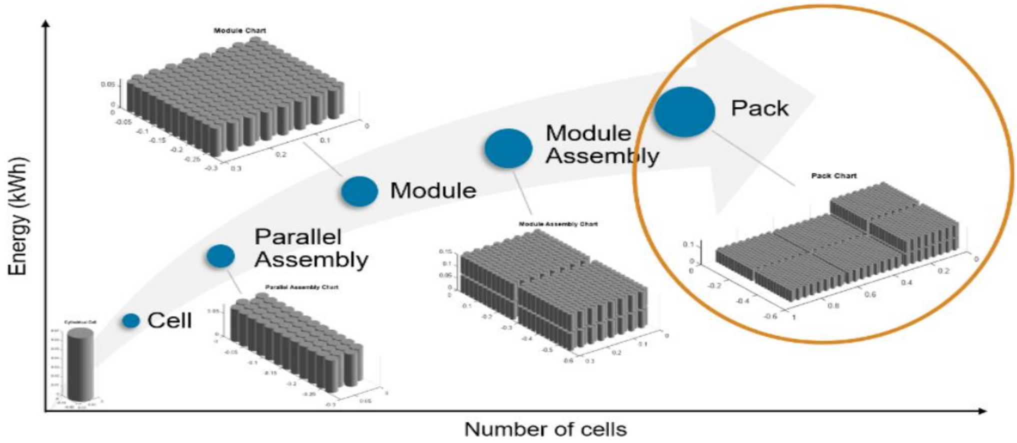
[79] TfL (2022) *Public Transport Accessibility Levels* https://data.london.gov.uk/dataset/public-transport-accessibility-levels

[80] The Business Research Company (August 2022) *Lithium Iron Phosphate Battery Global Market Report 2022* https://www.thebusinessresearchcompany.com/report/lithium-iron-phosphate-battery-global-market-report

[81] LMC (June 2022) *Alternatives to graphite in EV batteries* https://lmc-auto.com/news-and-insights/alternatives-to-graphite-in-ev-batteries/

[82] Utkarsh Chadha et al. (November 2022) *Theoretical progresses in silicon anode substitutes for Lithium-ion batteries* Journal of Energy Storage v. 55 Part A https://www.sciencedirect.com/science/article/abs/pii/S2352152X22013469

Figures 14a and 14b
Cylindrical cells assembled in a battery pack[83]

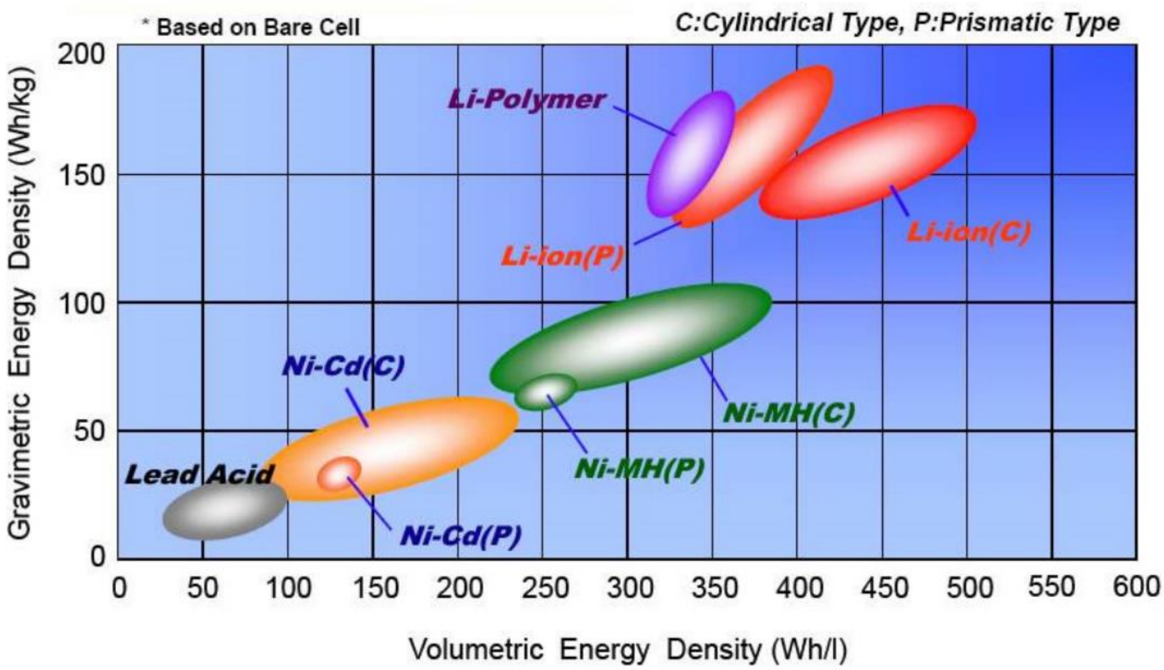


Prismatic LiFePO4 battery and charger package[84]

The performance reliability requirements of modern batteries are also reflected in a trend towards prismatic cell stacks or rows of rectangular cells mounted directly in a stack casing to save connectors, in preference to smaller traditional cylindrical cells stacked in clusters with many connectors – see Figures 14a and 14b.[85] The prismatic formation is appropriate for heavy duty

[83] MathWorks (2022) *Build Detailed Model of Battery Pack From Cylindrical Cells* https://www.mathworks.com/help/simscape-battery/ug/build-battery-pack-from-cylindrical-cells.html
[84] AA Portable Power Corp (2022) *LiFeMnPO4 Prismatic Battery and Charger Package* https://www.batteryspace.com/LiFePO4-Prismatic-Battery-Package-36V-10C-Rate-With-LED-Balancing.aspx
[85] A pouch battery is a third formation used, for example, in cell phone rechargers.

Figure 15
Comparison of Cylindrical and Prismatic gravimetric and volumetric densities[86]



Source: epectec (2022)

vehicles offering greater energy density due to the connected rectangular cells, and the cylindrical formation more appropriate for high performance vehicles due to the greater power density of the smaller cylindrical cells. The comparison in Figure 15 of gravimetric and volumetric energy levels of cylindrical and prismatic cell types in battery packs can be compared with Figure 2 above.

Table 1
Li-ion vs LiFePO4 Cells and Battery Packs

	Li-ion	**LFP**
Cathode safety	NCM – toxic mineral oxides as in nickel, cobalt and magnesium; prone to combustion without a BTMS	LiFePO4 – non-toxic phosphate and iron; thermally stable but likely include BTMS for extra safety
Anode	Graphite	Graphite
Energy density = Battery Hours/ Weight	150/250+ Watt-Hours per Kg = longer distances per Wh/Kg; specific power density also higher than LFP	100/150+ Watt-Hours per Kg = lower energy density can be partially offset by pyramid cell stacking
Nominal voltage	3.6V	3.20V/3.30V
Weight	NCM high density minerals	Iron phosphate lighter weight
Cost	Supply issues slow price decline	Plentiful supplies keep prices low
Charge cycle	2,000-2,500 cycles = 3-4 years	10,00 cycles = 7-10 years
Charge rate	0.7C up to 1.0C – state of charge; 1C @ 1A = should provide 1A for 1 hour	1.0C – state of charge; 1C @ 1A = should provide 1A for 1 hour
Depth of Discharge (DoD)	1C = depth of discharge (DoD) ~ 80% ideally	1.25C = better performance ~ 100% possible
Cylindrical cells in battery stack	Currently most used in vehicle batteries, but signs of change. Smaller in size and encased in rounded cylinders which prevents swelling, the cells can	

[86] Epectec (2022) *Battery Cell Comparison* https://www.epectec.com/batteries/cell-comparison.html

	collectively fit into any vehicle or be used in smaller devices; store less energy (energy density) than larger rectangular cells, but more power per cell (power density) hence better for high performance vehicles.
Prismatic cells in battery stack	Rectangular, larger and therefore contain more energy per cell (up to x100) and stacking them means fewer connections to go wrong; stacked they offer more *collective* energy than cylindrical cells but less per cell performance, so more suitable for buses and trucks.
Trend towards prismatic cell stacks	There are strong signals that LFP prismatic cells are emerging. In Asia, EV manufacturers already use LiFePO4 batteries, a type of LFP battery in the prismatic format. Tesla also stated that it has begun using prismatic batteries manufactured in China for the standard range versions of its cars – see video.[87] The LFP chemistry has important downsides, however. For one, it contains less energy than other chemistries currently in use and, as such, can't be used for high-performance vehicles like Formula 1 electric cars. In addition, battery management systems (BMS) have a hard time predicting the battery's charge level. [88]

Basic Parameters for a Bus Battery

The power consumption of a bus, and therefore the longevity and cost of an electric battery to support a bus, varies according to a number of parameters. These include, *inter alia*

- The model of the bus, whether single, articulated, double-decker, mini, maxi or tram, and its weight, including the battery which could be one-third of the weight of the unoccupied bus
- The nature of the route and terrain, whether local urban or semi-urban and rural
- The frequency of stops and starts and of door openings/closures
- Whether heating or air conditioning is in use and its operating temperature
- The frequency of battery recharging facilities, such as overnight at depots and terminals, or pantographs and fast charging at selected bus stops, or battery swaps
- The type of battery, such as Li-ion or LFP, its specific power and energy densities, its depth of discharge and charging cycles and therefore its longevity and total cost of ownership over a lifetime

Each vendor of buses and batteries has their own specifications, and over time each improves the efficiency of their manufactured products.

Box 7

Tests on BEV Buses for Distances and Energy Densities
Sustainable Bus[89] magazine reports the findings of an annual 'Ebuse Test' in Germany in 2018 of BEV buses from three different vendors as follows:

[87] INSIDEEVs (October 2021) *See Inside Of The Tesla Model 3's LFP Prismatic Battery Pack* https://insideevs.com/news/542064/tesla-model3-lfp-battery-pack/
[88] LaserAX Blog (April 2022) *Prismatic Cells vs. Cylindrical Cells: What is the Difference?* https://www.laserax.com/blog/prismatic-vs-cylindrical-cells
[89] Sustainable Bus (July 2022) *Electric bus range, focus on electricity consumption. A sum-up* https://www.sustainable-bus.com/news/ebus-test-2018-1-articulated-electric-buses-vdl-sileo-solaris/

- 18-meter buses with 350 kWh of capacity (kW/Kg) can cover a range between 190 and 210 kilometres.
- The specific energy density of the batteries was between 1.65 and 1.84 kWh/km after three days of trial with heating off and air conditioning on.
- A capacity loss of around 20% during recharging operations.
- When fitted with diesel (fossil fuel) auxiliary heating it was found that auxiliary battery heating was more power consuming, up to 1.4 kWh/km on buses with fossil fuelled heating systems, and up to 2.35 kWh/km on electrically heated ones.

For buses that require heating, for example in Northern Europe and North America during the colder months, it seems that battery heating is far less economical than fossil fuel. Also quoted by *Sustainable Bus*, the COO of a Dutch telematic company says that on average, "a 12-meter bus has in the best conditions a consumption of 0.8 kWh per km… We are talking of operations in a normal day with 20 degrees, not much traffic and a skilled driver. Everything depends on the heating. A bus operating in the winter, for instance at minus 10 degrees, with electric heating turned on can reach a consumption of 2.3 – 2.5 kWh per km. With diesel heating it could be 1.5." The COO highlights the importance of the driver and regenerative breaking; when the driver brakes hard this directly activates the mechanical brake, reducing regenerative energy from 35-40% down to only 5%.

A separate study in the US in 2019, similarly cited by *Sustainable Bus*, suggests that cold weather, between -5 and 0° C can reduce the range of battery-electric buses by up to 38% and of hydrogen fuelled buses by up to 23%. On the other hand, and under artificial conditions of a clear flat surface, in October 2019 a 12 meter "Iveco Bus marked a new record … covered as many as 527km on a single charge during a test day. The bus travelled for 12 hours at an average speed of 46 km/h. Heating and air conditioning were turned off." And during yet another reported test in May 2021 a 12-meter BEV bus travelled 550 km on a single charge. These distances under ideal conditions will never be realised in practical situations, but they do illustrate the continuing improvements in the technology.
Source: *Sustainable Bus*

Battery Depth of Discharge and Longevity

The depth of discharge (DoD) determines how far a battery can be safely discharged before it is necessary to recharge it. LiFeP04 batteries can be fully discharged 100% without a problem. Modern large lithium NCM batteries can typically be discharged 80% and in some cases fully discharged. However this is advised against because discharge below 80% can result in individual cells memorising different depths of discharge which may destroy the battery's functioning unless fitted with a power gauge to measure the state of charge.[90] At the same time laboratory evidence using LiFePO4 batteries suggests that at 55^{0}C, counterintuitively higher levels of DoD reduce battery fading less than shallow DoD.

The reported longevity of e-bus batteries varies according to sources. One report suggests vendors are now offering 12-year warranties on bus batteries,[91] while an academic paper by McGrath et al.

[90] Foxtron (December 2021) *Depth of Discharge: What It Is and Why It's Important* https://www.foxtronpowersolutions.com/depth-of-discharge/#fully-discharged
[91] Plug in Canada (2019) *Electric Bus FAQ* https://www.plugincanada.ca/electric-bus-faq/

published in 2022 suggests life cycles of between 5-10 years.[92] The paper also cites a range of bus battery costs from a variety of research reports, from higher values estimated in 2018 in the US at 750–850 USD/kWh for NMC batteries (lithium nickel–cobalt–manganese), 900–1540 USD/kWh for LFP (lithium ferrophosphate) and 1,500–2,000 USD/kWh for LTO (lithium-titanate) batteries to lower values in Europe between 500 and 800 €/kWh. A study in 2021 by the IEA's *Global EV Outlook* is cited with a weighted average costs of battery packs notably cheaper at 137 USD/kWh. As mentioned above, USD100 is widely regarded by vehicle manufacturers as the BEV breakeven point with ICEs, noting that an electric car battery may be 40 kWh up to 100 kWh or beyond – a Hummer EV sports vehicle in the US carries a 212 kWh battery and is good for a range of up to 329 miles (529 km)[93] – depending upon the size and nature of the vehicle.[94] A study published in 2021 of five types of bus services in Paris (city, inter-City, shuttle, regional and rapid-transit) concluded that often over-sized and therefore more expensive batteries were being used, and that only inter-City buses really needed batteries as large as 320-680 kWh.[95] In 2020 the German manufacturer MAN introduced even larger batteries, 480 kWh for the 12-metre 'solobus' model and 640 kWh for the 18-metre articulated vehicle.[96] In the USA, the Proterra ZX5 electric bus carries a gigantic 738 kWh battery,[97] and another articulated model a battery of 818 kWh.[98] But these are battery sizes, purchase and installation costs, not life cycle costs of the BEV buses themselves.

Lifecycle Total Costs of Ownership (TOC) of BEV Buses

Research papers and trials of electric buses over recent years suggest it is not BEV bus prices but the costs of the necessary supporting recharging infrastructure keeping them out of range without government support for infrastructure developments in one way or another. This was the conclusion in 2017 of Tan et al. who "found that all alternative fuel options lead to higher life cycle ownership and external costs than conventional diesel… We recognize that there are still practical barriers for BEVs, e.g. range limits, land to build the charging infrastructure, and coordination with utilities. However, favorable trends such as better battery performance and economics, cleaner electricity grid, improved technology maturity, and accumulated operation experience may favor use of BEBs where feasible."[99] The infrastructure costs were also highlighted a year later by an academic study in Europe that suggested when the cost of infrastructure to support BEV buses is accounted for, the overall costs for an electric bus after a 10-year lifespan are €691,073 as against €559,256 for the

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[92] Teresa McGrath et al. (August 2022) *UK battery electric bus operation: Examining battery degradation, carbon emissions and cost* Science Direct: Transportation and Research Part D: Transport and the Environment Volume 109 https://www.sciencedirect.com/science/article/pii/S1361920922002012

[93]The Drive (April 2022)*This Electric Bus Has a Battery Pack Over 3 Times Bigger Than a Hummer EV's* https://www.thedrive.com/news/this-electric-bus-has-a-battery-pack-over-3-times-bigger-than-a-hummer-evs

[94] E.on (2022) *Electric car battery and lifespan* https://www.eonenergy.com/electric-vehicle-charging/costs-and-benefits/battery-capacity-and-lifespan.html

[95] Hussein Basma et al.(January 2022) *Energy consumption and battery sizing for different types of electric bus service* Energy V.239, Part E (https://www.sciencedirect.com/science/article/abs/pii/S0360544221027031

[96] Sustainable Bus (July 2022) *Electric bus, main fleets and projects around the world* https://www.sustainable-bus.com/electric-bus/electric-bus-public-transport-main-fleets-projects-around-world/

[97]The Drive (April 2022)*This Electric Bus Has a Battery Pack Over 3 Times Bigger Than a Hummer EV's* https://www.thedrive.com/news/this-electric-bus-has-a-battery-pack-over-3-times-bigger-than-a-hummer-evs

[98] Commercial Vehicles (2019) *China's Electric Bus Market Dominance Driving Demand for Lithium-Iron-Phosphate Batteries* https://www.interactanalysis.com/chinas-electric-bus-market-dominance-driving-demand-for-lithium-iron-phosphate-batteries/

[99] Fan Tong et al (2017) *Life cycle ownership cost and environmental externality of alternative fuel options for transit buses* Transportation Research Part D https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwjkxujBzI_8AhXumFYBHTpuDe4QFnoECA4QAQ&url=https%3A%2F%2Fwww.sciencedirect.com%2Fscience%2Farticle%2Fpii%2FS136192091630476X&usg=AOvVaw0WjzZG-4wBLpwKrB4vnhM4

diesel version.[100] But taken on its own, the TCO of an electric bus according to an academic from India published in 2019 was estimated over a life cycle of 25 years, as 5-10% less compared to a diesel bus.[101]

Numerous lifecycle research studies have been and are being conducted, including the proposed research study of the Hong Kong-based Data Trust 2.0 project in 2023-5, but most of them contrast with field trials such as the 'Ebus Test' (see Box 7) in Germany as they work with assumed battery pack energy densities and costs rather than market case studies. So for example, the study by Chaoru at al. published in May 2022 finds that lifecycle estimates will vary such that a mix of hybrid and e-buses is more optimal in terms of balancing costs and environment factors, according to localities, than a wholesale shift to e-buses, but they add that "the parameters of the battery models are based on laboratory results and not calibrated based on the data collected from the real-world operated electric buses. With more realistic battery models developed in the future, a more precise life cycle cost and detailed bus composition plan will be provided."[102]

A study of BEV mini-buses in Italy published in 2020 examined three options, the use of lead-acid batteries, LFP batteries and hybrid mini-buses using supercapacitors which are a means of storing energy from a battery source for intermittent discharge rather than a steady continuous energy stream, and therefore more suited to the stop-start behaviour of a minibus. The conclusion favoured the use of lithium batteries with a supercapacitor – they store energy – which, despite similar revenues but varying costs between the alternatives, resulted in a higher lifetime Net Present Value (NPV) than the other options.[103] The issue with supercapacitors is that while they deliver more energy over a short period of time than batteries (by having higher specific power), batteries store more energy over longer periods (they have higher specific energy).[104] Although supercapacitors can charge quickly they also require recharging more frequently, so an extensive recharging infrastructure, such as fast-charging pantographs at selected bus stops, needs to be in place. In Korea, Hyundai has chosen to use 128-kWh lithium-ion-polymer batteries for its 15-33 seat mini/maxi-buses that provide a range of 250 km on a full charge.[105] On its 70-seater 300km range double-decker Hyundai is using a polymer 384kWh battery, with a full charge only taking 72 minutes.[106]

[100] Marek Potkány, et al (2018) *Comparison of the Lifecycle Cost Structure of Electric and Diesel Buses* Nase More Journal https://www.semanticscholar.org/paper/Comparison-of-the-Lifecycle-Cost-Structure-of-and-Potk%C3%A1ny-Hlatk%C3%A1/6ca2878fc66d620548e9a05a2e1c463e37959526
[101] Anal Sheth and Debasis Sarkar *Life Cycle Cost Analysis for Electric vs. Diesel Bus Transit in an Indian Scenario* International Journey of Technology V.10.1 https://ijtech.eng.ui.ac.id/article/view/1958
[102] Chaoru (2022) *The role of alternative fuel buses in the transition period of public transport electrification in Europe: a lifecycle perspective* International Journal of Sustainable Transportation , DOI: 10.1080/15568318.2022.2079445 https://www.tandfonline.com/doi/full/10.1080/15568318.2022.2079445
[103] Fabio Cignini, et al. (April 2020) *Experimental Data Comparison of an Electric Minibus Equipped with Different Energy Storage Systems* Batteries V.6.2 https://www.researchgate.net/publication/340967063_Experimental_Data_Comparison_of_an_Electric_Minibus_Equipped_with_Different_Energy_Storage_Systems
[104] CT (April 2022) *Batteries vs. Supercapacitors? The Answer is Both* https://www.capacitechenergy.com/blog/batteries-vs-supercapacitors-the-answer-is-both
[105] electrek (June 2020) *Hyundai launches first electric minibus with 128kWh battery pack* https://electrek.co/2020/06/30/hyundai-electric-minibus-128-kwh-battery-pack/
[106] electrek (May 2019) *Hyundai debuts 70-passenger electric double-decker* bushttps://electrek.co/2019/05/29/hyundai-double-decker-electric-bus/

Operational Considerations

The operational details of electric buses and their batteries inevitably vary widely according to local environmental factors and the demands placed upon them. The commercial interests of the transport operators will be best served if the size and nature of BEV buses and the batteries to drive them are carefully selected to match the profile of the services to be offered, which in turn may call for a review of the routing and timetables of public transport services to achieve optimum operational efficiencies. An example of the operational cost-benefit trade-offs bus operators could face is provided by the following research paper which simulated a bus powered by a battery of 324kWh and EV charger power of 90 kW, with a minimum proactive charging time of 2 hours.

> "Reducing battery capacity is particularly attractive for electric vehicle cost reduction since the battery cost is a major portion of electric vehicle life cost. Not surprisingly, electric bus performance changes significantly with different battery sizes… With a decrease of the battery size from 324 kWh to 150 kWh, the proactive charging days increases up to 208 days of the overall 610 days, and the lost drive time is 971 hours, which is nearly 30% of the total 3287 route driving hours. This means significant additional bus purchases would be necessary to make up the bus service lost due to EV battery range limitations. Evidently, it is not an optimal to reduce battery size."[107]

Optimisation however does not stop there. Local demands for services to uneconomic or sparsely-populated areas, or for high frequency services to densely populated areas become sensitive local political issues, and not least the fares structures. Bus payloads not only vary according to time and locality but are reduced by the space occupied by battery packs onboard BEV buses. The availability and type of recharging infrastructure, its level of utilisation and how widely can it be shared to spread its costs are issues of prime importance. Alternatively, a battery-swapping business arrangement could be put in place. Further, inexperienced driving such as speeding and undue acceleration and breaking will degrade the battery's energy, while a lack of management experience in the recharging process will hamper the maintenance of the vehicle. These issues, including the rate of the shift away from diesel and hybrids towards full BEV bus fleets, are issues that require a holistic approach to transport, public and private. Encouraging a movement away from non-electric private passenger vehicles towards e-buses or e-trains or e-metros, changes the parameters of *all* the above cost-benefit calculations. Further, a successful shift towards electric vehicles places an existential demand upon renewable sources of energy, otherwise a reduced kerbside GHG effect – reduced particulates, including from less tyre burn if the total number of vehicles is reduced – is simply replaced by a greater electricity production GHG effect.

The Recharging Infrastructure

E-bus battery chargers come in a variety of options, including different wattage (power) from slow overnight charging to fast chargers operating at 400kW or more, and as depot-charging located in bus terminals or stations, or as opportunity-charging located at vantage points along bus routes

- Plug-in charging
- Top-down pantographs descending onto the roof of the bus
- Top-up pantographs rising from the roof of the bus
- Ground-based induction plates

[107] Zhiming Gao, et al. (2017) *Battery capacity and recharging needs for electric buses in city transit service* submitted to an International Journal made available under Elsevier open access licence https://www.sciencedirect.com/science/article/abs/pii/S0360544217301081

- Battery-swapping arrangements

The creation of BEV-bus battery charging infrastructure in any country follows that country's national standards. In the US and in Europe there are two standards setting bodies for road transport.

> "For the U.S. auto industry, the governing document for electric vehicle (EV) charging is the Society of Automotive Engineers (SAE) standard J1772. In Europe, the standard is IEC 61851. These documents define the requirements for 'Electric Vehicle Supply Equipment' (EVSE). J1772 says EVSE has three functions: ac-dc rectification, voltage regulation to a level that permits a managed charge rate, and physically coupling the charger to the vehicle. It also defines several 'levels' of charging. The levels correspond to different voltage levels and current flows."[108]

The important need for interoperable standards is outlined by the EU's *Assured* project.[109]

Plug-in, Pantographs or Induction

The options available to bus operators are overnight slow-charging (65kWh to 150kWh) for up to 5 hours when the fleet has completed its run time, or fast charging (350kW to 600kW) within 15-20 minutes using DC from pantographs located either within a depot or along the routes, or fast induction charging. Pantograph on-route charging is however fraught with problems as outlined in an *Atlas Public Policy* document from the USA in June 2022.[110]

> "On-route charging tends to be more expensive and logistically challenging than depot charging. Agencies may have to acquire land or rights of way in order to install charging stations along their routes. On-route charging requires fast chargers (350kW+) which are more expensive than slower chargers that can be used during longer parking windows. Agencies have little control over when on-route charging occurs, which can lead to high electricity costs due to demand charges and time-of-use-rates. There are also a number of risks associated with locating chargers in public outdoor spaces. Challenges experienced by interviewees included intentional vandalism of on-route chargers, a wayward recycling truck destroying charging structures, complaints from neighbors who don't appreciate having chargers being located next to their residences, and on-route chargers shutting off below -20°F [temperatures]. When these or other problems occur, it can be more challenging for agencies to fix or maintain on-route chargers because maintenance staff must travel to reach them."

Figures 16a and 16b show one of several new pantograph charging points at Bexleyheath bus garage in South London, and a plug-in for slow charging. In many cases, bus depots will include a fast charger in addition to slow-chargers, the latter may be equipped with more than one dispenser – a cable and plug – to service different buses. But fast charging can hasten battery degradation. Pantographs have another problem besides the more costly support structures they require, they

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[108] Electronic Design (March 2012) *Electric-Vehicle Charging* https://www.electronicdesign.com/power-management/article/21751240/understanding-us-and-european-standards-for-electricvehicle-charging

[109] ASSURED (March 2022) *D4.4 - ASSURED 1.1 Interoperability Reference* https://assured-project.eu/storage/files/d44-assured-11-interoperability-reference-pdf

[110] Nicole Lepre, et al. (June 2022) *Deploying Charging Infrastructure for Electric Transit Buses* Atlas Public Policy https://trid.trb.org/view/2005687

connect to buses wirelessly using WiFi which can lead to interference problems; hence research is looking at ways to replace WiFi with RFID.

Figure 16a – fast Pantograph charger[111] **Figure 16b – slow Plug-in charger**[112]

TFL Pantograph charger

Photo: Ashley Tan

A third option is induction charging – see Figure 17. Primary coils are implanted into the ground, and they make contact with secondary coils that are lowered from underneath the bus. These can range from 75kW upwards of 300kW located variously along a route to provide episodic or opportunistic recharging. Under the name Inductive Power Transfer (IPT) the technology is in use in Madrid where on average a State of Charge of 55Ah is maintained, sufficient to keep a single decker running the full route. Several other European cities such as Turin, Utrecht, Milton Keynes and London have also deployed the technology.[113] But it remains for manufacturers to agree on common standards.

The recharging time is critical for public service vehicles, and is determined by the size of the battery kWh/kW (the power of the charger) The chemical composition of the battery will also make a difference. For example, Lithium-titanate batteries charge much faster than their lithium-ion counterparts, and fast charging doesn't degrade them which it otherwise tends to do with other batteries.[114] Another consideration is how much peak-hour/peak price electricity is used from the public grid. A research paper found that time of day and V2G (vehicle-2-grid) availability have the greatest impact on reducing peak consumption whereas pre-emptive recharging before the discharge is deep, and fleet splitting "have the greatest impact on the computational time but an insignificant impact on peak reduction."[115]

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[111] CITYA.M (October 2022) *TfL unveils state-of-the-art pantograph electric bus chargers in renewed green push* https://www.cityam.com/tfl-unveils-state-of-the-art-pantograph-electric-bus-chargers-in-renewed-green-push/

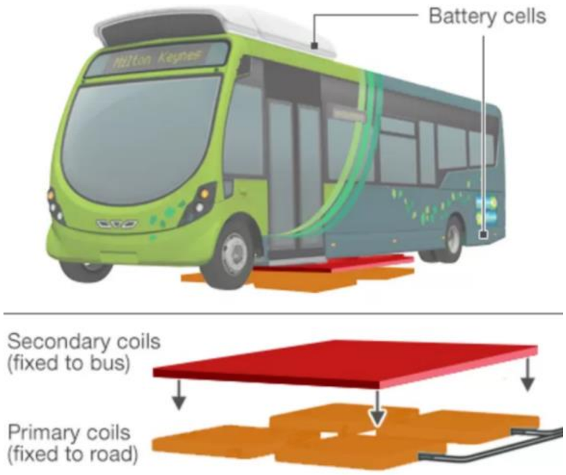
[112] Mothership (October 2020) *10 double-deck electric buses to be deployed in S'pore* from Oct. 27, 2020 https://mothership.sg/2020/10/double-deck-electric-buses-singapore/

[113] Power Technology (2022) *Wireless Opportunity Charging buses in Madrid* https://ipt-technology.com/case-opportunity-charging-madrid/

[114] WIRED (October 2014) A *Giant Charger That Juices Up Electric Buses in Three Minutes* https://www.wired.com/2014/10/giant-charger-juices-electric-buses-three-minutes/

[115] Enrico Toniato, et al. (*Peak load minimization of an e-bus depot: impacts of user-set conditions in optimization algorithms* Proceedings of the 10th DACH+ Conference on Energy Informatics, Energy Informatics V.4.23 https://energyinformatics.springeropen.com/articles/10.1186/s42162-021-00174-4

Figure 17 – Inductive Charging



Source: BBC News Technology[116]

A study in 2022 sponsored by the US-based Environmental Defense Fund cites one engineering company suggesting operators should focus more on an energy-based assessment than a mileage-based assessment by taking into account local environmental factors that drive up costs. The study also highlights that rather than force battery-buses to perform as diesel buses, a more flexible approach to routes and schedules would avoid mid-life battery failures. The same source cites "14 out of 25 interviewed" as having "emphasised the importance of engaging with utilities early." [117] Two additional considerations, also highlighted by the same source, are the training of staff in the safe use and maintenance of the recharging equipment, and electricity-supply redundancy. The *Atlas Public Policy* document (see above) suggests four insurance policies

- Grid hardening – most outages can arise from accidents, such as falling trees in a storm
- Generator ports and mobile power source – an available diesel or natural gas mobile generator
- Redundant electricity service – two feeds from nearby power stations
- Microgrid – renewable energy sources from an independent backup grid

In all these cases, and in other operational areas such as spare parts, outsourcing is always an option, although this can also give rise to confusion over the use of different standards, such as charging equipment. But in many cases the constraining factor is not so much the availability, cost and use of electricity but finding suitable locations for the recharging apparatus. As bus depots are the most likely choices this may work against on-route fast-charging pantograph solutions in smaller environments such as Hong Kong, Singapore and Taiwan, or in high density cities in many Asia and South American countries. Besides land availability and land costs, are the initial infrastructure costs. The Atlas Public Policy document gives examples in the USA of charging equipment costs for fleet-level services ranging from under USD1 billion to over USD2 billion, and total costs including installation, hardware and power rising to over USD3 billion. Offsetting some of these costs are grants and subsidies designed to promote clean air.

[116] BBC News (January 2014) *Wirelessly charged electric buses set for Milton Keynes* https://www.bbc.com/news/technology-25621426

[117] Nicole Lepre, et al. (September 2022) *Deploying Charging Infrastructure for Electric Transit Buses: Best Practices and Lessons Learned From Deployments to Date* https://trid.trb.org/view/2005687

Battery Swapping

The alternative strategy is battery swapping, but for several reasons the question arises how sustainable is this as a long-term business. First, different models of e-buses not only host their battery packs in different areas, such as the chassis and the roof, but their batteries come from a range of manufacturers and there is no industry standard model. The equipment required to extract the batteries and replace them therefore also has to vary, which is quite unlike recharging technology. For example, in Poland, the bus manufacturer Autosan, the National Centre for Research and Development, and the Lukasiewicz-PIMOT consortium have been piloting an e-bus battery swapping project where the batteries are located at the back of the bus.[118] Second, the capital costs of robotic battery lifting gear is very high and "the necessary space to build a battery swapping station is much larger than that for a charging station."[119] For example, the swapping stations of Chinese vehicle and battery manufacturer Nio, which operates a Battery-as-a-Service (BaaS) business model, so the car is sold separately, and the battery is provided on a swap basis for the lifetime of the car, are "as large as three parking spaces, making them convenient to install in parking facilities and even crowded public places. By 2021, Nio had installed 301 battery swapping stations across China, with plans to expand to 3,000 swapping stations globally by 2025."[120] Third, battery technology is continuously improving, extending the runtime and distances before recharging is necessary and extending the battery lifecycle, which threatens to undermine the demand for swaps.

Figure 18: Robotic Swapping Gear in South Korea

https://www.youtube.com/watch?v=Gz68yBbtmaM

Despite these hurdles, the BaaS model is being considered elsewhere, for example in the UK,[121] where Nio is also investing. Incentivising the swap business model in China are two factors. One is the lack of residential charging points for personal EVs, so extending the model to e-buses offers economies of scale, and the other are the subsidies that China provides to the manufacturers of so-called New Energy Vehicles (NEVs) of all kinds. A China Briefing paper in 2022 points out, "a 6-meter-long battery electric bus might have earned up to RMB 0.6 million (US$87,000) in subsidies, half from the national government and half from the local government" and "if the government invests in NEV charging stations on a large scale, the sector will be strengthened and NEVs will become more appealing to the ordinary customer." Despite concerns about fraud as subsidies for larger BEVs may end up funding smaller BEVs, the subsidies are to be extended into 2023.[122] For a

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118 Electrive.com (April 2020) *Poland developing e-bus with swappable battery* https://www.electrive.com/2020/04/14/poland-developing-e-bus-with-swappable-battery/

119 Shashank Arora, et al. (2021) *EV Battery Pack Engineering—Electrical Design and Mechanical Design* chapter 5 Heavy Duty Electric Vehicles pp.105-134 Science Direct https://www.sciencedirect.com/topics/engineering/battery-swapping-station

120 Shantanu Bhattacharya and Lipika Bhattacharya (May 2022) *NIO's Battery-as-a-Service Strategy: A game changer in the EV industry?* SMU Case in Point V.9.1 https://cmp.smu.edu.sg/ami/article/20220529/nios-battery-service-strategy

121 Autocar (November 2022) *How to make electric vehicle battery swapping work in the UK* https://www.autocar.co.uk/car-news/business-electric-vehicles/how-make-electric-vehicle-battery-swapping-work-uk

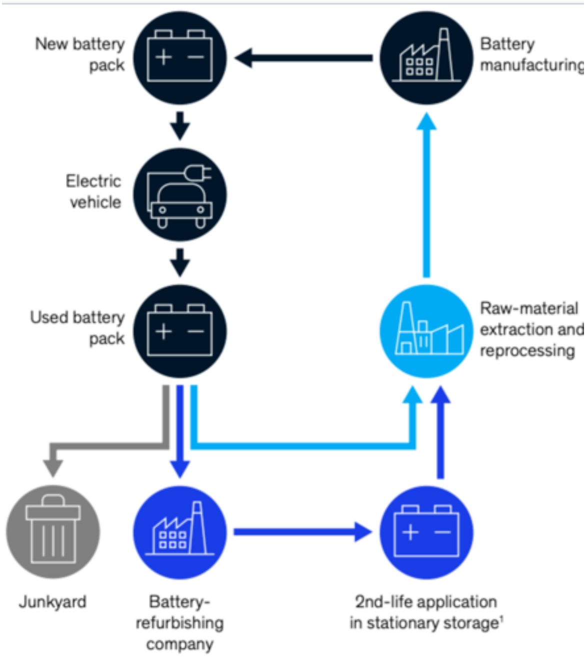
122 China Briefing (September 2022) *China Considers Extending its EV Subsidies to 2023 (updated)* https://www.china-briefing.com/news/china-considers-extending-its-ev-subsidies-to-2023/

comprehensive background to China's subsidies to electricity-powered buses, see GIZ (2020),[123] and for an update, see GIZ (2022).[124]

Part 3: Recycling Batteries for E-Vehicle (BEV) Buses

One possible advantage of the battery swapping model is that the batteries can be collected and recycled *en masse*. But as battery chemistry shifts towards less scarce and therefore cheaper as well

Figure 19



Source: Wikipedia *Electric Vehicle Battery*[125]

as less combustible, mineral components, so the value in their recycling diminishes making the business case less compelling. The repurposing of some batteries as storage batteries can offer a second life in a circular economy as illustrated in Figure 19.

EV batteries which are replaced after they lose 20% or more of their capacity then become available as stationary storage applications, a policy being adopted by several car manufacturers such as Nissan.[126] But as battery storage costs continue to fall even these recycling projects may not be sustainable. In 2019 researchers from Carnegie Mellon University published a paper in *Nature Sustainability* examining three methods for recycling three types of batteries: nickel manganese cobalt oxide (NMC), nickel cobalt aluminium oxide (NCA), and iron phosphate (LFP). The research methods included

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[123] GIZ (2020) *New Energy Buses in China Overview on Policies and Impact* https://transition-china.org/wp-content/uploads/2021/01/2020_GIZ_New-Energy-Buses-in-China.pdf

[124] GIZ (January 2022) *E-Bus Development in China: From Fleet Electrification to Refined Management* https://transition-china.org/mobilityposts/e-bus-development-in-china-from-fleet-electrification-to-refined-management/

[125] Wikipedia *Electric Battery Vehicles* *"Electric vehicles, second life batteries, and their effect on the power sector | McKinsey". www.mckinsey.com. Retrieved 10 May 2021.* https://www.google.com/search?client=firefox-b-d&q=Wikipedia+Electric+Vehicle+Battery

[126] AZO Cleantech (July 2022) *Latest Developments in Electric Vehicle Battery Recycling* https://www.azocleantech.com/article.aspx?ArticleID=1597

"pyrometallurgical recycling (exposing the valuable parts of the battery to high temperatures and then recovering those metals as alloys), hydrometallurgical recycling (leaching valuable metals from batteries and separating the desired metals from the resulting solution), and 'direct cathode recycling,' where the battery's cathode is retained as-is, but new lithium is added in such a way that the battery regains its original performance."[127]

The research found that owing to the mining of LFP minerals being rather efficient, a smaller GHG emissions offset from the recovered materials was insufficient to offset the energy and GHG emissions associated with the recycling processes. For the other battery types, only direct cathode recycling had the potential to be cost-competitive for new batteries. Pyrometallurgical recycling, which is more used in Europe where 50% of the total weight of bus batteries is required to be recycled, enables cathode and cannister casing materials to be reduced to metal alloys, with the rest a slag that can repurposed for cement production. Cement production is the third largest producer of GHGs.

Strong fluctuations in mineral prices (see Figure 8), for example cobalt and nickel, can temporarily make recycling commercially profitable but not on a sustainable basis. The scale of the problem will only grow as the total number of BEVs grows. The forecast end-of-life (EOL) batteries in the USA by 2027 is to reach 200,000 metric tons and globally 800,000 metric tons,[128] possibly an underestimate depending upon the speed of transition to BEVs. In the Netherlands, for example, where electricity generator RWE and EV manufacturer VDL have combined in Project Anubis for recycling batteries, the forecast after 2030 if all vehicles are electric is 150,000 metric tons.[129] The other major dilemma is that if recycling at the EOL is a problem, the carbon footprint of electricity generation to charge and recharge all these batteries will simply replace roadside tailpipe emissions with a rise in general atmospheric GHGs, unless the deployment of renewables makes a giant leap forward.

Part 4: Electricity Production

Only by rapidly replacing carbon fuels with renewable energy will the GHG balance between carbon-producing electricity generation and roadside tailpipe emissions be swung in favour of clean air.

Carbon

For the purposes of gauging the scale of the problem, the following comes from the US Energy Information Administration (EIA).

Table 2

US electricity net generation and resulting CO_2 emissions 2021

Fuel	Electricity generation	CO_2 emissions	
Coal	897,885 kWh	919 mill. metric tons	2.26 lbs/kWh
Natural Gas	1,579,361 kWh	696 mill. Metric tons	0.97 lbs/kWh
Petroleum	19,176 kWh	21 mill. Metric tons	2.44 lbs/kWh

[127] ARS Technica (February 2019) *Electric car batteries might be worth recycling, but bus batteries aren't yet* https://arstechnica.com/science/2019/02/electric-car-batteries-might-be-worth-recycling-but-bus-batteries-arent-yet/
[128] Congressional Research Service (August 2022) Critical Minerals in Electric Vehicle Batteries https://www.google.com/search?client=firefox-b-d&q=Critical+minerals+in+Electric+Vehicle+Batter
[129] PV Europe (May 2022) *RWE gives old batteries from electric busses a second life* https://www.pveurope.eu/e-mobility/battery-recycling-rwe-gives-old-batteries-electric-busses-second-life

"In 2021, utility-scale electric power plants that burned coal, natural gas, and petroleum fuels were the source of about 61% of total annual U.S. utility-scale electricity net generation, but they accounted for 99% of U.S. CO_2 emissions associated with utility-scale electric power generation. The other 1% of CO_2 emissions were from other fuels and gases derived from fossil fuels and some types of geothermal power plants. EIA considers electricity generation from biomass, hydro, solar, and wind to be carbon neutral."[130]

Renewables

Per capita other countries are in worse situation than the USA, and each has its own trajectory to overcome carbon emissions, none of which look too hopeful as things stand, although in terms of EVs, China is one of the front runners. However, in 2022 the International Energy Agency (IEA) came out with a surprisingly optimistic forecast for renewable energy. Box 8 links the forecasts to EVs.

Box 8

IEA – World Energy Outlook 2022[131]

1. **The IEA's *World Energy Outlook 2022*** offers a substantial revision of forecasts from just one year earlier, brought about by several factors difficult to foresee, most dramatically President Putin's decision to invade the Ukraine. The global reaction has been to accelerate longer-term policy and investment shifts away from a dependency upon fossil fuel and natural gas exports and encouraged by a growing pressure to generate electricity more from renewable sources of energy. As a consequence, the IEA which previously forecast renewable energy by 2030 as being no more than 20% of total energy demand now forecasts renewables will overtake carbon fuels by 2025.[132]

2. **The IEA report discusses three scenarios:**
   - **Stated Policies Scenario (STEPS)** – assumes national policies will be fully implemented
     - CO2 emissions by 2050 = 32 Gt (billion tonnes); IEA estimates the required investment as USD2 trillion by 2030.
   - **Announced Pledges Scenario (APS)** – assumes investment pledges will be fully implemented
     - CO2 emissions by 2050 = 12 Gt (billion tonnes)
   - **Net Zero Emissions by 2050 Scenario (NZE)** – assumes the COP target of zero-net emissions by 2050 will be met
     - CO2 emissions by 2030 = 23 Gt (billion tonnes) and by 2050 = zero; IEA estimates the required investment as USD4 trillion by 2030.

3. **EV and battery demand** – the demand for cooling is the second largest demand for electricity globally, but the demand from various modes of transport heads the list. The role of renewables in meeting that demand will be critical to the three scenarios. "Today's growth rates for deployment of solar PV, wind, EVs and batteries, if maintained, would lead to a much faster transformation than projected in the STEPS, although this would require supportive policies not just in the leading markets for these technologies but across the world. By 2030, if countries deliver on their climate pledges, every second car sold in the European Union, China and the United States is electric… In the EV sector, the expansion of battery manufacturing capacity reflects the shift underway in the automotive industry, which at times has moved faster than governments in setting targets for electrified mobility." (p.22)

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[130] EIA (November 2022) *How much carbon dioxide is produced per kilowatthour of U.S. electricity generation?* https://www.eia.gov/tools/faqs/faq.php?id=74&t=11
[131] IEA *World Energy Outlook 2022* https://www.iea.org/reports/world-energy-outlook-2022/key-findings
[132] NHK World-Japan (December 2022) *IEA: Renewable energy will be largest source of electricity by 2025* https://www3.nhk.or.jp/nhkworld/en/news/20221207_07/

4. **Costs and Gestation** – (i) Higher costs for many emerging economies, for example, "The capital cost for a solar PV plant in 2021 in key emerging economies was between two to three times than in advanced economies and China"; (ii) the time needed to create physical supply chains for renewables can be extensive, such as "permitting and construction of a single overhead electricity transmission line can take up to 13 years, with some of the longest lead times in the advanced economies. Developing new deposits of critical minerals has historically taken over 16 years on average, with 12 years spent in lining up all aspects of permitting and financing, and 4-5 years for construction." (pp. 23-24)

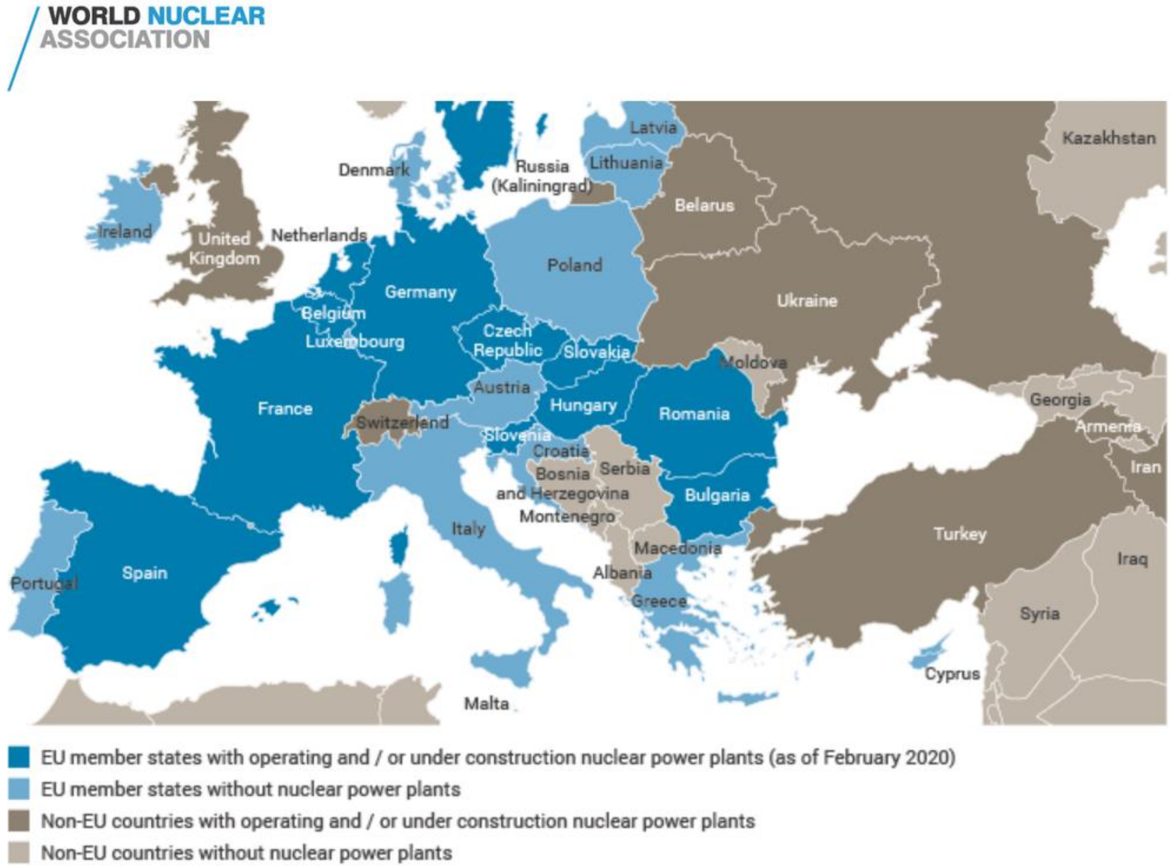
5. **Hydrogen as a fuel** was covered in the Primer *Hydrogen as a Fuel for Public Transport*.[133] The IEA has an updated view.
   "In the APS, global low-emissions hydrogen production rises from very low levels today to reach over 30 million tonnes (Mt) per year in 2030, equivalent to over 100 bcm (billion cubic metres) of natural gas (although not all low-emissions hydrogen would replace natural gas). Much of this is produced close to the point of use, but there is growing momentum behind international trade in hydrogen and hydrogen-based fuels. Projects representing a potential 12 Mt of export capacity are in various stages of planning, although these are more numerous and more advanced than corresponding projects to underpin import infrastructure and demand. Carbon capture, utilisation and storage projects are also advancing more rapidly than before, spurred by greater policy support to aid industrial decarbonisation, to produce low- or lower-emissions fuels, and to allow for direct air capture projects that remove carbon from the atmosphere." (pp. 22-23)

Nuclear Energy

Besides renewables, nuclear power (fission) is also regaining policy traction despite the enormity of the radioactive waste disposal problems. For example, in December 2022, Poland announced plans for two new nuclear reactors, not least as a response to Russia's politicisation of gas exports.[134]
Despite the IEA optimism, a study in February 2021 called into question the sustainability of renewable energy across Europe. The study of two European countries "found that, in realistic scenarios, there is insufficient land to meet all the power demand of the Netherlands – 'a country along the North Sea with abundant wind' – and the Czech Republic – 'a landlocked country with no

[133] John Ure (2022) *Hydrogen as a Fuel for Public Transport* https://accesspartnership.com/a-primer-hydrogen-fuel-for-public-transport/ and https://www.wcbc.online/publications
[134] Financial Times (29 December 2022) *Poland takes steps to enter nuclear energy age: Two reactor projects are envisioned as part of push to reduce reliance on Russia*

Figure 20



Source: European Union (October 2022)

access to the sea and a geographically more challenging landscape – if they were to rely solely or predominantly on wind and solar power."[135] The same source highlights there "are 103 nuclear power reactors (100 GWe or GigaWatt electrical) operating in 13 of the 27 EU member states accounting for around 25% of the electricity generated across the EU. Over half of the EU's nuclear electricity is produced in only one country – France. The 56 units operating in three non-EU countries (Russia, Ukraine and Switzerland) account for about 15-20% of the electricity in the rest of Europe."

It may well be that renewables cannot bridge the gap between the demands for electricity and the demands for clean air, let alone the need to combat global warming, even if they become price competitive with coal, gas and oil. If the urgency is, or becomes, existential for health or survival reasons, the trade-off with nuclear seems unavoidable short of a dramatic reduction in demand. The glimmer of hope on the supply side on the distant horizon, but not the 2050 net zero emissions horizon, is the Holy Grail of energy creation, nuclear fusion. As the following account makes clear, for the first time since British astronomer Arthur Eddington theorised in 1920 that the sun was powered by a fusion reaction that could be replicated on Earth to generate abundant power, a net positive sum of energy has been generated.

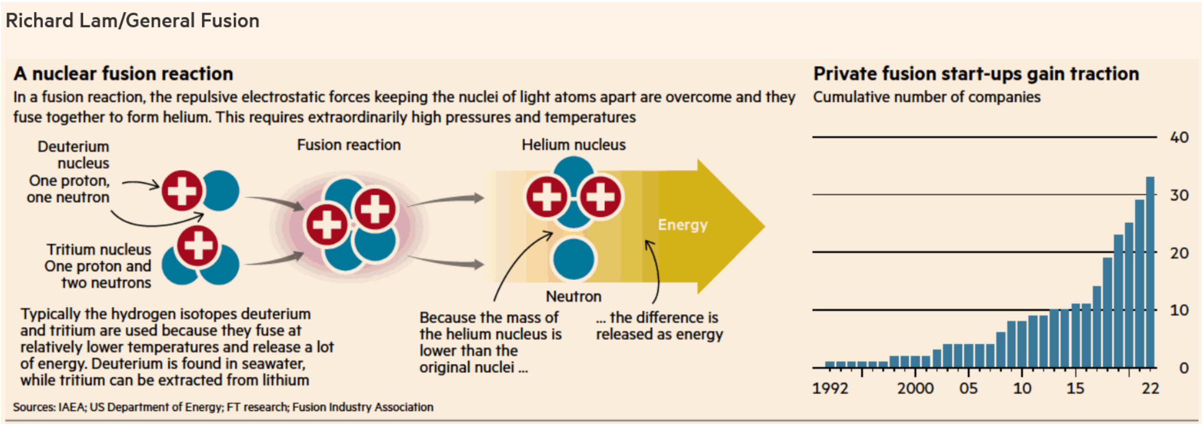
> "On December 5, an array of lasers at the National Ignition Facility (NIF), part of the Lawrence Livermore National Laboratory in California, fired 2.05 megajoules of energy at a tiny cylinder holding a pellet of frozen deuterium and tritium, heavier forms of hydrogen.

[135] European Union (October 2022) *Nuclear Power in the European Union* https://world-nuclear.org/information-library/country-profiles/others/european-union.aspx

The pellet compressed and generated temperatures and pressures intense enough to cause the hydrogen inside it to fuse. In a tiny blaze lasting less than a billionth of a second, the fusing atomic nuclei released 3.15 megajoules of energy—about 50 percent more than had been used to heat the pellet."[136]

A bridge too far? Maybe, but there are reported to be over 30 fusion start-ups, giving some grounds for hope in what sadly looks like a race against time.

Figure 21[137]



Source. Financial Times 17th December 2022

Part 5: Selected Country Studies

China

China's share of e-buses globally is estimated at 17%, with all other places in single decimals.[138] Two studies by GIZ (2020, 2022[139]) provide a comprehensive assessment of China's leading role in e-bus development from which the following information is drawn. The introduction to the 2022 study begins:

> Against the backdrop of the 2030 carbon dioxide emission peaking and 2060 carbon neutrality goals proclaimed by Chinese President Xi Jinping, China's "14th Five Year Plan for a Modern and Comprehensive Transportation System (2021-2025)" was published on January 18th, 2022. The plan highlights the development principle of green transition, people-oriented development, and innovation. It also confirms the significant role of New Energy Buses (NEB) in China's strategy to carbon emission reduction in cities. As one of the indicators for "Green & Innovative Mobility", 72% of China's urban public buses are expected to be electric by 2025.

China's early start ran up against bottlenecks, early technical and quality issues and a lack of recharging infrastructure. For example, in China's colder regions only plug-in recharging is used. But

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[136] National Geographic (14 December 2022) *Scientists achieve a breakthrough in nuclear fusion. Here's what it means* https://www.nationalgeographic.com/science/article/scientists-achieve-breakthrough-nuclear-fusion
[137] Financial Times 17 December 2022 'Fusion energy takes its first tentative step beyond realm of science fiction'
[138] Sustainable Bus (July 2022) *Electric bus, main fleets and projects around the world* https://www.sustainable-bus.com/electric-bus/electric-bus-public-transport-main-fleets-projects-around-world/
[139] GIZ (January 2022) *E-Bus Development in China: From Fleet Electrification to Refined Management* https://transition-china.org/mobilityposts/e-bus-development-in-china-from-fleet-electrification-to-refined-management/

GIZ also notes early problems during the period of rapid vehicle electrification, such as "lacking capacities for effective NEB system integration and procurement strategies, low operating efficiency, unreasonable layout planning of supporting and charging infrastructure facilities, and poor maintenance and service levels, are faced by many cities." These pioneer teething problems are being resolved. Subsidies support the development of China's battery manufacturers who have pioneered the use of lithium ferrous phosphate (LiFeP04 or LFP) battery packs and upgraded gravimetric-energy densities from 140Wh/kg (2014) to 180Wh/kg (2022). China has been innovative, for example in using smart scheduling to maximise the efficient use of e-buses, and adopting a cloud-based energy analysis system in the southern city of Guangzhou. GIZ also forecasts the introduction of on-demand services and smaller buses to provide a more granulated approach to timetables. The Nio BaaS (Battery-as-a-Service) infrastructure business model is another example of innovative thinking, where the bus operator does not buy but pays per usage of the battery, and Nio is among China's main manufacturers of batteries and of cars (see Figure 5) who are investing heavily in international markets.

Hong Kong

Hong Kong's operating environment is challenging, often with long routes up hilly terrain in humid weather. Following the Government's Climate Action Plan 2050 published 2017,[140] the Policy Address of 2022 announced that 700 electric buses and 3,000 electric taxis would be introduced by 2027.[141] The first trial electric bus trial was by the Kowloon Motor Bus Company (KMB) of a single decker BYD vehicle in 2013. The vehicle was returned the same year. Then with a government grant in 2014, KMB and New World First Bus and Citybus (now both part of Bravo Bus) trialed diesel-electric hybrids buses.[142]

E-Buses

The introduction of e-buses came in April 2022 when KMB launched 16 BYD 12A single decker buses which are designed 4% lighter than the older K9R model with a passenger capacity increased by 16% to 81 people. The recharging time is reported as 1 hour and 40 minutes,[143] 2 hours faster than previously, and the driving range is 200 km.[144] From the same report it is learned that KMB has also purchased fifty-two 12 metres long double-deck electric buses from BYD and the United Kingdom's Alexander Dennis Limited ("ADL") for delivery in 2023. Charging time is reported to be 2.5 hours and range 300 km. KMB's target is an additional 500 e-buses by 2025. Three innovations are 5G Wi-Fi, the inclusion of solar panels on the roof and the use of a 'Blade Battery' arrangement which, according to BYD, increases the space utilization of the battery pack by over 50% compared to conventional lithium iron phosphate block batteries.[145]

However the first e-double decked bus and the first hydro-fueled double-decker bus were introduced in 2022 by Bravo Bus – for the latter, see *Primer: Hydrogen as a Fuel for Public Transport*. The e-double decker carries a 450kWh battery, with an estimated range of over 200km and a passenger

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[140] HKG (2017) Hong Kong's Climate Action Plan 2030+ https://www.info.gov.hk/gia/general/202110/08/P2021100800588.htm
[141] HKG (2022) The Chief Executive's 2022 Policy Address https://www.policyaddress.gov.hk/2022/en/policy.html
[142] Wikipedia (February 2022) *History of bus transport in Hong Kong* https://en.wikipedia.org/wiki/History_of_bus_transport_in_Hong_Kong
[143] The Standard (27 January 2022) *KMB to roll out fleet of 16 new electric buses after LNY* https://www.thestandard.com.hk/breaking-news/section/4/186536/KMB-to-roll-out-fleet-of-16-new-electric-buses-after-LNY
[144] FutureIOT(26th April 2022) *KMB deployed 16 new electric buses on HK streets* https://futureiot.tech/kmb-deployed-16-new-electric-buses-on-hk-streets/
[145] BYD (2022) *BYD Blade Battery Pack* https://en.byd.com/news/byds-new-blade-battery-set-to-redefine-ev-safety-standards/

capacity of 113 with 79 seats and 34 standing. Bravo is committed to 100% non-emissions by 2045.[146] The relatively compact size of the battery is far less than might have been required just a few years back, and aluminum bodywork reduces the weight to be driven, an essential detail in Hong Kong's hilly environment. Smaller batteries also offer more options for opportunity recharging along routes if the infrastructure – pantographs or induction recharging – becomes available. One bus consultant suggests using opportunity charging a double-decker – over 90% of Hong Kong buses are double-deckers – only needs 200 kWh of batteries for an 'all-day-charge' approach.[147] But this is a trade-off, the cost of larger heavier batteries or the cost of the infrastructure assuming the optimal locations in a very crowded Hong Kong are available.

E-Minibuses

Fixed route/fixed fares Green minibuses (GMB), officially known as Public Light Buses (PLB), and free-routing/variable fares Red minibuses (RMB) are widely used in Hong Kong as are taxis. The Transport Department has contracted the Hong Kong Productivity Council (HKPC) to trial three electric GMBs supplied by the Chinese manufacturer Ev Dynamics. The seven-meter long GMBs use LiFePO4 batteries, can travel up to 230 km on one charge, and take 30-60 minutes roof fast charging. [148] Various earlier trials of both e-GMB and e-RMB failed due to a number of reasons, some related to the inadequacies of the batteries, some to the excessive stop-start demands, one case of fire, and extra maintenance requirements where supercapacitors were used.[149]

E-Taxis and Ferries

In the previous trials of 2013 the time taken to charge up taxi batteries together with too few recharging points was a show-stopper for taxi drivers. The Policy Address target of 3,000 electric taxis by 2027 therefore seems ambitious but the installation of ten fast chargers in 2022 on Lantau Island and the Sai Kung district of the New Territories heralds new trials.[150] This was announced in 2020 by the Environmental Protection Department (EPD), funded by the New Energy Transport Fund established in 2011, including HK$350 million (USD45 million) to support the four Victoria Harbour ferry operators to buy electric vessels and build charging facilities.[151]

Singapore

At the time of the first trial of a BYD electric bus in 2016, followed by trials of two MAN single and double-deckers in 2017, Singapore's Land Transport Authority (LTA) ran a fleet of around 3,000 buses operated by four bus companies.[152] The first tender for 60 fully electric buses and 50 hybrids was issued in 2018, with the LTA noting that in Singapore's hot and humid climate batteries are less

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[146] Cision (3rd May 2022) *Hong Kong's First-ever Double-decker Electric Bus is Launched Today* https://en.prnasia.com/releases/apac/hong-kong-s-first-ever-double-decker-electric-bus-is-launched-today-360041.shtml

[147] Transit Jam (16th April 2020) 'Ditching Heavy Batteries will save e-Buses, says Bus Expert' https://transitjam.com/2020/04/16/ditching-heavy-batteries-will-save-e-buses-says-bus-expert/

[148] ACNnewswire (16th September 2022) *Ev Dynamics's First Pure Electric Fully Accessible Public Minibus Will Soon Commence Service in Hong Kong* https://www.acnnewswire.com/press-release/english/77983/ev-dynamics%27s-first-pure-electric-fully-accessible-public-minibus-will-soon-commence-service-in-hong-kong

[149] Transit Jam (17th February 2020) *Pilot-Funded E-Buses & Hybrid Minibuses Disappoint* https://transitjam.com/2020/02/17/pilot-fund-e-buses-hybrid-minibuses-disappoint/

[150] RTHK.HK (4th May 2022) *Govt making preparations for e-taxi trial runs* https://news.rthk.hk/rthk/en/component/k2/1646991-20220504.htm

[151] SCMP (27th February 2020) *Hongkongers can test ride electric minibuses and cross-harbour ferries in 2023 as budget allocates HK$430 million for green-energy transport* https://www.scmp.com/news/hong-kong/health-environment/article/3052761/hongkongers-can-test-ride-electric-minibuses-and

[152] Land Transport Guru (January 2018) *Electric Buses in Singapore* https://landtransportguru.net/electric-buses-in-singapore/

cost effective than in cooler and drier climates.[153] The LTA also notes that a lack of excess capacity in the existing electricity grid as being a "major hurdle to widespread electric bus adoption in Singapore." While 95% of Singapore's electricity is generated using natural gas, the aim is to deploy at least 2GW of solar by 2030, but there will still be a requirement to import 4GW of low-carbon electricity by 2035.[154] To put that into perspective, Singapore consumes 47.7GW annually and produces 48.7GW annually.[155]

Nevertheless, the LTA's aim is to have half of the fleet electric by 2030.

Under the Singapore *Green Plan 2030*,[156] the LTA has a comprehensive *EV Roadmap* to drive EV adoption, including 100% electric buses by 2040.[157] Additionally, there are several privately-operated electric mini-buses and shuttle buses from hotels, shopping malls and universities.

Europe

In 2019 the EU-27 adopted the *Clean Vehicles Directive* (CVD) with clean air targets, set for vehicle emissions from a variety of vehicle types. [158] The targets for the minimum percentage of zero-emission buses vary according to each country's population and GDP, resulting in their national policy frameworks (NPFs) having been mostly set at 45% up to December 2025 and at 65% up to December 2030. At least half these targets are to be met through the purchase of new e-buses. The targets feed into the European Commission's *Green Deal* proposals to reduce GHG emissions by at least 55% by 2030, compared to 1990 levels,[159] subsequently enhanced under the *Ambient Air Quality Directive* to bring them closer to the WHO's guidelines on PM2.5 particulates.[160] They have become part of the *'Fit for 55'* package which includes a revision of the 2018 renewable energy directive (RED), which currently sets a collectively binding target of a minimum 32% EU share of renewable energy sources (RES) in final energy consumption (FEC) by 2030.[161] This is important because if the use of EVs increases so does the need for electricity generation.

Air Quality and Energy Sources

In 2014 the *Alternative Fuels Infrastructure Directive* (AFID) defined "power sources of energy for transport, such as electricity and hydrogen" that release oxides neither through combustion or non-combustion.[162] This was followed in 2015 by the EC creating the *European Alternative Fuels Observatory* (EAFO) covering all Member States, the EFTA-EEA Member States (Iceland,

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153 Land Transport Guru (October 2018) *60 Electric Buses Procured by LTA* https://landtransportguru.net/electric-buses-procured-by-lta/#google_vignette
154 NCCS (December 2022) *Power Generation* https://www.nccs.gov.sg/singapores-climate-action/power-generation/
155 WorldData.info (2020) *Energy consumption in Singapore* https://www.worlddata.info/asia/singapore/energy-consumption.php
156 SG Agency (December 2022) *A City of Green Possibilities* https://www.greenplan.gov.sg/
157 LTA (December 2022) *Our EV Vision* https://www.lta.gov.sg/content/ltagov/en/industry_innovations/technologies/electric_vehicles/our_ev_vision.html
158 EC (2019) *Clean Vehicles Directive* https://transport.ec.europa.eu/transport-themes/clean-transport-urban-transport/clean-and-energy-efficient-vehicles/clean-vehicles-directive_en
159 EC (December 2022) *Delivering the European Green Deal* https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en
160 EC (22nd October 2022) *European Green Deal: Commission proposes rules for cleaner air and water* https://ec.europa.eu/commission/presscorner/detail/en/ip_22_6278
161 European Parliament (September 2022) *'Fit for 55'* https://www.google.com/search?client=firefox-b-d&q=Fit+for+55+package%3A+Renewable+Energy+Directive
162 EUR-Lex (2014) *Directive 2014/94/EU of the European Parliament and of the Council of 22 October 2014 on the deployment of alternative fuels infrastructure* https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32014L0094

Liechtenstein, Norway and Switzerland), the UK and Turkey.[163] The role of the EAFO is to monitor air quality along the *Trans-European Transport Network* (TEN-T) which promotes the development of a "Europe-wide network of railway lines, roads, inland waterways, maritime shipping routes, ports, airports and railroad terminals."[164]

Euro-7 Standard

In November 2022, the EC also proposed that as from 2027 all new buses must conform to Euro-7 standards,[165] the standards applying to the first 200,000km (previously 100,000km) and 10 years (previously 5 years) of their service life. The new regulations also for the first time set limits on particulate emissions from brakes and on microplastic emissions from tyres.[166] Further, the vehicles will include onboard digital sensors to measure and monitor emission levels.[167] It should be noted the regulations do not impose any obligations on manufacturers, many of whom are non-European companies, but upon the public procurement agencies.

E-buses across the EU

A briefing in 2022 from the International Council on Clean Transport (ICCT)[168] reviews the adoption of e-buses in Europe, which increased from 5% share of bus sales in 2016 to 10% by 2021. On the supply side, by 2019, 17% of electric buses sold in Europe were from Chinese manufacturers and the remainder from smaller manufacturers. Figure 22 groups the manufacturers of e-buses into the leading 4 and 'Others' by total sales 2021 within the EU. Such a crowded market leaves open the question of interoperable standards.

On the demand side, e-bus adoption is being led by the pledge of some EU Member States to zero-emission targets by buses by early 2030, led by Amsterdam (Netherlands) and Copenhagen (Denmark) which will both achieve the target by 2025, and over half of EU capital cities by 2040. "However, most of the ambition is driven by high-income Western Europe countries, with less of a transition evident from lower-income Eastern European countries."[169]

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[163] EC *About the European Alternative Fuels Observatory* https://alternative-fuels-observatory.ec.europa.eu/general-information/about-european-alternative-fuels-observatory

[164] EC *Trans-European Transport Network (TEN-T)* https://transport.ec.europa.eu/transport-themes/infrastructure-and-investment/trans-european-transport-network-ten-t_en

[165] EC (November 2022) *Commission proposes new Euro 7 standards to reduce pollutant emissions from vehicles and improve air quality* https://ec.europa.eu/commission/presscorner/detail/en/ip_22_6495

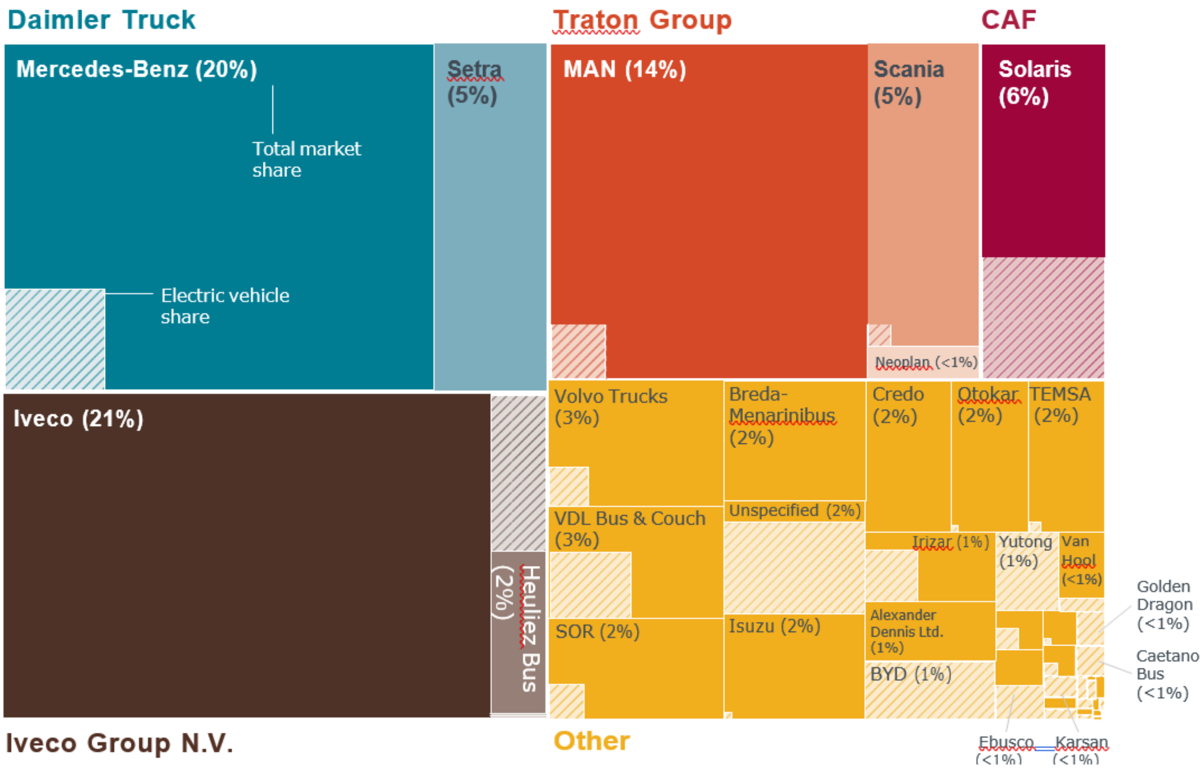
[166] EC (10th November 2022) *Commission proposes new Euro 7 standards to reduce pollutant emissions from vehicles and improve air quality* https://ec.europa.eu/commission/presscorner/detail/en/ip_22_6495

[167] Parkers (November 2022) *What is Euro 7 and what will it mean for your van and car?* https://www.parkers.co.uk/what-is/euro-7/

[168] ICCT (December 2022) *Decarbonizing transportation* https://theicct.org/

[169] ICCT (September 2022) *The rapid deployment of zero-emission buses in Europe* https://theicct.org/publication/the-rapid-deployment-of-zero-emission-buses-in-europe/

Figure 22
EU E-bus market shares 2021



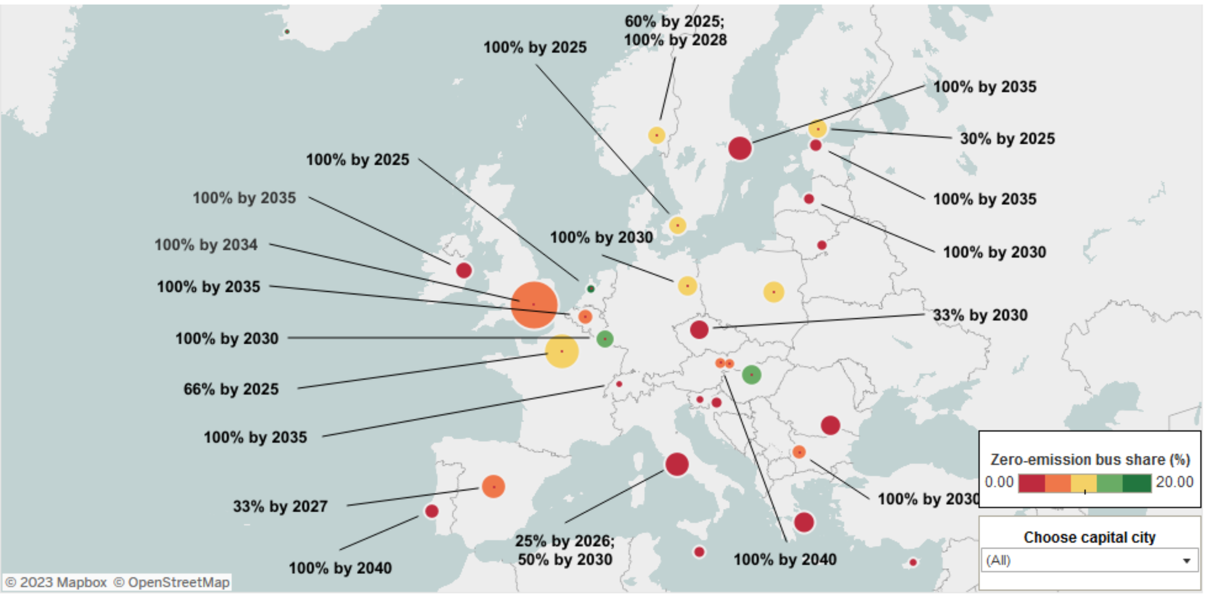
Source: ICCT (2022)

From ZeEUS to ASSURED

The ZeEUS consortium of transport authorities, manufacturers and service providers was launched in 2014 by the EU-funded Belgium-headquartered International Union of Public Transport (UITP) to run trials in the electrification of transport in Europe.[170] The 2016 *ZeEUS eBus Report* [171] – an update was published 2017 – showcased the electrification of transport in 92 cities worldwide and, as described in the ASSURED *Clean Bus Report*, "represented a real breakthrough for the deployment of battery electric buses and trolleybuses in the demonstration cities, where project partners started literally from scratch to test and play with the new technology, learning by doing, and creating an enormous knowledge body that is today the basis of the operations we see in many cities."[172] Figure 23 displays the status in June 2022 of zero emissions targets for capital cities across Europe.

[170] BUSride (March 2014) *Europe launches the ZeEUS project* https://busride.com/europe-launches-the-zeeus-project/
[171] ZeEUS (2016) *ZeEUS eBus Report: An overview of electric buses in Europe* https://www.bing.com/search?q=ZeEUS+eBus+Report+An+overview+of+electric+buses+in+Europe&aqs=edge..69i57j69i11004.5952j0j4&FORM=ANAB01&PC=HCTS
[172] UITP ASSURED Clean Bus Report https://www.uitp.org/publications/assured-clean-bus-report/

Figure 23
Zero-emission bus targets for Europe's capital cities: Status June 2022



Source: ICCT (September 2022)

From 2017 to March 2022 the EU funded the ASSURED project with the specific aim to develop and test types of vehicles and infrastructure to promote clean buses. ASSURED produced a *Clean Bus Report* which, following the pioneering work of ZeEUS, highlighted the progress made in the electrification of public transport. It provides a comprehensive review across capital cities and major bus manufacturers. The report makes the distinction between, and provides a comprehensive review of, progress across the EU towards 'clean' buses fuelled by electricity, hydrogen, natural gas (CNG, LNG), biofuels not blended with fossil fuels, or liquefied petroleum gas (LPG) and 'net-zero' emissions buses without an internal combustion engine or with an internal combustion engine only for back-up and emitting less than 1g CO2/kWh or less than 1g CO2/km, not to be confused with a non-clean hybrid bus. However, ASSURED most significant technical work has been to promote e-bus charging/recharging infrastructure standards for interoperability – a challenge with so many manufacturers, see Figure 23 – along with smart tools for optimised fleet operation, charging and energy storage,[173] and the publication of the 'ASSURED 1.1 Interoperability Reference'[174] with a video link here.[175]

Latin America

Despite generally low GDP per capita incomes,[176] Latin American countries and their capital cities especially are facing the challenges of shifting towards electrification of public transport motivated by high levels of kerbside pollution and the imperative of improving energy efficiency. As of April

[173] ASSURED (February 2022) *D 4.1 - Pre-normative technology roadmap and new use cases in electric bus and truck charging* https://www.semanticscholar.org/paper/D-4.1-Pre-normative-technology-roadmap-and-new-use/967cdee58c720793c2c2b4235739cc011815a8df
[174] ASSURED (18th March 2022) *ASSURED project releases new milestone on interoperability testing with 'ASSURED Interoperability Reference 1.1'* https://assured-project.eu/news-and-events/news/assured-releases-new-milestone-with-interoperability-reference-1-1
[175] ASSURED – Enabling standardisation and interoperability to boost electric fleets https://www.youtube.com/watch?v=jn6MFSdn7pQ
[176] The average GDP per capita across Latin America and the Caribbean in 2020 measured USD8,300 compared with USD68,300 for North America. See World Bank GDP per capita (current US$) https://data.worldbank.org/indicator/NY.GDP.PCAP.CD

2022 it is reported that the continent runs over 3,000 electric buses, but one-third of these are existing trolly-buses, and of the remaining over 2,000 battery-powered electric buses, Santiago (Chile) and Bogotá (Colombia) account for 85% of them.[177]

And the Global South

The ZEBRA partnership formed in 2019 is aiming at accelerating the deployment of zero emission buses in major Latin American cities along with the supporting infrastructure.[178] The partnership is supported by the Pioneering Green Partnerships (P4G),[179] the C40 network of around 100 city mayors,[180] the ICCT (see above) – "ICCT's Zero-emission Fleets Center (ZFC) builds upon the concept successfully employed through the ZEBRA initiative in Latin America"[181] – the World Resource Institute (WRI) and others including the Centro Mario Molina-Chile. In parallel the TUMI E-Bus Mission[182]

> "is an international coalition of 20 cities assisting in creating world-leading electric bus fleets and scaling e-bus adoption to hundreds more through city-to-city mentorship…. WRI and partners will work with the 20 deep dive cities to disseminate technical assistance, trainings, and workshops to the mentee cities located in their regions. These materials explore overall planning for e-bus mass adoption, operations and logistics considerations, financing, procurement strategies, and training requirements for bus operators and maintenance teams."

Figure 24

Source: TUMI https://www.transformative-mobility.org/campaigns/tumi-e-bus-mission

[177] Sustainable Bus (July 2022) *Electric bus deployment speeding up in Latin America [TUMI E-Bus Mission #3]* https://www.sustainable-bus.com/news/electric-bus-deployment-latin-america-tumi/

[178] C40 (2023) *Zero Emission Bus Rapid-deployment Accelerator (ZEBRA) Partnership* https://www.c40.org/what-we-do/scaling-up-climate-action/transportation/zero-emission-rapid-deployment-accelerator-zebra-partnership/

[179] P4G *About the P4G Call for Partnerships* https://p4gpartnerships.org/p4g-call-partnerships

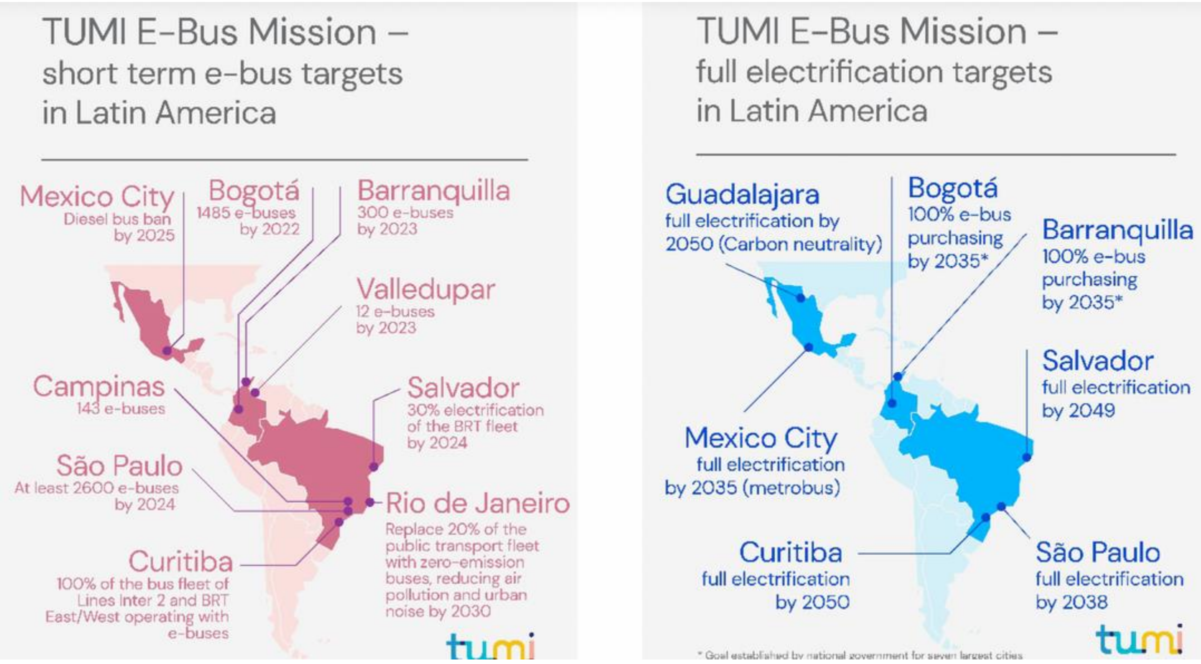
[180] C40 (2023) *About C40* https://www.c40.org/about-c40/

[181] ICCT (December 2022) *Fleets* https://theicct.org/decarbonizing/fleets/

[182] WRI (2023)TUMI E-Bus Mission https://www.wri.org/initiatives/tumi-e-bus-mission

The TUMI E-Bus Mission[183] webpage, as of January 2023, contains 20 cases, ten of them from Latin America, the others of the Global South are from Africa to Asia – see Figure 24 for current Global South initiatives. Figure 25 provides the short- and longer-term e-bus targets for various Latin American cities

Figure 25[184]



Source: Sustainable Bus

Latin American Business Models

Part of the TUMI E-Bus focus is to promote financial business models for e-bus adoption, such as private-public bus leasing alongside direct public sector investment and subsidies. Bus manufacturers such as Scania in Mexico, Electra and Mercedes Benz in Brazil are entering these markets.[185] A study by ZEBRA illustrates the case of Metbus in Santiago with BYD buses and technical support by Enel, including a 40-bus stop e-bus corridor, and a longer lifecycle for e-buses which allows the municipality to spread the financing over 14 years rather than the 10 years with diesel buses. As explained by the Executive Director of Santiago de Chile's Metropolitan Public Transport Authority: "This model has proven to reduce payment risks, which lowers credit rates and funding costs. At the same time, it allows us to handle shorter contracts with the operators, and we're no longer required to pay the cost of buses during the public transport operator's contract."[186] The offset however is that as many of the diesel buses are pre-Euro VI it is often less costly to upgrade diesel buses to achieve a partial reduction in emission levels despite an estimated 64,000 premature deaths a year from kerbside particulates.[187] For a comprehensive review of initiatives and

[183] TUMI (2021) *TUMI E-Bus Mission: until 2025 we inspire 500+ cities to ensure the readiness for procurement of 100,000 e-buses* https://www.transformative-mobility.org/campaigns/tumi-e-bus-mission
[184] Sustainable Bus (2023) *Electric bus deployment speeding up in Latin America [TUMI E-Bus Mission #3]* https://www.sustainable-bus.com/news/electric-bus-deployment-latin-america-tumi/
[185] Sustainable Bus (July 2022) *Electric bus deployment speeding up in Latin America [TUMI E-Bus Mission #3]* https://www.sustainable-bus.com/news/electric-bus-deployment-latin-america-tumi/
[186] C40 (2023) *How we made e-bus a reality in Santiago, Chile* https://www.c40knowledgehub.org/s/article/How-we-made-e-bus-a-reality-in-Santiago-Chile?language=en_US
[187] Commercial Vehicles (2019) LATAM Electric Bus Market Strong but May Fail to Reach Potential https://www.interactanalysis.com/latam-electric-bus-market-strong-but-may-fail-to-reach-potential/

approaches to the electrification of buses and relevant business models in Latin America see *Accelerating a Market Transit in Latin America: New Business Models for Electric Bus Deployment.*[188]

USA

In most cities in the USA for decades public transport gave way to automobiles. This was famously documented in the case of Los Angeles by Mike Davis in *The City of Quartz*,[189] and highlighted in *The Guardian* by Colin Marshall[190]

> "Between 1938 and 1950, one company purchased and took over the transit systems of more than 25 American cities. Their name, National City Lines, sounded innocuous enough, but the list of their investors included General Motors, the Firestone Tire and Rubber Company, Standard Oil of California, Phillips Petroleum, Mack Trucks, and other companies who stood to benefit much more from a future running on gasoline and rubber than on electricity and rails. National City Lines acquired the Los Angeles Railway in 1945, and within 20 years diesel buses – or indeed private automobiles – would carry all the yellow cars' former passengers."

Unsurprisingly, by 2022 there are around only 60,000 public transit buses in the USA and only 2% are fully electric.[191] But under the *Bipartisan Infrastructure Law* which came into effect 2023,[192] the Federal Transit Administration offers competitive grants of USD5.5 billion under the *Buses and Bus Facilities* and the *Low-and-No-Emissions Vehicle Programs* to purchase 1,100 zero-emission buses from a total of 1,800 low-or-no-emission buses including related recharging equipment and maintenance facilities.[193] There are constraints however; 70% of the bus components and sub-components must be sourced within the USA. Further, the 2022 *Inflation Reduction Act* which offers investment incentives to the energy sector to reduce GHGs,[194] including tax incentives to battery and electric vehicle manufactures, also includes restrictive *Buy America* clauses that will put pressure on domestic battery and electrical component supply chains. Given the relatively small market to date and the supply restrictions, only one of the top five electric bus manufacturers supplying the US market in 2021 was Chinese – see Figure 26

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188 ZEBRA (February 2020) *Accelerating a Market Transit in Latin America: New Business Models for Electric Bus Deployment* https://www.c40knowledgehub.org/s/article/Accelerating-a-market-transition-in-Latin-America-New-business-models-for-electric-bus-deployment?language=en_US

189 Amazon (September 2006) *City of Quartz: Excavating the Future in Los Angeles Paperback* https://www.amazon.com/City-Quartz-Excavating-Future-Angeles/dp/1844675688

190 The Guardian (25th April 2016) *Story of cities #29: Los Angeles and the 'great American streetcar scandal'* https://www.theguardian.com/cities/2016/apr/25/story-cities-los-angeles-great-american-streetcar-scandal

191 StreetsBlog USA (16th April 2022) *US DOT Will Double the Nation's Electric Bus Fleet (But It Will Still Be Tiny)* https://usa.streetsblog.org/2022/08/16/us-dot-seeks-to-double-the-nations-electric-bus-fleet-which-is-currently-tiny-and-will-still-be/

192 The White House (2022) *President Biden's Bipartisan Infrastructure Law* https://www.whitehouse.gov/bipartisan-infrastructure-law/

193 FTA (16th August 2022) *Biden-Harris Administration Announces Over $1.6 Billion in Bipartisan Infrastructure Law Funding to Nearly Double the Number of Clean Transit Buses on America's Roads* https://www.transit.dot.gov/1800buses

194 DoE (2022) *Inflation Reduction Act of 2022* https://www.energy.gov/lpo/inflation-reduction-act-2022

Figure 26

ELECTRIC BUS MODELS	PASSENGER CAPACITY	MOTOR SPECIFICATIONS	TRAVEL RANGE CAPACITY
 PROTERRA ZX5	29	PRODRIVE DRIVETRAIN AND DUOPOWER	240 MILES
 BYD MOTORS K12	250	DUAL IN-WHEEL MOTOR SOLUTION	186 MILES
 GILLIG ZERO EMISSION ELECTRIC BATTERY BUS	38	DIRECT-DRIVE TRACTION MOTOR WITH PEAK TORQUE OF 3500 NM	150 MILES
 GREENPOWER EV STAR	19	TM4 PMSM ELECTRIC TRACTION MOTOR	150 MILES
 NFI GROUP XCELSIOR CHARGE™	32	SIEMENS ELFA2 ELECTRIC DRIVE SYSTEM	200 MILES

Source: TechSci Research[195]

Besides Federal initiatives, municipalities have been increasingly responding to the GHG effects of diesel buses. For example, *Wikipedia* lists 14 US cities as being C40 partners committed to clean air policies.[196] Leading the way are school buses. As of June 2022, "school districts have committed to 12,275 electric school buses in 38 states" [197] although this is only 2.5% of an estimated 500,000 school buses. However, the Environmental Protection Agency (EPA) has allocated USD5 billion 2022-2026 under a new *Clean School Bus Program* to replace existing school buses with zero-emission and low-emission models.[198] In parallel the National Grid is providing significant grants to help build the recharging infrastructure for many cities across the USA.[199]

[195] TechSciResearch (August 2021) *Top Five Electric Buses in the United States of America* https://www.techsciresearch.com/blog/top-five-electric-buses-in-the-united-states-of-america/232.html
[196] Wikipedia (3rd January 2023) *C40 Cities Climate Leadership Group* https://en.wikipedia.org/wiki/C40_Cities_Climate_Leadership_Group
[197] Environmental America (October 2022) *Electric Buses In America: Lessons from Cities Pioneering Clean Transportation* https://www.nationalgrid.com/stories/journey-to-net-zero-stories/electric-school-buses-us
[198] EPA (December 2022) *Clean School Bus Program* https://www.epa.gov/cleanschoolbus
[199] National Grid (October 2022) *Electric school buses are helping drive the U.S. toward net zero* https://www.nationalgrid.com/stories/journey-to-net-zero-stories/electric-school-buses-us

A review of the experiences up-to-date of six municipalities can be found in The Frontier Group's 2019 *Electric Buses in America* report.[200] The Frontier Group is the research and policy hub of environmental NGO the Public Interest Network.[201] Not all the experiences of the six early e-bus adopters were initially successful, and from these the report draws policy conclusions such as: municipal authorities exploring business models such as allowing operators to 'pay as you save' on their electricity bills, off-peak charging rates and early collaboration with the utility companies, manufacturers' guarantees to protect against performance failures, route modelling so vendors 'shadow' diesel buses with their e-bus route-testing, and subsequent smart routing by operators, aiming for economies of scale in the recharging infrastructure (terminal and on-route), the gathering of as much operational data as possible, and factoring in environmental and health benefits to the cost-benefit analysis.

Conclusions

- The e-bus sector is the fastest growing part of the global electrification of public transport.
- This is placing runaway demands upon the supplies of batteries and the mineral components that go into their manufacture.
- Supply-chain challenges beyond market demand, such as regional conflicts and global trade frictions, are adding to the high volatility of mineral prices.
- Historically the cost of batteries for driving heavy vehicles such as BEV buses has been in continuous decline and brought them closer to the USD100 kWh price point where industry sees them as competitive to internal combustion engine-driven diesel vehicles on the lifecycle basis.
- The major cost and operational challenge is having the right charging infrastructure, whether plug-in, pantograph or induction and the right business model, whether it is direct purchase, leasing of rechargeable vehicles, battery swapping, BaaS or other. What works in the developed North may not be the best fit for the Global South. The greater the economies of scale achieved by vehicular sharing of the infrastructure the more financially viable BEV buses become.
- Smart and flexible route planning, including the appropriate sizing of buses and batteries for different routes with different characteristics, such as flat, hilly, dense, sparse, humid, cold, long and short distances, multiple stops or few, and a locational and financial planning of charging facilities will require an enhanced set of management skills.
- Data gathering and analysis will be an opportunity and a necessity for daily operational functions as well as services planning. Skills sets will be required in data analysis and running algorithms as well as in electronic, radio and mechanical maintenance.
- Data sharing with planning authorities and with utility partners amongst other stakeholders will need to be developed along with secure data sharing frameworks.
- The cost of electricity is a crucial factor not only in the lifecycle costs of running e-buses but also in determining whether the carbon footprint is net zero or net positive. The commitment to renewables in the generation of electricity may need to be supplemented by carbon capture or the use of nuclear fission if climate change targets for GHG levels are to be met by 2050.
- At the life-end of batteries the challenges of recycling the component materials or repurposing batteries to store energy are yet to be resolved and may require direct policy interventions if commercial models are insufficient.

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[200] The Frontier Group (October 2019) *Electric Buses In America: Lessons from Cities Pioneering Clean Transportation* https://environmentamerica.org/center/resources/electric-buses-in-america-2/
[201] PIRG (December 2022) *The Public Interest Network* https://publicinterestnetwork.org/

- Electrification will complement and be complemented by hydrogen as a fuel for public transport, with the role of regulation (safety in the case of hydrogen fuel) important. They will be options or 'horses for courses'.
- The electrification of public transport is a classic case of balancing out the financial costs and the economic benefits, including health benefits and existential climate benefits.

ADDENDUM A – E-Ferries

Battery electric ferries

(Based partly upon Riviera Newsletters, 16th September 2015[202])

> Having gone from [renewable] wind power to coal/oil-powered steam, to oil-powered and gas-powered ICE, ferries are now in the vanguard of battery electric vessels, and without the need for an engine room, more passenger space can be [made] available.

Battery-driven ferries coming into service
The Horizon 2020 was the EU's Innovation and Networks Executive Agency (INEA) nearly €80 billion R&D programme for 2014-2020, in the areas of transport and energy, including support for the E-ferry project to build a 100% electric ferry and test it in Danish waters,[203] as part of a Green Ferry Vision[204] – "one of the top five projects within the EU Horizon 2020 initiative." The ferry named *Ellen* uses the world's largest 4.2 MW/h Lithium-ion battery system, aiming to reduce CO2 and NOX emissions by 2,000 tonnes and 41.5 tonnes respectively, by using light-weight materials in a modular design. In 2002 *Ellen* set a world record by sailing 50 nautical miles – 92 kilometres – on a single battery charge.[205]

- **Scandinavia** – leads the world in electric ferries. **Sweden's** *Movitz* tourist ferry was retrofitted in 2014 operating with twin 180kWh Nickel Metal Hybrid battery packs; [206] the *Tycho Brahe* and the *Aurora* were retrofitted in 2017 with 4MkWh battery packs;[207] **Norway's,** and *the world's first newly-designed electric ferry,* the *Ampere* began operations from 2015 with twin 450kWh battery packs. Larger vessels have increasingly been powered with larger battery packs giving them greater payload and longer range. They each need high-capacity fast plug-in port-based connectors to charge them for their voyage. **Norway** launched the *Medstraum* the world's all-electric fast or 'high-speed' ferry in July 2022,[208] supported by the EU's *Transport: Advanced and Modular (TrAM)* project which is also part of Horizon 2020.[209] Also launched in 2022 was the first large ocean-going ship the *Maersk Minder* anchor handler – it provides anchors for deep sea oil rigs – with a container-based hybrid diesel/electric battery system of 132 small batteries

[202] Rivera (16th September 2015) *Battery electric ferries lead the charge* https://www.rivieramm.com/opinion/opinion/battery-electric-ferries-lead-the-charge-35811
[203] EC INEA (January 2023) *E-Ferry* https://ec.europa.eu/inea/en/horizon-2020/projects/h2020-transport/waterborne/e-ferry
[204] EC Cordis (August 2022) *E-ferry – prototype and full-scale demonstration of next generation 100% electrically powered ferry for passengers and vehicles* https://cordis.europa.eu/project/id/636027
[205] The Maritime Executive (June 2022) *Electric Ferry Sets Distance Record for Single Battery Charge* https://maritime-executive.com/article/electric-ferry-sets-distance-record-for-single-battery-charge
[206] Rivera (16th September 2015) *Battery electric ferries lead the charge* https://www.rivieramm.com/opinion/opinion/battery-electric-ferries-lead-the-charge-35811
[207] Wikipedia (July 2021) *MF Tycho Brahe* https://en.wikipedia.org/wiki/MF_Tycho_Brahe and ABB(2023) *ForSea - Zero Emission operation* https://new.abb.com/marine/marine-references/forsea
[208] Offshore Energy (July 2022) *World's first electric fast ferry is here* https://www.offshore-energy.biz/worlds-first-electric-fast-ferry-is-here/
[209] EC Cordis (September 2022) *Transport: Advanced and Modular* https://cordis.europa.eu/project/id/769303

acting as an energy storage system (ESS) that meets *International Maritime Organisation's (IMO) Tier III* emissions standards,[210] aiming to reduce NOx emissions by up to 80%.[211] Maersk also launched the world's first sea-going battery charging system vessel to support the removal of "5.5 million tons of CO2 within five years of commercial rollout".[212]

- **Germany** in 2022 introduced the **Antonia vom Kamp** as one of the first all-electric passenger ferries in the Baltic, with a 4.3kWh solar installation on the roof and twin 80kWh battery packs. The boatbuilders estimate the solar-electric propulsion system will save twenty tonnes of CO2 every year.[213]
- **Singapore –** in 2021 Shell awarded a contract to local company, Penguin International Ltd, for Singapore's first three fully-electric ferries, also a global first for Shell, to go into service in 2023 to serve the Chemical Park on Bukom Island.[214]
- **Goa** – an all-electric-cum-solar powered ferry was launched in November 2022.[215]
- **Canada** – is still in catch-up mode with the delivery in 2021 of six battery-hybrid-electric-island-class ferries in British Columbia with shore-based plug-in battery chargers and diesel generators as backup.[216]
- **China** – the *Junlyu* was China's first electric ferry launched in November 2019 carrying passengers on sightseeing trips along the Yangtze River in Wuhan.[217] A research paper advocates policymakers "to focus first on electrifying smaller ships and shorter legs."[218]
- **Hong Kong** – seems to be taking an even more cautious route than Canada. From 2023 onwards nine hybrid high-speed ferries will be delivered under the Hong Kong Government Vessel Subsidy Scheme, eight built entirely of carbon fibre composite while one of aluminium, to serve the outlying islands. The main propulsion will be diesel "compliant with IMO Tier III requirements" and "solar panels and battery systems to capture solar energy for on-board electricity consumption. The hybrid vessels will also be fitted with air-cooled Lithium-ion modular battery systems as an alternative propulsion system." Two of the nine "will be propelled by diesel-electric hybrid propulsion systems as part of a trial program led by Hong Kong's Environmental Protection Department."[219]
- **New Zealand** – launched its first all-electric ferry, the *Ika Rere* in 2021 powered by twin 550kWh battery packs. Unfortunately, the *Ika Rere* and its passengers had to be rescued by the police when it ran out of power in September 2022.[220]

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[210] Emission Standards (2023) *IMO Marine Engine Regulations* https://dieselnet.com/standards/inter/imo.php
[211] Maersk Supply Service (2022) *Maersk Minder takes to sea on hybrid-electric propulsion* https://www.maersksupplyservice.com/2022/06/29/maersk-minder-hybrid-electric-propulsion/
[212] Electrek (January 2022) *Maersk launches the world's first offshore electric vessel-charging station venture* https://electrek.co/2022/01/27/maersk-launches-the-worlds-first-offshore-electric-vessel-charging-station-venture/
[213] Workboat 365 (July 2022) *A solar-electric ferry connects the German island vacation paradise of Usedom to the mainland* https://workboat365.com/power-propulsion-news/a-solar-electric-ferry-connects-the-german-island-vacation-paradise-of-usedom-to-the-mainland-2/
[214] Shell (September 2022) *Shell to launch Singapore's first fully-electric ferry service* https://www.shell.com.sg/media/2021-media-releases/shell-to-launch-singapores-first-fully-electric-ferry-service.html
[215] The Times of India (28th October 2022) *Goa's first solar ferry to be operational before International Film Festival of India* https://timesofindia.indiatimes.com/city/goa/goas-first-solar-ferry-to-be-operational-before-iffi/articleshow/95130488.cms?utm_source=contentofinterest&utm_medium=text&utm_campaign=cppst
[216] Workboat (10th November 2022) *New hybrid-electric ferries provide bridge to zero emissions* https://www.workboat.com/shipbuilding/new-hybrid-electric-ferries-provide-bridge-to-zero-emissions
[217] Plugboats.com (10th December 2019) *China's electric ferry is first in the country* https://plugboats.com/chinas-electric-ferry-is-first-in-the-country/
[218] ICCT (April 2021) *Repowering Chinese coastal ferries with battery-electric technology* https://theicct.org/publication/repowering-chinese-coastal-ferries-with-battery-electric-technology/
[219] Maritime Executive (September 2022) *Hong Kong Adding Batteries and Solar Panels to Next Generation Ferries* https://maritime-executive.com/article/hong-kong-adding-batteries-and-solar-panels-to-next-generation-ferries
[220] Ship & Bunker (30th September 2022) *Wellington Police Rescue Electric Ferry After Battery Runs Flat* https://shipandbunker.com/news/apac/646245-wellington-police-rescue-electric-ferry-after-battery-runs-flat

- **USA** – Gee's Bend Ferry on the Alabama River was America's first passenger ferry to be converted to all-electric in 2019 with twin 135kWh battery packs. Twenty-year batteries were considered too large so 10 years was settled upon. Charges on either side of the river take 20-25 minutes on one side or 10-15 minutes on both sides of the ferry. The hurdles to overcome were the lack of Coast Guard regulations governing Lithium-ion powered batteries and training the crews in case of a fire. The USD1.8 million project was funded in part with a USD1.09 million Environmental Protection Agency (EPA) Diesel Emissions Reduction Act (DERA) grant, with the rest coming from the state.[221]
- **Japan** – launched its first ocean-going ferry the *e-Oshima* in 2019. Its new state-of-art 340-ton marine ferry runs entirely on Lithium-ion batteries.[222] Separately, the *world's first electric-powered bunker tanker* the *Asahi* went into service in April 2022. The 492-ton vessel is powered entirely by large-capacity Lithium-ion batteries with a capacity of 3.5GWh providing sufficient power for around 100 miles (160 kilometres) and takes 10 hours recharging.[223]
- **Korea** – commissioned in 2021 the building of its first all-electric ferry for the Busan Port Authority as part of a long-term plan to replace all 140 South Korean state-owned vessels with new, clean-power models by 2030.[224]

Electric driven ferry-boat between Denmark and Sweden – Dreamstime Electric Ferries[225]

The Economics of Battery-driven Ferries vs ICE

- The advantages of electric motors are higher torque therefore high acceleration, better manoeuvring, less fuel consumption and no emissions.
- But e-ferries need more time in port to charge up for a whole day's journey, and hence a greater number of smaller ferries operating more frequently is both a technically better solution and a more economical one.

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221 WorkBoat (August 2020) *First all-electric ferry in U.S. reaches milestone* https://www.workboat.com/passenger-vessels/first-all-electric-ferry-in-u-s-reaches-milestone

222 UPS (July 2019) *Japan's First Battery Ship by E-Oshima* https://www.upsbatterycenter.com/blog/japans-first-battery-ship-e-oshima/

223 Maritime Executive (27th April 2022) *World's First All Electric Bunker Tanker Enters Service in Japan* https://maritime-executive.com/article/world-s-first-all-electric-bunker-tanker-enters-service-in-japan

224 Maritime Executive (28th January 2021) *South Korea Gets its First Electric Ferry* https://maritime-executive.com/article/south-korea-gets-its-first-electric-ferry

225 Dreamstime (2000-2023) *Electric Ferries* https://www.dreamstime.com/electric-driven-ferry-boat-denmark-sweden-helsingborg-june-image153593070

- Battery 'fuel' is cheaper than fossil fuel, but storage is the issue. Batteries are heavier per kWh than the weight of the fossil-fuel, so e-ferries can be made hydrodynamically more efficient, for example, making extensive use of aluminium in hulls and possibly carbon fibre.
- No engineering room means fewer operations and maintenance crew.
- Fuel oil and electricity are taxed quite differently disadvantaging marine transport.
- Ferries tend to be designed for 30-year operational lifespans, whereas, with careful battery management, Li-Ion batteries will last somewhere between 10 and 15 years, after which they can be used in shore-side energy storage systems and still have a further 20 years of useful life left. Often smaller battery packs are suitable for smaller ferries carrying lighter loads.

ADDENDUM B – E-Taxis

The slow spread of e-Taxis

Introduction

1. A big drawback for e-taxis is insufficient charging stations, but a bigger one is the time to recharge the battery. Oslo (Norway) will become first city in the world to install wireless charging systems for electric taxis, to speed up recharging and make it more efficient.[226] Otherwise even fast charging for 15-20 minutes implies a loss of paying passengers, notably during rush-hours, and accounts for the reluctance of taxi drivers to switch to e-vehicles despite lower running costs. Partial, incremental and opportunity fast charging may be part of the answer, as a research paper in 2019 suggests, noting that battery discharge only down to 50% can increase the battery lifetime by 4 years or more.[227] But another research paper in 2019 suggests distance rather than depth of charging is the critical factor behind battery life.[228] The alternative could be hydrogen fuel cells that refill as fast as diesel – see *Primer: Hydrogen as a Fuel for Public Transport* at https://accesspartnership.com/a-primer-hydrogen-fuel-for-public-transport/ and at https://www.wcbc.online/publications.
2. According to the UITP's *The Case For Electrification Of Taxis & Ride-Hailing: Knowledge Brief,*[229] "electric taxis are used in a few cities worldwide, from Hong Kong, Macao and Shenzhen (China) to London (UK), passing through Nairobi (Kenya), Columbus and New York City (US). China seems to be at the forefront with Shenzhen operating almost 100% of its taxi fleet electrically." The assessment of Hong Kong was premature – see below. It is important also not to confuse e-taxis with private taxis responding to e-hailing platforms, and which it turns out can easily add to rather than relieve traffic volumes and carbon emissions.[230]
3. One recent 'taxi' innovation has been the development of eVTOLs (electric vertical take-off and landing aircraft) also providing a taxi service between city centres and to and from airports.[231] But the regulatory hurdles to be overcome are many.[232]

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Country Developments

- **UK** – the London Electric Vehicle Company (LEVC) introduced a hybrid/e-taxi in 2018. By 2022 there were 5,000 of them in London accounting for one-third of London's taxi fleet. They each have a range of over 103km when just using electric; but as hybrids the range extends to 512 km. Using a 50kW charger the battery pack can be recharged up to 80% capacity in around 30 minutes.[233]
- **Singapore** – in 2020 HDT and its fleet of BYD-supplied e-taxis from 2014 onwards,[234] shut down due to COVID.[235] Post-COVID, Strides Taxi, the e-taxi arm of SMRT Singapore's public transport operator, introduced 15 fully electric taxis in August 2022, to be followed by 300 China-made electric taxis in a SGD30 million (USD23 million) contract.[236] SMRT's existing 1,780 taxis are all hybrids. A fast charger developed by the National Research Foundation in 2021 can recharge an EVA prototype e-taxi in 15 minutes to cover a range of 200km.[237] In parallel, Singapore's largest private taxi operator, ComfortDelGro Taxi, announced up to 400 fully electric taxis to be on the roads during 2022 and up to 1,000 fully electric taxis by 2023, resulting in about 10% of ComfortDelGro 10,000 fleet being fully electric by 2023. A further 70% will be hybrid.[238]
- **China** – in 2019, Shenzhen reached around 99% of its 21,689 taxis as electric.[239]
- **Hong Kong** – a trial of 45 BYD e-taxis in 2013 ended in failure following a backlash from taxi drivers owing to "a lack of charging infrastructure and prolonged charging times."[240] Currently, there are only Toyota hybrids and no e-taxis or dedicated chargers, but in May 2022 the Environment minister announced plans to install at least 10 quick chargers in Lantau Island and in Sai Kung in the New Territories to "promote trials of various public and commercial electric vehicles including electric taxis."[241] Sponsoring the trials will be the government's *New Energy Transport Fund* set up in 2011.
- **Japan** – four companies (Daiichi Koutsu, two Sumitomo Corporation affiliates, and the Kyushu Electric Power Co., Ltd.) have established 'the Project' to electrify taxis with an initial 100 EV taxis nationwide by March 2023.[242]

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233 EuroNews:Travel (June 2022) *Travelling to London this Jubilee weekend? Try hailing one of London's 5,000 electric cabs* https://www.euronews.com/travel/2022/06/01/travelling-to-london-this-jubilee-weekend-try-hailing-one-of-london-s-5-000-electric-cabs

234 Paultan.org (February 2017) *BYD introduces biggest e-taxi fleet in Southeast Asia* https://paultan.org/2017/02/24/byd-introduces-biggest-e-taxi-fleet-in-southeast-asia/

235 Vulcan Post (30th November 2020) *S'pore's Electric Taxi Firm HDT Closes Down Due To COVID-19 – About 90 Drivers Retrenched* https://vulcanpost.com/724222/hdt-closes-taxi-business-singapore/

236 Straits Times (7th January 2022) *SMRT rolls out first batch of fully electric cabs under new brand Strides Taxi* https://www.straitstimes.com/singapore/smrt-rolls-out-15-fully-electric-taxis-under-new-brand-strides-taxi-300-electric-cabs-to

237 National Research Foundation (2021) *EVA Electric Taxi* https://www.nrf.gov.sg/innovation-enterprise/innovative-projects/urban-solutions-and-sustainability/eva-electric-taxi

238 Straits Time (5th January 2022) *Up to 400 ComfortDelGro e-taxis to be put on roads this year, in first for operator* https://www.straitstimes.com/singapore/up-to-400-comfortdelgro-e-taxis-to-be-put-on-roads-this-year-in-first-for-operator

239 Mordor Intelligence (2023) *EV Taxi Market - Growth, Trends, COVID-19 Impact, and Forecasts (2023 - 2028)* https://www.mordorintelligence.com/industry-reports/ev-taxi-market

240 SCMP (20th February 2017) *After Hong Kong failure, China's BYD joins Singapore to launch electric fleet* https://www.scmp.com/business/companies/article/2072410/after-hong-kong-failure-chinas-byd-joins-singapore-launch

241 RTHK.HK (May 2022) *Govt making preparations for e-taxi trial runs* https://news.rthk.hk/rthk/en/component/k2/1646991-20220504.htm

242 Sumitomo Corp (2022) *From Fukuoka to nationwide; Launching the Taxi Electrification -To Realize Environment Friendly Taxi Business* https://www.sumitomocorp.com/en/jp/news/release/2022/group/15380

- **Korea** – of the over 20,000 new taxi registrations in the first six months of 2022, 36.4% were battery electric vehicles. The Ministry of Transport data also shows that 86.8% of EV taxis are owned privately, by individual taxi drivers.[243]
- **USA** - New York City (NYC) is famous for its Yellow Cabs and as from December 2021 e-Yellow cabs are offered by start-up Gravity Inc, the authorization coming from an EV pilot program adopted by NYC's *Taxi and Limousine Commission* earlier in 2021.[244] Even earlier Tesla vehicles were introduced by the Yellow Cab firm in Columbus, Ohio.[245] Some cities such as Chicago in 2011 used a USD1 million *Clean Cities* grant from the *American Recovery and Reinvestment Act (ARRA)* to reimburse taxi owners who switch to hybrid and alternative fuel vehicles.[246] But a Wikipedia report, updated 28th November 2022, that estimates there are over 230,000 licensed taxis in the USA, has no reference to electric taxis.[247] Taxi numbers are restricted by local laws but there are fewer restrictions on e-hailing cabs. California has become the first State to licence all-electric autonomous vehicles as taxis.[248]
- **Canada** – one year after the bankruptcy of Montreal's first app-based electric taxi service which saw 450 drivers laid off and 190 electric taxis shelved, an *E-Taxi* start-up in December 2019 announced the import of 25 e-taxis from BYD and their distribution to drivers.[249]
- **Australia** – a fleet of 120 electric taxis offering a "zero contact" transport alternative announced launch plans in April 2020 in Sydney as the first tranche of a planned 2,000 vehicle fleet as part of a "Clean Air Taxi" initiative by new e-taxi platform ETaxiCo.[250] The taxis are being imported from BYD by Australian company Nexport. ETaxiCO will be a fleet company providing electric taxis to existing network operators and will have a corporate platform enabling businesses to use the electric taxis.[251]
- **Latin America** – BYD was reported in 2019 to be delivering to Panama the first fleet of e-taxis in Central America.[252] BYD is also providing e-taxis to Chile under a programme making available ClD8 million (USD11,000) of financing towards buying an electric taxi, and installing a home charging station. The implementing agency, the Energy Sustainability Agency, estimates a taxi travelling 80,000km per year would consume ClD4 million (USD5,539) of fuel, whereas an electric taxi would require around ClD1.7 million (USD2,354) in electric power. In addition, the maintenance costs of the EVs are cheaper than a conventional vehicle.[253] A wholesale shift towards EV taxis in Latin America is unlikely any time soon as commercially-owned taxi fleets are not large, and drivers respond more to a market dominated by ride hailing apps that is

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[243] WapCar (25th August 2022) *Over 35 percent of taxis in Korea are now EVs - Ioniq 5 and Kia EV6 lead* https://www.wapcar.my/news/over-35-percent-of-taxis-in-korea-are-now-evs--ioniq-5-and-kia-ev6-lead-52616
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[247] Wikipedia (November 2022) *Taxis of the United States* https://en.wikipedia.org/wiki/Taxis_of_the_United_States
[248] Insider (June 2022) *Driverless taxis approved in California for the first time – but the rollout will be gradual* https://www.businessinsider.com/driverless-taxis-california-for-the-first-time-2022-6
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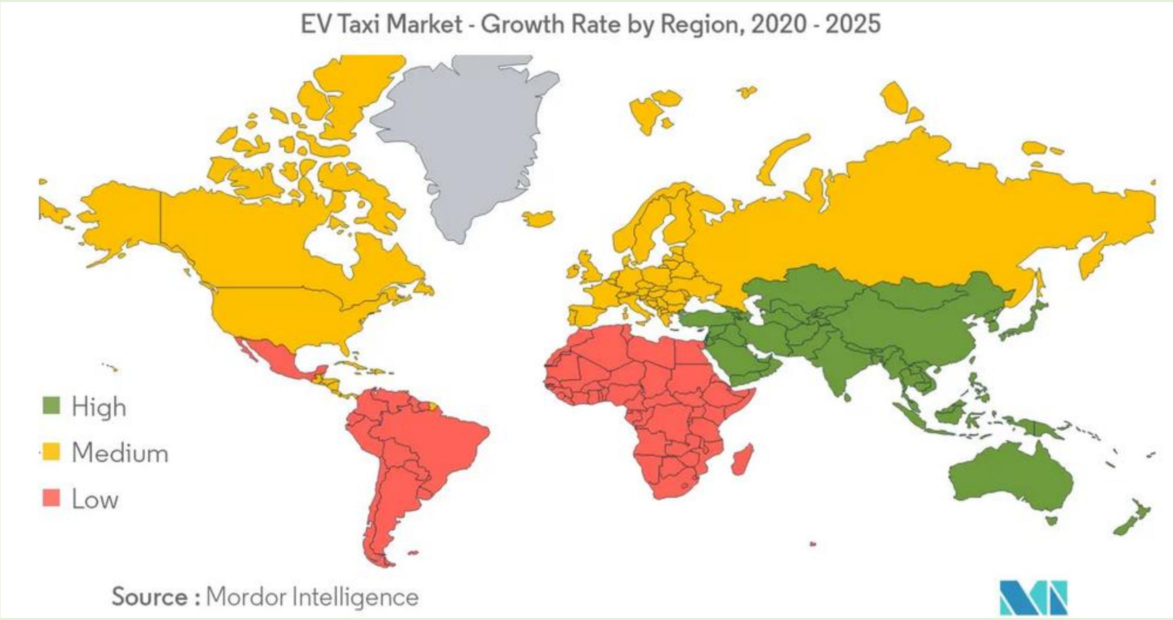
[251] True Green (December 2020) *NEXPORT to launch EV taxis* https://truegreengroup.com/nexport-to-launch-ev-taxis/
[252] Electrive.com (June 2019) *Panama: BYD delivers first e-taxi fleet in Central America* https://www.electrive.com/2019/06/06/panama-the-first-e-taxi-fleet-in-central-america/
[253] Smart Energy International (January 2021) *Chile launches a taxi electric vehicle exchange programme* https://www.smart-energy.com/industry-sectors/electric-vehicles/chile-launches-a-taxi-electric-vehicle-exchange-programme/

forecast to reach USD1 billion by 2023.[254] Somewhat contrary to BYD, Toyota's CEO for Latin America and the Caribbean suggests that Latin America is not yet ready for EVs.[255]

- **India** – the government is pushing the major fleet operators like Ola, Uber and others to expand their electric vehicle fleet and convert 40% of vehicles to electric by the end of 2026. For instance, Ola Cabs, the biggest fleet operator in India, started a pilot operation of EV taxis in the city of Nagpur testing the viability of the project, in 2019. [256] Uber began offering e-taxi services in October 2022.[257]



[254] Elluminati (2022) *Ride-Hailing App Market Growth in Latin America* https://www.elluminatiinc.com/top-10-ride-hailing-app-in-latin-america/
[255] Bloomberg Linea (23rd March 2022) *Latin America Not Yet Prepared for EVs, Toyota's Regional CEO Says* https://www.bloomberglinea.com/2022/03/23/latin-america-not-prepared-for-evs-toyotas-regional-ceo-says/
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