

# The potential for hydrogen buses in Europe: Analysis of alternatives

Technical Report  
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## JIVES / MEHRLIN projects



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## Abbreviations

| <b>Term</b> | <b>Explanation</b>  |
|-------------|---|
| BEB         | Battery electric bus  |
| BESS        | Battery Energy Storage System   |
| BMS         | Battery Management System   |
| BNEF        | Bloomberg New Energy Finance  |
| BTMS        | Battery Thermal Management System   |
| °C          | Celsius degrees   |
| CAPEX       | Capital expenditure (upfront cost)  |
| C-rate      | The rate of charge or discharge of electrical current relative to a battery's maximum capacity                        |
| DC          | Direct Current  |
| DOD         | Depth Of Discharge, the permitted range of a battery's state of charge (SOC)  |
| EU          | European Union  |
| FCE         | Full cycle equivalent, a unit of measurement of a battery's energy throughput   |
| FCEB        | Hydrogen fuel cell electric bus   |
| GTFS        | General Transit Feed Specification, a standard interchange format for passenger-facing public transport schedule data |
| HDV         | Heavy Duty Vehicle (including buses)  |
| HRS         | Hydrogen Refuelling Station   |
| HVAC        | Heating, Ventilation and Air Conditioning   |
| HVO         | Hydrogenated vegetable oil, used as an alternative vehicle fuel   |
| ICE         | Internal Combustion Engine (typically diesel for bus)   |
| kg          | Kilogram  |
| km          | Kilometre   |
| kW          | Kilowatt, a measure of power  |
| kWh         | Kilowatt hour, a measure of energy storage and use  |
| ICCT        | The International Council on Clean Transportation   |
| ICE         | Internal Combustion Engine (vehicle)  |
| IMC         | In-motion charging  |
| JIVE        | Joint Initiative for hydrogen Vehicles across Europe  |
| LFP         | Lithium Iron Phosphate, a battery chemistry used in electric vehicles   |
| Li-ion      | Lithium-ion, the most popular category of battery chemistries for electric vehicles                                   |
| LMFP        | Lithium Manganese Iron Phosphate, a newer battery chemistry for electric vehicles                                     |
| LNMO        | Lithium Nickel Manganese Oxide, a newer battery chemistry for electric vehicles                                       |
| LTO         | Lithium Titanate Oxide, a battery chemistry used in electric vehicles   |
| MW          | Megawatt, a measure of power  |
| NMC         | Nickel Manganese Cobalt, a battery chemistry used in electric vehicles  |
| NREL        | National Renewable Energy Laboratory (U.S.)   |
| NUTS        | Nomenclature of territorial units for statistics  |

| Term  | Explanation   |
|-------|---|
| OEM   | Original Equipment Manufacturer, which in the bus sector can be an amalgam of separate chassis, bodywork, and battery suppliers |
| OPEX  | Operating expenditure (day-to-day running costs)  |
| SOC   | State Of Charge, the amount of charge a battery has relative to its maximum capacity  |
| SOH   | State of Health, the measurement of a battery's usable energy capacity  |
| sqm   | Square metre  |
| TCO   | Total cost of ownership   |
| UITP  | The International Association of Public Transport   |
| VECTO | Vehicle Energy Consumption calculation Tool from the European Commission  |
| WPT   | Wireless Power Transmission   |
| ZEB   | Zero emission bus (at tailpipe), including BEB and FCEB, but excluding other gas buses  |

## Context and purpose

The JIVE project was established to help commercialise hydrogen Fuel Cell Electric Buses (FCEBs) across Europe. Our original report, [The potential for hydrogen buses in Europe: Results from the bulk analysis of passenger schedules](#), identified a niche market of hard-to-decarbonise bus routes, where existing schedules could not be maintained using Battery Electric Buses (BEBs) charged daily at depot. All options for these routes were assumed to add cost, and thus FCEBs might be competitive in this niche despite the relatively high expected price of green hydrogen.

Our original report quantified this niche market but could only estimate how competitive FCEBs might be within it. This report provides a much more comprehensive analysis of how competitive FCEBs might be within this niche.

This report evaluates a variety of BEB-based solutions to hard-to-decarbonise routes. This report contains a substantial technical evidence base to help guide operator and agency decision-making when trying to decarbonise such routes, including an appraisal of the evolving future role and residual value of Bus batteries.

We take three options forward for detailed Total Cost of Ownership (TCO) modelling:

- Use of **Alternative fuels for heating and cooling** the passenger cabin, with battery energy used for traction only.
- **Use of extra BEBs** on the route, with depot-based charging.
- Installation of **Opportunity charging** infrastructure to allow BEBs to recharge while in-service.

Our TCO modelling approach is practical and pragmatic, by:

- applying TCO calculations to individual bus routes, across a dataset representing about ¾ of all local bus services in Europe,
- sensitivity testing the most uncertain input variables and assumptions, and
- estimating FCEB potential at a range of green hydrogen price points.

The analysis benefitted from ERM's TCO modelling tool, introduced in the TCO modelling approach subsection, as well as ten operator/agency inputs collected through interviews (see *Appendix: TCO tool and inputs*).

The report provides two conclusions on parallel themes:

1. **Summary of how to decarbonise challenging local bus routes with BEBs**, which summarises which approaches work best.
2. **Summary of the potential for hydrogen**, which re-evaluates the potential for FCEBs, augmenting the "Potential for hydrogen" section of the original report.

This report is accompanied by an introductory "Guide to options for hard-to-decarbonise bus routes", which distils the key issues into guidance for operators and agencies.

## Summary of how to decarbonise challenging local bus routes with BEBs

Decarbonising challenging routes requires operators and agencies to strategically consider:

1. How much operational and scheduling flexibility exists.
2. How much financial, process and policy risk can be managed.
3. A few basic characteristics of each route's operation.

That is not to belittle the third step, which is crucial before the deployment of ZEBs (Zero Emission Buses) to bus routes. Rather, to highlight that once the first two steps have been understood, the broad choice of technical solution becomes relatively straightforward. Ignore the first two steps, as is common in pure TCO analysis, and one may determine an arithmetically cheapest solution that will not be implementable in practice.

### Flexibility

Operational and scheduling flexibility ranges from:

- **Complete freedom to optimise services for BEBs:** Optimisations might include dropping service frequency at certain times of day to allow downtime to charge, splitting long routes into local segments, or interworking peak or daytime-only routes into full-day routes. None of the local bus operators or agencies we interviewed were willing and able to alter passenger schedules or routes. Some *edge cases* may emerge under cost pressure, but most local bus passenger *services* will remain unchanged by decarbonisation.
- **Freedom to optimise internal operations, but not passenger schedules:** Changing how vehicles are deployed, crewed, and in some cases maintained, can allow the energy limitations of BEBs to be managed without altering passenger services. This may mean bringing BEBs back to depot for charging between daytime peaks, when there is slack in the fleet, as assumed in our original analysis. This is a reasonable expectation long-term, but may require operator organisations and processes to evolve, and thus may not be the initial reaction to local bus decarbonisation.
- **No ability to change vehicle operations to better suit BEBs:** Established diesel-era practices, including labour agreements which limit the scope to re-roster drivers or change maintenance patterns, and depot constraints on the amount of space available to install chargers or house additional BEBs, can lead operators to seek 1:1 diesel to ZEB replacement strategies in the short-to-mid-term. It can take time for management to appreciate that vehicle decarbonisation is not just technical but organisational.

Our analysis here focuses on the middle position, where operational details can change, but the resulting services remain the same. There are two main exceptions:

- Optimisation of services to match the capabilities of BEBs is most likely to become common in long-distance intercity coach operation, where passengers tend to be time-rich but cash-poor, and services primarily reflect commercial

market signals, not public contracts. Ember's model (box in the *Alternatives to FCEBs* section) is set to disrupt European intercity scheduled coach markets over the next decade, logically competing away what is otherwise a natural technical niche for hydrogen fuel cell coaches (due to their very high daily range on relatively infrequent routes remote from home base).

- Any inability to change internal operations will create opportunities for hydrogen in the short-to-mid-term, because FCEBs can generally replace diesel buses 1:1 because fuelling time and daily range is similar. Similar niches may emerge where existing depot sites cannot easily be converted to support BEBs. However, at current green hydrogen prices, FCEBs are only cost-effective for most local bus with substantial *hydrogen-specific* subsidies. Many of our interviewees were keen to keep FCEBs as an option because FCEBs minimise or help manage wider change, while simultaneously acknowledging that advantage currently tends to come at a price which is too high to be viable.

FCEBs aside, more flexible operations will tend to tilt decarbonisation choices towards Extra BEB solutions, since the extra vehicles can be most efficiently deployed and managed within such operations. Inflexible operations will tend to favour HVO heaters/coolers, and to a lesser degree opportunity charging. These are theoretically easier to deploy while mimicking prior operating patterns, although are themselves riskier to implement, as described below.

### Risk

Risk is a combination of financial/asset, implementation/operation, and policy/cost risks:

- **Financial and asset risk:** ZEBs roughly double the capital cost of each bus compared to diesel. BEBs are generally more precisely specified to a route so have fewer natural redeployment options. These alone increase the absolute level of financial risk per vehicle, should a ZEB not be usefully employed for its whole life. The transition to ZEBs adds risk, particularly on those aspects of the technology which were initially unfamiliar to operators or have insufficient history to be predictable, notably battery degradation and residual value. The need to reappraise battery life risk expectations is discussed in the box below.
- **Implementation and operation risk:** Any transition to ZEBs requires often technically complex depot conversions, involves energy sector organisations that bus operators/agencies have not previously work with, and introduces initially unfamiliar topics and processes – all of which add risk vs simply procuring a new diesel bus. However, some solutions to hard-to-decarbonise routes multiply these risks, notably opportunity charging, which adds further sites, both as added implementation risks, and as remote operating infrastructure, which adds further locations for technical failure.
- **External policy and cost risk:** European policy on ZEBs is only clear and consistent on traction decarbonisation, not the use of secondary heating or cooling. Different policymakers and contracting agencies across Europe differ in their current, and therefore potentially future, acceptance of what our analysis shows to often be the cheapest near-Zero Emission solution to hard-to-

decarbonise routes. Likewise, the future price of the HVO assumed in such secondary heaters/coolers could reasonably rise such as to make alternatives cheaper in most use cases.

Long-established municipal operators and agencies may be better able to manage implementation/operation risks, as their operations tend to be more predictable over very long periods, so may tilt solutions toward opportunity charging. In contrast, multi-national groups pursuing competitive route contracts may find financial risks relatively easy to manage across multiple fleets and investors, so may tilt towards extra BEBs. Operators with a strong local focus may be better attuned to their local policy and biofuel supply environment and thus be more inclined to risk secondary heater/cooler solutions, although they may still be exposed to unexpected national or international policy or price pressures.

#### **Box: The need to reappraise battery life risk expectations**

Battery degradation is widely perceived by the bus sector as a key decarbonisation risk: Operators have sought to transfer battery risks to third parties, through leasing or warranties, although all our interviewees with long-term BEB operating experience reported battery degradation had been far less than originally expected. We have nonetheless dedicated a section of this report to *Bus batteries*, because both fully-Zero Emission BEB solutions to hard-to-decarbonise bus routes analysed in this report involve using batteries more extensively or charging them more rapidly, which will have some impact on degradation and life.

Battery degradation consists of both calendar (which occurs over time regardless of use) and cycle (which occurs when the battery is discharged and recharged). Adding extra cycles to a fixed calendar degradation (more cycles per year) will tend to give a better lifetime payback on investment than using the battery more sparingly over a potentially longer life, if those extra cycles are converted into in-service, revenue-earning, bus operation.

This emphasis on better utilising batteries and being slightly less concerned about maintaining their residual value, will become increasingly important as bus battery chemistries continue to shift towards LFP (Lithium Iron Phosphate). LFP batteries may pragmatically be assumed to have no *net* residual value at end of life, unlike NMC (Nickel Manganese Cobalt) batteries which contain more high value metals. Meanwhile LFP tends to better suit route decarbonisation solutions which involve more than overnight charging, because LFP tends to degrade less per cycle than NMC. LFP has slightly lower energy density, meaning lower maximum onboard battery capacity, and thus LFP-operated routes are more likely to need one of the options outlined in this report.

#### Route

Table 1 summarises the main arithmetic patterns from TCO modelling, showing how options tend to be cheapest for certain route characteristics. Two scenarios are presented, one where all 3 main options are included, one where only pure Zero Emission options are acceptable. Route characteristics are not mutually exclusive: the data shown is indicative of the strongest tendencies, but there will be many exceptions to these patterns, as described fully in the full Cost evaluation of main options for

hard-to-decarbonise local bus routes. The final two rows summarise the most relevant flexibility and risk considerations from the previous two subsections.

Table 1: Indicative guide to the cheapest option for hard-to-decarbonise routes of given characteristics, considering TCO only (final two columns show the choice matrix if HVO heaters/coolers are excluded, characteristics are not mutually exclusive)

| Route characteristic  | 3 main options                   |                                   |                                      | Pure ZE options only                |                                  |
|---|----------------------------------|-----------------------------------|--------------------------------------|-------------------------------------|----------------------------------|
|   | HVO heaters /coolers             | Extra BEBs                        | Opportunity charging                 | Extra BEBs                          | Opportunity charging             |
| Average energy per bus (worst climatic day, kWh) <sup>1</sup> | < 650                            | > 950                             | 650-950                              | > 900                               | < 900                            |
| Peak vehicle requirement (buses)                              | 4-8                              | < 4                               | > 8                                  | < 4                                 | > 4                              |
| Daily operating hours of route                                | < 21                             | Lower <sup>2</sup>                | > 21                                 | < 17                                | > 17                             |
| Common route associations                                     | Slow and short, especially urban | Lower intensity, especially Rural | High intensity, including Interurban | Lower intensity, including Suburban | Higher intensity, including City |
| Optimal required operator flexibility                         | Minimal                          | High                              | Low                                  | High                                | Low                              |
| Key additional risk   | Fuel policy and cost             | Minimal                           | Multi-site implementation            | Minimal                             | Multi-site implementation        |

Pricing in those additional risks could significantly change these conclusions, as detailed in the TCO sensitivity analysis:

- A doubling of HVO price, which is a plausible future scenario given inherent supply constraints, would make HVO heaters/coolers a secondary solution at all but the lowest energy requirements, with daily bus requirements below about 750 kWh shifting to opportunity charging, and those above favouring Extra BEBs.
- Alternatively, doubling the costs of opportunity charging, as a simple proxy for the elevated risks around implementing this solution, renders opportunity

<sup>1</sup> Daily bus duty mileage can be used as a crude proxy – kilometres is roughly equivalent to 2/3 kWh.

<sup>2</sup> Extra BEBs are not a dominant strategy at any specific number of operating hours, but skew towards 12, not 24, hour routes.

charging the cheapest option only for routes operated with more than 13 buses.

While pure arithmetical TCO tends not to favour Extra BEB strategies for solving hard-to-decarbonise local bus routes, the option carries the least risk. How much weight operators will give these non-TCO considerations is more difficult to judge and is likely to evolve over the transition, as new technologies become more familiar, and implementation and operational processes mature.

**Box: Lifetime cost of decarbonising challenging local bus routes**

All options add to the cost of the most basic BEB with overnight depot charging. However, by 2040 we expect most hard-to-decarbonise mileage to be cheaper than the diesel equivalent, as shown in the graph below.

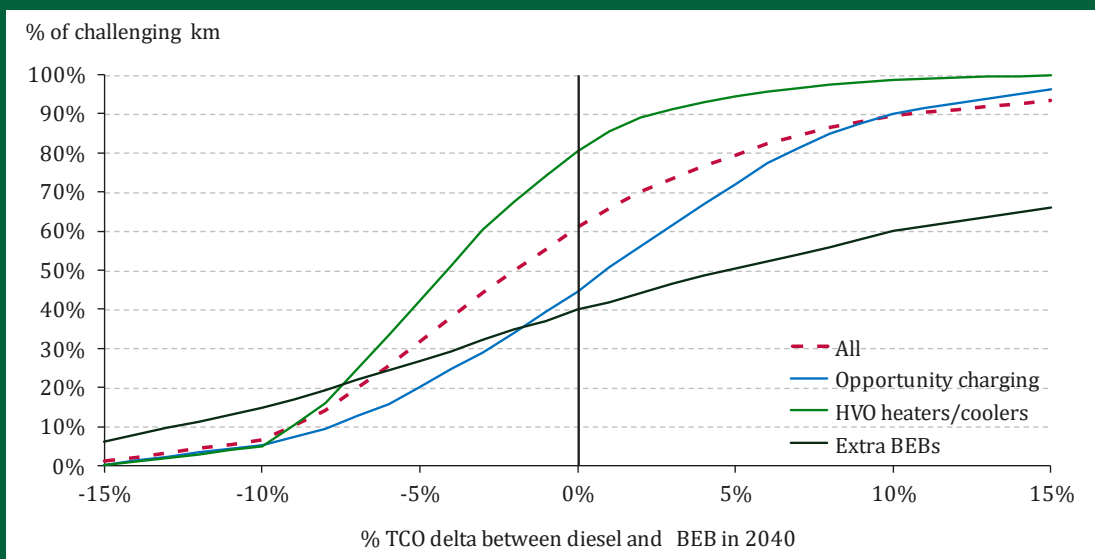


Figure 1: Distribution of the cost of the cheapest option vs diesel in 2040, across all European hard-to-decarbonise local bus mileage analysed

As detailed in *Costs of decarbonisation vs diesel*, without an HVO heater/cooler option, the proportion of European route mileage that costs more than the diesel equivalent rises to two thirds. Any policy pursuit of fully Zero Emission options can be expected to come at tangible additional financial cost.

## Summary of the potential for hydrogen

Hydrogen FCEBs are technically well suited to local bus decarbonisation and can be operated in much the same way as diesel buses, unlike the pure Zero Emission BEB-based options for hard-to-decarbonise routes reviewed in the previous section. The key long-term disadvantage of FCEBs is hydrogen fuel cost, and in turn niche market opportunities which foster an insufficiently large scale of supply chain. Routes that can be operated from home depot without additional buses may be presumed to favour BEB on cost. However, where additional assets would be required to deploy BEBs – what this report refers to as challenging or hard-to-decarbonise routes – FCEBs could be competitive.

This study is thought to be the first that assesses the competitiveness of FCEBs vs the main BEB-based alternatives in this market niche. Our analysis is based on the application of TCO modelling to around  $\frac{3}{4}$  of all European scheduled local bus routes, excluding long-distance routes over 100 km (and thus is not applicable to coach). The proportion of the market in which FCEBs and hydrogen can expect to be competitive at different price points is shown in Figure 1. Further in-depth analysis can be found in the *Price of hydrogen to be competitive* and *Potential FCEB and hydrogen market* subsections of this report.

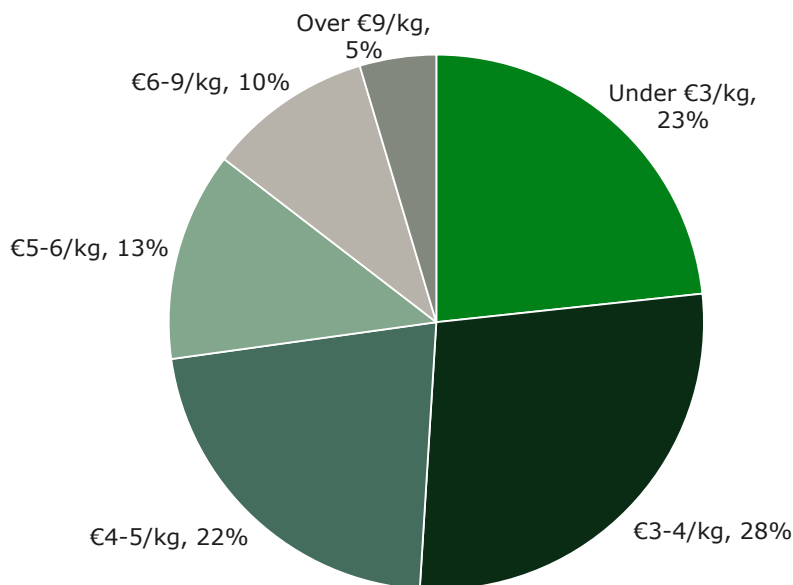


Figure 1: Proportion of potential hard-to-decarbonise European local bus market contestable for FCEBs and hydrogen, by green hydrogen price paid by operators (2025 prices, distribution shown is by hydrogen volume in 2050, but associated FCEB vehicle parc and trends to 2050 are almost identical patterns)

The total 2050 European local bus market estimated in the graph above consists of a FCEB parc of **about 57 thousand buses and associated daily green hydrogen demand averaging 1075 tonnes per day**. The current green hydrogen price paid by local bus operators typically exceeds €10/kg, a price point at which only a few percent of this long-term market would be commercially contestable. Halving prevailing hydrogen fuel prices would still only favour about a quarter of opportunities. If €6-10/kg were considered more pragmatic, FCEBs could expect to attain no more than 15% of the hard-to-decarbonise market – about 4% of the total local bus market.

Within Europe, some national markets will be much stronger for FCEBs than others, especially at mid-price points. For example, roughly half the hard-to-decarbonise local bus market in Denmark and Ireland is expected to be competitive at €5/kg. Germany and Sweden are expected to be the strongest markets overall, both with relatively large absolute potential and with a reasonably well-balanced distribution of potential demand across the full range of price points.

However, as summarised in the previous section, pure arithmetic TCO is not the only guide to decarbonisation decision-making. Critically, FCEBs tend to be most price-competitive against extra BEBs (as summarised in Figure 2 below), and extra BEBs are the least risky of the 3 main BEB-based options for hard to decarbonise routes. Operators and agencies that price these risks into their decisions can be expected to view FCEBs more favourably. This is especially true of operators that lack the organisational flexibility to pursue extra BEB strategies efficiently, especially in the initial stages of their transition to ZEBs.

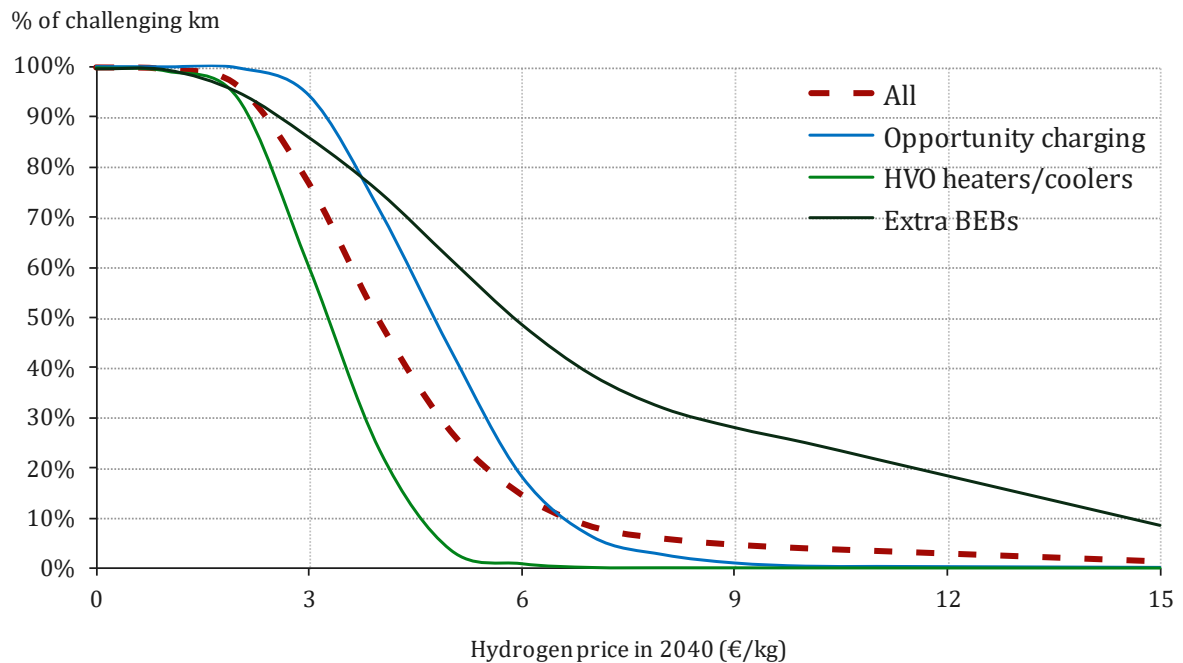


Figure 2: Proportion of hard-to-decarbonise local bus mileage analysed for which FCEBs would be cost-competitive with BEBs by hydrogen price and cheapest BEB option in 2040.

Yet while risk factors could perhaps convert a 5% market shared into 20% at current prices, substantial reductions in green hydrogen price would still be needed for FCEBs to become a common solution to hard-to-decarbonise local bus routes. Meanwhile, as the transition to ZEBs progresses, operators and agencies can be expected to become better at both managing decarbonisation risks and affecting organisational change, even if short-term structural limitations, such as depot constraints, can seem to promote FCEBs as the *only practical solution*.

## Alternatives to FCEBs

### Context

Our original report identified several alternative technologies and strategies that might compete with FCEBs in the hard-to-decarbonise route niche.<sup>3</sup> These were reasoned assumptions, but without detailed research or modelling. This report seeks to address those limitations.

The original schedule-based modelling assumed that operators would not attempt to change those schedules. This assumption was repeatedly confirmed by our operator/agency interviewees (listed in Appendix: Interviewees), who either considered it commercially or politically impossible, or at best highly undesirable, to significantly alter established service patterns or schedules to decarbonise routes.

However, the original modelling made three further assumptions about operators' flexibility, which while broadly correct, were found not always to apply:

1. Our original energy modelling assumed fully-battery operation of BEBs. However, as discussed in Alternative fuels for heating and cooling, some operators expect to continue to use secondary heaters, currently powered by diesel. As explained in Energy management strategies, non-battery-based heating greatly reduces both BEBs' required battery capacity and associated route compatibility challenges. This report therefore considers the continued use of secondary heaters in BEBs, with HVO rather than diesel, as a competitor to FCEBs.
2. Our original analysis presumed operators would be able to change their *internal* operating practices to optimise the use of BEBs. Yet some local bus operators were, at least for now, unable to modify established practices such as crew rostering or vehicle maintenance periods. They were thus unable to affect the BEB decarbonisation of routes considered "manageable" - those which might require BEBs to be switched in and out of service across the day. This finding reinforces the idea that adoption of ZEBs is not just a *vehicle* transition. Indeed, many operators have found that the vehicle is *easier* to convert than their own human organisations. FCEBs are especially well suited to directly replacing diesel buses with minimal operational change. While we expect operators to evolve their internal practices in the long term, and thus will continue not to group this "manageable" segment as a natural market for FCEBs, greater opportunities for FCEBs may arise here in the short-to-mid-term.
3. We originally presumed high daily vehicle duty range (expressed as energy) to be the main competitive advantage of FCEBs, which remains the dominant long-term theme, however:
  - a. The availability of subsidies (both directly of new FCEBs and indirectly through investment in the local hydrogen supply chain) emerged as

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<sup>3</sup> <https://fuelcellbuses.eu/public-transport-hydrogen/d336-potential-hydrogen-buses-europe-results-bulk-analysis-passenger>

common factors in FCEB adoption.<sup>4</sup> These subsidies are not expected to be maintain long-term, so remain excluded from our modelling.

- b. FCEBs were noted as performing relatively well in very low speed environments, as fuel cells can produce a constant low-power stream, which gradually augments the bus's regenerative braking. Our original energy modelling did not specifically account for speed, which can significantly increase BEB energy consumption per km when averaging under about 20 km/h.<sup>5</sup>
- c. Large battery capacities are currently difficult to engineer onto the smallest buses, notably those used for scheduled local "neighbourhood" or community paratransit services, that need to operate a full daytime and evening service while maintaining a high proportion of accessible (low floor) space for passengers with limited personal mobility. This may present a niche market opportunity for hydrogen.<sup>6</sup>
- d. Where triaxles buses were already operating on City routes, the BEB challenge has been to manage the reduced passenger capacity caused by the carriage of batteries. One interviewee noted that an 18-metre BEB artic could only carry about 15% more passengers than a 12-metre bus powered by Compressed Natural Gas. In assuming all City buses generic, we thus understated the difficulty of decarbonising those routes with the greatest passenger loads.
- e. While depot grid connection challenges are a *transitional* barrier to BEBs, and thus reasonably not part of long-term modelling assumptions, some depot sites cannot be converted to house BEB chargers. For example, when located under residential or similar buildings, where fire risk may be a significant factor. In these cases, the ability to specifically fuel FCEBs away from their home depot may be an advantage long-term.

A recurrent theme of this report is that while a techno-economic assessment of options for hard-to-decarbonise bus routes is possible, ultimate decision-making will be heavily influence by one question: How much flexibility does the operator/agency have to change beyond mere vehicle decarbonisation?

As the Ember example in the box below highlights, almost any bus route can now be converted to battery electric, *if* the operator is able to reconfigure both passenger

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<sup>4</sup> Subsidies can come in forms not explicitly intended to skew decision-making towards FCEBs: For example, for a period in 2024 the Spanish government offered incentives for new FCEBs but had not renewed its financial support for new BEBs. Local strategic projects, such as Hydrogen Valleys or EU Alternative Fuels Infrastructure Regulation compliance, can effectively cross-subsidise FCEBs by providing hydrogen infrastructure on a marginal basis. In Vienna, our interviewee outlined a collective civic approach that utilised sister municipal companies' hydrogen supply and refuelling systems, which lowed cost, for example through favourable electricity rates to electrolyse hydrogen.

<sup>5</sup> <https://www.gov.uk/government/publications/ultra-low-emission-vehicles-speed-emission-and-fuelenergy-consumption-rates>

<sup>6</sup> One provider in this niche, Mellor/Treka, recently dropped BEB models in favour of FCEB development - <https://www.route-one.net/news/hydrogen-combustion-seen-as-endgame-by-mellor-and-treka-owner/>

schedule and vehicle deployment to match certain limitations of the technology. While evolving, many local bus operators have little flexibility, and in some cases are attempting to deploy BEBs on a like-for-like operational basis to the diesel buses replaced. The less flexibility, the more likely that FCEBs will be seen as appealing ZEB solutions by operators and agencies, even at higher lifetime cost than BEB options.

#### Case study: How Ember optimise schedules and operations around BEBs

In 2024, Scottish longer-distance BEB operator, Ember, introduced a fleet of Yutong GTe14s on a new route between Aberdeen and Edinburgh (about 220km each way). These triaxle 563kWh BEBs are too long to operate most bus routes, and Ember's limited stopping pattern is untypical of most urban bus. However, Ember's broad operational strategy could be applied elsewhere.

BEBs operate for 8 hours from Aberdeen to Edinburgh and back, then in most cases are out of service for just over an hour, before repeating the loop to Edinburgh and back again. The period out of service is optimised to match the time taken to charge at 600kW, which is achieved by dual cable plug charging.

Ember thus routinely attains 17 hours of vehicle operation with just over an hour of carefully planned intermediate downtime to rapid charge. A similar, but less aggressive strategy has evolved for lower battery capacity TCe12s, which typically operate one round trip from Dundee to Edinburgh or Glasgow, before returning to depot for just under two hours to fully recharge. Ember's BEBs do take some longer breaks during each week, but overall fleet in-service time is high, especially for newer vehicles.

As illustrated above, Ember optimises both service schedule and charging processes to maximise the use of its BEBs. As a startup in a relatively deregulated part of the bus market, Ember has the flexibility to build a strategy around the limitations of BEBs.

*Source: Author's analysis of real-time data, and <https://www.route-one.net/features/behind-the-scenes-at-electric-intercity-coach-operator-ember/>*

#### Options for hard-to-decarbonise bus routes

This report evaluates three main BEB-based options for hard-to-decarbonise bus routes. These reflect the spread of prevailing approaches identified by both our operator/agency interviewees, and commonly observed in Europe. A spread is important because in practice each option contains many nuances and variations. Our aim is to identify the key tendencies and patterns between these main options, not to perfectly optimise each solution for each bus route in Europe. Each option is discussed fully in its own section:

- **Alternative fuels for heating and cooling:** HVO-fuelled secondary heaters/coolers, with BEB batteries only used for traction, not to manage the temperature of the passenger cabin. Local policy acceptance of this approach varies but is technically the easiest method of achieving BEB route compatibility in most "challenging" cases, and thus the option serves as a base case for their decarbonisation.

- **Use of extra BEBs:** Additional BEBs, which may charge during the day using depot infrastructure, and are swapped in and out of service to maintain existing schedules. This approach is akin to that originally modelled as “manageable”, merely acknowledging that more BEBs will be required than prior diesel buses. This is the most common solution identified by especially operators, so serves as a default case for hard-to-decarbonise routes.
- **Opportunity charging:** Use of dedicated pantograph-based rapid chargers at fixed locations on the bus route. These typically top-up a proportion of a large BEB battery, but alternatively may routinely fully-charge a much smaller BEB battery. A proven technical solution for hard-to-decarbonise routes, but whose initial implementation is the most complex, and thereafter least flexible operationally, of the three options.

We considered several alternative technologies before shortlisting the three options above. These alternatives were not shortlisted because they:

- were appropriate only in specific niches or localities, so could have only limited impact on the overall European hard-to-decarbonise “potential FCEB” market,
- demonstrated technological immaturity or lack of market readiness, some the focus of short-term trials with no evidence of long-term perpetuation, or
- showed no clear business case or operational advantage over the main three options selected above.

Many key bus decarbonisation decisions will need to be taken in the 2030s, which means the window for further technological and business case improvement is in practice about to close. It is therefore pragmatic to focus our evaluation on proven solutions.

A description and discussive evaluation of each non-shortlisted alternative is given towards the end of this report, but in summary:

- **Energy management strategies:** Aside from the use of alternative fuels for heating or cooling the passenger cabin (one of the three main options), we found the advantages either marginal (and thus only a potential part of another solution) or inconsistent (and thus unlikely to relieve any one bus route of its energy constraints). So, while there are clear advantages to BEB operators of pursuing some of these strategies, they do not constitute a singular solution to most hard-to-decarbonise routes.
- **Wireless charging:** We found no clear operational or cost advantage to static wireless charging. Dynamic (in-motion) wireless charging has the theoretical advantage of removing all downtime to opportunity charge. However high capital cost, plus a range of implementation and maintenance concerns, led us to conclude that the technology is not yet ready for mainstream adoption by the local bus sector.
- **Trolleybus:** Wiring cities currently without trolleybuses would be prohibitively expensive. Only where wiring already exists could it allow in-motion charging of BEBs whose routes partially travel under wires. This potentially avoids the need to pursue one of the three main options above. However, in practice this option

is limited to urban routes in the small proportion of European cities with existing trolleybus networks, so cannot be considered a mainstream solution.

- Battery swapping: We found no clear use case for bus battery swapping. The technology's limited deployment in Asia tends to act as a means of financing batteries, not just a way of managing range limitations. While finance is a challenge for many European bus operators, financing models already exist for batteries permanently attached to the bus.
- Rooftop solar: While potentially a cost-effective technology for diesel buses, negligible energy savings would be attained from deploying solar panels on BEBs.

One further option was mooted in our original report, that has not been taken forward: the widespread deployment of triaxle buses, with the extra weight allowance used to carry more batteries. This is not a new technology, just an enlargement of existing engineering, so not an option described in detail. Many of our operator interviewees pushed back against the idea, noting:

- Local highway engineering, bus terminal design, and overall traffic volumes greatly limit the practical scope to replace dual axle buses with triaxle buses, which are normally longer and always harder to manoeuvre.
- As noted above, the limited internal volume of smaller buses already makes it difficult to install larger battery capacities without reducing passenger capacity, and an extra axle would exacerbate this pattern.
- Likewise, as noted above, existing articulated BEBs cannot carry the same weight of passengers as buses powered by other fuels, inverting the triaxle *solution* to become itself a problem where a third axle was previously needed to manage high patronage.

All this frames triaxle BEBs as a locally specific niche solution.

#### TCO modelling approach

Conventional Total Cost of Ownership (TCO) modelling considers vehicle types in abstract and applies fixed input cost assumptions, to determine the lowest cost option over a vehicle's lifetime. This was broadly the approach adopted by prior TCO work for the JIVE project.<sup>7</sup> Our approach to the comparative TCO of the three main options for hard-to-decarbonise bus routes is more practical and pragmatic, while still being highly strategic:

- Calculations are applied to each bus route (or inter-worked group) in our original schedule analysis – a dataset covering about three quarters of all scheduled local bus services in Europe.<sup>8</sup> Our modelling thus accounts for key route-specific operational details, such as energy requirements, hours of operations, mileage and current vehicle allocation.

<sup>7</sup>

[https://www.fuelcellbuses.eu/sites/default/files/documents/Deliverables\\_JIVE%20D3.22\\_%20JIVE%20D3.6\\_D4.3\\_final.pdf](https://www.fuelcellbuses.eu/sites/default/files/documents/Deliverables_JIVE%20D3.22_%20JIVE%20D3.6_D4.3_final.pdf)

<sup>8</sup> <https://fuelcellbuses.eu/public-transport-hydrogen/d336-potential-hydrogen-buses-europe-results-bulk-analysis-passenger>

- While operationally detailed, there are many unknowns or uncertainties related to specific operations, such as the cost of expanding a local depot or the ease of connecting an opportunity charger in a specific location. To help understand this, our model assigns sensitivity ranges to key inputs. A pseudo-random set of TCO results are produced for each route, reflecting the full range of sensitivities.
- Perhaps the most contentious sensitivity, the future price of green hydrogen, is not an input, but an output: Our modelling assesses the price (per kilogram) that green hydrogen would have to attain to make the fuel cost-competitive against the optimum BEB solution. Since this is calculated by route, a full distribution of the proportion of the potential FCEB market that is achievable at different price points can be produced and segmented.

Some caveats to our approach:

- While operational analysis is local, most TCO inputs factors are generalised to Europe, and never include location-specific variables, such as individual operators' labour costs or local grid connection difficulty factors.
- Modelling does not consider advanced energy management strategies, such as static battery storage to manage peak charging demand, nor marginal use of BEBs for vehicle-to-grid (V2G). Neither is expected to be widespread or radically alter the bus sector's overall ZEB TCO.
- Like the original schedule modelling work, there is no consideration of non-battery fuels (beyond HVO specifically for heating/cooling and the consequences for hydrogen and FCEBs), nor non-scheduled or non-public "bus and coach", including most uses of coach-bodied vehicles. Note that while intercity coach is included in the schedule dataset, our modelling focuses on options for local bus.

## Alternative fuels for heating and cooling

### Context

Depending on local climate, up to half the installed battery capacity onboard a BEB is needed simply to heat or cool the passenger cabin, as further discussed in the *Energy management strategies* section. Such temperature-related energy losses are especially pronounced in northeast Europe (where winter temperatures are coldest) and in some urban operations (where multiple doors and frequent stops create the most opportunities for conditioned passenger cabin air to escape).

Most European bus routes previously categorised as “challenging” to converted to BEB would cease to be challenging if *only* their traction were decarbonised with battery electric technology. An alternative fuel with much greater energy density than batteries could be used to heat or cool the passenger cabin as required by variations in local daily temperatures, without adding significant weight to the vehicle. Since the alternative fuel would be needed in relatively low quantities on more temperate days, the potentially higher cost of that fuel may not be prohibitively expensive.

The use of diesel heaters for non-traction BEB energy is already established practice in some parts of Europe. The control and reporting of emissions from these auxiliary heaters has been described as “lax”.<sup>9</sup> The EU’s VECTO calculation tool now allows the categorisation of different Heating, Ventilation, and Air Conditioning (HVAC) types, however these differences are not yet obviously reflected in OEM emissions reporting.<sup>10,11,12</sup> It may legitimately be difficult for an OEM to know, at the time the bus is sold, what the annual emissions of a seasonal heater might be. The formal application of EU CO<sub>2</sub> regulations to such heaters is thus unclear.<sup>13</sup>

In the absence of clear policy at European level, divergent local policy positions are already emerging, which are likely to perpetuate and guide future acceptance of secondary heaters as part of a bus decarbonisation solution. For example, our operator/agency interviewees told us:

- In Belgium it is currently acceptable practice for new BEBs to use non-battery diesel energy for heating and cooling the passenger cabin when required.
- In Norway the approach to such heaters has historically been pragmatic, reflecting the prevailing energy limitations of BEBs, and only in recent years have contracts expected the use of pure battery-based heating. Biogas was cited by interviewee Ruter as an example of the potential for local policy divergence: each of the two local governments in Ruter’s area has a different view on whether biogas is an acceptable “zero emission” solution or not.

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<sup>9</sup> <https://www.mdpi.com/1996-1073/16/8/3578>

<sup>10</sup> [https://climate.ec.europa.eu/eu-action/transport/road-transport-reducing-co2-emissions-vehicles/vehicle-energy-consumption-calculation-tool-vecto\\_en](https://climate.ec.europa.eu/eu-action/transport/road-transport-reducing-co2-emissions-vehicles/vehicle-energy-consumption-calculation-tool-vecto_en)

<sup>11</sup> <https://www.sciencedirect.com/science/article/pii/S0360544223005492>

<sup>12</sup> <https://discomap.eea.europa.eu/App/CO2HDV/>

<sup>13</sup> [https://climate.ec.europa.eu/eu-action/transport/road-transport-reducing-co2-emissions-vehicles/reducing-co2-emissions-heavy-duty-vehicles\\_en](https://climate.ec.europa.eu/eu-action/transport/road-transport-reducing-co2-emissions-vehicles/reducing-co2-emissions-heavy-duty-vehicles_en)

- In the United Kingdom, ZEB certification (and thus government subsidy) specifically excludes any on-board combustion engines, including diesel heaters.<sup>14</sup>

During the transition to Zero Emission vehicles, it may be argued that a BEB with a diesel heater represents a significant CO<sub>2</sub> reduction when compared to a fully diesel bus. However, ultimately an alternative Zero Emission fuel would be needed, so this is the focus of our assessment of this option in the long-term.

Hydrogen is potentially such a fuel. However, its use to augment a primarily battery-powered bus raises similar problems to hydrogen fuel cell “range extenders” for buses: Reliance on hydrogen for solely heating and cooling would greatly exacerbate the challenges of scaling hydrogen supply locally. Our original report identified significant challenges supplying buses entirely powered by hydrogen.

Our analysis is thus limited to low emission “drop in” fuels, to be used as a direct replacement for the current fuel in diesel heaters.

Hydrogenated vegetable oil (HVO) is the most used such fuel in the bus sector. Under the EU Renewable Energy Directive, HVO can provide GHG reductions up to 87% using waste feedstocks,<sup>15</sup> so would not offer sufficient reductions to meet long-term European emission regulations when fuelling the whole bus. However, the annual energy volumes implied by merely heating and cooling are far less, and thus more plausible as a near-zero emission solution. Ultimately, synthetic fuels may provide an alternative to HVO.

The option to use HVO heaters/coolers serves as a baseline for the easiest approach to decarbonising challenging routes, as no significant additional assets or operational changes are implied beyond a secondary, largely seasonal fuel.

### Supply and cost projections

HVO is a fuel that is already widely produced, with many existing production facilities in Europe and a further 400Mt of capacity is due to come online in 2025.<sup>16</sup> HVO today is generally ca. 7% more expensive<sup>17</sup> and ca. 7% less energy dense than fossil diesel per litre<sup>18</sup>. This means that refuelling with HVO over diesel on a like-for-like energy basis would cost consumers ca. 15% more. HVO prices showed significant volatility during 2024, rising by up to 50% following production problems at one refinery in Rotterdam.<sup>19</sup> HVO prices are expected to increase because they primarily rely on supply-constrained advanced feedstocks such as agricultural residues and animal fats to meet the EU Renewable Energy Directive (RED) requirements, although the extent

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<sup>14</sup> <https://www.zemo.org.uk/work-with-us/buses-coaches/low-emission-buses/certificates-hub.htm>

<sup>15</sup> Annex V: <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02018L2001-20240716>

<sup>16</sup> <https://www.argusmedia.com/en/news-and-insights/latest-market-news/2641460-viewpoint-european-hvo-demand-to-rise-in-2025>

<sup>17</sup> Argus Biofuels Daily international market prices and commentary for Class III HVO, Issue 24-213, 25<sup>th</sup> October 2024

<sup>18</sup> <https://www.cummins.com/news/2022/07/01/hydrotreated-vegetable-oil-hvo-explained>

<sup>19</sup> <https://www.route-one.net/suppliers/hvo-price-rise-again-outpaces-fossil-diesel-in-november-portland/>

to which the price will change is unpredictable and unclear in beyond the very near term.<sup>20</sup>

E-fuels (otherwise known as synthetic fuels) are another form of low-carbon fuels produced from captured CO<sub>2</sub> and green hydrogen.<sup>21</sup> The EU RED allows e-fuels that provide at least a 70% emissions reduction compared to fossil diesel.<sup>22</sup> There are no examples of commercial e-fuels production facilities today, but plans for around 30 large-scale plants have been announced in Europe (as of October 2024).<sup>23</sup>

The price of HVO and e-fuels may be linked in the future as they both have the same purpose (i.e., as a direct replacement for fossil fuels), and as such customers have the choice to use the most cost-effective option or the lower-carbon option. As a result, HVO prices may define a base price for e-fuels, as they provide similar carbon reduction outcomes: logically, customers expect a similar price for a similar product.

Given the large scope of uncertainty in the price of alternative fuels in the future, this is approached by utilising a highly variable sensitivity parameter within the TCO modelling (see *TCO modelling approach* for more detail).

### Modelling the cost of using alternative fuels for heating and cooling

To model the cost of using a separate heater/cooler powered by alternative fuels, three things first need to be determined: the split of energy use between traction and heating/cooling on peak days and average, whether the bus has enough battery capacity to perform the route only powering the traction demand, and the efficiency of the diesel/HVO heater compared to a heat pump.

#### *Splitting energy use between traction and heating/cooling*

As done in the previous report,<sup>24</sup> the average monthly temperature in each country (increased by 1°C to account for use mainly in the daytime) is combined with the energy consumption per km curve (shown later in Figure 45, Page 82) to estimate the heating/cooling requirements in each month. From these twelve values, the average and maximum heating/cooling demand are calculated. These are multiplied by the average and maximum distance travelled and subtracted from the average and maximum daily energy use respectively to calculate the average and maximum traction energy daily demand.

#### *Assess route suitability for alternative fuel climate control*

For alternative fuel climate control be suitable, the bus battery must be sufficient to fulfil the traction energy requirements on the most demanding day, whilst the alternative fuel heater/cooler provides the climate control energy. If the battery

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<sup>20</sup> [https://joint-research-centre.ec.europa.eu/welcome-jec-website/reference-regulatory-framework/renewable-energy-recast-2030-red-ii\\_en](https://joint-research-centre.ec.europa.eu/welcome-jec-website/reference-regulatory-framework/renewable-energy-recast-2030-red-ii_en)

<sup>21</sup> Green hydrogen is made from the electrolysis of water where the electricity used is from renewable energy sources (e.g. wind or solar).

<sup>22</sup> <https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32023R1185&qid=1693820063812>

<sup>23</sup> [https://project-skypower.org/sites/default/files/2024-10/Project%20SkyPower%20Insights%20Report%20Oct%202024\\_final.pdf](https://project-skypower.org/sites/default/files/2024-10/Project%20SkyPower%20Insights%20Report%20Oct%202024_final.pdf)

<sup>24</sup> Page 54, <https://fuelcellbuses.eu/public-transport-hydrogen/d336-potential-hydrogen-buses-europe-results-bulk-analysis-passenger>

capacity is insufficient to provide the traction energy, this option is deemed unsuitable, and the total cost of ownership is not calculated for this year and route.

#### *Efficiency of a diesel/HVO heater compared to a heat pump*

This is used to convert the kWh/km energy requirement of a heat pump (from Figure 45, Page 82) into a litre of fuel per km for an alternative fuel heater. For this analysis, a conservative ratio of 2.5 kWh diesel/HVO to kWh electricity has been assumed. This is lower than the ratio of up to 4 that can be quoted from heat pump manufacturers, but accounts for reports that current heat pumps can sometimes perform less well than advertised by manufacturers. This conservative value will provide a reasonable upper limit to the required volume and cost of alternative fuels used for heating and cooling on the specified route.

#### *Calculating the cost of alternative fuel heating and cooling*

For the TCO calculations, it is assumed that the bus battery only provides the traction energy, and the alternative fuel heater provides all the heating and cooling demand, even on less demanding days where a BEB with a heat pump could feasibly operate successfully. This assumption is valid for most current buses, which do not have a hybrid heat pump/diesel heater climate control system, as there is no electric heater supplied on the vehicle. The vehicle CAPEX of a BEB with a diesel heater is assumed to be equivalent to that of a BEB with a heat pump, so no change in the purchase cost of the vehicle. While in practice a heat pump can be expected to add thousands of Euros to the cost of a BEB, the integration of a diesel-based heating/cooling system into an otherwise battery-based vehicle also represents a cost.

The fuel and electricity costs are calculated by multiplying the average traction electricity demand (kWh/km) and average heating/cooling demand (l fuel/km) by the annual kilometres travelled by the bus. This results in a cost entry for both electricity consumed as well as alternative fuel consumed (i.e. HVO, e-diesel).

## Bus batteries

Battery electric buses (BEBs) operate using one or more electric motors powered by an onboard battery pack. This section provides an overview of key considerations for BEB batteries, including the benefits and disadvantages of different battery chemistries, observed battery degradation and management strategies, and options for end-of-life.

### Role of battery chemistries

Lithium-ion is the most common type of battery used for electric vehicles. Lithium-ion refers to the fact that lithium ions are the main energy carrier. Other materials are also needed to create the electrodes (called anode and cathode) of a battery, and within the grouping of lithium-ion batteries, there are three main battery chemistries that are currently relevant to BEBs:<sup>25</sup>

1. **Nickel Manganese Cobalt (NMC):** This cathode chemistry is still the most common in new BEB models in Europe (based on market analysis by ERM). NMC has a balanced performance of energy density (the amount of energy stored in a given volume or mass of the battery), power output (the rate at which a battery can deliver energy) and thermal stability (the ability of a battery to maintain safe operating temperatures and resist overheating). NMC has the highest energy density compared to LFP or LTO batteries (Figure 3Figure ).<sup>26</sup> This allows the size of the battery to stay relatively small while providing good vehicle range. However, cobalt is a scarce material and the mining of cobalt in the Democratic Republic of Congo is associated with environmental and human rights risks.<sup>27,28</sup> Newer NMC battery technologies are emerging with lower concentrations of cobalt for this reason (e.g., NMC 532, with 20% cobalt instead of the original 33% cobalt in NMC 111 batteries).
2. **Lithium Iron Phosphate (LFP):** Batteries with LFP cathodes are the most common batteries for electric buses at a global level.<sup>26</sup> LFP batteries are less prone to overheating and have a long cycle life (meaning that they can be charged and discharged many times before the battery degrades significantly – see Battery degradation section below).<sup>29</sup> This is beneficial for buses which are heavily used and need to recharge often. However, LFP batteries have a lower energy density compared to NMC batteries, meaning that BEBs with LFP batteries need to be larger (and heavier) to achieve the same range, which can cause issues with vehicle weight restrictions (Figure 3). Sometimes this can create a trade-off between the range that is required and the battery size and weight. However, the energy density is improving over time (from about 90 Wh/kg in 2010, to 145 Wh/kg in 2020, to 160 Wh/kg in 2023 at pack level).<sup>26</sup> LFP cathodes use materials that are abundant in the environment, and

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<sup>25</sup> Centrale D'Achat du Transport Public, June 2024, Transition énergétique : étude comparative sur les différentes motorisations des autobus – Edition 2024. <https://www.agir-transport.org/wp-content/uploads/2024/07/Etude-comparative-des-differentes-motorisations-de-bus-2024.pdf>

<sup>26</sup> BNEF Long-Term Electric Vehicle Outlook 2023.

<sup>27</sup> <https://earth.org/cobalt-mining-in-congo/>

<sup>28</sup> World Bank, June 2021, Cobalt in the Democratic Republic of Congo.

<https://documents1.worldbank.org/curated/en/099500001312236438/pdf/P1723770a0f570093092050c1bddd6a29df.pdf>

<sup>29</sup> <https://batteryuniversity.com/article/bu-205-types-of-lithium-ion>

generally have a lower environmental impact than NMC cathodes: LFP cathodes do not contain nickel or cobalt, which have high environmental impacts during the mining and smelting process.<sup>30</sup> However, LFP batteries are currently not as widely recycled as NMC batteries (see Opportunities for batteries at end-of-life section below), although recent research has tested improvements of recycling techniques for LFP batteries, suggesting growing interest.<sup>31,32</sup>

- Lithium Titanate Oxide (LTO):** batteries with LTO anodes have high thermal stability and an even longer cycle life than LFP batteries.<sup>29</sup> The chemistry is particularly suitable for fast charging because the ion conductivity is higher than the graphite anode used in other chemistries.<sup>33</sup> For these reasons, LTO can be a good choice for bus batteries that need to recharge quickly and frequently, i.e., trolleybuses, or where traction energy requirements continually oscillate with regenerative braking, such as in urban areas. The better cold-temperature performance of LTO batteries compared to LFP and NMC batteries also make LTO more suitable in regions where cold start-ups are required.<sup>29</sup> Additionally, titanate (from titanium) is abundant and has fewer environmental risks associated with its extraction than nickel or cobalt. However, LTO has a much lower energy density than LFP or NMC, thus cannot provide the same range as NMC or LFP batteries (Figure 3). Cost per kWh is also higher than NMC and LFP batteries because of the more specialised manufacturing processes and smaller production volumes.

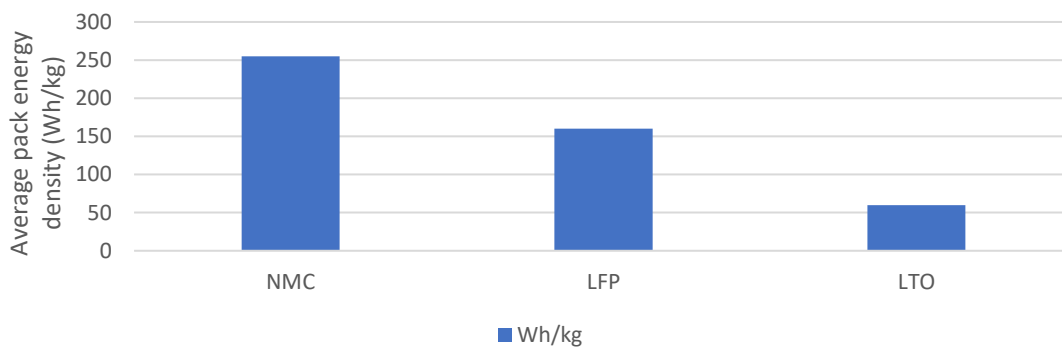


Figure 3: Average energy density of different passenger EV battery pack chemistries in Watt-hours per kg (from BNEF Long-Term Electric Vehicle Outlook 2023 and [BU-205: Types of Lithium-ion - Battery University](#)). NMC chemistry here is NMC 811.

<sup>30</sup> Quan et al., January 2022, Comparative life cycle assessment of LFP and NCM batteries including the secondary use and different recycling technologies.

<https://www.sciencedirect.com/science/article/abs/pii/S0048969722001954>

<sup>31</sup> Kumar et al., December 2021, Recent progress in sustainable recycling of LiFePO<sub>4</sub>-type lithium-ion batteries: Strategies for highly selective lithium recovery.

<https://www.sciencedirect.com/science/article/abs/pii/S1385894721055662>

<sup>32</sup> Velazquez et al., December 2019, A critical review of lithium-ion battery recycling process from a circular economy perspective.

[https://www.researchgate.net/publication/337063279\\_A\\_Critical\\_Review\\_of\\_Lithium-Ion\\_Battery\\_Recycling\\_Processes\\_from\\_a\\_Circular\\_Economy\\_Perspective](https://www.researchgate.net/publication/337063279_A_Critical_Review_of_Lithium-Ion_Battery_Recycling_Processes_from_a_Circular_Economy_Perspective)

<sup>33</sup> Wu et al., March 2022, Lithium-ion batteries. <https://doi.org/10.1016/B978-0-12-819723-3.00102-5>

Across NMC, LFP, and LTO battery chemistries, LFP batteries offer promising energy density, cycle life, and thermal stability at a low price point.

Globally, LFP is the most popular battery chemistry for electric buses, however, this is strongly influenced by electric bus sales in China as ~80% of electric buses are currently sold in China.<sup>34</sup> In Europe currently, just over half of new available electric bus models use NMC batteries, while around a third use LFP (Figure 4).<sup>25,35</sup> Note that this research is based on publicly advertised models in Europe, but some manufacturers can be flexible with battery specifications based on customer requirements.

Manufacturers that advertise the use of NMC batteries include Irizar, MAN, Mercedes, Solaris and Wright. Manufacturers that advertise the use of LFP batteries include BYD and Ebusco. Some manufacturers, like Yutong, offer both types; for example, the Yutong E12 uses NMC, while the Yutong U12 uses LFP. LTO batteries are much less common and are typically used in specialized applications where the bus requires frequent charging and discharging. For example, Irizar offer an LTO battery for their e-bus model used in Barcelona.<sup>36</sup>

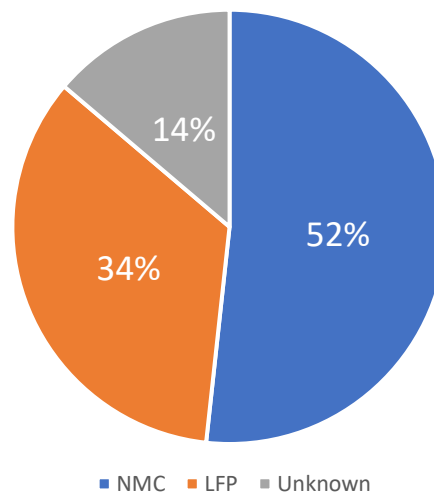


Figure 4: Proportion of newly available electric bus models in Europe that use NMC, LFP or do not state the battery chemistry ("Unknown"). Data from ERM research. Total number of models included = 58.

### Battery costs

Battery packs are made up of battery cells, which are the energy storage component, alongside other components including electronics and packaging. Modern BEBs typically carry 3-6 battery packs, and battery cells usually account for 50-70% of the cost of each battery pack. Cell production costs are a key driver of the price of a battery pack, alongside demand levels and pack design/manufacture.

<sup>34</sup> BNEF Long-Term Electric Vehicle Outlook 2023.

<sup>35</sup> ERM research.

<sup>36</sup> <https://irizar-emobility.com/en/events-and-latest-news/news/tmb-purchases-another-29-irizar-e-mobility-zero-emission-electric-buses-for-the-city-of-barcelona>

Average cell production costs in 2023 in China were \$80/kWh for NMC cells and \$65/kWh for LFP cells.<sup>37</sup> Cell production costs outside of China are higher than this (with the cost of manufacturing NMC cells in the USA ~80% higher than in China), although costs in China can be indicative of future cost reductions elsewhere in the world. Volta projections suggest that cell production costs in China will decrease to below \$65/kWh for NMC and below \$55/kWh for LFP by 2028.<sup>37</sup>

The cost of cell and pack production directly influences the price of battery packs. The price of lithium-ion battery packs has fallen over time, and prices are expected to fall with improved production costs and the adoption of lower cost technologies, such as LFP. The battery pack price for a BEB is expected to fall to \$120/kWh by 2035.<sup>38</sup>

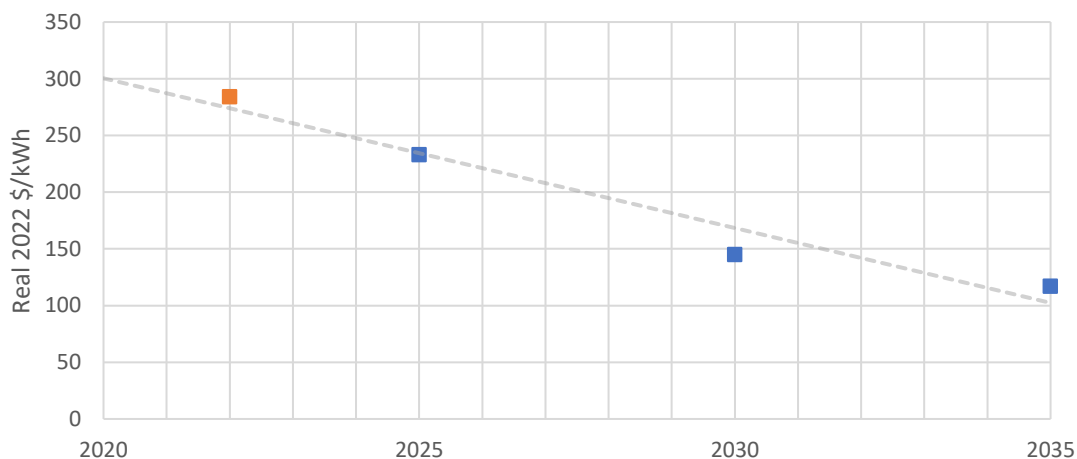


Figure 5: Projected electric bus battery pack costs (excl. China). 2022 cost is real data, 2025 onwards is projected data. (ERM modelling based on BNEF Long-term Electric Vehicle Outlook).

### Future battery technologies

Novel battery technologies are emerging, but most are not yet in the commercial stage. For example, a solid-state battery uses a solid electrolyte instead of liquid or gel polymer electrolytes used in conventional lithium-ion batteries. Solid-state battery research is ongoing, but no dominant electrolyte material has emerged yet. While solid-state batteries offer the potential for higher energy density, they face several challenges, including metallic dendrite formation that can lead to short circuits, poor performance at low temperatures, and limited cycle life. Additionally, solid-state batteries will remain subject to fluctuations in lithium prices, which may make them expensive once they reach commercialization. Consequently, solid-state batteries may only be applicable to niche markets when they become commercially available, although it is not yet clear what these markets will be.

There is also innovation in lithium-ion batteries based on liquid electrolyte. Some projections show that manganese-rich cathode chemistries (such as lithium nickel manganese oxide (LNMO) and lithium manganese iron phosphate (LMFP)) are more likely than solid-state batteries to increase in popularity in the electric bus market (Figure 6). These chemistries have high energy density due to the addition of

<sup>37</sup> Volta Foundation, Battery report 2023. <https://volta.foundation/battery-report>

<sup>38</sup> ERM research based on BNEF Long-Term Electric Vehicle Outlook 2023.

manganese and do not contain cobalt so have a lower environmental impact, although they are still in the research and development stages of innovation.

Despite the development of alternative technologies, LFP is projected by Bloomberg New Energy Finance to increasingly dominate the global battery chemistry mix for electric buses, and NMC will decrease in popularity, although will still remain an important chemistry into the 2030s (Figure 6). LNMO (lithium nickel manganese oxide) is projected to gain traction from 2030 onwards. As discussed above, although these projections are predominantly influenced by electric bus trends in China, this remains an important projection of global trends as Chinese battery manufacturing is likely to remain dominant.<sup>39</sup> China currently has the largest battery production capacity, allowing costs for Chinese batteries to remain significantly below European production costs.<sup>39</sup> These low costs will allow China to remain the leader in battery production, despite regulatory restrictions on imports in Europe.<sup>40,41</sup> Therefore, the future trends of bus batteries in China remain relevant for the future global trends.

Additionally, to ensure economic viability of BEB business models, European BEB manufacturers are likely to prioritise reducing battery pack costs rather than adopting higher cost or niche battery pack designs/chemistries.

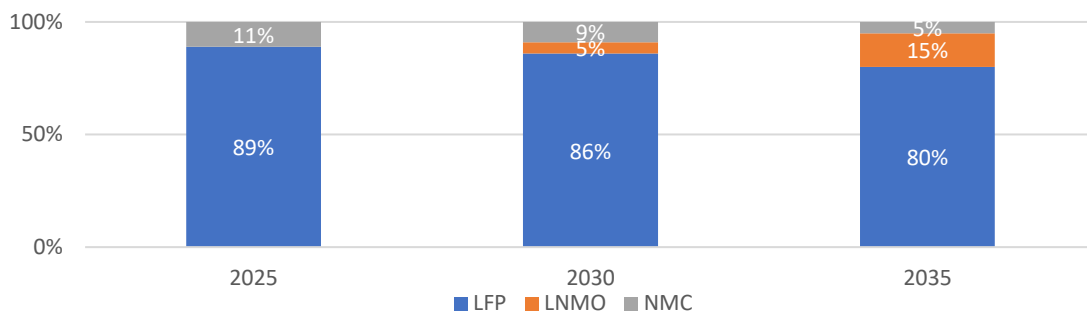


Figure 6: Evolution of electric bus battery chemistries globally, by number of buses sold that use each chemistry (from BNEF Long-Term Electric Vehicle Outlook 2023). Note that ~80% of electric buses are currently sold in China (BNEF), thus this graph is most representative of China battery chemistries.

### Battery degradation and residual value at end-of-life

#### Battery degradation

The total energy that can be provided by a battery is referred to as its energy capacity, measured in kWh. The charging and discharging of the battery is often referred to as the cycling of the battery, and the battery’s energy throughput can be measured in full cycle equivalents (FCEs).

<sup>39</sup> IEA, April 2024, Batteries and Secure Energy Transitions. <https://www.iea.org/reports/batteries-and-secure-energy-transitions>

<sup>40</sup> EU Commission, October 2024, EU imposes duties on unfairly subsidised electric vehicles from China while discussions on price undertakings continue. [https://ec.europa.eu/commission/presscorner/detail/en/ip\\_24\\_5589](https://ec.europa.eu/commission/presscorner/detail/en/ip_24_5589)

<sup>41</sup> Transport & Environment, October 2024, Trade defence: Where’s next for the EU’s EV and battery trade policy <https://www.transportenvironment.org/articles/batteries-the-next-frontier-in-trade-defence>

Lithium-ion batteries degrade over time and use, leading to a reduction in the battery's usable energy capacity. This is measured as the battery's state of health (SOH), as defined below.

$$\text{State of Health (\%)} = \text{Current usable capacity (kWh)} / \text{Initial usable capacity (kWh)}$$

Lithium-ion batteries' capacities degrade from both:

1. Cycling degradation: battery capacity diminishes when cycled, and therefore degradation increases with more use.
2. Calendar degradation: battery capacity fades over time even if not used, as the battery ages.

There is a complex interplay between cycling and calendar degradation, impacted by operating conditions including temperature management, charge and discharge rates, depth of discharge, and state of charge during storage. The degradation rate is also determined by the battery chemistry. Batteries with NMC chemistries typically see higher degradation than batteries with LFP chemistries. LTO batteries observe the longest cycle life of the three chemistries considered.

Lithium-ion battery degradation is typically non-linear, with degradation most impactful in the first year of operation before plateauing at a lower degradation rate. This is largely due to high calendar degradation in early years of operation, while cycling degradation remains more consistent over the battery lifetime,<sup>42</sup> as shown in Figure 7 and Figure 8. Additionally, towards the end of the EV battery's life the battery may see a steep increase in degradation rate.<sup>43,44</sup> This is often referred to as the capacity knee.

Vehicle OEMs use battery management systems (BMS) to carefully control the operation of their batteries to minimise degradation. OEMs may additionally under specify the initial total capacity of batteries in their EVs so that the initial degradation of the battery is not apparent in the range observed by drivers. Several of the operators interviewed as part of this project stated that it was difficult to know the true extent of degradation because only limited data, typically overall State of Health, is available to an operator's own staff. This in turn helps explain why there is little published data on bus battery degradation over time – in the early years many operators can see none, and many European BEB fleets are still very young.

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<sup>42</sup> Thingvad et al. (DTU – Technical University of Denmark), *Empirical Capacity Measurements of Electric Vehicles Subject to Battery Degradation From V2G Services* (2021)

<sup>43</sup> [Geotab](#)

<sup>44</sup> Zhang et al. (Chalmers University of Technology and Volvo), *Battery capacity knee-onset identification and early prediction using degradation curvature* (2024)

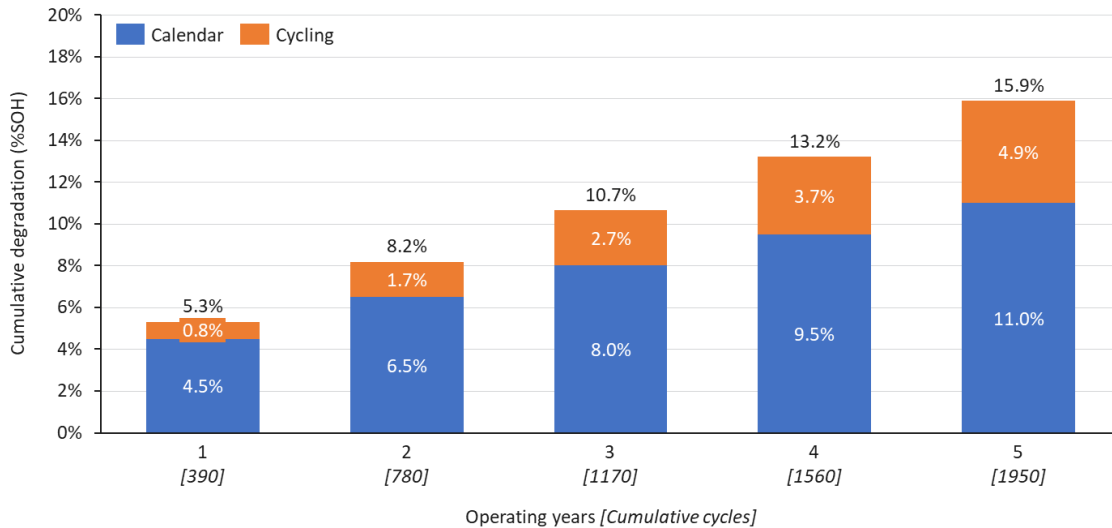


Figure 7: Semi-empirically modelled total battery degradation, split by cycling and calendar degradation<sup>42</sup>. Note: assumes ca. 390 cycles per year (1.07 cycles per day, ca. 130 km/day assuming electricity consumption of 0.2 kWh/km and battery size 23 kWh) and NMC battery chemistry.

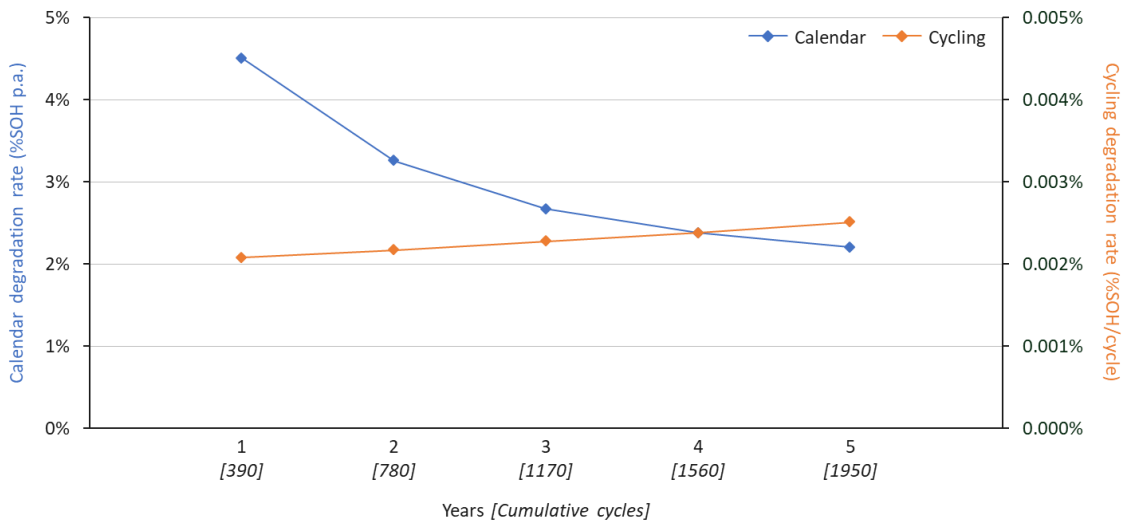


Figure 8: Semi-empirically modelled calendar degradation rate (%SOH p.a.) and cycling degradation rate (%SOH/cycle) over 5 years operation of an EV battery<sup>42</sup>. Note: cycling & calendar degradation additive, assumes ca. 390 cycles per year (1.07 cycles per day, ca. 130 km/day assuming electricity consumption of 0.2 kWh/km and battery size 23 kWh) and NMC battery chemistry.

### Battery electric bus case studies

There is currently limited real-world data on the battery degradation observed for battery electric buses (BEBs), however, real-world data from battery electric cars have shown significantly lower degradation than expected. For example, Geotab have observed an annual degradation of ca. 1.8% SOH per annum from their fleet, however, their sample fleet is assumed to be largely made up of light duty vehicles, with different scale and intensities of use than buses (i.e. assumed ca. 45 battery full cycle equivalents (FCEs) per annum).<sup>45</sup>

As a central purchaser for public mobility in France, Centrale d’Achat du Transport Public (CATP) expects to typically observe a ca. 22 – 25% battery capacity degradation

<sup>45</sup> [Geotab](#) – fleet assumed to be made up largely of cars, approximate annual cycles calculated assuming mileage of 15,000 km p.a., 59.6 kWh usable battery capacity, and 0.17 kWh/km electricity consumption

after 9 years of operation.<sup>46</sup> CATP suggest that bus operators could plan to replace their batteries after 9 years of operation, noting that battery lifetimes are improving and this has increased from a previous recommendation of 7.5 years. However, they also highlight that if operators are willing to operate with a reduced range, BEBs could survive for 15 years without battery replacement. For example, operators could cascade older BEBs to routes or duty cycles with lower energy requirements to manage a vehicle’s full commercial life without replacing batteries.

Ruter, the public transport agency for Oslo, noted that local operators are now assuming just 20% battery degradation over 10 years. All agency/operator interviewees canvased (*Appendix: Interviewees*) agreed that actual battery degradation had been less than originally expected, with many abandoning planned mid-life battery replacements, and now presenting more optimistic business cases for new BEBs in contracts.

*Impact of charging strategies*

A study from WRI India<sup>47</sup> compares the battery degradation observed over one year for battery electric buses under different duty cycles, battery chemistries, and charging rates. The findings are summarised in Figure 9.

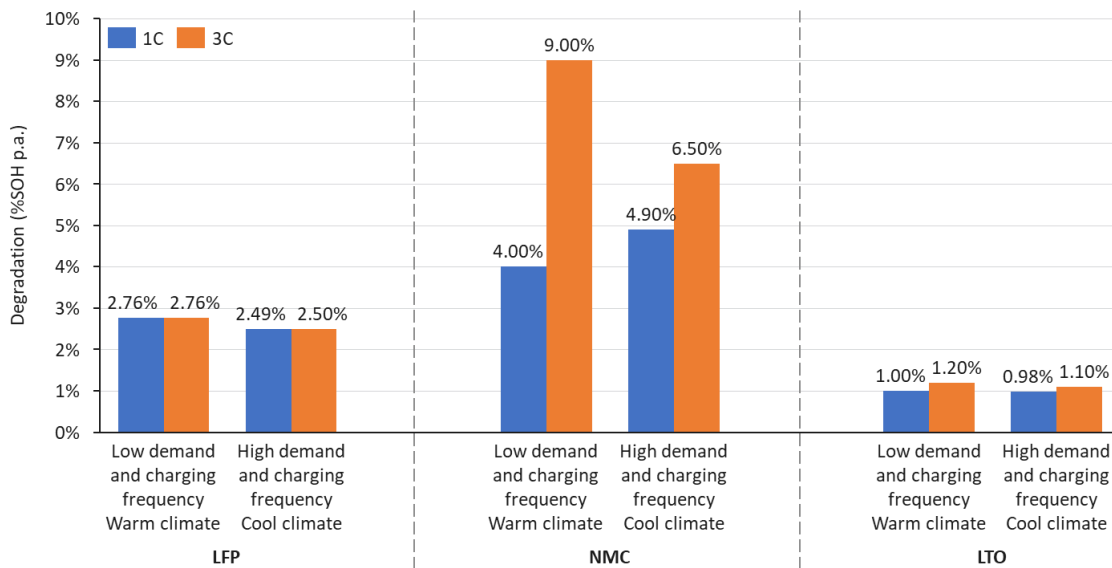


Figure 9: Comparison of the degradation over one year for an LFP, NMC and LTO BEB under different duty cycles (demand, charging frequency, and climate) and C-rates<sup>47</sup>

Battery charge and discharge rates can be measured by C-rates. A C-rate is the rate of charge or discharge of electric current relative to the battery’s maximum capacity. For example, a 1 Ah (Amp hour) battery can discharge 1A for an hour at a C-rate of 1C, 2A for 30 minutes at a C-rate of 2C, and 0.5A for 2 hours at a C-rate of 0.5C. The WRI India study<sup>47</sup> showed that NMC battery degradation is highly sensitive to high C-rates (rate

<sup>46</sup> Centrale d’Achat du Transport Public (CATP), [Transition énergétique : étude comparative sur les différentes motorisations des autobus – Edition 2024](#), June 2024;

<sup>47</sup> WRI India, [Real-world electric bus operation: Trend in technology, performance, degradation, and lifespan of batteries](#), January 2024; and Al-Saadi, M., J. Olmos, A. Saez-de-Ibarra, J.V. Mierlo, and M. Berecibar. 2022. [“Fast Charging Impact on the Lithium-Ion Batteries’ Lifetime and Cost-Effective Battery Sizing in Heavy-Duty Electric Vehicles Applications.”](#)

of charge or discharge). Fast charging may therefore reduce the lifespan of an NMC BEB compared to slow overnight charging. As shown in Figure 9, the degradation of LFP and LTO batteries is not as sensitive to C-rate. These battery chemistries, in particular LFP, are therefore likely to be able to support fast charging although with some decrease in lifespan.

Fast charging leads to increased battery degradation, largely because it generates significant heat.<sup>47</sup> Thermal management of the battery during both charging and discharging is important to minimise degradation. The two main types of battery thermal management system (BTMS) are air cooling and liquid cooling. Air cooling systems are typically lower cost and more easily maintained, however, liquid cooling systems have better heat transfer coefficients and more uniformed cooling distributions. Liquid cooling systems are therefore better suited for larger battery packs or EVs designed for high energy throughput.<sup>48</sup> There is significant innovation in BTMS to enable higher speed charging, such as the rumoured release of BYD's Gen 2 blade batteries in 2025 which would use a direct cooling system with a larger cooling area and better temperature uniformity to enable charging rates up to 8C.<sup>49,50</sup>

Interviewee TMB noted that inconsistent cooling across cells within a BEB battery pack can lead to inconsistent degradation across cells and reduced overall performance.

The permitted depth of discharge (DOD) is also an important aspect of a BEB's charging strategy, where DOD is the permitted range of battery state of charge (SOC). Typically, lithium-ion battery degradation can be optimised by restricting battery charging and discharging to a limited SOC window.<sup>47</sup> The WRI India study considered the degradation impact of frequently charging with a limited DOD, as shown in Figure 9. The introduction of more frequent charging led to lower annual degradation of LFP and LTO battery chemistries. This suggests they are well suited to more frequent, enroute charging.

Interviewee TMB additionally noted the importance of allowing time to regularly rebalance the cells within a BEB battery pack, by slow charging, to minimise degradation on vehicles that routinely opportunity charge. Opportunity charged buses can therefore not *continually* operate in service – every few days they require a period of extended downtime to charge at relatively low power. Cell balancing ensures that all cells in a battery pack have the same state of charge and voltage, which is important to avoid overcharging or overheating. Battery management systems (BMS) within the BEB battery pack should ensure cells are balanced.

#### Opportunities for batteries at end-of-life

In this section of the report, the first life of a BEB battery is considered as its use within the bus. The battery reaches end-of-life is when the capacity of the battery has degraded to a level no longer considered suitable for commercial bus duty cycles. As described above (see Battery degradation section), operators can choose to retire BEB batteries at a range of degradation levels depending on their priorities. Operators whose primary focus is on maintaining high range may replace BEB batteries after a

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<sup>48</sup> Hwang et al., Review of battery thermal management systems in electric vehicles, Renewable and Sustainable Energy Reviews, 2024.

<sup>49</sup> <https://www.sciencedirect.com/science/article/pii/S1364032123010298?via%3Dihub>

<sup>49</sup> <https://kr-asia.com/catl-and-byd-lead-the-charge-in-developing-6c-batteries-for-evs>

<sup>50</sup> <https://www.electrive.com/2024/12/09/first-details-of-byds-new-blade-battery-leaked/>

few years of operation, whereas operators who are looking to extract maximum value from the battery and can move buses to less energy intensive routes, may run the battery for longer to a lower SOH.<sup>46</sup>

Battery life represents a poorly understood risk for most bus operators. Many have sought to transfer that risk to third parties – financiers<sup>51</sup> or battery and bus OEMs via warranties. OEMs have responded with increasingly long battery warranty periods. CATL's (the largest battery manufacturer in the world) latest 15-year warrantied bus battery now matches the typical commercial lifespan of many local buses.<sup>52</sup> Likewise, Alexander Dennis has outlined how its latest generation of BEB will be able to cover two consecutive seven-year contract terms on typical Transport for London routes without a battery change.<sup>53</sup> As battery technology matures and more bus operators start to understand the true risks, larger bus operators are more likely to carry those risks themselves. It is therefore useful to understand potential strategies for doing so.

### *Second-hand BEBs*

In Britain, Internal Combustion Engine (ICE) buses typically move between 3 or 4 different operations over their lives.<sup>54</sup> In contrast, the UITP found that across European city buses, only 10-20% of vehicles find a second life, with most scrapped by the operator that first deployed them.<sup>55</sup> In largely deregulated Britain, vehicle moves have historically been driven by a commercial imperative to maximise the financial earnings of newer vehicles. Elsewhere in Europe, vehicle moves tend to reflect differing acceptance of vehicle emission standards, with countries to the north and west favouring the latest EURO standards. Neither of these patterns will necessarily transfer directly onto BEBs, which are less generic than ICE buses: BEBs are range-defined, while battery state adds risk, especially once the battery's warranty has expired.

In Europe, there is currently a very limited market for second-hand BEBs compared to their diesel equivalents. This is a contrast to the situation in China, which has a considerable second-hand BEB market due to the large volumes of buses and the high market share of electric buses in the country.<sup>56</sup>

While the second-hand BEB market in Europe is complex, UITP conclude in their study on second-hand city buses in Europe that bus operators seek greater standardisation of the main e-bus components (battery, drivetrain, and charging components) to ensure smooth pathways for selling used BEBs within Europe. This is particularly important to ensure countries with lower BEB penetration can access spare parts, charging equipment, and maintenance expertise, as these markets are likely to be the key buyers of second-hand BEBs in the near term.<sup>55</sup>

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<sup>51</sup> Notably First Group's use of Hitachi Zero Carbon to finance 1000 BEB batteries - <https://www.hitachi.com/New/cnews/month/2023/11/231117.html>

<sup>52</sup> <https://cnevpost.com/2024/09/14/catl-launches-battery-electric-buses/>

<sup>53</sup> <https://www.alexander-dennis.com/alexander-dennis-unveils-next-generation-electric-buses/>

<sup>54</sup> Element Energy (ERM) for ClimateXChange (CXC), December 2022, The impact of electric buses on the Scottish second-hand bus market. <https://www.climateexchange.org.uk/projects/the-impact-of-electric-buses-on-the-scottish-second-hand-bus-market/>

<sup>55</sup> UITP, May 2021, A study on the second-hand city bus market in Europe.

<https://www.uitp.org/publications/a-study-on-the-secondhand-city-bus-market-in-europe/>

<sup>56</sup> <https://www.iea.org/data-and-statistics/charts/electric-bus-registrations-and-sales-share-by-region-2015-2023>

Further, companies such as Zenobe are prioritising the uniform degradation of their BEB fleets' batteries.<sup>57</sup> This can be achieved through several mechanisms, such as closely controlling depth of discharge and minimising the energy throughput of the battery, as discussed in the *Battery degradation* section. Equally, buses can be allocated to routes according to their state of health, meaning that instead of running the same routes every day, routes are varied such that each bus in the fleet covers the same number of miles in a year. Zenobe's modelling found that this approach could extend the bus battery's life by up to 3 years.<sup>57</sup> This approach means that buses on this regimen hold greater value because they have a lower and more consistent level of degradation across a fleet, which is a more attractive proposition for second-hand bus buyers than the alternative.

The counterpoint to any strategy that primarily seeks to proactively manage residual value is calendar degradation: It may be argued that the inevitable degradation of batteries over time implies operators should primarily focus on fully utilising newer BEBs.

#### *Second-life batteries from BEBs*

When BEB traction batteries are deemed to be unsuitable for their original application, they can be repurposed for second life. This can be at a range of states of degradation and ages, depending on the priorities of the operators. At this point, they may be repurposed for second life as stationary battery energy storage systems (BESS). Repurposing is the process of removing the traction battery from a BEB and reassembling the pack in a new casing as a BESS (other steps such as disassembly and testing of the cells may also be completed). This process can be costly depending on the level of remanufacturing that a repurposer completes. The specific target markets can include:

- Grid-scale storage: large-scale energy storage (i.e. hundreds of MWh) which can participate in grid flexibility services (e.g. energy arbitrage: charging the BESS when electricity is cheap and discharging back to the grid when electricity is expensive, generating revenue).
- Data centre backups: back-up power for data centres to avoid data losses in the event of a power cut.
- Construction sites/off-grid electricity provision: electricity provision for off-grid sites, such as charging for electric machinery at construction sites.

A range of market prices are cited for repurposed second-life batteries, depending on the specific use case and context. However, the cost of second-life battery capacity is expected to be less than that of equivalent new batteries. Further, the market price may be influenced by the age and state of health of the battery cells as well as the approach of the individual repurposer. A 2023 report by the ICCT on battery end-of-life provides a range of ca. \$20-\$300/kWh at the time of publishing.<sup>58</sup> Estimates from NREL for the sale value of new lithium-ion batteries today are on the upper end of this

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<sup>57</sup> <https://www.zenobe.com/insights-and-guides/electric-bus-battery-degradation-what-causes-battery-degradation-and-how-to-manage-it/>

<sup>58</sup> ICCT, February 2023, Scaling up reuse and recycling of electric vehicle batteries: assessing challenges and policy approaches. <https://theicct.org/wp-content/uploads/2023/02/recycling-electric-vehicle-batteries-feb-23.pdf>

estimate (ca. \$300/kWh),<sup>59</sup> although the loss of value due to the used condition of the battery has been estimated as 50% or more.<sup>60</sup> Given that the purchase price of batteries is predicted to drop by more than 20% by 2035 and almost 40% by 2050,<sup>61</sup> the opportunity for generating revenue from second-life batteries is likely to be limited, if not zero, in the long-term. Recycling, discussed below, may be a more likely outcome for end-of-life batteries from buses.

### *Battery recycling*

In addition to repurposing for second life, BEB owners could consider recycling of batteries at the end of their useful life – either following the end of their first life in the BEB or at the end of a second life.

Europe's lithium-ion battery recycling industry is expected to scale-up significantly to manage the growing volume of end-of-life batteries and to reduce import dependencies for raw materials. In addition to improving the economic viability of lithium-ion battery recycling, the expansion is driven by the EU Battery Regulation which includes collection and recycling obligations, as well as minimum recycled content of new batteries.<sup>62</sup>

The value of battery recycling is highly dependent on the chemistry of the batteries being recycled, as the revenues are determined by the value of the raw materials recovered. The value is also impacted by the scale of the facility, the technology used, and the location of recycling which determines the cost of electricity and labour. Due to the value of the recovered materials, BEB OEMs may expect to be paid by recyclers for NMC battery packs but may have to pay recyclers to take LFP battery packs. For example, hydrometallurgical recycling of an NMC battery pack at end-of-life is expected to generate a net revenue of ca. \$4.2 per kg while an LFP battery is expected to have a net revenue of -\$0.1 per kg, as illustrated in Figure 10.<sup>63</sup>

It remains unclear how the value will flow between the BEB OEM, owner and recycling facility. To comply with the EU Battery Regulation's Extended Producer Responsibility requirements, OEMs will likely form relationships with recycling facilities, such as Nova Bus' recently announced collaboration with Canadian battery recycler Lithion Technologies.<sup>64</sup>

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<sup>59</sup> [https://atb.nrel.gov/electricity/2023/commercial\\_battery\\_storage](https://atb.nrel.gov/electricity/2023/commercial_battery_storage)

<sup>60</sup> Kampker et al., April 2023, Cost-benefit analysis of downstream applications for retired electric vehicle batteries. <https://www.mdpi.com/2032-6653/14/4/110>

<sup>61</sup> <https://atb.nrel.gov/electricity/2023/data>

<sup>62</sup> EU Battery Regulation: Regulation (EU) 2023/1542 of the European Parliament and of the Council of 12 July 2023 concerning batteries and waste batteries, amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and repealing Directive 2006/66/EC. <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32023R1542>

<sup>63</sup> ERM modelling using Argonne National Laboratory's EverBatt 2023. Revenues and costs calculated considering a hydrometallurgical recycling facility in the USA with a throughput capacity of 10,000 tonnes p.a. of end-of-life battery packs.

<sup>64</sup> <https://www.lithiontechnologies.com/en/news/nova-bus-partners-with-lithion-technologies-to-strengthen-the-sustainable-electri/>

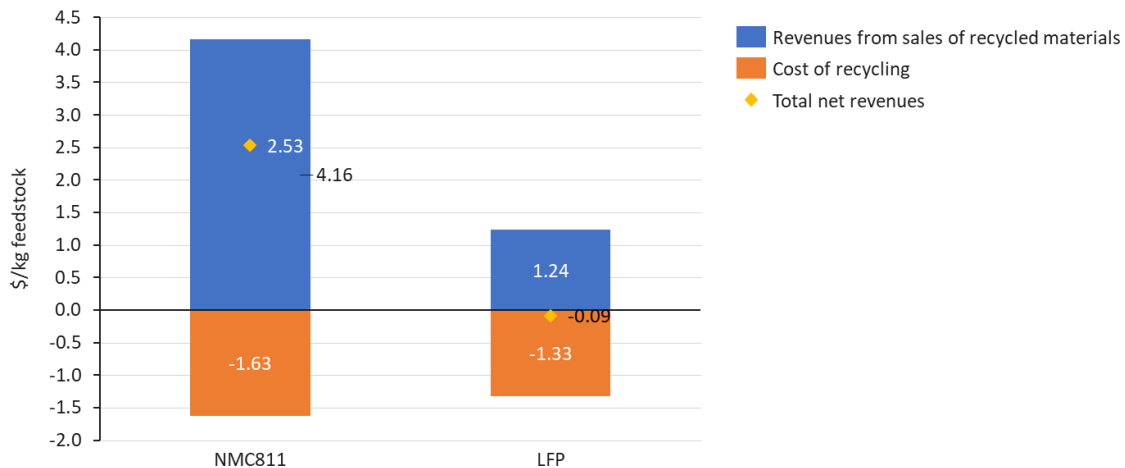


Figure 10: Cost of recycling and revenues from sales of recycled materials per unit of end-of-life battery pack feedstock (\$/kg) for NMC811 and LFP battery chemistries, calculated for hydrometallurgical recycling facility with annual throughput of 10,000 tonnes per year in the USA (EverBatt, 2023)<sup>63</sup>

### Summary of key findings

Lithium-ion batteries with nickel manganese cobalt (NMC), lithium iron phosphate (LFP), and lithium titanium oxide (LTO) chemistries are commonly considered for battery electric bus (BEB) applications. When selecting the most suitable battery chemistry, BEB operators should consider duty cycle, battery pack weight and size requirements, potential charging strategies, and costs.

- While NMC batteries have high energy densities allowing small and lightweight battery packs, they experience higher degradation than LFP and LTO chemistries, with cycle life particularly sensitive to fast charging rates such as during opportunity or enroute charging.
- LTO batteries have the highest cycle life across the three chemistries, and their thermal stability and ability to withstand high charging rates with low degradation impacts make them suitable for frequent opportunity charging and rapid charging. However, their low energy density and high cost means that LTO battery packs can likely only be paired with opportunity charging and not traditional charging.
- Overall, LFP batteries offer promising energy density, cycle life, and thermal stability, at a low price point. Additionally, LFP batteries currently dominate BEB batteries at a global level, largely influenced by the Chinese BEB market. Due to the lower costs of LFP battery chemistries and the dominance of Chinese battery manufacturing, LFP batteries are expected to become increasingly prominent in the European BEB market, although NMC battery chemistries will remain widespread.

Batteries degrade with use and with time (even if not being cycled).

- OEMs design battery packs with systems to restrict operating conditions and carefully manage cooling to minimise degradation. Battery thermal management systems are particularly important in enabling fast charging without excessive degradation.

- BEB operators can also minimise battery degradation through charging strategy design, for example by ensuring batteries are not regularly fully charged or discharged (from 0% to 100% state of charge), or by considering the frequency of rapid charging.
- Although there is limited real-world data on the battery degradation observed for BEBs, operators have noted that battery lifetime has been better than expected and assumptions set out in contracts or business case planning are becoming more optimistic.
- As battery capacities fade over the operating life of the BEB, the operator could consider a mid-life battery replacement (e.g. after 7 – 9 years) to maintain a high range capability. Alternatively, if operators are able to manage reduced range, batteries could be used over the full lifetime of the bus. For example, operators could cascade older BEBs with reduced range to routes or duty cycles with lower energy requirements.

When batteries are deemed no longer suitable for use in BEBs, owners may be able to access some residual value through a second-life application or battery recycling.

- BEB batteries can be repurposed for second-life as stationary storage systems. However, battery repurposing may be costly, and it is unclear if the sale of second-life battery systems will remain an economically viable business model in the future.
- Alternatively, batteries can be recycled in order to recover valuable critical materials. As NMC batteries contain higher value materials, recycling of this chemistry is expected to generate more significant revenues than LFP. Recyclers are expected to purchase end-of-life NMC batteries but may have to be paid to recycle LFP batteries. However, this is highly dependent on the price of critical materials, and if the value of lithium and/or recycled materials increases, recycling of all battery chemistries may become more valuable in the future.
- Given the expected shift of BEB chemistries towards LFP, and the poor market prospects for non-bus battery second life, it is pragmatic to assume future BEB batteries will have no residual value once their life in commercial bus work is over. While there is a potential upside, especially for NMC batteries, there is a risk that residual value could be negative, as recycling cost could exceed revenue from recycled materials.

## Use of extra BEBs

### Context

Additional BEBs, which in part charge during the day using depot infrastructure, may be swapped in and out of service to maintain existing schedules. This approach is akin to that originally modelled as “manageable” but acknowledges that more BEBs will be required to operate the route than prior diesel buses, and thus the overall costs of operating the route will significantly increase. Operators will not *just* have to acquire and house more buses, but the extra “dead mileage” (to and from depot) will add to route operating costs, not least as driver time.

The acquisition and deployment of extra BEBs tended to be seen by most of our operator/agency interviewees as the most intuitive response to hard-to-decarbonise routes. While the solution adds day-to-day managerial complexity, these extra complexities are of the type that is already familiar to bus operators and can typically occur within established operating norms. The underlying process of crewing and charging an extra BEB at depot is the same – the use of extra BEBs to solve hard-to-decarbonise routes merely implies more of that activity. This was commonly expressed by interviewees through words such as “control” and “trust”.

For example, in Oslo, there had been a clear shift from opportunity charging to depot charging for urban routes. The agency, Ruter, continue to support opportunity charging solutions within its route contracting process, so this shift clearly reflects operator preference. As Ruter begin to contract (higher energy) interurban routes as BEB, both opportunity charging and plug-charger solutions are once again being considered, and operator preferences will once again be tested.

As discussed in the introduction to Alternatives to FCEBs, optimal extra BEB strategies require operators to exhibit flexibility in their internal processes, to be able to switch BEBs between passenger service and depot charging. In addition, this switching will be much more challenging where that depot is distant from the route. As outlined below, our modelling of this option assumes flexibility that may not exist in practice. Likewise, some operators may be able to manage extra BEBs across multiple routes, and in doing so deliver services with fewer extra vehicles. Advanced strategies may, for example, consider merging peak-only routes (such as school contracts) into core frequent services, something our original modelling only assumed between geographically local groups of infrequent routes.

### BEB depot charging

Unlike light duty electric vehicles, local bus fleets do not utilise public charging. In most cases electric local bus vehicles charge at mid-power overnight at their home depot.

There are some exceptions where BEBs charge at “out-stations” (typically reserved parking) at or close to a remote route terminus.<sup>65</sup> Some operators see a shift away from traditional large depot sites as an advantage possible with electrification:

- The lower maintenance requirements of BEBs (which have fewer mechanical parts than diesel buses) should make out-stationing strategies more viable because BEBs are less likely to need the support of maintenance technicians.
- Charging devices are feasible to install in small numbers (in comparison to traditional depot diesel tanks and related fuelling infrastructure) and multiple sites allow grid connections to be more evenly distributed.
- More local depots tend to make staff recruitment and retention easier by reducing commuting time.

However, many of our operator interviewees voiced concern over any move away from traditional depot-centric operations, citing the increased difficulty in managing staff and security, and the overall lack of redundancy at out-station locations.

Local bus fleets tend to be assigned one overnight charger per bus as the simplest strategy to deploy sufficient charging infrastructure: one charger per bus greatly simplifies depot parking operations, even if 10-15% of the fleet do not enter service on a typical day. Our modelling assumes one overnight charger exists per in-service bus. An “extra BEB” strategy thus requires both additional overnight parking space and an additional charger.

Many bus depots, especially traditional urban sites, have limited space, thus are increasingly focused on charger implementations that minimise the parking space lost. The ad-hoc ground installation of a charger for each bus typically loses about a quarter of prior depot space (based on discussion with British bus operating groups). In contrast, overhead gantries with reel/pulley cables (illustrated in the “First Bus depot charging” case study box) or pantograph charging (see the *Pantograph charging* section) lose only about 10% of prior space. Adding further vehicles to the fleet will only exacerbate these local space challenges.

An entirely newly built electric depot has been a solution pursued by several major European bus operators, including one of our interviewees, Wiener Linien: In addition to providing extra space for their overall fleet, this approach allowed the depot design to be optimised for electrification, for example by inclusion of a roof to support pantograph charging and solar panels, with use elsewhere in the depot of waste heat from charging. However, most operators expect to convert existing sites. For example, Atlas Public Policy interviewed U.S. bus fleets that have started to electrify their vehicles, and found only six out of fourteen interviewees “expect[ed] to construct a new electric-ready depot as part of their transition”.<sup>66</sup>

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<sup>65</sup> For example, corporate contractor Passenger Plus over-night charges BEBs at a route termini -

<https://www.route-one.net/features/passenger-plus-a-guide-to-running-evs-on-a-corporate-contract/>

<sup>66</sup> <https://atlaspolicy.com/wp-content/uploads/2022/05/Deploying-Charging-Infrastructure-for-Electric-Transit-Buses.pdf>

### Case study: First Bus depot charging

Britain's First Bus aims to achieve a zero-emission bus fleet by 2035. By the start of 2025, First Bus operated over 600 BEBs across 10 depots, including some of Britain's first entirely electric bus depot conversions.

First Bus's electric charging infrastructure is diverse but is evolving to minimize the space lost to park buses, notably using overhead gantries (illustrated below) to reduce the depot space lost from electrification to about 10%. Use of modularisation (satellite chargers) is also common, again to maximise space for vehicles.

Charger power broadly matches that required to recharge BEBs overnight at the lowest price periods, typically after 23:00, with powers in the range 60-180 kW. First currently charge BEBs only in depot and only use plug connections.



Figure 11: Overhead charging gantries at First Bus's depot in Leicester.

Source: First Bus (compilation of conference and trade press material)

Depot charger power is typically between 100 and 150 kW, although some operators reported using chargers between 50 kW and 200 kW. Increasingly chargers are optimised, both in power and by management software, so that BEBs recharge in the 4-6 hour overnight period when few services operate, and electricity prices are generally cheapest. Additional daytime charging, which may be required as part of any "extra BEB" or "manageable" route operating strategy, may be assumed to use the same charger, but at a higher electricity cost, as most bus depots support only their own fleets.<sup>67</sup> Where vehicle downtime is more limited, slightly faster changers may be added to the mix of powers within the depot.

The cost per charger depends on the power, brand, location of installation and whether grid upgrades are needed to cover the additional power that will be drawn. In

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<sup>67</sup> There is growing interest in opening up bus depot chargers, on a marginal basis, to support other commercial fleets, but overall daytime utilisation tends to remain low.

Europe, the typical cost of bus chargers per 100 kW is approximately €30,000 to €60,000, and per 300 kW charger the cost is approximately €90,000 to €120,000.<sup>68,69,70</sup> While basic chargers of this power may be cheaper per kW, equipment routinely used for buses benefits from very high efficiency (reflecting the high volume of electricity delivered over a bus charger’s life) and tend to use the best cooling systems, all of which adds to CAPEX.

### Modelling the number of extra buses required

The number of extra buses required has been estimated on an energy basis, minimising the number of buses required to provide the energy required (including dead mileage to/from depot) on the worst-case days. This has been estimated with the following formula:

$$\begin{aligned} \# \text{ buses required (rounded up)} \\ = \text{Current bus number} * \frac{\text{Worst case day energy usage (kWh)}}{\text{Bus usable battery capacity (kWh)}} \end{aligned}$$

The current bus number is the route’s Peak Vehicle Requirement, as modelled by our original schedule analysis.<sup>71</sup> The “Worst case day energy usage (kWh)” is the maximum energy consumption expected on the most demanding day, plus additional energy consumption from an additional trip to-and-from the depot. From analysis of the location of routes and depots in Britain, the out-of-service running to/from a depot adds on average 5% to the energy use of buses, though this can be as high as 15-20% for smaller operators with less ideal depot locations. Patterns elsewhere in Europe have not been analysed and may differ from the 5% assumed in our modelling, especially within localities.

### Modelling the cost of additional buses

The costs associated with additional buses can be broadly split into three categories: capital costs from more buses, additional operational costs, and increased land costs from depot expansions.

The additional capital costs are calculated by multiplying the equivalent annualised cost (EAC) of bus purchase, bus insurance and depot charging infrastructure by the % increase in buses required (shown below):

$$\begin{aligned} \text{Additional capital costs} \\ = \% \text{ increase in buses} * (\text{bus purchase} + \text{insurance} \\ + \text{depot charging infrastructure}) \end{aligned}$$

The additional operational costs are associated with the increase of bus operation due to the additional trip between the route and depot when swapping buses. This is

<sup>68</sup> <https://www.agir-transport.org/wp-content/uploads/2024/07/Etude-comparative-des-differentes-motorisations-de-bus-2024.pdf>

<sup>69</sup> <https://www.averre-france.org/wp-content/uploads/site/documents/1632231132a3a1871eb36d22aa1acb6519aa46d6c7-GuidebuslectriquesAverre-Francevdef.pdf>

<sup>70</sup> ERM charger internal database.

<sup>71</sup> The original modelling method is detailed in <https://fuelcellbuses.eu/public-transport-hydrogen/d336-potential-hydrogen-buses-europe-results-bulk-analysis-passenger>

calculated by multiplying the equivalent annual cost of driver salaries and electricity consumption by the % increase in bus operation time (average of 5% as described in “Number of extra buses required” above):

$$\begin{aligned} & \textit{Additional operational costs} \\ & = \% \textit{ increase in bus operation} * (\textit{driver salary} \\ & \quad + \textit{electricity fuel costs}) \end{aligned}$$

Land costs for additional depot space have been calculated as the land requirement for an additional bus (in sqm) multiplied by an average cost of land:

$$\begin{aligned} & \textit{Additional land costs} \\ & = \% \textit{ increase in buses} * \textit{required footprint per bus} * \textit{land cost} \end{aligned}$$

Any increase in maintenance costs have not been factored in, as whilst there will be more buses requiring maintenance, the annual mileage for each bus will be lower. The net impact of these competing factors is uncertain, so have not been included in this analysis.

As deploying extra buses reduces the annual mileage of each bus, for extremely high mileage services (above 100,000km/year), this can result in a longer lifetime being used in this scenario compared to the other BEB options or the diesel comparator, as buses reach the 15 year/1.5million km threshold later when the mileage is distributed between more buses. Since all TCO analysis performed has been converted to an equivalent annualised cost, it is still valid to compare the TCO of this option with other options with different lifetimes.

## Opportunity charging

### Context

For BEBs, opportunity charging refers to operations when a bus recharges at least part of its battery during small break times in the normal in-service operation of a bus route, especially at route termini. Opportunity charging is a proven technological solution for energy-limited BEBs that operate on routes with frequent headways, where many vehicles can share the same remote infrastructure as part of operating the route, keeping charger utilisation reasonably high, and in-service downtime reasonably low.

Our definition differentiates opportunity charging from *depot* charging, where charging of the BEB occurs overnight or while the vehicle is similarly parked during longer breaks. Such a clear distinction simplifies the analysis of approaches. However, in practice these two forms of charging can blur. Both with opportunity charging potentially occurring within depot sites, and rapid plug charging being deployed at bus termini to much the same effect as opportunity charging, merely with greater delay: Delay both due to time lost manually connecting a cable to the bus, and due to the lower powers currently supported by plug connections in comparison to pantographs.

In assessing the broad viability of opportunity charging to solve hard-to-decarbonise bus routes it has been necessary to start with a narrow definition: The use of a BEB with a full-size battery that tops-up the energy in that battery at least once per round (out and back) trip along the route from fixed pantograph opportunity charging equipment installed at a route terminus. However, there are several key variations to this approach, notable the use of much smaller batteries, different styles of pantograph, and the installation of additional chargers to provide operational redundancy. These variations are later sensitivity-tested, see TCO sensitivity analysis.

### Pantograph charging

Pantograph charging is a vehicle charging mechanism, similar to that originally conceived for trains and trams, that can be used to opportunity charge a BEB in a static location.<sup>72</sup> It involves an apparatus comprised of contact arms that extend to or from the vehicle and attach to electric charging systems to collect current, allowing the vehicle batteries to recharge, typically rapidly, at high power.<sup>73</sup> The technology allows very rapid charging at powers of up to 600 kW, allowing batteries to be topped-up during a 3-6 minute scheduled layover at a route terminus of a typical hour-duration urban bus route.<sup>74,75,76</sup> MegaWatt-capable opportunity chargers are expected once vehicles support such standards, keeping such chargers competitive with future plug-charging standards.<sup>77</sup>

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<sup>72</sup> <https://archive.org/details/streetrailwayjo241904newy/page/116/mode/2up?view=theater>

<sup>73</sup> <https://www.sciencedirect.com/topics/engineering/pantograph>

<sup>74</sup> <https://www.linkedin.com/pulse/pantograph-electric-buses-from-opportunity-charging-depot-daliah/>

<sup>75</sup> <https://www.vev.com/blog/opportunity-charging-for-ev-buses-pantograph-technology/>

<sup>76</sup> <https://global.abb/group/en/technology/did-you-know/pantograph-up-for-electric-bus>

<sup>77</sup> Ekoenergetyka report having developed such a technology but are awaiting compatible vehicles.

Charging normally occurs overhead (illustrated in the box below) but can occur horizontally or through the underbody of the vehicle.<sup>78</sup> Inverted pantographs refer to the case when the contact arms extend from the charging system to the vehicle instead.<sup>78</sup> See the *Technological factors and variations* section for more information on pantograph variations. Trolleybuses use a similar apparatus with a two-wire circuit and a slightly different design, using poles instead of arms, and maintain a connection in-motion (see the *Trolleybus* section for more information).

#### Case study: London route 358

Inverted pantograph charging was implemented on route 358 in London. The BEB operator (contractor Go-Ahead) remained responsible for delivering the infrastructure, as is normal practice when electrifying bus depots in London.

However, the agency, Transport for London, took ownership of this infrastructure and leased the land it occupies. The life of the charger exceeded the route contract, yet was inherently a part of the route, and thus the operator could not simply redeploy it elsewhere after a 7-year route contract period.

The case gives insight into the procedural complexities arising from the implementation of opportunity charging infrastructure, and how agencies and operators may need to rethink their traditional roles and responsibilities.



Figure 12: Pantograph charging of a BEB at Crystal Palace in London, UK.

Source: Transport for London

#### Technological factors and variations

Figure 13 presents the four main variations of pantograph technology for buses. Note the difference between the roof mounted pantograph with the pantograph arm extending from the bus, and the inverted pantograph with the arm extending from the charging system initiated by a wireless connection. Terminology may vary slightly by

<sup>78</sup> [https://cdn.vector.com/cms/content/know-how/technical-articles/Emobility\\_Pantograph\\_ElektronikAutomotive\\_202010\\_PressArticle\\_EN.pdf](https://cdn.vector.com/cms/content/know-how/technical-articles/Emobility_Pantograph_ElektronikAutomotive_202010_PressArticle_EN.pdf)

OEM, for example, Kempter describes its roof mounted pantograph technology as ‘Pantograph Up’ and its inverted pantograph technology as ‘Pantograph Down’.<sup>79</sup>

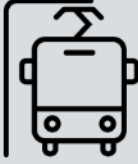



| Roofmounted Pantograph  | Inverted Pantograph   | Horizontal Pantograph  | Underbody Pantograph  |
|---|---|--|---|
|  |  |  |  |
| Control Pilot   | Wireless  | Control Pilot / Wireless   | Control Pilot / Wireless  |

Figure 13: Different pantograph configurations, with control method shown on the bottom row. Source: [https://cdn.vector.com/cms/content/know-how/technical-articles/Emobility\\_Pantograph\\_ElektronikAutomotive\\_202010\\_PressArticle\\_EN.pdf](https://cdn.vector.com/cms/content/know-how/technical-articles/Emobility_Pantograph_ElektronikAutomotive_202010_PressArticle_EN.pdf).

Roof-mounted and inverted pantographs have different advantages:<sup>80,81,82,83</sup>

- Benefits of roof-mounted “up” pantographs:
  - Simpler on-street charging infrastructure, thus fewer remote maintenance requirements and security risks. Any mechanical failure of the pantograph affects only one vehicle, not the whole bus route. The reduced risk of single mechanical failure preventing all services operating was cited by multiple interviewees as a reason for pantograph-up choices.
  - Pushing a button to start charging is straightforward for drivers. In contrast, the specific wireless communication system used by inverted pantographs can become complex to manage across many installations and vehicles.
- Benefits of inverted “down” pantographs:
  - Lower cost of installation per bus as fewer pantograph arms required for fleet charging overall, assuming more buses on the route than chargers, which is typical for routes best suited to opportunity charging (as shown later in the *Cost evaluation of main options for hard-to-decarbonise local bus routes* section).
  - There is greater standardisation of inverted pantograph technology, noted as an important consideration for a public contracting body such as Transport for London.
  - Lower height and weight of the charging system on the bus.

<sup>79</sup> <https://kempter.com/glossary/pantograph-charger/>

<sup>80</sup> <https://www.sciencedirect.com/topics/engineering/pantograph>

<sup>81</sup> [https://cdn.vector.com/cms/content/know-how/technical-articles/Emobility\\_Pantograph\\_ElektronikAutomotive\\_202010\\_PressArticle\\_EN.pdf](https://cdn.vector.com/cms/content/know-how/technical-articles/Emobility_Pantograph_ElektronikAutomotive_202010_PressArticle_EN.pdf)

<sup>82</sup> <https://kempter.com/glossary/pantograph-charger/>

<sup>83</sup> <https://www.chargesim.com/blog/pantograph-up-or-down>

Several established suppliers provide pantograph charging technologies for buses, including:

- ABB<sup>84</sup>
- Ekoenergytyka<sup>85</sup>
- Heliox (now part of Siemens)<sup>86</sup>
- Kempower<sup>87</sup>
- Luobinsen<sup>88</sup>
- Schunk<sup>89</sup>
- Siemens<sup>90</sup>
- Valmont Structures<sup>91</sup>
- Wabtech<sup>92</sup>

## Costs

Analysis of a sample of published data shows that the CAPEX, including installation, cost of pantograph-based opportunity charging solutions ranges significantly.<sup>93,94</sup> The sample predominantly includes inverted pantographs, which have slightly more complex structural components and communication systems than for roof-mounted pantograph charging systems, which contribute to higher cost per fixed site installation, although there is a small saving per vehicle.<sup>95</sup>

Figure 14 shows that while both enroute and depot charger costs rise with charger power, enroute pantograph chargers tend to cost about €250 thousand more than equivalent in-depot pantographs. This margin is indicative of the additional cost of installing an opportunity charger in a remote (enroute) location, vs an established (in-depot) location.

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<sup>84</sup> <https://new.abb.com/ev-charging>

<sup>85</sup> <https://ekoenergytyka.com/products/link-one/>

<sup>86</sup> <https://www.heliox-energy.com/case-studies/different-electric-buses-one-rapid-charging-system-by-heliox>

<sup>87</sup> <https://kempower.com/solution/kempower-pantograph-up/>

<sup>88</sup> <https://luobinsen-charger.com/products/pantograph-charger/>

<sup>89</sup> <https://www.schunk-group.com/transit-systems/en/applications/electric-buses/roof-mounted-pantograph-sls-102-&-sls-103~p6384>

<sup>90</sup> <https://www.siemens.com/global/en/products/energy/emobility/charging-pantograph.html>

<sup>91</sup> <https://www.valmontstructures.eu/products-solutions/mass-transit/electric-bus-charging>

<sup>92</sup> <https://www.wabteccorp.com/transit-bus/e-bus-charging/chargingpanto>

<sup>93</sup> <https://www.mdpi.com/1996-1073/15/17/6107>, [https://bcdcog.com/wp-content/uploads/2022/05/CARTA-Electric-Bus-Master-Plan\\_Final-Draft\\_5.25.22.pdf](https://bcdcog.com/wp-content/uploads/2022/05/CARTA-Electric-Bus-Master-Plan_Final-Draft_5.25.22.pdf), <https://www.potsdam.de/system/files/documents/2022-04-30-vip-elektrifizierungsstrategie.pdf>, <https://www.mdpi.com/1996-1073/14/14/4384>, <https://www.parlament-berlin.de/adosservice/19/Haupt/vorgang/h19-0387-v.pdf>, [https://www.communaute-paysbasque.fr/fileadmin/user\\_upload/mediatheque/Mobilites/A\\_telecharger/Informe\\_final\\_de\\_las\\_exp\\_enricencias\\_con\\_autobuses\\_100\\_electricos\\_en\\_Baiona\\_y\\_San\\_Sebastian.pdf](https://www.communaute-paysbasque.fr/fileadmin/user_upload/mediatheque/Mobilites/A_telecharger/Informe_final_de_las_exp_enricencias_con_autobuses_100_electricos_en_Baiona_y_San_Sebastian.pdf), [https://ww2.arb.ca.gov/sites/default/files/2020-09/C\\_Burns\\_McDonnell\\_Foothill%20Transit\\_ROP\\_ADA08182020.pdf](https://ww2.arb.ca.gov/sites/default/files/2020-09/C_Burns_McDonnell_Foothill%20Transit_ROP_ADA08182020.pdf), [https://bcdcog.com/wp-content/uploads/2022/05/CARTA\\_Electric-Bus-Master-Plan\\_Existing-Conditions\\_Final-Draft\\_5.25.22.pdf](https://bcdcog.com/wp-content/uploads/2022/05/CARTA_Electric-Bus-Master-Plan_Existing-Conditions_Final-Draft_5.25.22.pdf)

<sup>94</sup> For example, the in-depot charging and planning study for Foothill Transit states that “installation, commissioning, and other features vary by vendor” - [https://ww2.arb.ca.gov/sites/default/files/2020-09/C\\_Burns\\_McDonnell\\_Foothill%20Transit\\_ROP\\_ADA08182020.pdf](https://ww2.arb.ca.gov/sites/default/files/2020-09/C_Burns_McDonnell_Foothill%20Transit_ROP_ADA08182020.pdf)

<sup>95</sup> <https://www.chargesim.com/blog/pantograph-up-or-down>

When installing remote chargers in public areas, additional approvals and costs are required, such as land acquisition and higher maintenance costs. One of our interviewees in Germany cited how different noise regulations apply to diesel and battery system: A relatively noisy bus engine idle is less strictly regulated than a cooling fan in an opportunity charger at the same site.

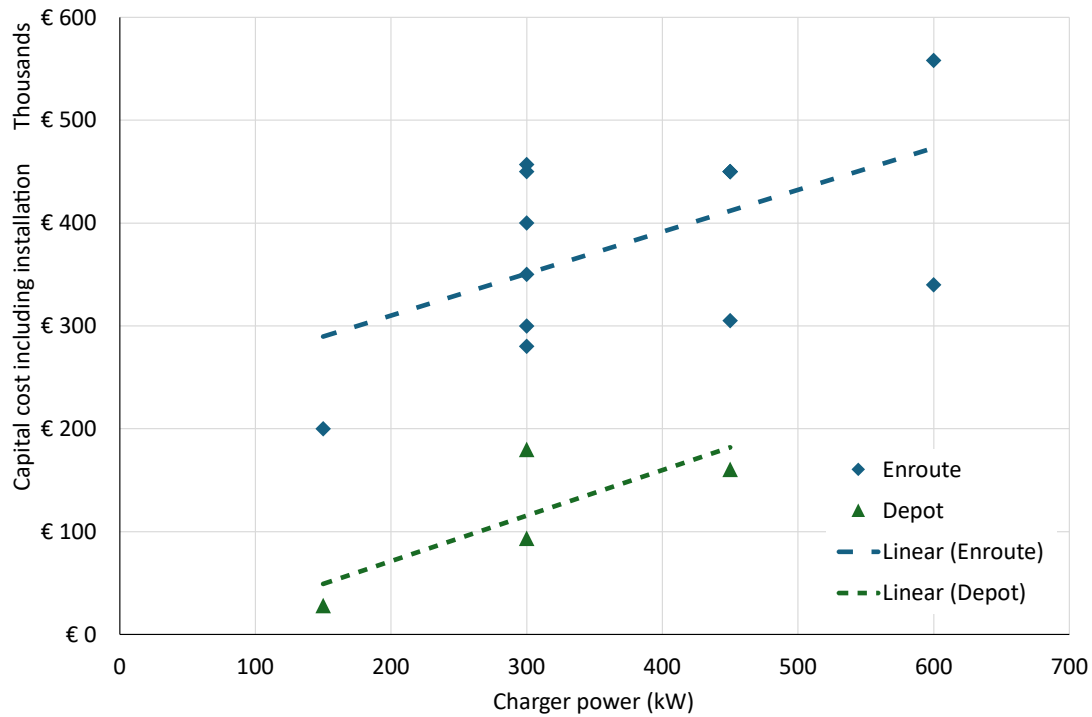


Figure 14: Sample CAPEX costs of pantograph charging systems, including installation

Processes vary across Europe, which make these costs hard to generalise: Our operator/agency interviewees revealed a wide range of planning processes, installation costs and lead-times. ERM analysis of a range of projects suggests the cost of civil engineering work to install chargers can range between €50/kW to €500/kW, before any grid connection costs.

Installation costs can vary greatly depending on precise location.<sup>94</sup> Underlying this pattern is that opportunity charging, especially at non-depots sites, may add significant planning process and civil engineering risk: It is difficult to assign a fixed unit cost to opportunity charging. This difficulty varies by place, and while most of our operator/agency interviewees raised similar concerns, the risks and maturity of processes varied considerably between interviewees. For example:

- In London, where the process behind deploying opportunity charging is still evolving, current plans to add pantograph opportunity charging are now aimed at a location that would benefit several bus routes, to maximise the value of a hub installation against a complex, but location-specific, planning processes.
- One of our interviewees in Germany had intentionally over-sized and geographically clustered future opportunity charger sites. Effort was focused on fewer sites than originally intended and allowed the number of chargers installed at each site to grow over time, thereby ensuring the newest charger technology could be procured when needed by later route decarbonisations.

- In Oslo, the agency starts planning appropriate opportunity charging connections and permits 3-4 years before the beginning of each route contract. This keeps the route tender technology-neutral, even if the winning contractor decides not to install and use opportunity charging equipment.

For many agencies and operators, the installation of opportunity charging requires significant additional partnership work, sometimes with organisations that would not otherwise become involved with the topic of bus operation. Complex deployment issues can arise around land ownership, power supply, and regulation. One of our interviewees in Germany found an opportunity charging-based project stalled when the implementation process exceeded the time made available by state funders, something less likely to have afflicted a simple bus procurement.

Opportunity charging infrastructure often blurs traditional demarcation of responsibilities between operator and agency, requiring contractual systems to be redrawn. While hard to quantify, this is an additional cost, and until established as a routine practice, a source of considerable risk – both uncertainty of outcome and potential for implementation delay.

#### Case study: Foothill Transit (California) pantograph costs

Foothill Transit (California, U.S.) acquired a 500-kW pantograph charger for use by the buses at the depot. The charger cost \$665,000 including installation. Maintenance of the same type of chargers and associated equipment cost at the Pomona Transit Center cost \$1,500 per month. Preventative maintenance cost \$500 per charger per month and \$1,000 per charger every 6 months. Annual inspections cost \$5,200 including labour and parts.



Figure 15: Pantograph chargers at the Pomona Transit Center.

Source: <https://www.nrel.gov/docs/fy21osti/80022.pdf>

Opportunity charging reduces the scope for electricity price arbitrage, since charging tends to occur throughout the daytime, not overnight when prices are commonly lowest. One of our interviewees in Germany was planning to better optimise the timing of opportunity chargers against electricity prices, much as is common for depot charging, although the process will be complex: In practice this optimisation varies from day-to-day, as BEBs with sufficient onboard battery capacity to operate through the most extreme climatic conditions have lower energy requirements on more temperate days, and so on those days can de-emphasise opportunity charging at the

most expensive times of day. The use of diesel heaters (but not coolers) further complicates the equation.

### Benefits and challenges of the technology

Pantograph charging has several key benefits compared to plug charging:

- Pantographs can allow an electric bus's operating range to be extended without significant downtime. Pantographs have historically allowed higher charging power to be delivered than is technically possible through plug cable connections, although the emergence of the MegaWatt Charging System is likely to soon nullify this advantage.<sup>96</sup>
- Pantographs can automate and simplify the bus charging process compared to plug-in charging, with less human actions and safety risks, including avoiding day-to-day cable management challenges.
- The ability of opportunity charging to utilise electricity connections across several potential sites on a route, not just one home depot, could better match charging requirements to locations with grid capacity. This was cited as strategically important by interviewee Transport for London, a city with significant emerging grid constraints. However, as discussed under challenges below, this approach creates many more grid-related discussions with differing timescales, greatly complicating the overall process of bus electrification.
- Within a depot environment, pantographs can save space for additional buses to park or charge, compared to most plug-in charging. This is because pantograph equipment is easily mounted on gantries or in the depot roof. One of our interviewees in Germany cited this feature as saving around 50 thousand Euros per bus that would otherwise have been spent on new bus parking facilities.

However, there are also challenges with pantograph charging:

- Opportunity charging is fundamentally less flexible a solution than at-depot charging. Long-term, such chargers can be expected to last at least 15 years, which may be less than a route's contract period.<sup>97</sup> Short-term single, especially inverted pantograph, chargers are particularly vulnerable to a failure preventing the operation of buses along an entire route. Many opportunity charging implementations deploy multiple chargers to mitigate such risks, but at extra cost. Excessive variability in journey time, such as that caused by road congestion, may inhibit regular charging patterns. This could be especially problematic where BEBs have small batteries and need to charge after every journey.
- As discussed in the context of installation cost, the process of installing charging infrastructure in locations remote from depots is complex and differs by place. Our interviewees identified the need to engage with a broad range of stakeholders, adding cost and risk. Long-term, these costs and risks can be moderated by standard processes – but processes will not become as

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<sup>96</sup> <https://www.charin.global/technology/mcs/>

<sup>97</sup> For example, Ekoenergetyka offer a 15-year warranty in some markets.

straightforward as depot-centric solutions, primarily because of the need to install pantograph chargers in different public places.

- Interviewees mentioned grid constraints as a factor for consideration before the installation of pantograph chargers.<sup>98</sup> Interviewees generally stated that due to grid constraint concerns, efforts were made to procure sufficient grid connection for opportunity charging far ahead of bus procurement, to ensure grid capacity is available, extending overall timescales.
- Where a mix of vehicle sizes are used across the fleet, especially single and double deck buses, it may be difficult to standardise pantograph charger position and height. When installed over public roads, high clearances may be required to avoid collision with non-bus traffic.
- Like other fixed chargers, installation in under-crofts or similarly enclosed spaces may not be possible due to the increased fire risk for buildings above.

Assessments of opportunity charging may be made in abstract as arithmetic optimisations of time and cost. Yet the deployment and operation of such infrastructure is driven by process and tends to suit organisational structures which are relatively stable over the long-term.

For example, it is notable that currently only six, out of several hundred primarily BEB-operated routes in the United Kingdom are known to use opportunity chargers. Contrast that to the Netherlands, where by 2021, pantograph opportunity charging accounted for 70% of all BEBs.<sup>99</sup> One possible explanation for that difference is the greater level of deregulation and commercial market impetus in the UK bus sector, which more highly values flexibility of vehicle deployment, and is less stabilised by long contract or concession periods. Although it should also be noted (from our original schedule analysis) that the Netherlands has one of the highest proportions of challenging routes to decarbonise in Europe, and thus was far less likely to be able to rely on depot-charged BEBs, especially prior to 2021 when BEB battery capacity tended to be smaller.

### TCO modelling approach

To model the cost of opportunity charging, two main parameters need to be calculated based on the route data: the number of opportunity chargers required, and the proportion of electricity provided through the opportunity chargers (rather than through overnight charging).

Opportunity charging is costed for each bus route, with no sharing of infrastructure between routes assumed possible. This reflects how opportunity charging infrastructure tends to be deployed and clarifies strategic investment rational against specific route characteristics. Consequently, we also assumed that interworked bus routes (where a single bus is likely to operate two or more infrequent bus routes) are incompatible with opportunity charging, given that they will be operating different routes in a day and may not have a common location to site a charger along all routes.

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<sup>98</sup> [https://kiepe-group.com/fileadmin/kiepe\\_website/news/%C3%AEile-de-france\\_mobilite%C3%A9s/press-release-kiepe-electric-ile-de-france-mobilite-tzen4-2024-en.pdf](https://kiepe-group.com/fileadmin/kiepe_website/news/%C3%AEile-de-france_mobilite%C3%A9s/press-release-kiepe-electric-ile-de-france-mobilite-tzen4-2024-en.pdf)

<sup>99</sup> <https://cleanbusplatform.eu/storage/files/monitor-ze-bussen-3e-kwartaal-2021.pdf>

*Number of opportunity chargers required*

The number of opportunity chargers required on a route has been estimated based on the minimum time required for a full (out and back) loop, the maximum energy consumed by running a full loop, the power of the opportunity charger and the maximum number of buses operating on the route. Through this, the peak utilisation of the charger can be estimated (maximum charging time per loop \* maximum number of buses / minimum time for a loop), resulting in additional chargers required if the peak utilisation is greater than 100%.

$$\text{Minimum \# opportunity chargers (rounded up)} = \frac{\text{Maximum energy per loop (kWh)} * \text{Maximum number of buses}}{\text{Charger power (kW)} * \text{Minimum time required for a loop (hours)}}$$

Once the minimum number of chargers required is calculated, an additional opportunity charger is assumed to be installed to give  $n+1$  contingency. This leads to the minimum number of opportunity chargers installed on a route being two. In practice a wide range of strategies have been adopted to opportunity charger redundancy.

*Proportion of energy supplied by opportunity chargers*

In many cases, the electricity supplied at opportunity chargers will be a different price to depot-charging due to the time of day of the charging. Often, cheaper tariffs are available for overnight consumption, meaning electricity supplied at opportunity chargers will be more expensive than that at depot.

To estimate the proportion of energy provided by opportunity chargers, we assumed a triangular distribution of energy demand in a day (shown in Figure 16), where the highest probability occurs at the average energy demand, and decreases linearly to zero at the maximum energy demand.

The average energy demand from opportunity charging was then calculated by integrating the normalised probability multiplied by (energy consumption in a day – energy supplied overnight), assuming the bus leaves in the morning with a full battery and returns with an empty one.

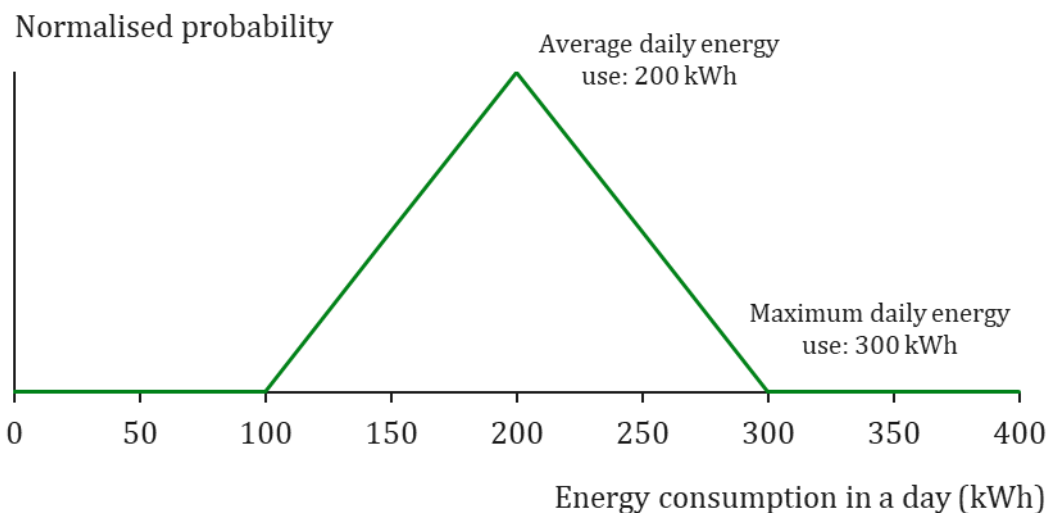


Figure 16: Illustrative example of the distribution of energy consumption in a day assumed for opportunity charging calculations.

For the case where the bus has a small LTO battery optimised to perform a single loop on one charge and fully charge each loop, the average energy provided by opportunity charging can generally be simplified to (average daily energy use – overnight energy supplied), where overnight energy supplied is the size of the LTO battery.

*Calculation the additional costs of opportunity charging*

Once the number of opportunity chargers needed and proportion of energy supplied by opportunity charging is calculated, the additional costs associated with opportunity charging can be determined.

The costs of the charger (CAPEX, grid capacity upgrades, operational and maintenance OPEX) are converted to equivalent annualised costs, then multiplied by the number of chargers per bus on the route (e.g. an 8-bus route with two chargers would be multiplied by 0.25). Any additional CAPEX required on the bus (e.g. a pantograph arm attached to each bus) is added on to the cost of the bus.

The cost of electricity is calculated as:

$$\begin{aligned}
 & \text{Annual electricity cost (€)} \\
 & = \text{Annual electricity use (kWh)} * (\text{Depot electricity cost} \\
 & * \% \text{ charging at depot} + \text{Opportunity charging electricity cost} \\
 & * \% \text{ opportunity charging}
 \end{aligned}$$

## Cost evaluation of main options for hard-to-decarbonise local bus routes

### Balance of cheapest options over time

Our approach to TCO modelling was outlined in the TCO modelling approach subsection, with the method underlying each main option for hard-to-decarbonise local bus routes detailed in its respective section above, and key model inputs listed in *Appendix: TCO tool and inputs*. TCO modelling and consequent analysis is focused only on:

- local bus routes – those under 100 km, excluding routes originally modelled as “long distance”, typically intercity coach routes whose decarbonisation options cannot be accurately evaluated using this report’s method – which were
- originally modelled as “challenging” to decarbonising – where the route’s existing Peak Vehicle Requirement was too small to maintain existing schedules as BEB, even with optimal BEB duty management.

Analysis in this section focuses on our central set of modelling assumptions, which notably presume:

- Opportunity charging is modelled with large-battery capacity BEBs, which is now common industry practice because it improves the operational and redeployment resilience of vehicles, even though a purely rational TCO analysis concludes that small capacity LTO battery buses tend to represent a slightly lower overall lifetime cost.
- HVO heaters/coolers are included but, as discussed in the *Alternative fuels for heating and cooling* section, could logically be limited by policy, as already seen for the United Kingdom’s ZEBs. Where relevant, parallel analysis has been shown presuming only the remaining two options (extra BEBs and opportunity charging).

Both these two topics, and a range of other sensitivities in the TCO modelling are further evaluated and discussed later in this section.

Figure 45 shows the cheapest option as a proportion of all challenging mileage, by year of decarbonisation. Challenging mileage is shown as a proportion of the challenging mileage in 2025, to clarify that almost half the challenges could be *solved* by waiting till 2050. No assessment is made here on when routes will be decarbonised, only the cheapest option in each year. The left graph considers all three main options. The right graph shows the balance of options if HVO heaters/coolers are excluded.

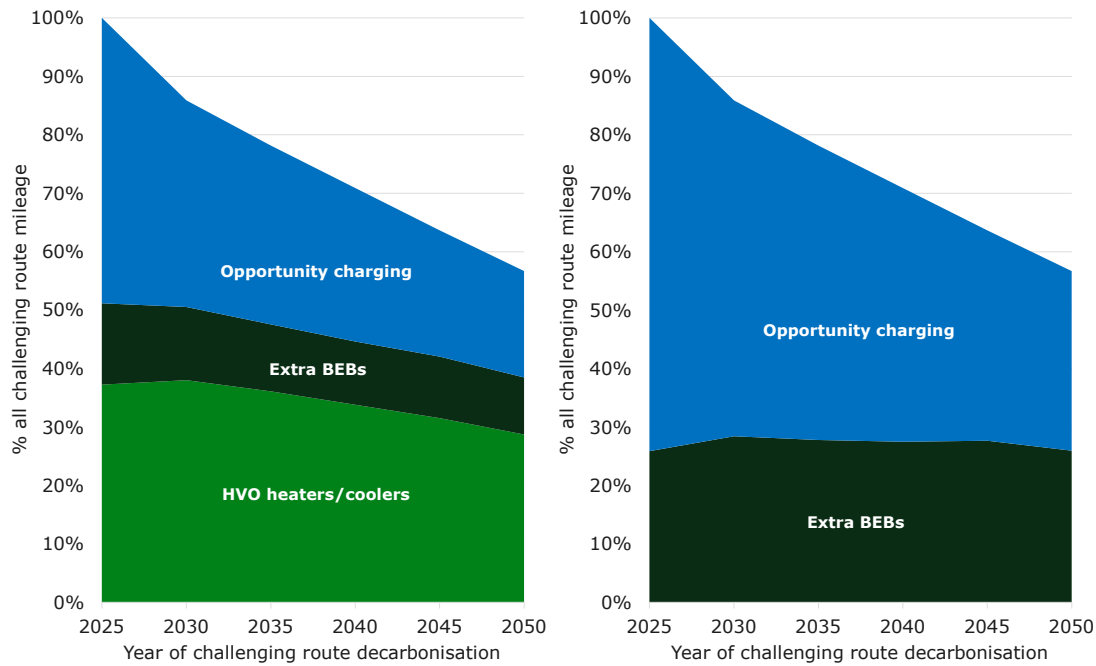


Figure 17: Cheapest lifetime option for decarbonising challenging local bus routes by year of decarbonisation – left shows all 3 main options, right shows options if limited to those fully Zero Emission

Opportunity charging is the most common cheapest option in 2025, but its appeal declines more rapidly than other options: In both cases graphed, opportunity charging loses about 60% of its current potential by 2050. Where HVO heaters/coolers are excluded, the entire decline is in opportunity charging, with Extra BEBs applicable to almost consistent mileage throughout the transition (across the sector as a whole). This rapid decline in the appeal of opportunity charging is paradoxical, as opportunity charging is the least flexible option, both in longer implementation periods and in limitation of redeployment and thus would most benefit from a steady long-term market.

Patterns after 2030 tend to follow a relatively consistent trend. Different operational archetypes shift away from opportunity charging as the cheapest solution at different rates over time, with Suburban routes declining fastest and Interurban routes declining slowest. However, all these declines are broadly linear after 2030. The challenging nature of routes makes them likely to be deprioritised for early decarbonisation by operators, so it is reasonable for subsequent analysis to focus on patterns after 2030, with 2040 taken as a representative mid-point for subsequent analysis.

### Cheapest option by archetype and territory

Bus routes were categorised by operational archetype, formal descriptions of which can be found in the original report.<sup>100</sup> Figure 46 shows the cheapest options vary considerably between archetype, and further that if the option of HVO heaters/coolers is removed (shown as “full ZE”, 100% Zero Emission), the reallocated mileage can strongly skew towards one of the remaining two options. For example, removing the HVO heaters/coolers option from the Rural archetype (which includes small town and non-interurban rural services) almost entirely reallocates mileage to extra BEBs,

<sup>100</sup> Table 2, page 43, <https://fuelcellbuses.eu/public-transport-hydrogen/d336-potential-hydrogen-buses-europe-results-bulk-analysis-passenger>

naturally reflecting the poor utilisation of fixed charging equipment on such sparse services.

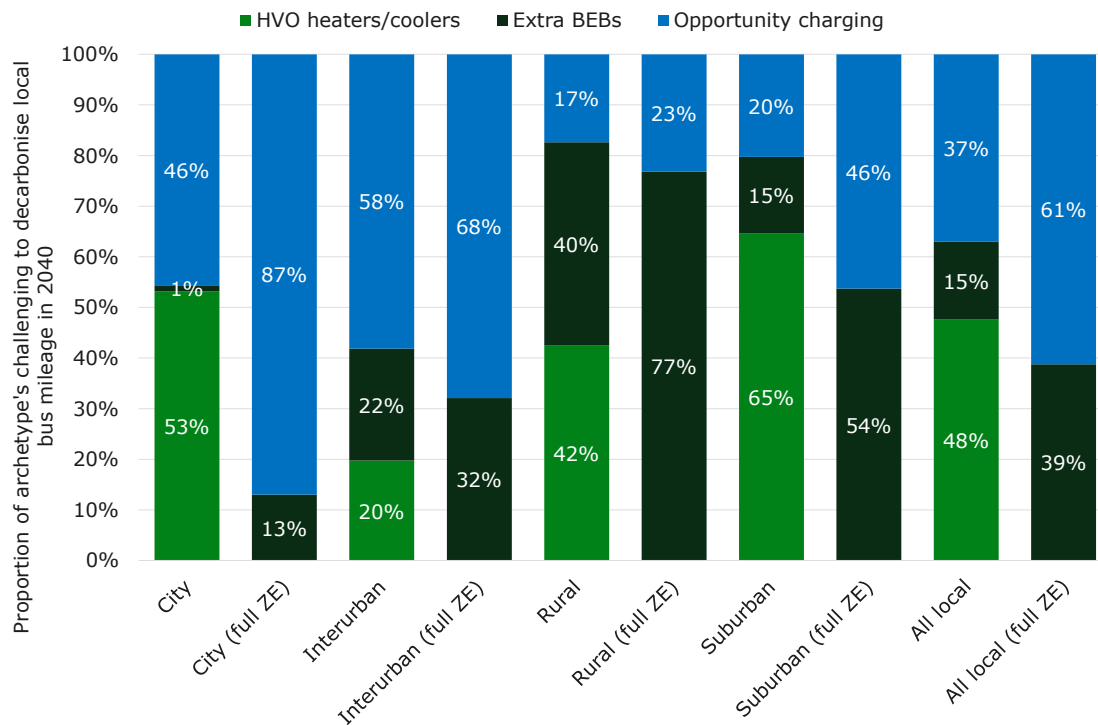


Figure 18: Cheapest lifetime option by operational archetype in 2040 (27% of all challenging local bus mileage is City, 27% Interurban, 8% Rural, and 38% Suburban)

More broadly, opportunity charging tends to skew towards higher intensity operations such as City, and to a lesser degree Interurban. Extra BEBs tend towards lower intensity operations. When included as an option, HVO heaters/coolers tend to favour urban operating styles.

- As discussed in our original report, we interpret the EU’s CO<sub>2</sub> regulations as in practice only *requiring* Class 1 (minority seated) buses be 100% Zero Emission, with other archetypes reasonably possible to operate with Class 2 vehicles, which have a later 90% emissions reduction target. While the formal application of those regulations to secondary heaters/coolers is unclear (see *Alternative fuels for heating and cooling* section)
- Alternative fuels for heating and cooling, the spirit of the policy implies no use of HVO heaters/coolers on City routes, but with potential elsewhere (as use of HVO heaters/coolers on BEBs can attain a 90% reduction in overall annual bus CO<sub>2</sub> emissions in comparison to full diesel).

The dominance of the HVO heaters/coolers option in urban operating styles parallels the higher policy uncertainty that HVO heaters/coolers will be acceptable there, making it difficult to draw firm conclusions on the eventual deployment of this option.

Bus routes were further categorised as to whether they primarily served rural or urban passenger markets, comparable to Eurostat urban-rural classifications.<sup>101</sup> Rural

<sup>101</sup> Page 42 of our original report describes the precise method used, <https://fuelcellbuses.eu/public-transport-hydrogen/d336-potential-hydrogen-buses-europe-results-bulk-analysis-passenger>

markets differ from the rural operational archetypes, most notably because the backbone of rural market services are interurban routes. This explains why opportunity charging is a significant part of the solutions mix in rural markets, as Figure 19 illustrates. The HVO heater/cooler skew noted for urban operational archetypes repeats in the urban market analysis.

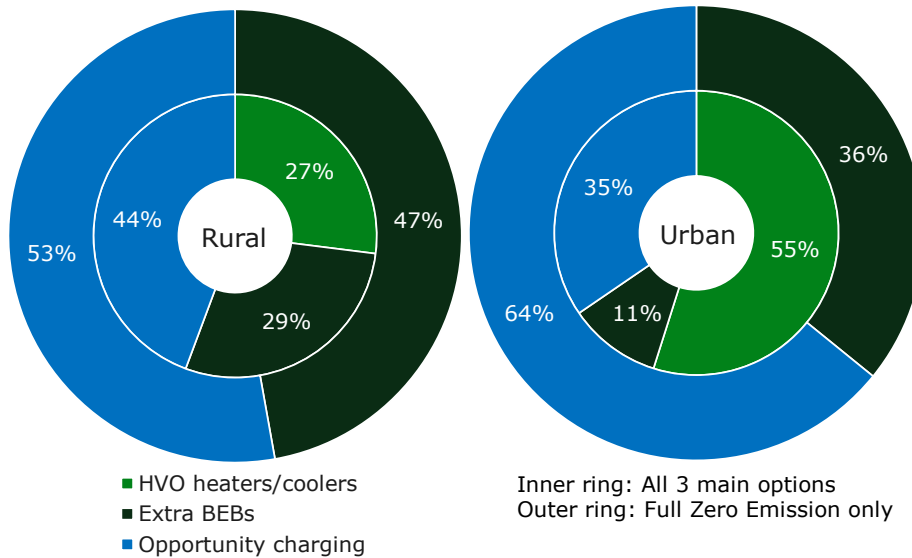


Figure 19: Cheapest lifetime option by primary market territory served, inner wheel shows 3 main options, outer shows options if limited to full Zero Emission, as percentage of territory's challenging local bus mileage in 2040 (26% of all challenging local bus mileage is serving primarily rural markets, 74% urban)

Figure 20 summarises national differences between the balance of cheapest options. Only countries where route data is reasonably representative of the whole country are shown:<sup>102</sup> 86% of the previously analysed mileage is mapped. Germany contains a third of all the challenging-to-decarbonise local bus route mileage mapped, and thus tends to mirror the overall European patterns previously analysed. Countries previously identified with the highest proportions of challenging to non-challenging mileage, such as the Netherlands and Scandinavia, are disproportionately likely to favour opportunity charging. One of the strongest markets for HVO heaters/coolers, the United Kingdom, is of course one of the places known to already ban them on ZEBs.

<sup>102</sup> Representativeness of at least 80%, as defined by Figure 18, page 40 of our original report, <https://fuelcellbuses.eu/public-transport-hydrogen/d336-potential-hydrogen-buses-europe-results-bulk-analysis-passenger>

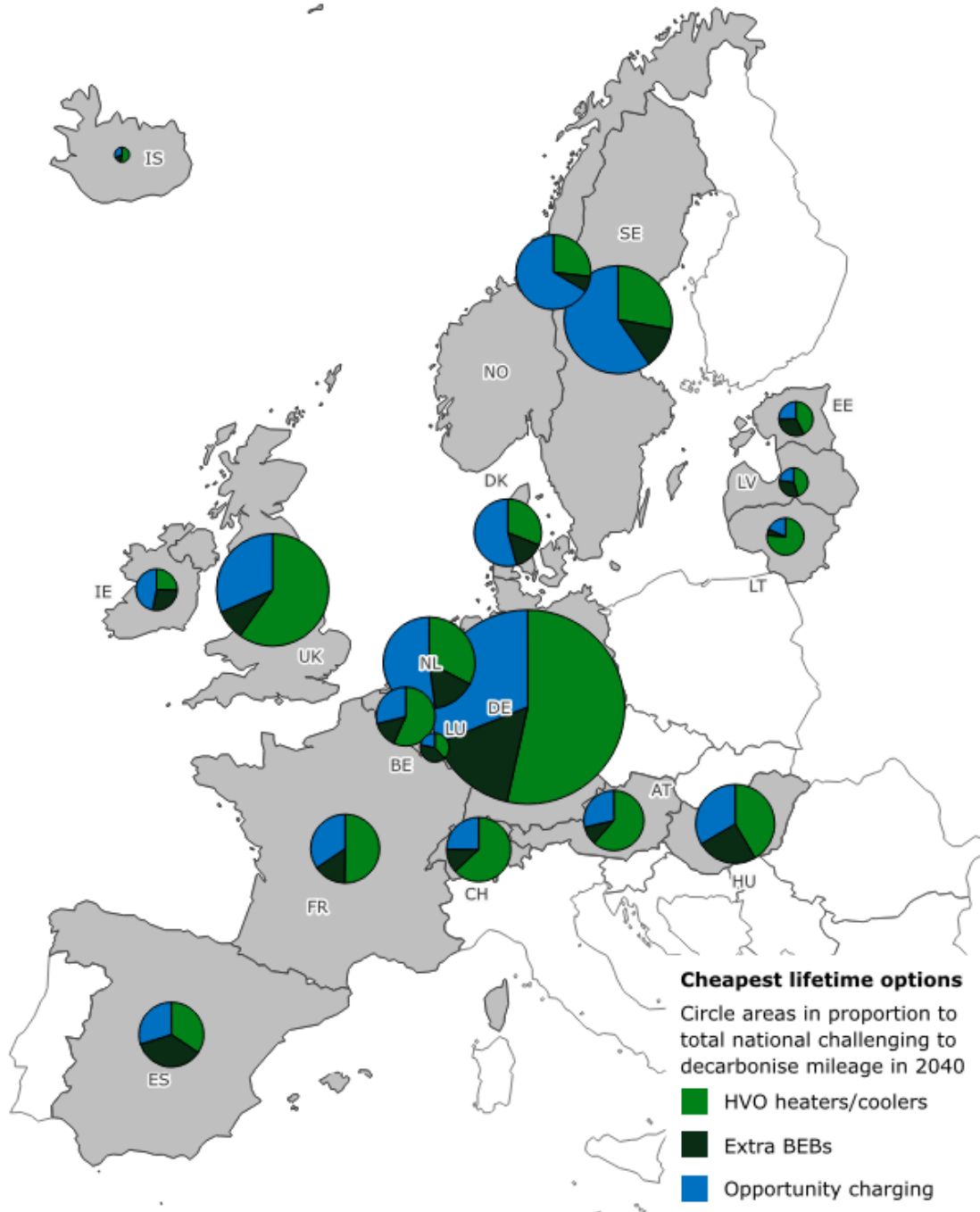


Figure 20: Cheapest lifetime options by country, all 3 main options, 2040 (only countries where data includes at least 80% of all expected local bus services, circle areas in proportion to total national challenging to decarbonise local bus mileage, including only routes primarily operating within each country)

Figure 21 considers just such a scenario for all the same nations, where options are limited to pure Zero Emission. Generally, the further north in Europe, the more likely opportunity charging is to provide the cheapest solution.

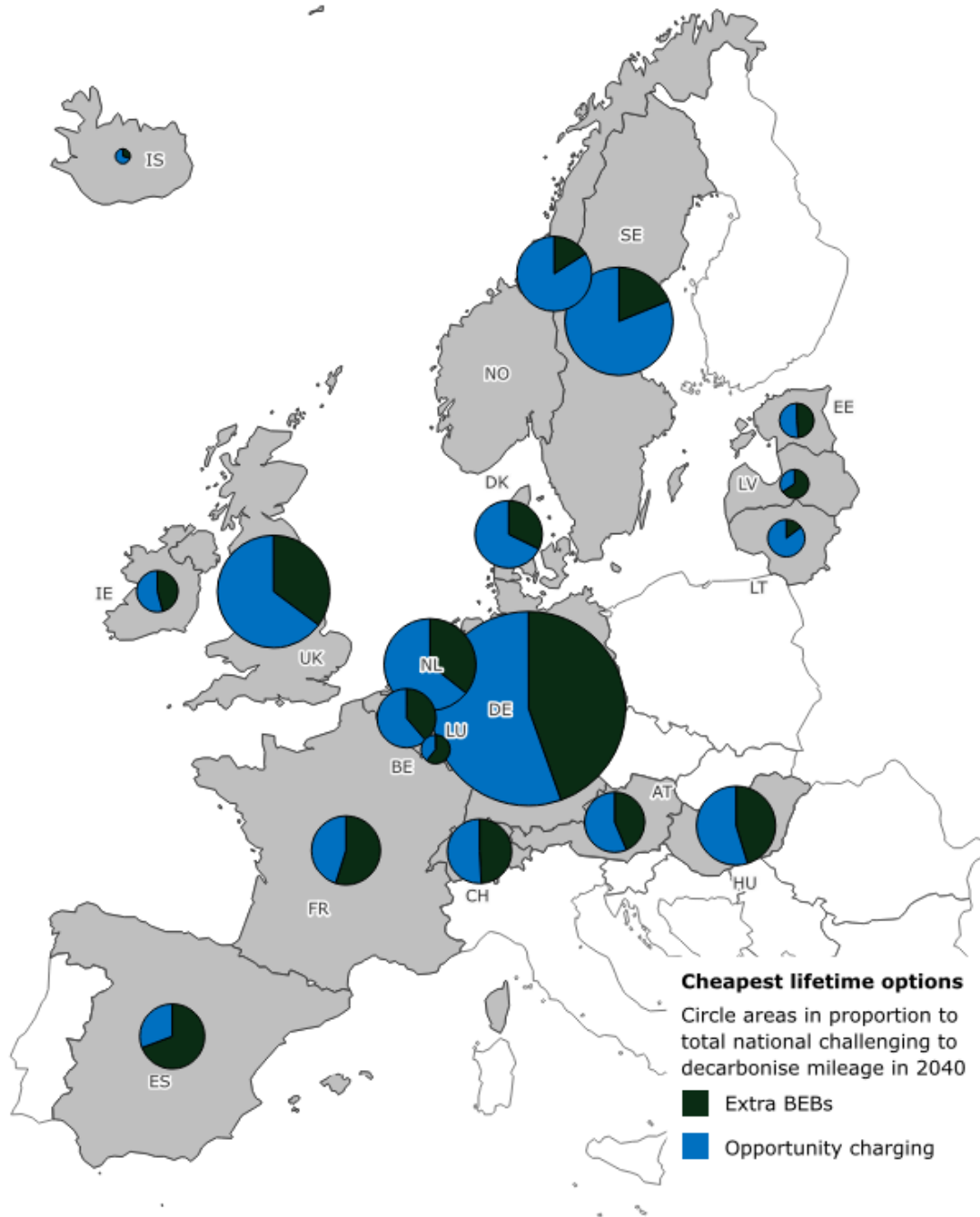


Figure 21: Cheapest lifetime options by country, if limited to full Zero Emission options, 2040 (only countries where data includes at least 80% of all expected local bus services, circle areas in proportion to total national challenging to decarbonise local bus mileage, including only routes primarily operating within each country)

### Key determinants of the cheapest option

The previous subsections discussed the results of TCO modelling as applied to existing local bus services and hinted at some of the correlations between options and operations. A series of graphs are presented below which explore these correlations further. The dashed lines show the distributions were pure Zero Emission solutions pursued (meaning no HVO heater/cooler option).

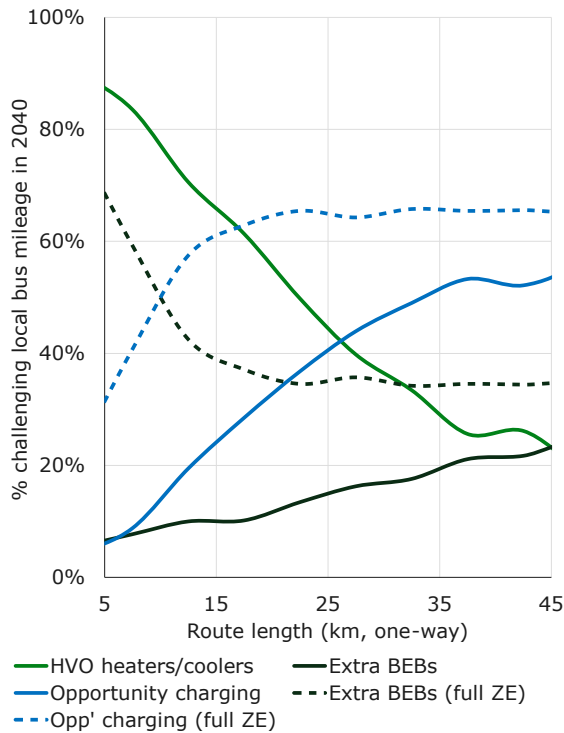


Figure 22: Cheapest lifetime options by route length

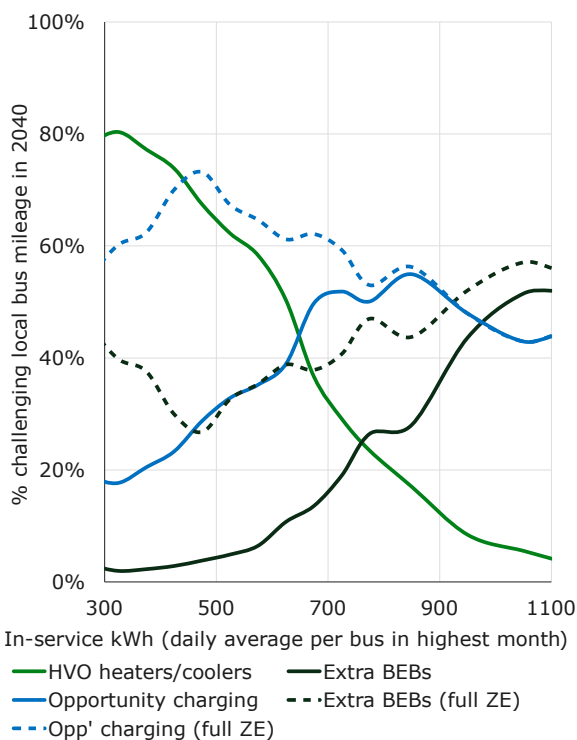


Figure 23: Cheapest lifetime options by energy consumption

Route length, illustrated left, provides a simple, and as detailed in subsequent distribution, *simplistic* set of patterns. It provides the clearest contrast between pure Zero Emission and all-option sets.

If HVO heaters/coolers are considered, the shorter the route the more applicable that option is. If pure Zero Emission options are considered, Extra BEBs are the major solution only for routes under 10km, with opportunity charging otherwise favoured.

As the next two graphs below reflect, short routes tend to be associated with slow urban operations, which tend to have lower energy requirements.

Daily vehicle energy consumption naturally guides deployment of HVO heaters/coolers: As energy requirements rise, it is more likely that solving only the heater/cooler part of the BEB's energy requirement will be insufficient to solve the overall energy challenges of the route's operation.

Only the highest energy requirements favour extra BEBs, where the utilisation of these extra BEBs becomes greatest.

Vehicle duty range mirrors these patterns, so has not been graphed separate: 600 km daily vehicle duties are equivalent to about 900 kWh graphed.

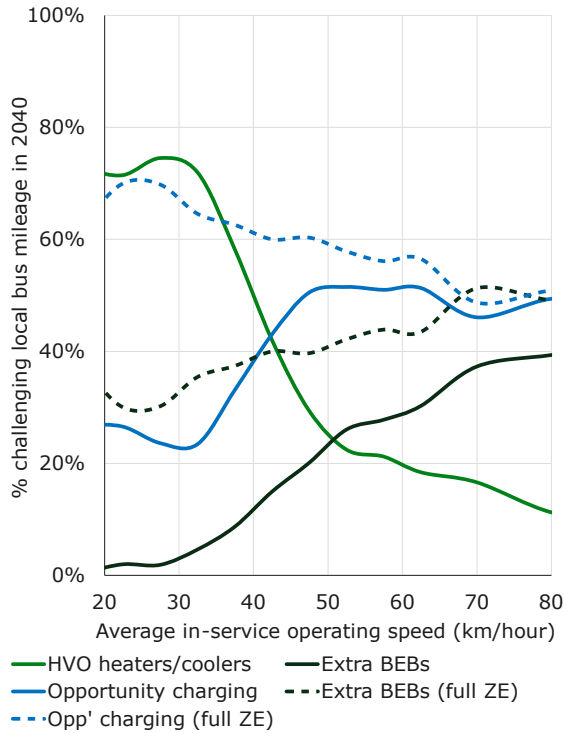


Figure 24: Cheapest lifetime options by operating speed

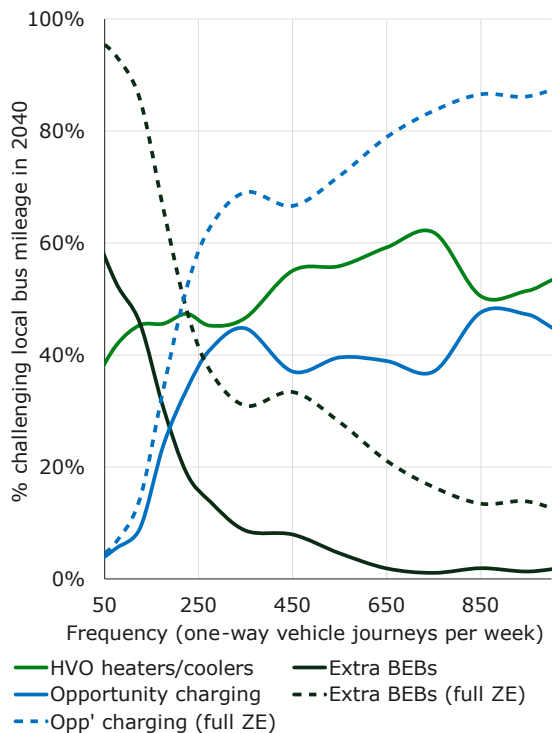


Figure 25: Cheapest lifetime options by service frequency

HVO heaters/coolers especially skew towards slower operating speeds. In our modelling this reflects a tendency to lower energy consumption, as slower operations naturally tend to achieve lower daily mileage. In practice slower operations tend to be slow because stops are frequent, with associated greater loss of heated/cooled air from the opening of doors.

Urban, especially City, operations tend to be slowest, so this pattern helps explain the dominance of HVO heater/cooler solutions for urban operations.

Service frequency has little direct influence on HVO heaters/coolers, as energy is used consistently across the day. Frequency is a natural determinant of the decision between extra BEBs and opportunity charging, since the utilisation of route-specific opportunity charging is greatest where buses operate more regularly.

Extra BEBs are only the most common options at roughly hourly and lesser service frequencies. Opportunity charging was modelled to assumed large-capacity bus batteries, which in turn means this pattern persists even where the number of out-and-back journeys each vehicle performs each day is low, meaning each BEB passes under chargers infrequently.

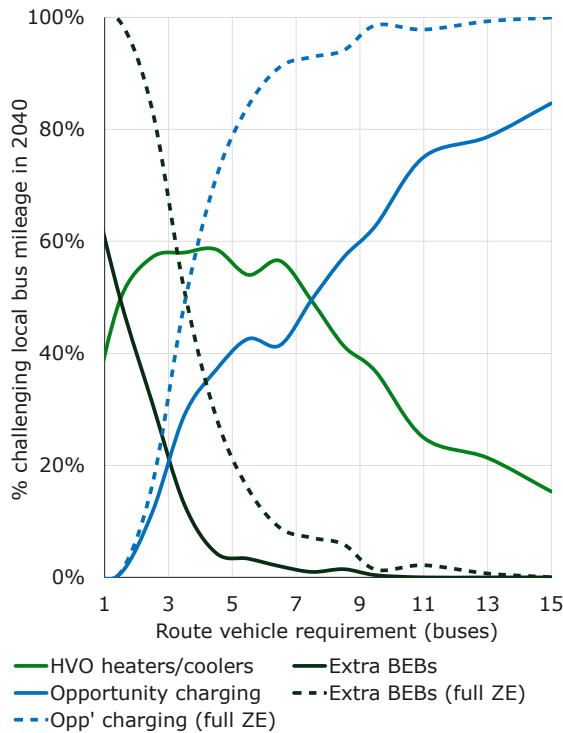


Figure 26: Cheapest lifetime options by vehicle requirement

A key related determinant of the balance between extra BEBs and opportunity charging is the route's Peak Vehicle Requirement: Less than about 4 buses makes opportunity charger utilisation too poor relative to operating extra buses. After about 7 buses, opportunity charging becomes more attractive than HVO heaters/coolers, again reflecting the natural economies of scale of more vehicles using the same fixed opportunity charging equipment.

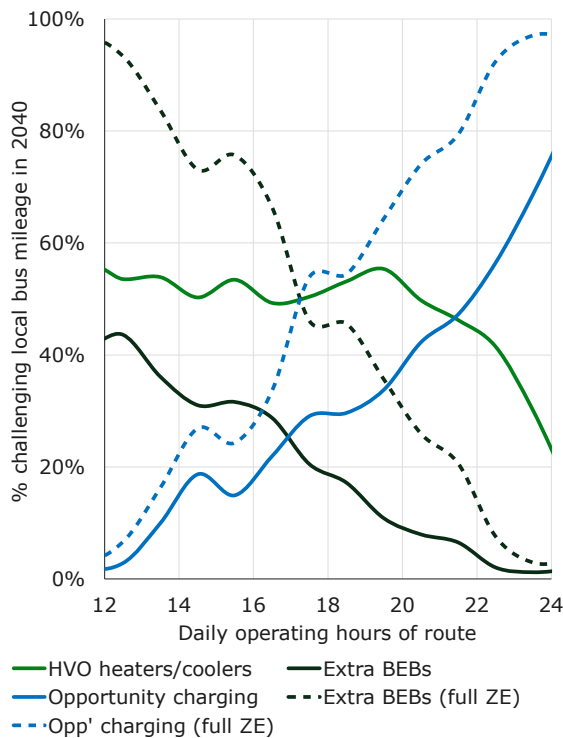


Figure 27: Cheapest lifetime options by operating hours

Continuing the theme above, longer route operating hours naturally favour opportunity charging as the charging equipment's utilisation rises.

With only pure Zero Emissions, there is a clear pattern of extra BEBs favouring shorter operating days, with days above 17 hours favouring opportunity charging. The additional nature of extra BEBs means there are no charging-time limitations on deploying them to routes which operate late and early. Rather, as reflected in this and the previous two graphs, extra BEBs tend to be the cheapest option only at relatively small scales.

Summarising the patterns above:

- **HVO heaters/coolers** favour routes with lower energy requirements (relative to all challenging routes, which by definition all have above average energy requirements), and is the cheapest option for vehicle duties under about 650 kWh in the worst climatic conditions. This is equivalent to a vehicle duty of

about 400 km or less. These operations are especially likely to be slower and shorter routes, under 40 km/h average and 25 km respectively – typical of City operations. However, as discussed in the *Alternative fuels for heating and cooling* section, national and local policy may not consider the use of HVO heaters/coolers valid on “Zero Emission” buses, forcing alternative, more expensive, options.

- **Extra BEBs** favour lower-intensity operations (relative to all challenging routes, which tend to be above average intensity) – lower frequencies, small vehicle fleets, and shorter operating days: If limited to only Zero Emission options, roughly hourly or less, Peak Vehicle Requirements of under 4, and routes operated under 17 hours per day, respectively. The longest routes and the highest energy requirements are more likely to favour extra BEBs, suggesting extra BEBs may be the only viable solution for long-distance routes – although as discussed in *Alternatives to FCEBs*, such non-local routes can be expected to manage challenges by altering schedule to enable mid-duty charging without significantly more vehicles.
- **Opportunity charging** favours routes with high Peak Vehicle Requirements – roughly 8 or more buses per route, or more than 4 if options are limited to pure Zero Emission. Opportunity charging is well suited to routes which operate 24-hours a day. Service frequency, and the number of daily in-service opportunity charges possible for each BEB is far less important than might be perceived, although this will affect the ability to deploy small-battery opportunity charging strategies.

As discussed in the context of sensitivities below, this rational appraisal of the role of extra BEBs vs opportunity charging can be at odds with practitioner reality: Extra BEBs may be seen as more flexible assets, both operationally hour-to-hour and over the life of the investment. In contrast, the implementation of opportunity charging adds time and risk.

### TCO sensitivity analysis

Key parts of our modelling and evaluation are inherently uncertain, and do not adequately capture risk, in particular lower probability scenarios with high impact on the cheapest outcome. To better gauge these risks we have varied key TCO modelling assumptions and re-run the model on a randomised 10% sample of routes.

In addition to the full Zero Emission alternative, extensively compared in the previous section, six sensitivity tests were found to alter the 2040 distribution of options by more than 10% and are analysed in this subsection. In descending order of risk:

- **High HVO price:** HVO price is 100% higher than base (3 main options), equivalent of 2.6 times diesel price. As discussed in *Supply and cost projections*, HVO is inherently supply constrained. It is possible that HVO’s price could be capped by future synthetic e-fuels, which are expected to be much more expensive.
- **Low cost opportunity charging:** CAPEX, OPEX, and grid connection costs are assumed 50% lower for opportunity charging. A theoretical position to contrast to high cost opportunity charging (described below), intended to reflect human

process efficiencies which might stem from the widespread deployment of such chargers in a locality. Our TCO model's base costs tend to reflect early or first adoption.

- **High cost opportunity charging:** CAPEX, OPEX, and grid connection costs are assumed 100% higher for opportunity charging. This is intended to reflect the higher risk of implementing opportunity charging on any one route, a theme commonly identified by practitioners. Decision makers may reasonably price in this higher risk.
- **Full City Zero Emission:** HVO heaters/coolers are allowed for all routes except City archetypes, which are limited to fully Zero Emission options. This reflects the *spirit* of EU CO<sub>2</sub> regulations, since we presume only City services require class 1 vehicles, and thus require a 100% Zero Emission solution.
- **Small battery opportunity charging:** Opportunity charging is done by BEBs with small (typically around 100 kWh) capacity LTO batteries. Rationally, this is the cheapest overall approach in most cases, however many operators consider it insufficiently flexible, so our base TCO model assumed BEBs with full-sized batteries.
- **Remote depots:** Driving distance from nearest route termini to home depot is multiplied by three. Less well established or smaller operators are less likely to have the centrally located depots assumed in our base TCO model. This test also captures the risk that an existing centrally located depot site might not be possible to electrify, forcing a route's operational base to a more peripheral location.

The figure below quantifies the change in each option's 2040 mileage under each of these test cases.

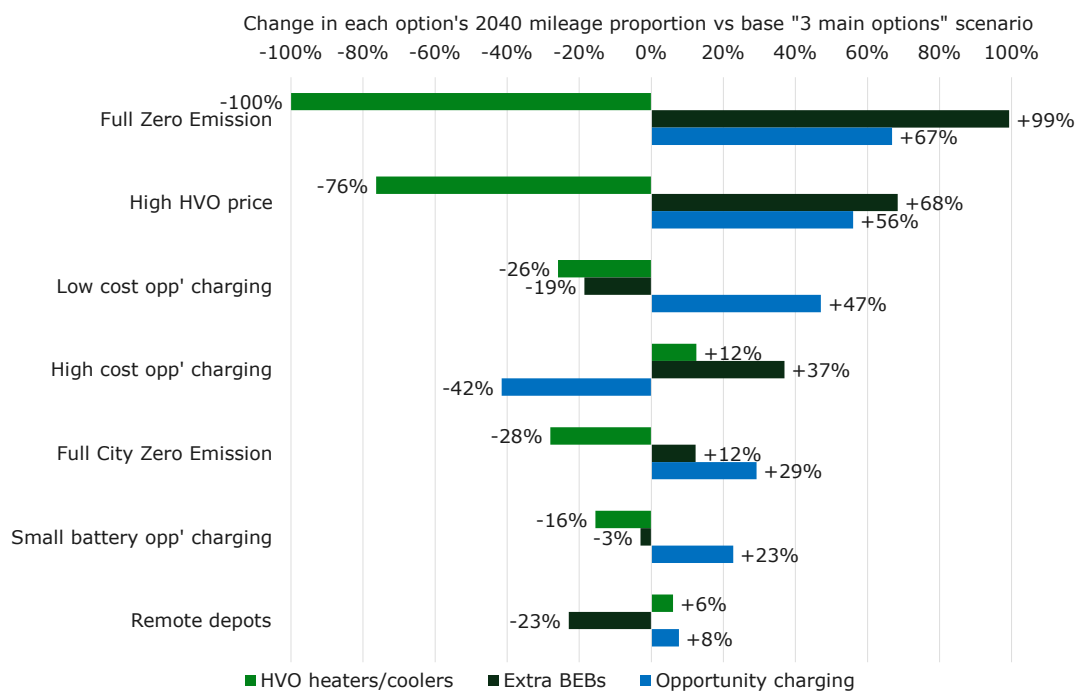


Figure 28: Sensitivity tests vs base "3 main options", showing resulting change in each option's 2040 mileage (based on 10% sample of originally analysed routes)

*Risk of future high HVO prices*

HVO emerges as not just high risk due to policy uncertainty, but high risk due to unknown future fuel prices. Prior analysis characterised the HVO cooler/heater option as optimal in cases where marginally (especially seasonally) more energy was required than available as onboard battery capacity. This *marginality* helps explain why the option is especially vulnerable to fuel price changes. And since many routes fall into this category, a doubling of fuel price reduces the market for HVO coolers/heaters by a substantial three quarters.

The graph below confirms this hypothesis: In the high HVO price case, HVO coolers/heaters solutions skew only to the lowest energy requirements, where a very marginal amount of expensive energy is still cheaper than investing in extra operational assets.

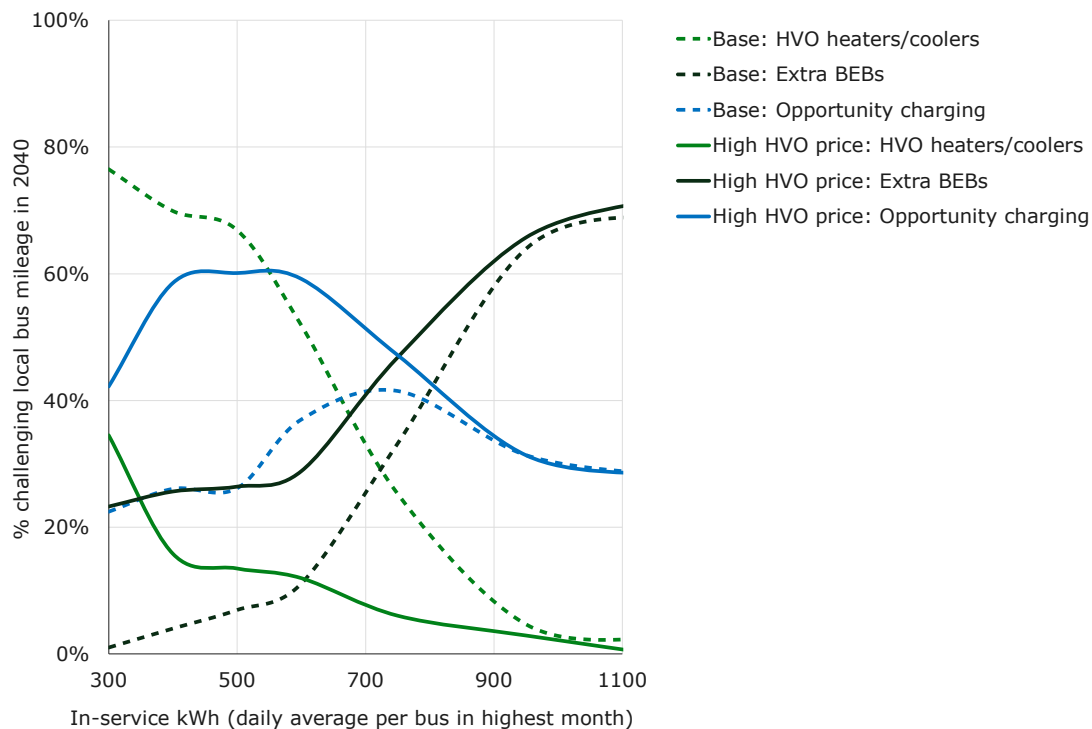


Figure 29: Impact of high HVO prices on cheapest options, by energy consumption<sup>103</sup>

Within this headline pattern, City operations almost entirely shift away from HVO coolers/heaters at high HVO price. About 40% of the Interurban and Rural operational archetype mileage that favoured HVO heaters/coolers in the base case continue to do so at the high fuel price.

Separate analysis further reveals that the rate of decline in HVO cooler/heater mileage between 2030 and 2050 under the high HVO price test case is 30% greater than in the base case, which is the highest rate of change of any test case: With consistently high HVO prices, the absolute market size (by mileage) halves for HVO coolers/heaters over twenty years. This pattern would be exacerbated by any gradual rise in HVO prices from current levels to the high price point modelled. All this *could* make BEBs designed only for HVO heating/cooling both relatively expensive to operate and difficult to

<sup>103</sup> 10% sampling, and consequent data smoothing, has been applied to both base and test case for fair comparison, so exact base case values may not perfectly match those in the earlier Figure 23.

redeploy in later stages of life, a risk that can be moderated by ensuring BEBs have both battery and HVO-based heating/cooling systems.

*Risks around opportunity charging implementation*

Opportunity charging involves a less consistent package of measures than extra buses or the use of alternative fuels. It is therefore not surprising that our modelling of it contains several key sensitivities, not least the costs associated with the charger and its deployment. Pricing in the risk of an opportunity charging deployment *being difficult* results in significantly less routes favouring opportunity charging, as shown in the figure below. The figure graphs options against route vehicle requirement, which was previously identified as the best single guide to optimal opportunity charger routes.

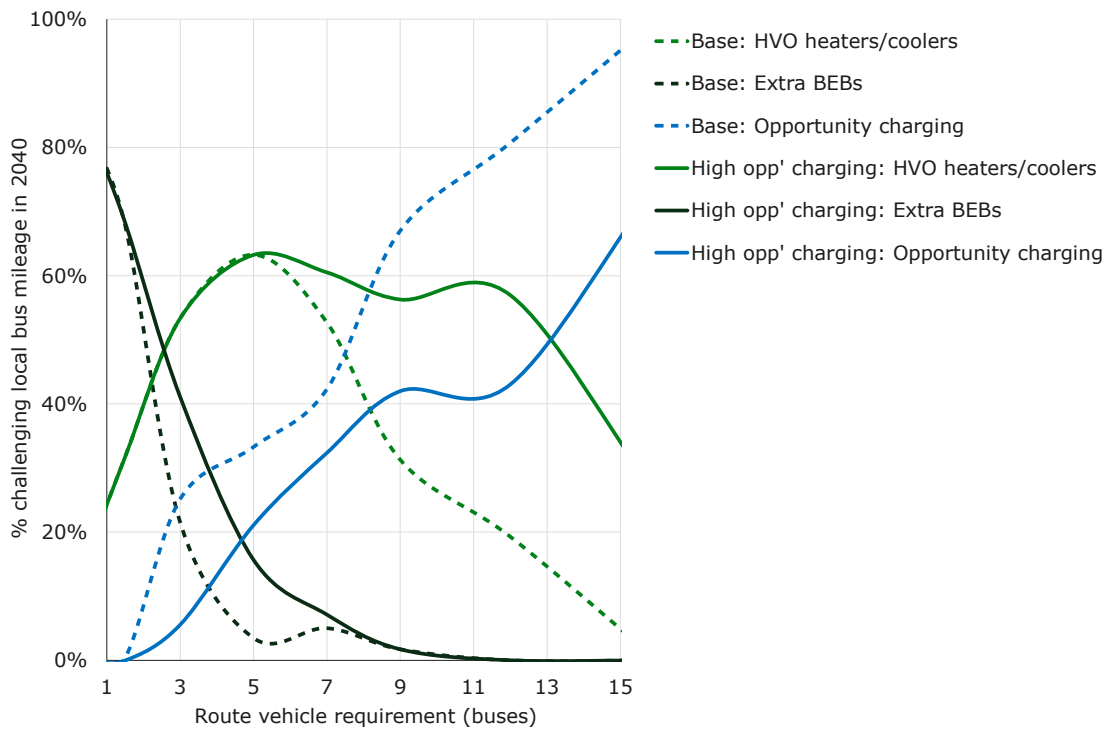


Figure 30: Impact of high opportunity charger costs on cheapest options, by route vehicle requirement<sup>104</sup>

The reduction in the appeal of opportunity charging with higher cost is relatively uniform across all operational archetypes, but the alternative option favoured is not: City routes almost entirely shift to HVO heaters/coolers, while other archetypes almost entirely shift to Extra BEBs.

Operational risks, primarily the lack of flexibility in deployment that is associated with well-optimised opportunity charging is captured in the small battery test case. The use of such vehicles is arithmetically cheaper, yet many practitioners saw this option as too limiting.

Figure 31 shows how use of small-battery LTO-based BEBs further favours those more frequent routes where opportunity charging performed well in the base case. The mileage shift, from base to smaller-battery case almost entirely effects urban

<sup>104</sup> 10% sampling, and consequent data smoothing, has been applied to both base and test case for fair comparison, so exact base case values may not perfectly match those in the earlier analysis.

operating styles, especially City. Interurban routes, where about half of base case mileage favours opportunity charging, are unchanged by the LTO case. Since there is no additional advantage to LTO-based approaches for Interurban routes, larger-battery LFP BEBs are likely to emerge as the optimal opportunity charging, as such technology is less operationally restrictive.

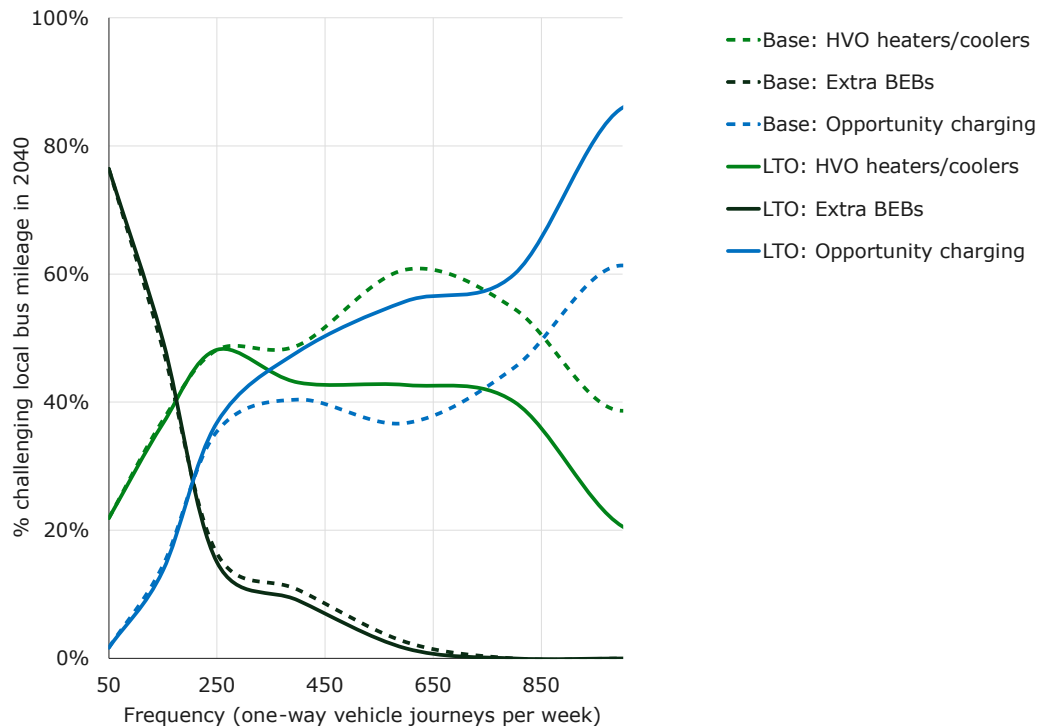


Figure 31: Impact of deploying small-capacity LTO-based BEBs on cheapest options, by route frequency<sup>105</sup>

### The resilience of extra buses

It is notable that all the main sensitivities that add cost result in the highest reassignment percentages to Extra BEBs. Extra buses do not just increase operational flexibility, something not captured by TCO analysis: Extra BEBs also tend to help manage investment risks.

As clearly highlighted by the remote depot test, Extra BEB strategies are less appropriate where route termini are distant from existing depots. In the remote depots case, Extra BEB mileage in the base case shifts into alternative options in broad proportion to those options' base case distributions – there is no one obvious best alternative, even within an operational archetype.

In practice, the two operational archetypes most likely to be operated from remote depots due to underlying geography are Interurban (longer routes) and Rural (geographically sparse). These are also the archetypes most likely to favour Extra BEBs. While both archetypes favour Extra BEBs less in the remote depot case, the drop is only about 10% of the base case Extra BEB mileage. So, while the remote depots will still add cost to the baseline TCO, this impact is modest in the situations remote depot risks are most likely to arise.

<sup>105</sup> 10% sampling, and consequent data smoothing, has been applied to both base and test case for fair comparison, so exact base case values may not perfectly match those in the earlier analysis.

### Other sensitivity tests

We also sensitivity tested, but found to be relatively unimportant in cheapest option choice:

- Lower assumed finance rates, from a base 5% per annum down to a tested 3%, reflecting the possibility (in what is often a public sector provision) of state-backed financing of BEBs. This resulted in a 6% increase in Extra BEB mileage.
- Pantograph down (charger mounted) opportunity chargers tended to be marginally more expensive than equipping BEBs with pantographs, so lowered opportunity charging-based mileage by 1.5%.
- Driver wages are logically an impediment to operating extra BEBs, as additional driver time is needed to bring buses to and from depot, however a 25% increase only resulted in a 3% decline in Extra BEB mileage.
- Battery residual value is often cited as important to investors, but assuming a higher residual price of half the retail price in year of resale made negligible difference to the distribution of cheapest options.

Further tests were conducted of FCEB costs, which are relevant only to the hydrogen price analysis in the next section. The only important sensitivity to emerge from those tests was FCEB maintenance cost: Our base TCO assumes FCEB maintenance cost mimics BEBs, which is logical as much of the vehicle engineering is similar. However, current small-scale parts supply chains, limited local fuel cell-related engineering skills, and uncertainties around fuel cell reliability over a lifetime can all be mapped onto higher maintenance costs.<sup>106</sup> Doubling FCEB maintenance costs maintains FCEB competitiveness only with roughly a 3 Euro reduction in the price of hydrogen per kilogram, which as discussed in the next section, would put hydrogen more firmly out of competitive reach for most challenging local bus decarbonisations. This finding underpins the importance of delivering the whole FCEB ecosystem reliably and at scale, to compete with BEBs in this hard-to-decarbonise route niche.

### Costs of decarbonisation vs diesel

For the routes analysed (challenging routes, excluding long-distance routes, as described earlier), the relative TCO between the cheapest BEB option was compared against diesel, as well as determining the required price of hydrogen for FCEB to be cost-competitive with BEBs.

Our initial assumption had been that all hard-to-decarbonise routes would add long-term cost, but we found that in most cases the cheapest option will be *cheaper* than diesel. There are two important caveats to that statement:

1. Our TCO analysis assesses the costs associated with the buses operating on each route, which implicitly assumes the operator/agency has already overcome initial organisational barriers to decarbonisation, such as understanding the local process for securing electricity grid connections.

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<sup>106</sup> Further evidence, from among current UK FCEB operators, is contained in <https://fuelcellbuses.eu/public-transport-hydrogen/fuel-cell-bus-deployment-uk-%E2%80%93-lessons-jive-and-next-steps>

2. As discussed below, this pattern is disproportionately skewed by HVO heaters/coolers, which may not sufficiently match “Zero Emission” ambitions.

The TCO comparison between BEBs and diesel buses in the base scenario in 2040 is shown in Figure 32. The general trend within challenging routes does not change significantly between 2030 and 2050, therefore 2040 is shown as the midpoint. The graph shows that 61% of challenging bus miles can be electrified at a lower cost vs diesel in 2040, with 6-7% of total mileage having a TCO increase of over 15% in each year.

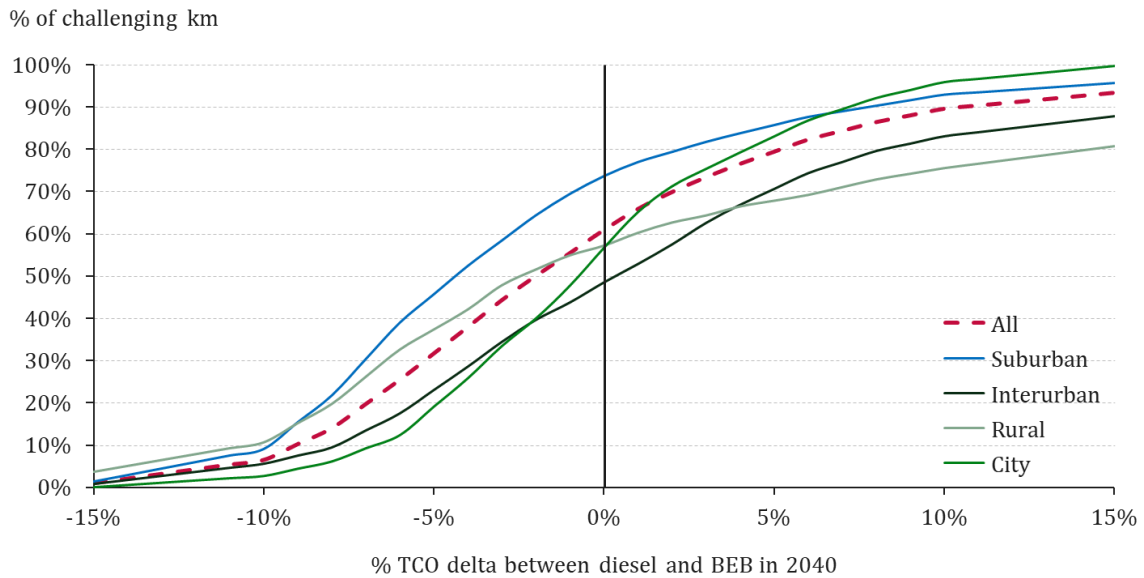


Figure 32: Cumulative graph showing the TCO comparison between the cheapest BEB option and diesel in 2040 by archetype, for the base scenario. Negative percentages indicate BEB is cheaper on a TCO basis compared to diesel.

A large proportion of the routes which are cheaper use HVO heaters, as shown in Figure 33. This phenomenon may be due to two factors: routes using HVO heaters/coolers tend to be the least challenging routes within this analysis, and when HVO heaters/coolers are used they may be substantially cheaper than the other options. This pattern reaffirms the core role of extra BEBs identified in earlier analysis, where extra BEBs tend to be cheapest for the most challenging and diverse routes, those where HVO heaters/coolers and opportunity charging are less suitable.

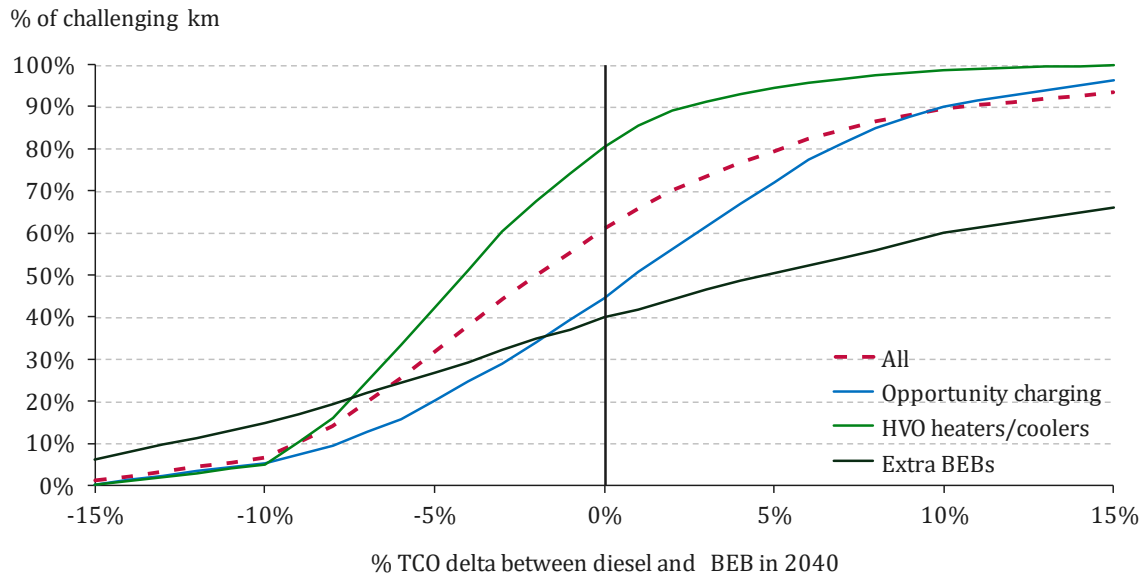


Figure 33: Cumulative graph showing the TCO comparison between the cheapest BEB option and diesel in 2040 split by the cheapest BEB solution, for the base scenario. Negative percentages indicate BEB is cheaper on a TCO basis compared to diesel.

For policymakers, the graphs below (Figure 34 and Figure 35) illustrate the potential financial impact on operators or contract prices of pursuing pure Zero Emission. Without access to HVO heaters/coolers, the proportion of challenging local bus mileage likely to be more expensive with a BEB compared to diesel in 2040 increases from 40% (seen in Figure 32) to 65%. Rural routes fare worst out of all the archetypes when comparing BEBs without HVO to diesel, with a tangibly higher proportion of more expensive mileage than other archetypes (as seen in Figure 34), whilst the other three archetypes vary less from the overall pattern.

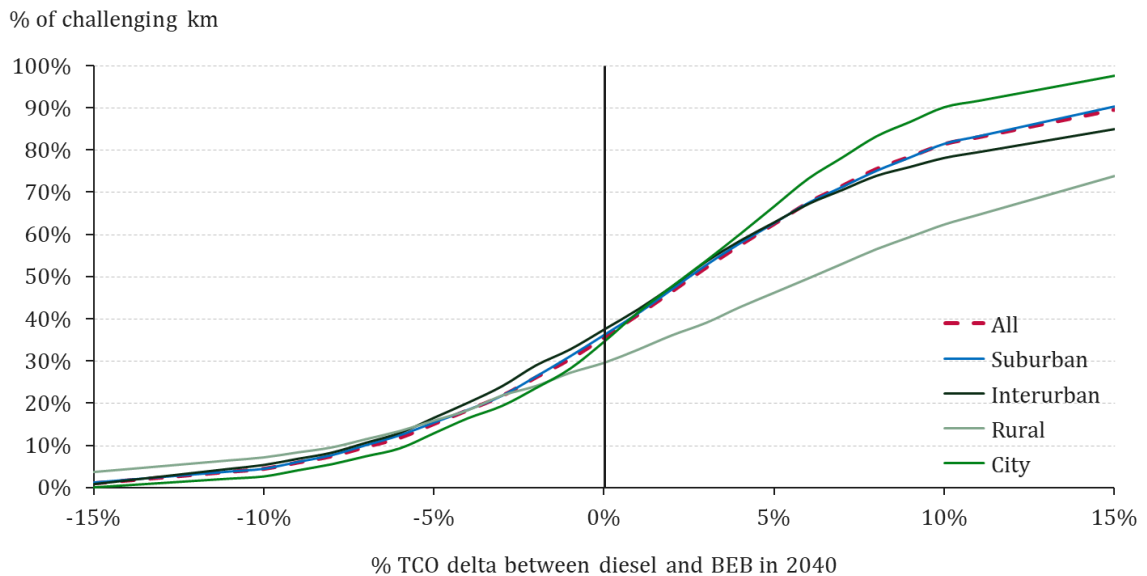


Figure 34: Cumulative graph showing the TCO comparison between the cheapest BEB option and diesel in 2040 split by archetype, for the scenario with HVO heaters/coolers banned for all routes. Negative percentages indicate BEB is cheaper on a TCO basis compared to diesel.

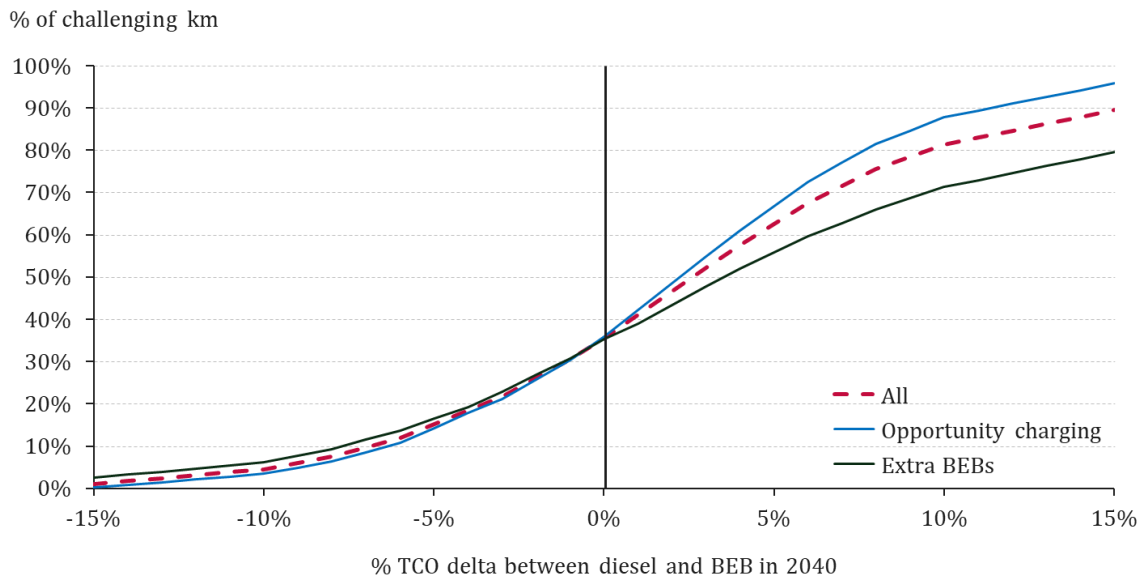


Figure 35: Cumulative graph showing the TCO comparison between the cheapest BEB option and diesel in 2040 split by the cheapest BEB solution, for the scenario with HVO heaters/coolers banned for all routes. Negative percentages indicate BEB is cheaper on a TCO basis compared to diesel.

For the base scenario (including HVO heaters/coolers), Figure 36 shows the distribution of bus challenging mileage within countries by the TCO difference between diesel and the cheapest BEB option, for countries with the most representative data.

As discussed further in *Appendix: TCO tool* and inputs, some TCO inputs are held constant across all countries for modelling simplicity. This includes vehicle and charging infrastructure CAPEX, vehicle and charger maintenance costs, insurance costs, cost of land, grid connection/reinforcement costs and vehicle/road tax (set to zero). As this analysis considers only the long-term competitiveness of different ZEB options, no grants or subsidies are considered: Current ZEB-specific support is assumed to be short term, with long-term support likely to mirror prior support levels for diesel bus operation. In current short-term practice, many of our operator/agency interviewees told us that the availability of financial support for ZEB adoption or operation was an important factor in their decarbonisation decision-making.

The variations between countries arise from differences in: Route characteristics, diesel/electricity costs and differences in fuel consumption (related to heating/cooling demand).

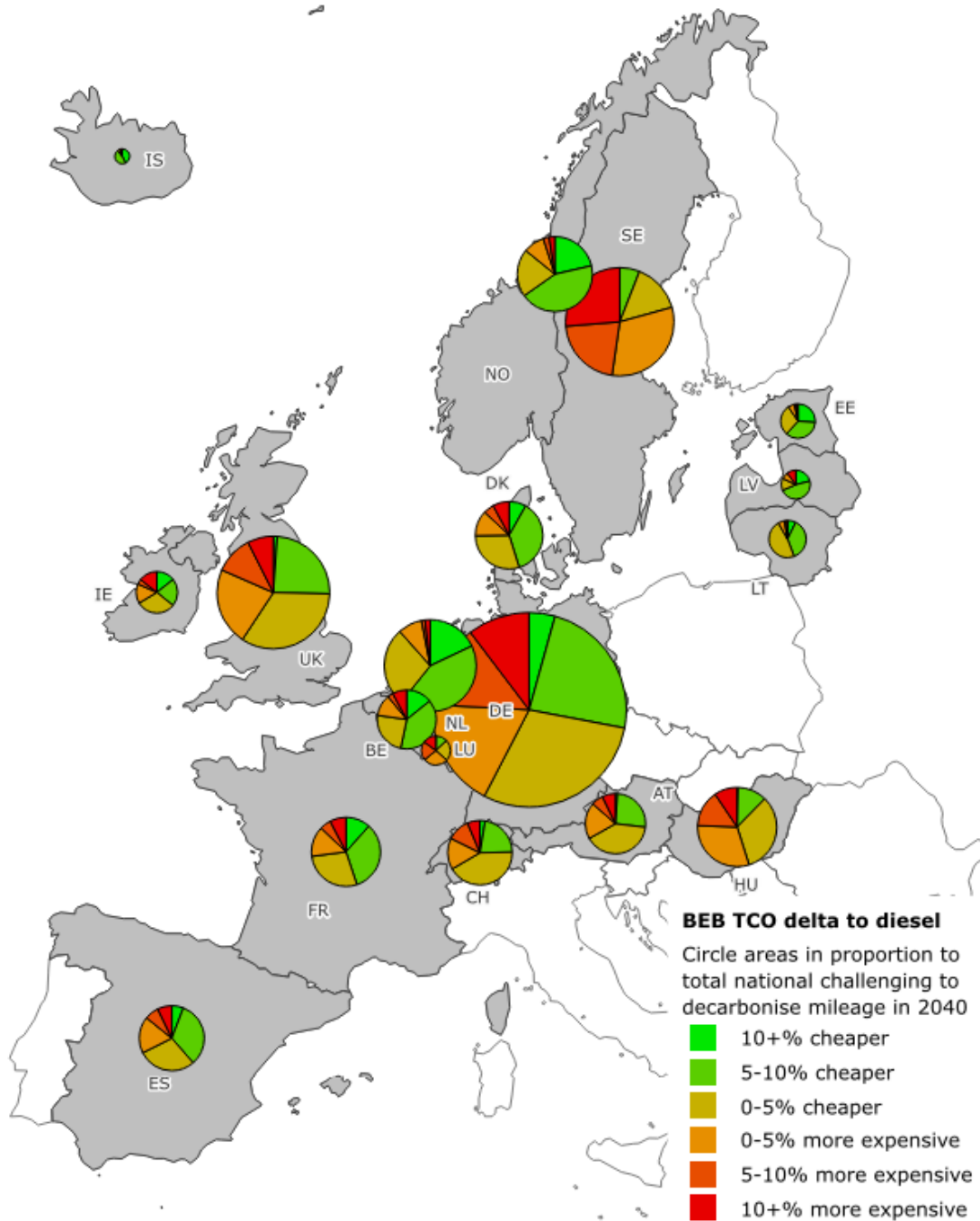


Figure 36: TCO cost change from diesel to cheapest BEB-based option (hard-to-decarbonise routes in countries with representative data only, 2040)

Countries which are better than average for BEBs compared to diesel include, the Baltics (Lithuania: 92%, Estonia: 91%, Latvia: 82%), Iceland: 95%, Norway: 86% and Netherlands: 88%, where over 80% of challenging routes are cheaper than diesel by 2040 (compared to European average of 61%). The reasons for the high competitiveness of BEBs vary between countries.

For Latvia, Iceland and Norway, this is due to low electricity prices and relatively high diesel prices maximising the fuel cost savings from electrification. For Lithuania and Estonia, over 75% of the routes are either suburban or city routes (compared to 65%

European average), which are the cheapest archetypes on average compared to diesel (see Figure 32), combined with reasonably cheap electricity prices. Whilst Netherlands has relatively high electricity prices, high diesel prices and high average weekly energy consumption<sup>107</sup> means significant fuel savings are still achieved, favouring BEB options.

Sweden, Luxembourg and Hungary have the largest proportion of challenging routes where BEBs are more expensive than diesel in 2040 (Sweden: 79%, Luxembourg: 63%, Hungary: 55%, compared to European average of 39%). The reasons for the poor competitiveness of BEBs vary between countries:

- For Luxembourg and Hungary, this is likely to be due to the relatively high electricity price compared to diesel prices, resulting in reduced fuel electricity savings compared to other countries.
- For Sweden, two factors may be at play. Firstly, electricity and diesel prices are relatively low, which reduces the fuel costs savings (as diesel is already relatively cheap). This increases the impact of CAPEX-intensive measures such as extra BEBs or opportunity charging on the TCO. Secondly, a disproportionately large proportion of Sweden's challenging bus routes in 2040 are interurban, which is the archetype with the worst TCO comparison to diesel (see Figure 32).

#### Price of hydrogen to be competitive

FCEBs are technically well suited to decarbonising local bus routes, requiring minimal change to operations or size of fleet. Their key long-term competitive disadvantage is hydrogen fuel cost. Our TCO modelling estimated the price point at which hydrogen could expect to become competitive for each route, vs its cheapest BEB-based option. The hydrogen supply sector can hence judge what price point is attainable, and thus what market might be commercial long-term. For current context, the price to bus operators of green hydrogen typically exceeds €10/kg.

The proportion of mileage for which FCEBs are cost competitive with BEBs depends on the hydrogen price, as shown in Figure 37 by operational archetype. All prices are current values, equivalent to 2025, not inflated. This shows that FCEBs would be cheaper than BEB for approximately 8% of challenging mileage in 2040 with a hydrogen price of €7/kg, increasing to 27% with a hydrogen price of €5/kg. This proportion of challenging routes stays roughly constant to 2050 (although the total number of routes which are considered challenging decreases with expected improvements to BEB battery energy density and hence route compatibility). Rural and interurban routes are the most likely to still be competitive at higher hydrogen prices, due to their demanding and varied nature increasing the cost of the BEB alternatives.

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<sup>107</sup> 30% higher than European average. As discussed in our original report, the Netherlands' bus network tends to contain longer and faster routes than much of Europe. The Netherlands' buses were theorised as less likely to serve short journeys than elsewhere in Europe, a pattern echoing low mode share for bus against high bicycle use.

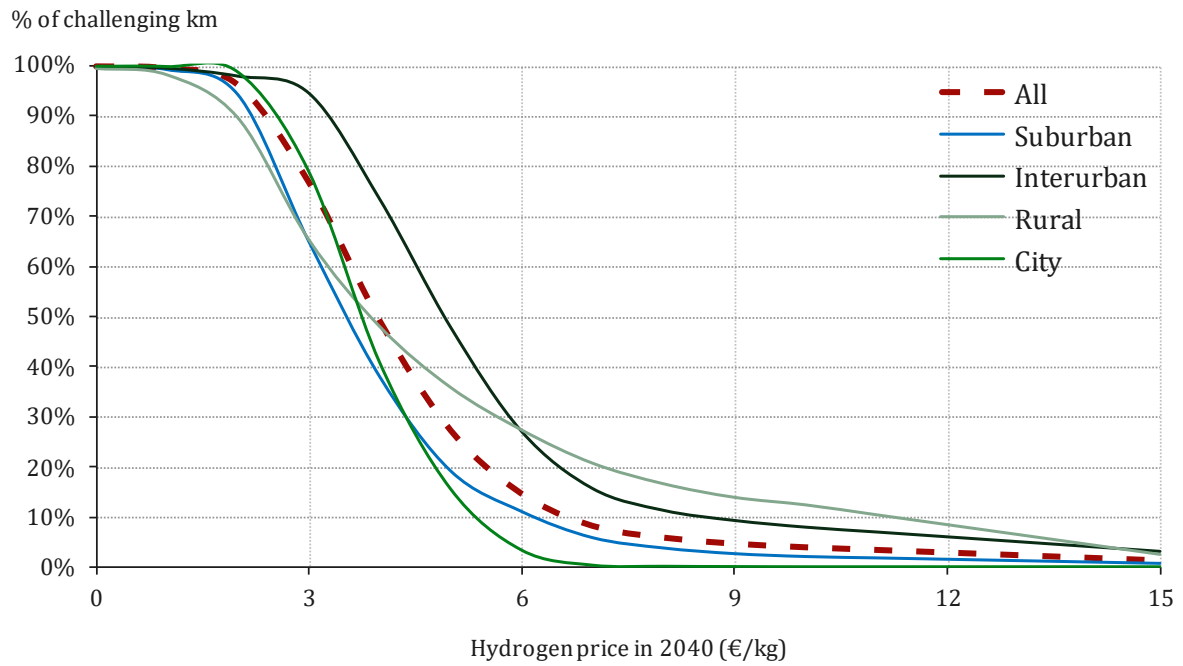


Figure 37: Proportion of challenging route distance which FCEBs would be cost-competitive with BEBs by hydrogen price and archetype in 2040, for the base scenario.

The breakdown of required hydrogen price by cheapest BEB option is shown in Figure 38. As was seen for the comparison to diesel, routes where HVO heaters/coolers are cheapest are the least competitive against FCEBs, with FCEB competitive in only 4% of HVO routes at €5/kg. In contrast, FCEBs are more competitive with BEBs on routes where extra BEBs is the cheapest option, with 62% at €5/kg and still 25% at €10/kg. This correlates with a larger proportion of these routes still being more expensive than diesel in 2040. The strongest market at higher prices (extra BEBs) is also that most likely to be favoured when non-TCO risk factors are priced in. This reinforces the role of FCEBs in solving decarbonisations challenges with the minimum of change.

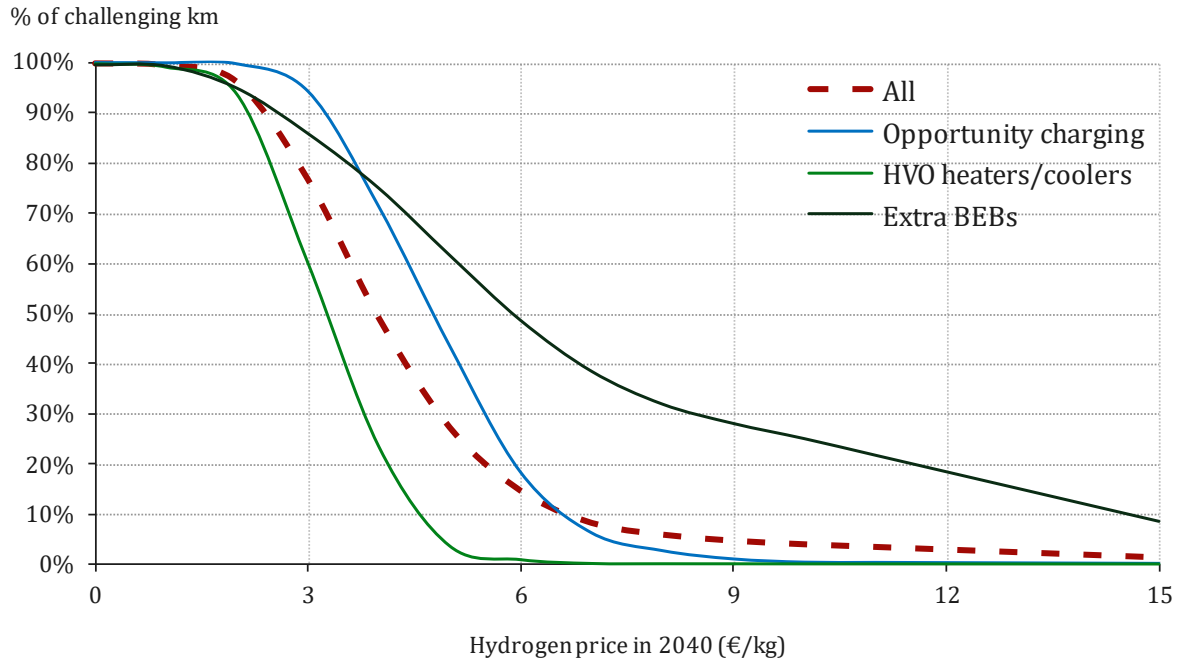


Figure 38: Proportion of challenging route distance which FCEBs would be cost-competitive with BEBs by hydrogen price and cheapest BEB option in 2040, for the base scenario.

Figure 39 and Figure 40 show that if HVO is banned for use in ZEBs for heating/cooling, the size of the addressable market for FCEBs increases, logically, as the cost of the cheapest BEB increases. In this scenario, FCEBs would be competitive in about 13% of challenging routes with prices at €7/kg (compared to 8% with HVO heaters/coolers), increasing to around 50% at €5/kg (compared to 27% with HVO heaters/coolers).

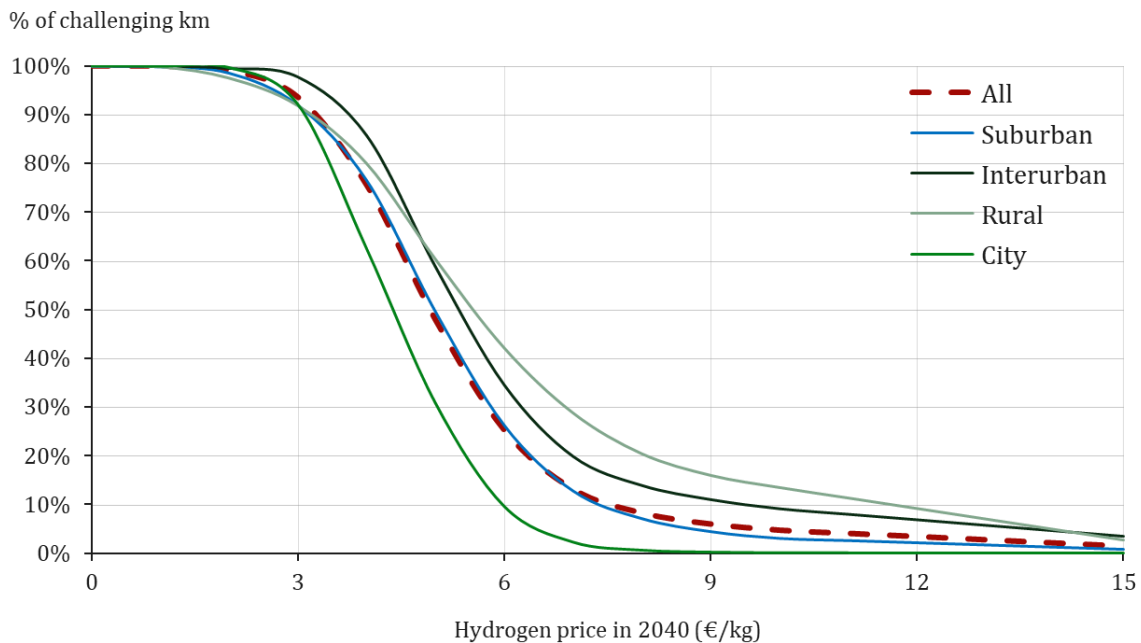


Figure 39: Proportion of challenging route distance which FCEBs would be cost-competitive with BEBs by hydrogen price and archetype in 2040, for a scenario with no HVO heaters/coolers.

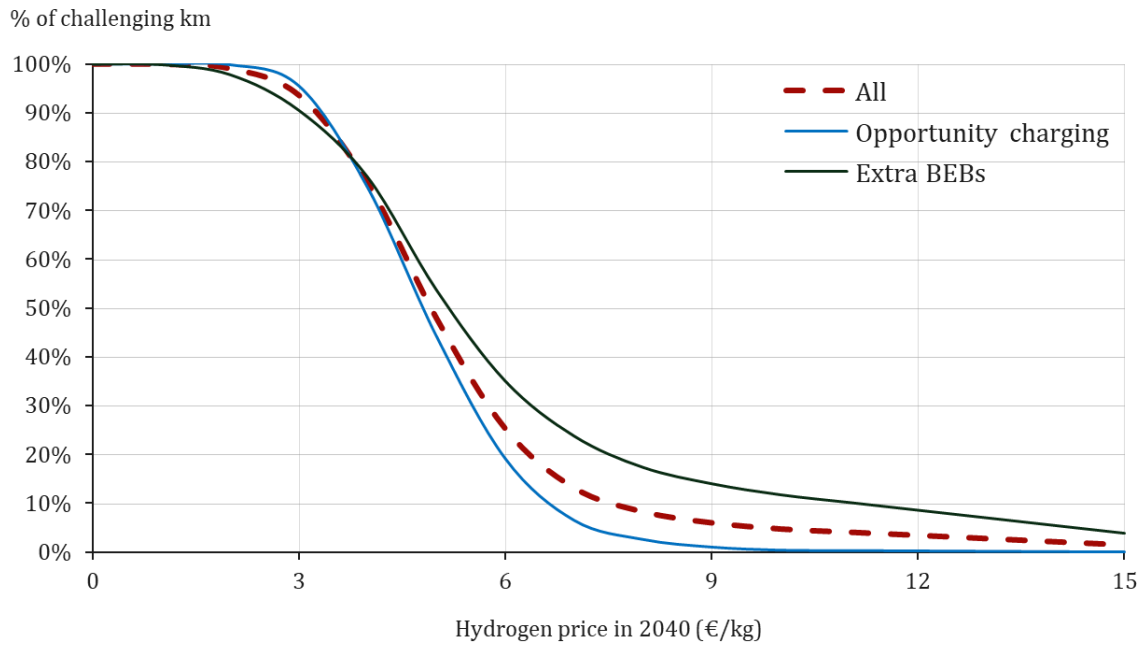


Figure 40: Proportion of challenging route distance which FCEBs would be cost-competitive with BEBs by hydrogen price and cheapest BEB option in 2040, for a scenario with no HVO heaters/coolers.

For the base scenario (including HVO heaters/coolers), Figure 41 shows the distribution of bus distance along challenging routes across countries by the maximum hydrogen price required in 2040 for a FCEB to be cost-competitive with the cheapest BEB option. In this graph, a higher hydrogen price means that a FCEB is more likely to be competitive with BEB, as it can be competitive even with a higher hydrogen price.

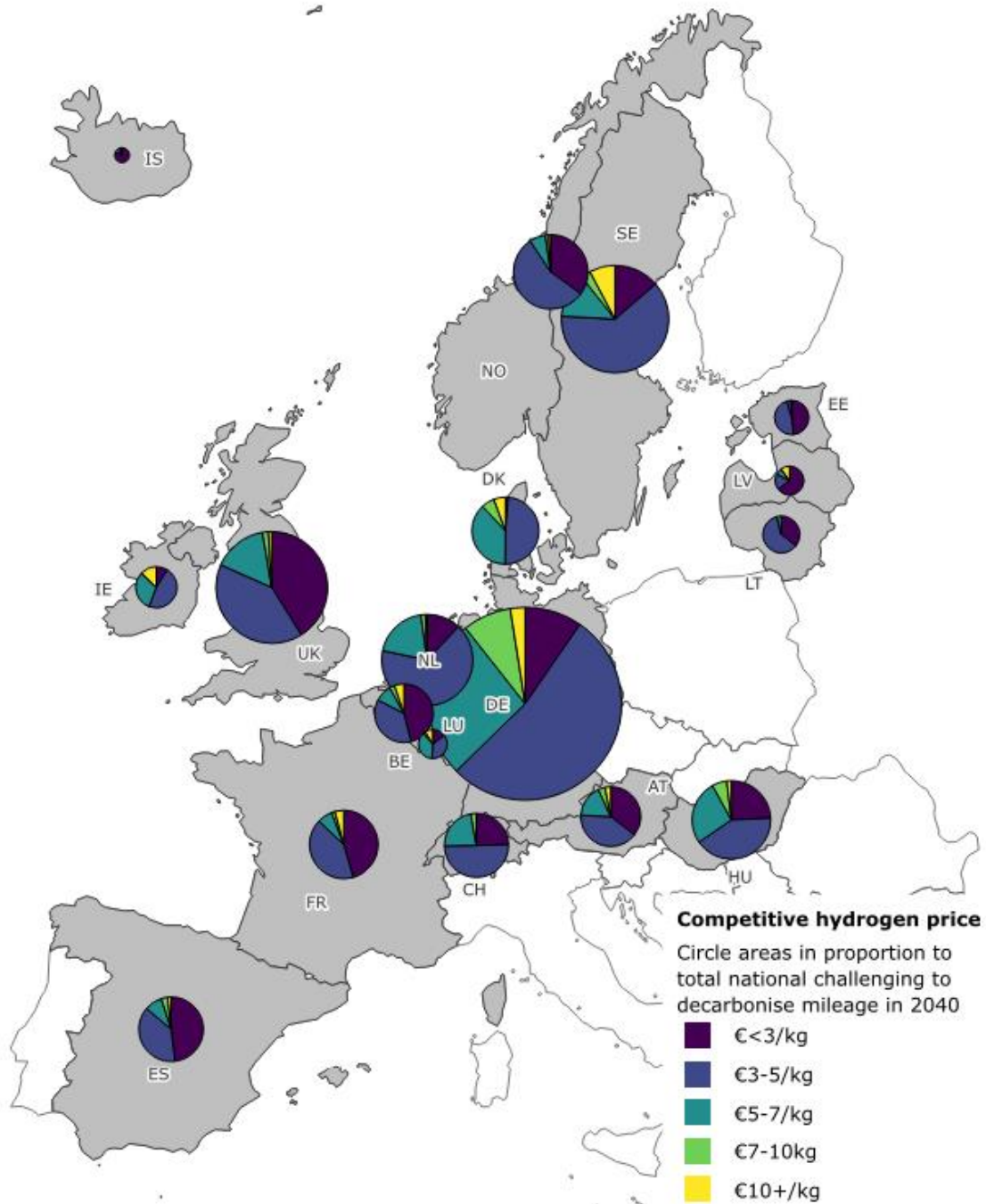


Figure 41: Green hydrogen price required to compete with BEB-based options (hard-to-decarbonise routes in countries with representative data only, 2040 proportions, 2025 prices)

Countries with larger than average potential markets with hydrogen prices above €7/kg include Germany (11%), Sweden (11%), Denmark (12%), Ireland (13%) and Luxembourg (11%), compared to the European average of 8%. If hydrogen prices of €5/kg are achieved, the list of countries with proportionally higher hydrogen markets than the European average (27% at €5/kg) only changes a small amount, with Sweden dropping off the list (24%) and Hungary joining (35%). Given Germany is the largest absolute market for hard-to-decarbonise bus services, Germany has the largest potential market for hydrogen in buses in Europe, representing approximately 40% of

the analysed market which could compete with BEBs if hydrogen prices of €5-7/kg are achieved.

These markets could be attractive for hydrogen for several reasons:

- For Germany, Hungary, Denmark and Ireland, higher than average electricity prices mean the fuel cost savings from BEBs are less, meaning higher hydrogen prices can still be competitive when including the additional costs for BEBs that are avoided with FCEBs (e.g. from extra buses, opportunity chargers).
- For Sweden and Luxembourg, there is a large proportion of routes which are more expensive than diesel for BEBs (see Figure 36), which implies that significant additional costs (e.g. extra buses, opportunity chargers, HVO) are required to deploy BEBs. These extra BEB costs enable FCEBs to be competitive in more of the market at higher hydrogen prices than in other countries.
- In contrast, Norway, France, Spain, Lithuania, Estonia and Iceland are unlikely to be major FCEB demand centres compared to other countries, as over 85% of distance requires hydrogen prices under €5/kg to be cost competitive (compared to 73% European average). This is mostly led by low electricity prices, which maximise the fuel cost savings of switching to BEBs.

#### Potential FCEB and hydrogen market

Our original analysis of the potential for hydrogen modelled FCEB uptake for vehicles operating on hard-to-decarbonise routes assuming EU CO<sub>2</sub> regulations were met on average 5 years ahead, the most challenging routes in a network were decarbonised last, and fleets were 15% larger than that required to operate services, to cover maintenance. With the evidence presented above, the competitiveness of FCEBs within that total potential market can now be more accurately assessed.

Figure 42 shows the size of the local bus FCEB vehicle parc (left graph) and its associated daily hydrogen demand (right graph) over time at a range of hydrogen prices. Prices are those paid by the operator, at 2025-constant values (not inflated).

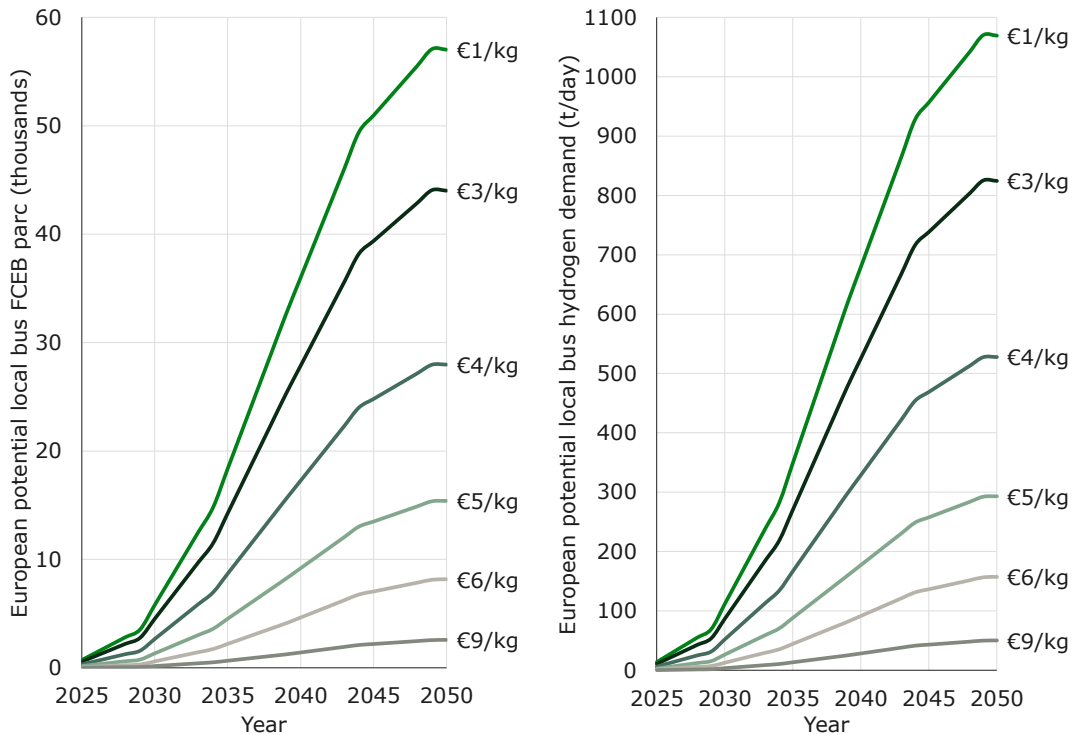


Figure 42: Potential future European local bus sector demand for FCEBs (left) and hydrogen (right), by hydrogen price per kilogram (2025 prices, excludes long-distance intercity coach)

Both FCEB parc and hydrogen demand patterns are broadly similar. No more than 5% of the market is attainable at current green hydrogen prices, typically €10/kg or greater. It is not until the price drops into the €4-5/kg range that FCEB becomes a common solution for hard-to-decarbonise local bus routes. It is not the purpose of this study to conclude whether such price levels are attainable, but it is worth noting that while some prior ERM studies have concluded a green hydrogen production cost of €4-5/kg *might* be possible, distribution to European bus operators at the relatively small local scales implied for bus (as analysed in our original report) will be commercially challenging. If €6-10/kg is considered a more pragmatic estimate of long-term green hydrogen prices, FCEBs attain no more than 15% of the hard-to-decarbonise market – about 4% of the total local bus market.

Long distance intercity coaches (routes over 100 km) have been excluded from the numerical analysis in this subsection, as our method cannot adequately evaluate the alternatives to FCEBs in this market segment. In many cases the only feasible option will be extra BEBs supported by extra remote rapid charging – if existing schedules are maintained. So, on pure TCO logic, long-distance coach is likely to remain one of the most likely use cases to adopt FCEBs. Up to 6 thousand might reasonably be added to the local bus parc (ramping up into the late 2040s), consuming an extra 600 tonnes of hydrogen per day (the average mileage per vehicle in this segment is around 5 times that of local bus, hence a disproportionately large fuel requirement per vehicle). However, as previously argued, scheduled coach passenger markets tend to be time rich and cash poor, so the optimal commercial solution is expected to be re-scheduling to optimise for BEBs (see Ember case study in earlier *Alternatives to FCEBs* section).

As hinted by the previous section, hydrogen will be more price-competitive for local bus decarbonisation in some European countries than in others. Small market niches

for FCEBs and hydrogen may still be commercially viable to supply if it is geographically concentrated. This is summarised in Figure 43 for selected larger nations.

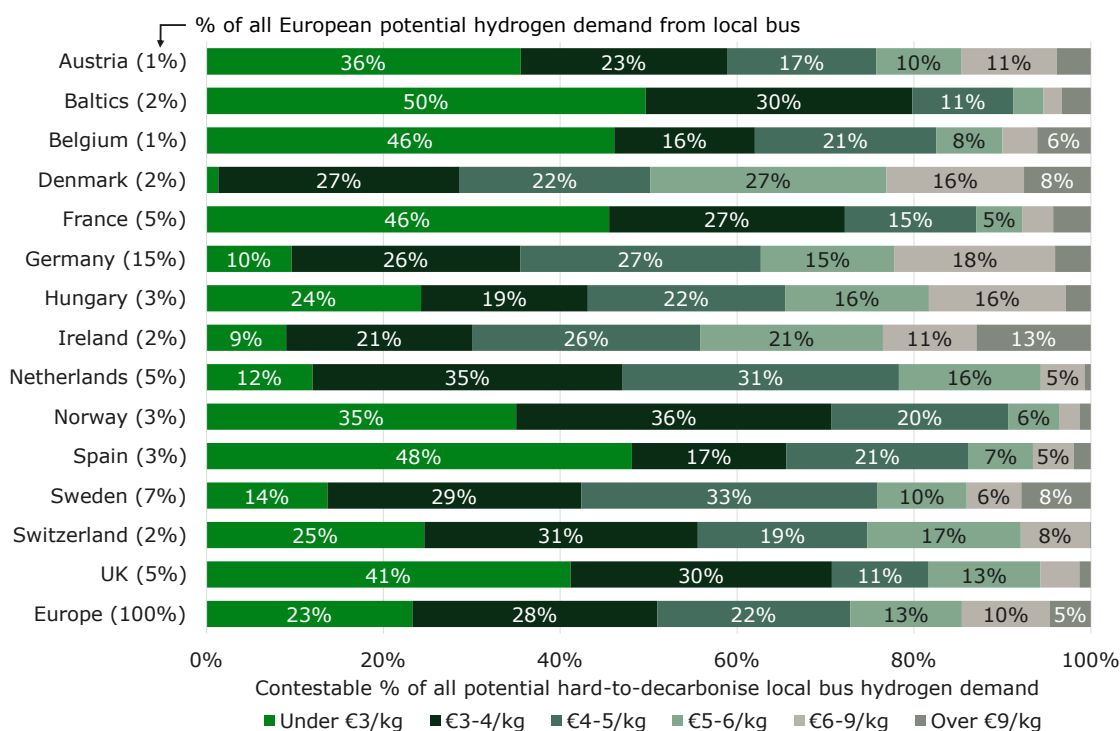


Figure 43: Distribution of potential hydrogen market for European local bus by price for selected nations (long-term demand, 2025 prices, segments under 5% not labelled)

Denmark and Ireland emerge as the countries with the highest proportion of their potential hydrogen market for local bus contestable at higher price points, but both are relatively small markets overall. In contrast, only 22% of one of the strongest markets identified in our original report, the Netherlands, is contestable above €5/kg. Germany and Sweden remain good targets for hydrogen, combining both high overall potential and reasonably balanced contestable price distributions.

As explored in our original report, in practice adequate scale of hydrogen supply and FCEB fleet is key to attaining the operational advantages FCEBs bring. For example, one of our interviewees with a fleet of just 7 FCEBs was reliant on a mobile hydrogen fuelling unit capped at 40 bar (in the order of a tenth the pressure of many permanent facilities) which meant refuelling took 4 hours, while lacking resilience against equipment failure. Likewise, their OEM was unable to offer local technical or training support for such a small fleet, making vehicle performance issues were more difficult to resolve. Broadly similar issues have been documented by JIVE partners in the UK.<sup>108</sup>

The analysis above assumes raw TCO is the only guide to decision-making. Earlier parts of this section’s analysis showed that there are substantial risks associated with many of the cheapest options, risks which many operators and agencies will choose to *price-in* to their decision-making. Likewise, one of the advantages of FCEBs is the *additional* aspect of their cost (beyond the basics costs of any ZEB adoption) in OPEX (as fuel), while comparable pure Zero Emission BEB-based options tend to emphasise CAPEX (as

<sup>108</sup> <https://fuelcellbuses.eu/public-transport-hydrogen/fuel-cell-bus-deployment-uk-%E2%80%93-lessons-jive-and-next-steps>

extra assets). Many operators have better access to revenue (not least as fares) than capital.

The least risk of the three BEB-based options for hard-to-decarbonise routes has previously been identified as deployment of extra BEBs, and as demonstrated in the previous section, FCEBs are much better able to compete against extra BEBs, even at relatively high hydrogen prices. While it is highly unlikely that all hard-to-decarbonise routes will opt to deploy extra BEBs, assuming they do gives insight into what the most optimistic scenario for local bus FCEBs and hydrogen could be.

Figure 42 illustrates the result of applying the TCO patterns for extra BEBs to all hard-to-decarbonise local bus. This is not the result of re-modelling TCO with only one BEB-based option, and there are clear skews in the type of routes where extra BEBs are cheapest, notably almost no city routes opt for extra BEBs. So, the results graphed are imprecise but broadly convey the magnitude of potential adjustment in favour of FCEBs were extra BEBs considered the only way to manage the risks of other options: Hydrogen becomes more competitive at high and middle price points, although a €6-10/kg price level would still only be competitive for a minority of the hard-to-decarbonise routes.

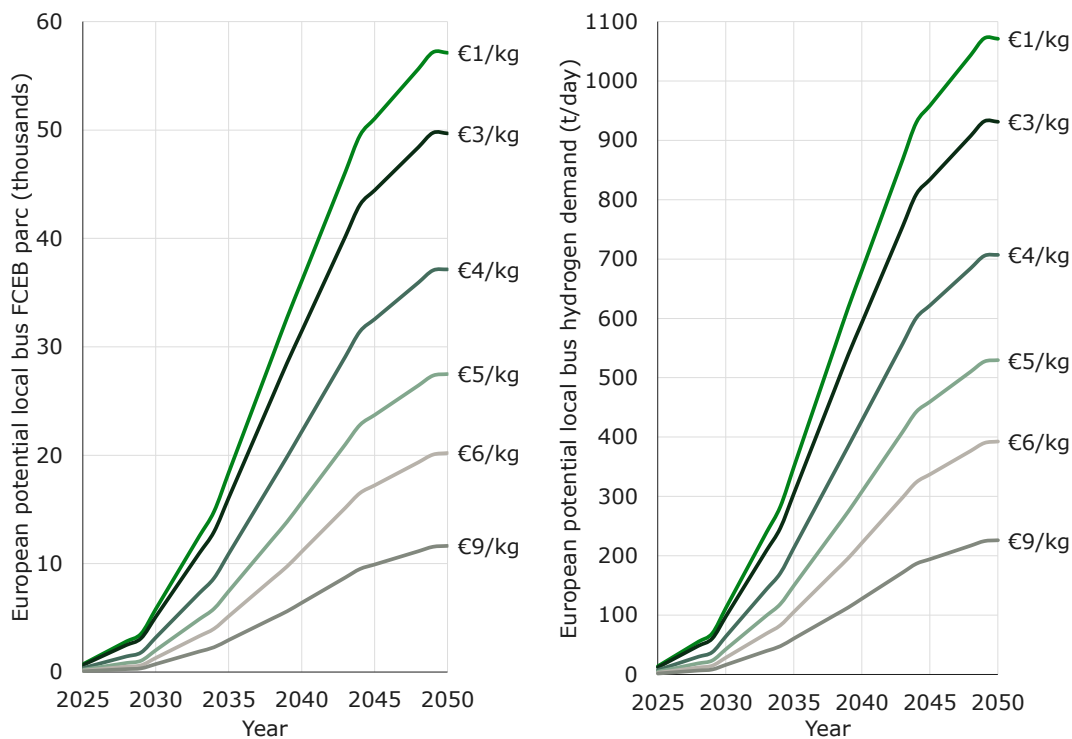


Figure 44: Indicative potential future European local bus sector demand for FCEBs (left) and hydrogen (right), if the whole hard-to-decarbonise market were to mirror FCEB contestability with only Extra BEBs, by hydrogen price per kilogram (2025 prices) – this scenario is illustrative of a theoretical extreme and should not be read as a likely outcome

## Secondary technologies

This section summarises bus decarbonisation solutions which are either highly situational in application or too technologically immature/ineffective to recommend as mainstream solutions.

### Energy management strategies

#### Overview

Energy management strategies are measures that operators can take to reduce the amount of energy consumed by buses. These measures can either target the energy used by auxiliary systems such as heating/cooling or a reduction in traction energy through eco-friendly driving techniques or optimised routing. Passenger cabin thermal management can account for up to half of a BEB’s energy consumption at temperatures below freezing (see figure below)<sup>109</sup>. As discussed in *Alternative fuels for heating and cooling*, any reduction in such energy demand from batteries allows more battery energy to be planned for traction. That extends daily duty range between charges, making routes less challenging to decarbonise with BEBs. Regardless of BEB route compatibility, such measures could potentially generate savings on capital or operating costs for operators, for example by allowing smaller batteries to be used, or simply buying less electricity to charge.

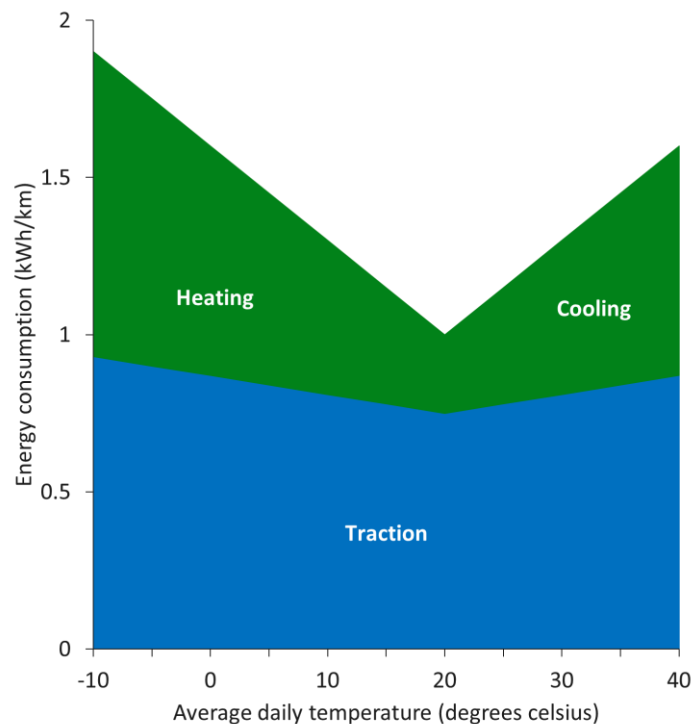


Figure 45: Indicative variation in BEB energy consumption due to external temperature (values will vary by vehicle type and operating style)<sup>109</sup>

<sup>109</sup> Values as modelled in the original JIVE report, “The potential for hydrogen buses in Europe: Results from the bulk analysis of passenger schedules”, page 53 – <https://fuelcellbuses.eu/public-transport-hydrogen/d336-potential-hydrogen-buses-europe-results-bulk-analysis-passenger> . These patterns were further validated by the experience of our interviewees Ruter in Oslo, see box, and by TMB in Barcelona, where summer air conditioning increased energy consumption by 40-50%.

### Case study: Electric bus operation in Norway

In Norway buses are required to operate in extremely challenging conditions during winter periods. During the winter of 2023, Ruter (the public transport authority in Oslo and Akershus) outlined that due to the especially harsh conditions there were significant issues with the operation of electric buses. Although this was in part attributed to new bus operation contracts starting at the same time, with both bus and charger infrastructure teething issues, Ruter saw a large increase in bus energy consumption over the winter. The challenging conditions saw bus energy consumption approximately double (from about 1.5 kWh/km in summer to 2-4 kWh/km in winter conditions). These recent experiences have led Ruter to consider opportunity charging for several upcoming tenders, even when not necessarily required for day-to-day operation.



Source: Interview with Ruter

Some examples of these energy management strategies are detailed below.

#### *Pre-conditioning of buses:*

In colder climates, this involves storing buses in temperature-controlled depots or sheds overnight or plugging them in to utilise power from the grid to ensure buses are at the required operating temperature ahead of departing onto their routes. This method reduces the energy drawn from the batteries to reach a suitable temperature during operation, which is particularly important to ensuring brake regeneration is efficient in the first hours of operation, as well as creating a comfortable environment for passengers.

Many urban operators, such as our interviewee Wiener Linien, affect basic pre-heating simply by managing overnight charging such that it finishes just before the bus is due to leave the depot for its first duty. Features that enable pre-conditioning of buses are already offered by several major OEMs, with software increasingly playing an important part in optimising the timing of overnight charging to balance cost and the need to pre-condition.<sup>110</sup> However, one interviewee was concerned that pre-heating could potentially increase battery fire risk without proper management. Restrictive (time-based) power supply agreements can also limit operational flexibility to pre-condition buses.

<sup>110</sup> <https://bydeurope.com/pdp-bus-coach>; <https://www.blue-bird.com/blue-bird-is-thawing-out-the-effects-of-cold-weather-on-electric-buses/>;  
[https://www.man.eu/ntg\\_media/media/en/content\\_medien/doc/bw\\_master/bus\\_1/man-eMobility-broschuere-de.pdf](https://www.man.eu/ntg_media/media/en/content_medien/doc/bw_master/bus_1/man-eMobility-broschuere-de.pdf)

In warmer climates, such as Barcelona, our interview noted pre-heating was available but not required. Likewise, there is no scope to save energy before the bus enters daily service, as active cooling of the passenger cabin is not required until later in the day.

*Thermal control of charging infrastructure:*

Such thermal management measures can be applied to the charging infrastructure as well as the buses, with studies showing that temperature can have an impact on charging times required.<sup>111</sup> In places with very hot climates like Qatar, mitigating strategies have been implemented such as housing chargers under complete shades and positioning inverters in air-conditioned kiosks.<sup>112</sup>

*Driver training and roster optimisation:*

Drivers can be trained to operate buses in a manner that reduces energy consumption. This could include taking advantage of regenerative braking features, reducing unnecessary acceleration/deceleration, and minimising time with the bus doors open. The impact of good practice when driving can be significant, with some operators reporting substantial variations in range between different drivers on the same bus and route.<sup>113</sup> Third party software exists that allows operators to monitor driving performance and identify the suitable practices for their routes and buses and claim energy consumption savings of 10-20% can be achieved.<sup>114</sup>

Some of our operator/agency interviewees were aware that some of their drivers were more energy-efficient than others. Anecdotes such as female drivers tending to be more energy-efficient than males are commonly shared within the sector. However, pro-actively rostering, or directly incentivising, the most energy-efficient drivers to the most energy-demanding routes risks labour relations or employee contractual disputes, especially where working practices have traditionally been relatively static.

Beyond the bus and driver, operators can optimise route scheduling to ensure bus downtime or “not in service” legs are minimised. While this is not necessarily a BEB-exclusive strategy (bus operators optimise scheduling and spend for all fuel types), BEBs require operators to incorporate charging dynamics into their operations. Depot management software solutions that can manage and optimise the charging and utilisation of BEBs exist and have been deployed by some operators.<sup>115</sup>

*Auxiliary diesel heaters on BEBs during colder months:*

Another strategy deployed in cooler climates is coupling BEBs with an auxiliary diesel heater, an approach analysed in more detail in the “Alternative fuels for heating and cooling” section above. This configuration allows the batteries to be used for traction, while relying on the diesel heaters for climate control. This can minimise the size of batteries required, or frequency of charging needed and offers a lower emissions solution than using a diesel bus year-round. Moreover, if HVO or an e/bio diesel is

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<sup>111</sup> Chapter 7 (7.1 & 7.3) in [https://itdp.org/wp-content/uploads/2021/09/ITDP\\_Ebus\\_singlepages.pdf](https://itdp.org/wp-content/uploads/2021/09/ITDP_Ebus_singlepages.pdf)

<sup>112</sup> <https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=10496690>

<sup>113</sup> [https://www.arlingtonva.us/files/sharedassets/public/v/1/transportation/documents/zero-emissions-buses/appendix-b-from-art-zeb-study\\_final-report\\_20230801.pdf](https://www.arlingtonva.us/files/sharedassets/public/v/1/transportation/documents/zero-emissions-buses/appendix-b-from-art-zeb-study_final-report_20230801.pdf)

<sup>114</sup> <https://bledsystem.com/eco-driving-for-ev-bus-fleets-a-must-have-for-operation-performance-case-studies-part-i/>

<sup>115</sup> [https://www.mobilityhouse.com/int\\_en/charging-solutions-for-electric-bus-fleets#whitepaper](https://www.mobilityhouse.com/int_en/charging-solutions-for-electric-bus-fleets#whitepaper);  
<https://www.siemens.com/global/en/products/energy/emobility/depot-charging-solutions.html>;  
<https://kempower.com/solution/chargeye-for-electric-bus-and-truck-fleet-depots-solution/>

used for heating, the solution could still be zero or very low emissions on a well-to-wheel basis. Auxiliary diesel heaters are offered by major OEMs (e.g. MAN's Lion City buses come with heat pumps and auxiliary heaters that can use biodiesel or HVO)<sup>116</sup> and have been deployed by several operators, particularly in extreme cold climates.<sup>117</sup>

#### Benefits and challenges

As stated above, the main benefits of these strategies are reductions in the battery sizes, in the frequency of charging required to support bus operations, or simply in total electricity bought.

The above strategies require buy-in from different stakeholders to ensure they are implemented, particularly those involving user behaviour or operational changes like eco-friendly driving or pre-conditioning. Due to the different factors involved, it is also difficult to quantify the exact benefits associated with some of these. Furthermore, continued monitoring is required to ensure that they are being implemented consistently. Some specific challenges are listed below.

- While pre-conditioning can be implemented manually through operational changes and timers applied to the HVAC system, this would be difficult to optimise and investing in automated software may be necessary. Suboptimal pre-conditioning could potentially result in increased total energy consumption if, for example, the bus reaches operating conditions too soon before departure and expends additional energy to maintain those conditions until needed.<sup>118</sup>
- As further discussed in the Alternative fuels for heating and cooling section, usage of auxiliary diesel heaters could potentially impact compliance with emissions standards, such as the EU's CO<sub>2</sub> Standard for heavy-duty vehicles. While this is currently unclear, regulations could be modified to address such measures and the associated emissions. At a local level, air quality emissions regulations, local policy decisions, or contractual terms could also limit operators' ability to deploy such a solution.
- Ensuring all drivers consistently follow best practice can be challenging to enforce or monitor. Allocating the most compliant drivers to the most challenging routes may trigger labour relations disputes, so operational standards may need to be established based on the capabilities of the worst performing driver.

Energy, especially thermal management, is emerging as a key area of interest to BEB operators seeking to optimise vehicle performance, especially in extreme climatic conditions. Many strategies bring marginal or inconsistent gains, which while potentially advantageous, are unlikely to alter overall energy use and BEB route compatibility by more than the accuracy inherent in our strategic modelling. However,

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<sup>116</sup> [https://www.man.eu/ntg\\_media/media/en/content\\_medien/doc/bw\\_master/bus\\_1/man-eMobility-broschuere-de.pdf](https://www.man.eu/ntg_media/media/en/content_medien/doc/bw_master/bus_1/man-eMobility-broschuere-de.pdf)

<sup>117</sup> <https://driveelectric.gov/files/esb-cold-weather-help-sheet.pdf>;  
<https://electricschoolbusinitiative.org/electric-school-bus-series-successfully-operating-cold-weather-three-rivers-michigan-0>

<sup>118</sup> Section 2.3.3 in [https://www.now-gmbh.de/wp-content/uploads/2022/09/220823\\_BeFo\\_Bus\\_Abschluss\\_ENG\\_DIGITAL\\_EZ.pdf](https://www.now-gmbh.de/wp-content/uploads/2022/09/220823_BeFo_Bus_Abschluss_ENG_DIGITAL_EZ.pdf)

the use of secondary, non-battery-dependant, heaters can enable a stark reduction in battery energy requirements. For this reason, the option has been taken forward for further analysis in Alternative fuels for heating and cooling, although as discussed there, policy towards this approach differs across Europe, which may limit application in practice.

## Wireless charging

### Overview

Wireless charging is a technology that uses magnetic resonance to charge EV batteries without plugs or cables. A standard Wireless Power Transmission (WPT) system is made up of a transmitting coil buried in the ground and a receiving coil built into the vehicle<sup>119</sup>. This means that buses must be fitted or retrofitted with the required connectivity and recharging equipment. There are two main options for wireless charging<sup>120</sup>:

- **Static** – wireless charging pads are built into the ground at depots or bus stops to allow stationary fleets to charge overnight or at stops along their routes (opportunity charging).
- **Dynamic** – wireless charging coils are installed under stretches of road to allow vehicles to charge as they drive.

To date, this technology has not been scaled commercially, and only pilot projects have been implemented. Two of our operator/agency interviewees had trialled the technology at different points in the last ten years, but neither had continued using it – a pattern widely repeated. The primary reason for this is the high cost of the additional equipment and civil works needed to install this equipment compared to traditional plug-in charging. The advantages and disadvantages of both types of this technology are discussed together below, with any nuances for static and dynamic charging explained in text.

### Benefits

- **Range extension and opportunity charging:** Opportunity charging with a WPT along bus routes (either static at bus stops or dynamic on parts of the route) can reduce the size of battery required on the bus, which can in turn reduce the battery costs of a bus or, more broadly, allow “challenging” routes with high energy requirements to be operated with BEBs.<sup>121</sup>
- **Smaller surface footprint for charging:** Especially in areas where space is highly constrained, static wireless chargers minimise the footprint requirement of charging equipment at depots and allow the available space to be optimised.<sup>120</sup> Depots lose between 10% (with gantry-based cables) and 30% (where non-modular chargers are installed next to parking bays) of vehicle space when installing plug-based charging.<sup>122</sup>

<sup>119</sup> <https://www.emobility-engineering.com/wireless-charging/>

<sup>120</sup> <https://www.mdpi.com/1996-1073/16/5/2138>

<sup>121</sup> <https://www.sciencedirect.com/science/article/abs/pii/S0306261924012959>

<sup>122</sup> Observations from First Group.

- **Simplicity of charging:** Unlike plug-in charging, and some pantograph systems, bus drivers do not need to remember to charge their vehicle as this is done automatically for WPTs. In the case of dynamic charging, no time is lost in returning to the depot or having an extended break at a bus stop, as the charging is done while the bus is in motion.

#### Case study: Wireless charging in Trondheim, Norway, to provide additional charging power for heating and cooling

In 2023, The Transportation Authority of Trøndelag County in Norway contracted Electreon to install their wireless Electric Road System to charge an electric bus on a specified route. Both Electreon and the customer will evaluate the effectiveness of this solution in meeting the extra power needs from the extreme climatic conditions in the region. The project was set to start operation in 2024, but results are yet to be published.



Source: <https://bus-news.com/norway-electreon-to-construct-electric-road-to-wirelessly-charge-buses/>

#### Challenges

- **Power transfer efficiency:** WPTs face issues in delivering highly efficient power transfer: distance and air between the coils and the receiver greatly reduces power transfer efficiency of this technology. The ratio of power efficiency to transmitter-to-receiver separation is inversely proportional, meaning that if the distance between the transmitter and receiver is doubled, the transmission efficiency is halved.<sup>120</sup> This is especially important for large vehicles such as buses which have a relatively large minimum ground clearance, so their receivers are inherently further from the transmitter coils in the ground. Historically, around 2015, this resulted in power loss in wireless charging being ca. 7-12% greater than in conventional plug-in charging.<sup>123</sup> One of our German operator/agency interviewees noted that the theoretically available downtime at the stops was often not available in practice. Current WPT manufacturers claim wireless charging has equivalent efficiency to wired charging<sup>124</sup>. The maximum power of these systems is also limited 450kW or less. That is broadly comparable to current pantograph opportunity charging, but significantly less than the MegaWatt opportunity chargers now emerging.

<sup>123</sup> <https://www.mdpi.com/1996-1073/16/5/2138>

<sup>124</sup> <https://www.inductev.com/>

- Cost of transmission equipment:** Compared to conventional plug-in charging, both dynamic and static wireless charging can be significantly more expensive to install due to cost of the equipment and the increased scale of civil works required. A suite of between 4 and 6 wireless charging pads (receiver coils) per bus reportedly cost \$30,000 (ca. €28,000) today<sup>125,126</sup>, with the transmission coils adding an additional \$2 million (ca. €1.9 million) per mile of electrified road<sup>126</sup> or ca. €180,000 per static charging pad<sup>129</sup>. WPT offers no cost advantage over pantograph opportunity charging and can cost multiple times the equivalent depot overnight plug charge. Operating and maintenance costs are higher due to the difficulty in accessing the transmission coils and cooling systems underground<sup>127</sup>. This means the whole WPT solution is expensive compared to the incumbent technology and pantograph. Costs for three pilot programs are summarised in the table below:

Table 2: Summary of costs of wireless charging based on available case studies

| Site                      | Charging type | Published Cost <sup>128</sup>   |
|---------------------------|---------------|---|
| EMT-Madrid <sup>129</sup> | Static        | Just over €366,000 per 100kW induction charging static site (two charge points) |
| Trondheim <sup>130</sup>  | Dynamic       | \$2.12 million of government funding for 0.1km of dynamic charging road         |
| Balingen <sup>131</sup>   | Dynamic       | €3.2 million for 1km of dynamic charging road                                   |

- Remaining reliance on plug-in charging:** In many WPT implementations, buses were also plugged in for their overnight charge, with wireless charging only used for top-up and opportunity charging. This means multiple charging systems need to be invested in, although this is also common when using non-depot pantograph opportunity charging.
- Additional equipment:** The cost and weight of the required receiver (for both static and dynamic charging) for buses reduces the operating efficiency of the vehicle and adds upfront cost, negating the majority of the available savings from battery downsizing (assuming a \$30,000 (ca. €28,000) receiver coil installation cost). While BEBs that exclusively use wireless charging may have

<sup>125</sup> <https://www.ft.com/content/720bc57b-944f-47a5-8d65-12439228571b>

<sup>126</sup> <https://www.bbc.com/future/article/20240130-wireless-charging-the-roads-where-electric-vehicles-never-need-to-plug-in>

<sup>127</sup> As noted in London's trial

<sup>128</sup> Costs provided as published, without comprehensive list and breakdown of included components

<sup>129</sup> <https://psecommunity.org/wp-content/plugins/wporg/includes/file/2302/LAPSE-2023.9890-1v1.pdf>

<sup>130</sup> <https://www.linkedin.com/pulse/norway-unveils-worlds-first-wireless-charging-road-electric-eraj-ali-ltxwc/>

<sup>131</sup> <https://bus-news.com/wp-content/uploads/sites/4/2023/07/Electreon-ELINA-Balingen-Project-Germany.pdf>

some weight advantages compared to plug-in BEBs<sup>132</sup>, the need to additionally support traditional chargers for overnight charging adds weight to the vehicle. Based on a previous study from the University of Michigan, the receiver coils add approximately 5% to the total mass of the BEB<sup>132</sup>: the impact on efficiency is assumed to be commensurate.

- **Stuck in the pilot project phase<sup>133</sup>:** Pilot WPT projects date back more than 10 years. All are thought to have been part-funded by government bodies with project-specific subsidies. Only one project has been publicly announced with significant numbers of wireless charging for bus parking<sup>134</sup>. Our interview with Transport for London highlighted a lack of industry standards for wireless charging<sup>127</sup>. This brings the risk of being locked to a particular wireless charging technology, which inhibits competition in public contracts and exposes the installation's owner to the risk of its sole supplier failing commercially. For example, one of our German interviewees found that their supplier of charging coils stopped supporting them within two years of installation.
- **Practical challenges:** One of our German interviewees noted that the civil engineering work to install WPT was extremely complex due to conflicts with other utilities: Large subterranean components raise some of the same risks as city centre tram construction. In London, there were practical difficulties in lining up buses with transmission coils, especially with the short time frames available for top-up charging between routes.<sup>127</sup>

#### Case study: Seattle to employ InductEV's wireless charging solution for buses



The Seattle area is set to purchase 33 zero-emission Enviro500EV buses produced by Alexander Dennis, featuring an inductive charging system produced by InductEV. In addition to recharging at their depots, the buses will charge during stops, parking over 300kW charging pads installed in the road. InductEV currently has 35 in-ground charging pads in the state and is aiming to replace wired charging.

InductEV's wireless charging technology was first installed in Washington in 2017 (Link Transit in Wenatchee). Buses using this wireless charging solution achieved a 17-hour duty cycle and a 1:1 diesel replacement ratio for enhanced range and operational efficiency.

Source: <https://www.inductev.com/press-releases/sound-transit-to-go-wireless-in-seattle>

In summary, wireless is a less technically and commercially mature charging technology than plug-in charging or pantograph. Wireless charging tends to have

<sup>132</sup> [https://css.umich.edu/sites/default/files/css\\_doc/CSS15-26.pdf](https://css.umich.edu/sites/default/files/css_doc/CSS15-26.pdf)

<sup>133</sup> <https://www.autoexpress.co.uk/features/100194/wireless-electric-car-charging-ev-charging-without-cables-future>

<sup>134</sup> <https://bus-news.com/electreon-unveils-commercial-wireless-charging-terminal-for-buses-in-israel/>

greater capital cost and installation risk and potentially lower efficiency. Static wireless offers no clear operational advantage in comparison to pantograph opportunity charging. Dynamic wireless charging has the theoretical operational advantage of not adding to in-service BEB downtime and could suit roads which many vehicles operate over. The fixed nature of bus routes makes bus one of the strongest natural markets for this technology. However, we found no evidence of a clear commercial business case for dynamic wireless charging. Consequently, we have not further considered wireless charging as mainstream option for most hard-to-decarbonise bus routes.

## Trolleybus

### Traditional trolleybus

A trolleybus is an electric bus that uses poles to connect to overhead wires to draw power for propelling the bus. Two wires overhead carry the positive and negative electrical currents, allowing the trolley bus to receive a constant supply of electricity while the poles are connected to the wires. Trolleybuses have been deployed in approximately 300 cities worldwide.<sup>137</sup> The traditional trolleybus does not have the ability to travel “off-wire”, which limits the use of the trolleybus to roads with overhead wires installed.

The cost of installing overhead wiring for routes without existing trolleybus infrastructure is significant. A Swedish report estimated the cost for the wiring at SEK 12.7m per km (€1.1m/km, 2014 prices),<sup>135</sup> and the 7 km trolleybus route extension in St Gallen, Switzerland cost CHF 1m per km (€1.1m/km, 2020 prices).<sup>138</sup> The cost of overhead wiring in France was estimated at €1m to €1.7m per km of line (2024 prices).<sup>136</sup> In Canada, the cost of overhead wiring was estimated at \$1m CAD per km (€0.7m/km, 2021 prices).<sup>138</sup> In addition, electrical substations may be required, depending on whether the existing grid connections of the area are large enough to provide for the additional power required by trolleybuses. 2024 costs in France are estimated at €750,000 for a rectifier substation.<sup>136</sup> A cost estimation for new substations in Canada in 2021 for a trolleybus route was estimated at \$25.2m CAD (€17m) for 20 substations with rectifiers for an 80 km route.<sup>138</sup>

Anonymised data for an operator in Southern Germany suggests the maintenance costs of overhead trolleybus wiring can be significant, at around €14,000 per km per year.

Another German interviewee noted that there had been considerable local resistance to extending overhead electrification, even within the city centre: A proposal was rejected by local referendum, despite being promoted by local government. Trolleybus network extension has a far higher set of land use planning policy barriers to overcome than for conventional bus operation.

In conclusion, the cost of wiring a route for trolleybuses can be expected at €1-1.5m per km, which even for short urban routes is likely to be a much more expensive decarbonisation solution than installing opportunity charging or operating extra BEBs. However, where trolleybus wiring already exists, it is possible to utilise that existing infrastructure to decarbonise routes that run only partly under those wires, as described in the next section.

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<sup>135</sup> [https://storstockholm.vansterpartiet.se/files/2014/06/V-SLL\\_tradbuss\\_screen.pdf](https://storstockholm.vansterpartiet.se/files/2014/06/V-SLL_tradbuss_screen.pdf)

### In-motion charging trolleybus

Many modern trolleybuses are now dual-mode, using a small diesel engine or battery to transport the bus short distances when it is not connected to overhead wires.<sup>136</sup>

When the bus uses a battery instead of a diesel engine, this dual-mode technology is also called “in-motion charging” or IMC.<sup>137</sup>

The battery is charged simultaneously while the bus is connected to the overhead lines and using the power to move. When the bus reaches parts of the route without overhead lines, the bus disconnects from the lines and the onboard battery is used to power the bus. This allows bus routes to be operated that only partly run under wires, allowing existing infrastructure to provide the equivalent of opportunity charging without the bus stopping and potentially without additional infrastructure investment. Several cities such as Zurich, Geneva, Berne, Budapest, St. Petersburg, Marrakech, Beijing and San Francisco are using dual-mode IMC trolleybuses.<sup>137</sup>

Sources suggest that the upfront cost of an IMC trolleybus can be comparable to a BEB when expressed for the same passenger capacity, if additional infrastructure is not needed.<sup>138</sup> Since most trolleybuses are above average length – 18 or 24 metres – average trolleybus vehicle costs tend to be much higher. The onboard battery can also be specifically sized for the portion of the route that it is needed, to reduce the cost of the battery while providing the range needed.<sup>139</sup> Additionally, few or no charging stations are needed for trolley buses, which provides an infrastructure cost advantage over opportunity charged BEBs. This approach also tends to reduce the requirement for dedicated new electricity grid connections, as trolleybuses are taking a constant, stable supply of power at approximately 600 V spread across a whole network instead of recharging at a rapid or ultra-fast charging station at a single location.<sup>140,141</sup>

However, IMC trolleybus batteries undergo many more charge cycles during operation than conventional BEBs, as shown in the figure below. Nevertheless, the LTO batteries used in trolleybuses can sustain far more frequent cycling than NMC and LFP batteries without experiencing significant degradation, and because they can frequently recharge, IMC trolleybus battery capacities are typically far smaller than BEBs, at around 100 kWh.<sup>142</sup>

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<sup>136</sup> <https://www.agir-transport.org/wp-content/uploads/2024/07/Etude-comparative-des-differentes-motorisations-de-bus-2024.pdf>

<sup>137</sup> <https://www.uitp.org/publications/in-motion-charging-innovative-trolleybus/>

<sup>138</sup> <https://www.ebrd.com/infrastructure/going-electric.pdf>

<sup>139</sup> <https://www.sciencedirect.com/science/article/abs/pii/S0378779619302494>

<sup>140</sup> <https://climateandcommunity.org/wp-content/uploads/2023/12/ElectrificationofSFMuni.FINAL-2.pdf>

<sup>141</sup> <https://www.sustainable-bus.com/news/tallinn-revives-trolleybus-technology-procurement-40-vehicles/>

<sup>142</sup> <https://www.sciencedirect.com/science/article/pii/S2590116824000304>



Figure 46: Illustrative daily number of cycles for a battery on a battery electric bus compared to a trolleybus with an onboard battery (in-motion charging bus). Estimation uses the metrics provided by Centrale d’Achat du Transport Public ([Etude-comparative-des-differentes-motorisations-de-bus-2024.pdf](#)): a battery size of 450 kWh and electricity consumption rate of 125 kWh/100 km for a BEB and a battery size of 50 kWh and electricity consumption rate of 190 kWh/100 km for an IMC bus, an average daily distance of 300 km for both bus types and an estimation of 40% of the IMC bus daily route requiring battery use instead of overhead power supply.

In summary, traditional trolleybuses are likely too expensive to introduce to routes that do not already have full coverage of trolleybus infrastructure. However, IMC trolleybuses could be an option for routes with existing fragmented trolleybus infrastructure, without the restriction in route flexibility that comes with traditional trolleybuses. Each route would need to consider the length of trolleybus overhead lines compared to the total route length and ensure that the battery size of the IMC trolleybus could fully recharge during the covered portion of each route.

While IMC has potential as a solution for hard-to-decarbonise bus routes, this is only true of cities with existing trolleybus wiring. Most European cities do not have trolleybus networks, and there is no effective coverage of some of the most challenging operational archetypes, notably interurban routes. Consequently, IMC trolleybus cannot be considered as a viable option for most European local bus routes.

### Battery swapping

#### Overview

Battery swapping is a technology for electric vehicles in which the battery is removed and swapped with a fully charged battery, as part of the routine operation of the vehicle. The process of swapping a Heavy Duty Vehicle (HDV, including buses) battery potentially takes less than 5 minutes.<sup>143</sup> Operationally, vehicle downtime is comparable to routine enroute pantograph opportunity charging. However, swaps can effectively replenish the entire battery capacity: swapping is potentially in the order of ten times quicker than current direct rapid charging technologies for HDVs.

Battery swapping is common for two-wheeler vehicles (e.g., scooters, motorcycles) in parts of Asia, with Gogoro as the largest provider of battery swapping stations.<sup>144</sup> Swaps are manual, serving customers who lack home charging options and/or access to finance purchase electric vehicles. While these examples demonstrate the viability of swapping technology at scale, neither their physical operations nor business case are transferrable to buses.

<sup>143</sup> <https://www.fleetnews.co.uk/news/tual-launches-swappable-batteries-for-electric-trucks> with truck battery swapping in China observed to take 3-6 minutes - <https://theicct.org/china-is-propelling-its-electric-truck-market-aug23/>

<sup>144</sup> <https://www.gogoro.com/>

There is currently limited deployment of robotic battery swapping stations for cars, with China leading deployment through provider Nio.<sup>145,146</sup> Battery swapping capability is common in China’s non-bus HDVs like tractor-trailers and dump trucks (Figure 47), although active battery swapping is far less common.<sup>147</sup> However, Chinese vehicle decarbonisation rationale can simply reflect specific government policy interventions, and is not always a good guide to optimal solutions elsewhere.

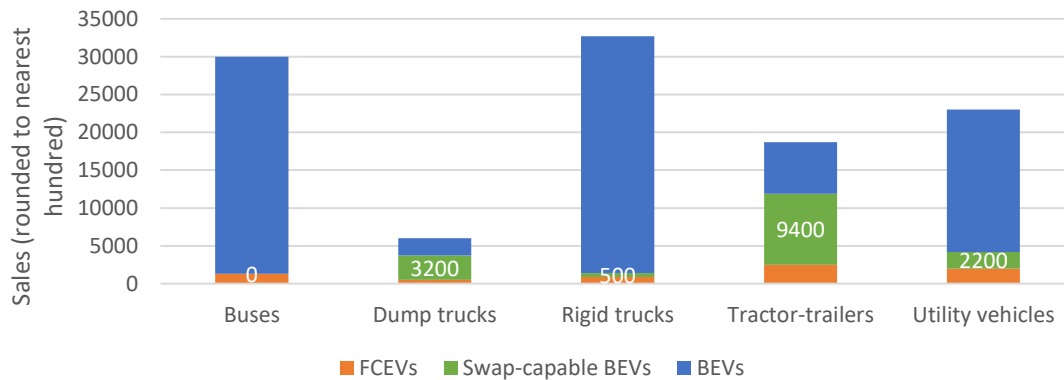


Figure 47: Sales of zero-emission technologies in China in 2023 ([https://theicct.org/wp-content/uploads/2024/08/ID-191-%E2%80%93-EU-R2Z-Q1\\_final-1.pdf](https://theicct.org/wp-content/uploads/2024/08/ID-191-%E2%80%93-EU-R2Z-Q1_final-1.pdf)).

Norway is trialling battery swapping for commuter ferries in Oslo, where relatively high ship energy requirements and short port dwell times would otherwise imply the need for multi-MegaWatt opportunity charging solutions which do not yet exist.<sup>148</sup>

Battery swapping is very unusual for buses. For example, in 2013 Pohang City in Korea trialled battery swapping for a shuttle bus route of 22 km with 3 bus stops and 2 buses.<sup>149</sup> The battery swapping station contained 6 batteries in total. By 2023 the battery swapping station had been converted into a regular electric vehicle charging station.<sup>150</sup> India’s Sun Mobility (with bus OEM Veera Vahana) has prototyped a battery swapping system for mid/long-distance buses, although it is marketed primarily as a means of reducing effective BEB capital cost.<sup>151</sup>

### Benefits and challenges

There are theoretical benefits that the technology could bring to local buses, all with significant caveats:

- The key advantage of battery swapping is to increase the flexibility of BEB operations by forgoing almost all the downtime otherwise needed to charge the bus directly. In practice local bus routes do not operate at constant

<sup>145</sup> <https://www.nio.com/nio-power>

<sup>146</sup> <https://www.fleetnews.co.uk/news/ev-manufacturer-nio-opens-30th-battery-swap-station-in-europe>

<sup>147</sup> <https://cleantechnica.com/2024/05/27/data-on-battery-swapping-for-heavy-and-light-vehicles-is-nuanced/>

<sup>148</sup> <https://businessnorway.com/solutions/shiftr-revolutionises-fast-ferries-with-autonomous-battery-swap> and interview with Ruter

<sup>149</sup> <https://www.iea.org/policies/3165-phoang-citys-e-bus-pilot-project>

<sup>150</sup> <https://en.namu.wiki/w/%ED%8F%AC%ED%95%AD%EB%B2%84%EC%8A%A4#fn-13>

<sup>151</sup> <https://www.sustainable-bus.com/news/sun-mobility-veera-vahana-battery-swapping-bus-india/>

headway throughout the day and night, limiting the practical utility of swapping large (maximum BEB capacity) batteries to no more than twice per day across a modern BEB fleet. Swapping smaller batteries regularly offers no significant downtime reduction compared to pantograph opportunity charging.

- Additional batteries could in theory be added to the pool to allow all batteries to be charged during off-peak hours, which could lower electricity costs. In practice most local bus operators are already able to take advantage of the cheapest overnight rates to conduct most daily charging, nullifying most of battery swapping's strategic advantage.
- Battery charging can be conducted at a slower rate compared to the rapid, especially opportunity, charging that may be required for non-swapping BEBs. This slower charging may help minimize battery degradation over time.<sup>152</sup> However, any degradation advantage is likely offset by the requirement to maintain more batteries overall: each battery has its own calendar degradation, which can be expected to exceed the degradation of charging less often and less rapidly.

There are significant costs and practical challenges to deploying battery swapping for local buses:

- Bus operators would need to install battery swapping stations at the end of a route to minimise downtime, or potentially in a nearby central location such as a depot. Safety, planning and reliability risks are likely to be higher than for equivalent conventional charging installations since bus battery swapping technology is currently immature.
- Swapping stations will tend to be more expensive than direct charging solutions: Stations must include battery charging, so raise similar grid connection, physical space, and capital cost issues to other forms of bus charging – plus the cost and space of the equipment to automate the swap and store batteries.
- Additional batteries need to be purchased. For example, the Shenzhen Bus Group estimated 50% battery redundancy to support battery swapping.<sup>153</sup> In a European context, an extra set of batteries for each BEB could add about 25% to the effective capital cost of the BEB.<sup>154</sup>
- Battery specification and packaging would need to be standardised for all buses using the same swapping station. This may only be practical to attain per route or group of similar routes, as it is increasingly common to match BEB specifications to each route's operating characteristics.
- It is not clear how battery swapping could take advantage of recent developments in BEB battery packaging and cooling, for example where batteries are mounted in the floor of the bus or placed around each wheel arch, rather than simply mounted as a block in the traditional engine space.

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<sup>152</sup> <https://www.forbes.com/sites/lbsbusinessstrategyreview/2024/04/15/the-rebirth-of-ev-battery-swapping-services-and-why-their-time-is-now/>

<sup>153</sup> <https://documents1.worldbank.org/curated/en/708531625052490238/pdf/Electrification-of-Public-Transport-A-Case-Study-of-the-Shenzhen-Bus-Group.pdf>

<sup>154</sup> Indicative example assuming USD \$250/kWh and installed capacity of 500kWh.

In summary, battery swapping is a technology that theoretically allows BEB batteries to be quickly exchanged for fully charged ones, a process that can take 5 minutes and thus minimises effective downtime for charging. However our review suggested no clear use case in local bus operation, while raising a significant number of practical challenges and additional costs. Battery swapping has not therefore been considered as a likely solution for hard-to-decarbonise local bus routes.

## Rooftop solar

### Overview

Bus rooftop solar involves the installation of solar panels onto the roofs of buses to supplement the main powertrain, typically providing energy to power auxiliary systems like HVAC, lighting, and media interfaces. The type of solar panels typically deployed onto vehicles utilise thin, light and flexible Copper Indium Gallium and Selenide (CIGS) module technology. While this technology offers lower efficiencies of up to 19% when compared to other solar products, they offer a much lower density of c. 2kg/m<sup>2</sup>, and thus add relatively little weight.<sup>155</sup> Companies have been offering these solutions for buses for a few years, with arrangements of up to 1.5kW<sub>p</sub> and a total system weight of <60kg.<sup>156</sup>

There is evidence of operators globally deploying such solutions on their fleets of buses. By the end of 2023, the Kowloon Motor Bus Co. in Hong Kong had almost 2,000 buses retrofitted with the technology (most of which being diesel buses).<sup>157</sup> In Europe, the technology was deployed by Flixbus on their London-Dortmund route, with diesel savings of c. 7% achieved during the pilot in February 2020.<sup>158</sup> The technology was also piloted in October 2022 in Sweden by LLT (a local bus operator), fitting 6 of their diesel buses with 1kW systems.<sup>159</sup> Stagecoach, Go-Ahead and others have also trialled the technology across Europe and Asia.<sup>160</sup>

### Benefits and challenges

Rooftop solar has largely been rolled out onto diesel bus fleets, where it has higher potential to generate savings for operators. When supplementing a bus with energy from solar panels, it is important to consider what energy or fuel from the main drivetrain is being displaced. In the case of a diesel bus, the solar energy is displacing diesel fuel that would otherwise go through the alternator and bus battery, resulting in a larger efficiency gain when switching to direct electricity from the solar array. However, for a BEB, the energy would be used to either displace or recharge the bus battery pack without any additional “switching” efficiency gains. The following example illustrates the cost saving potential of this technology for “BEB + solar” bus

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<sup>155</sup> <https://www.trailar.co.uk/post/solar-within-transport-cigs-vs-semi-flex>

<sup>156</sup> <https://www.trailar.co.uk/products>;

[https://sonomotors.com/site/assets/files/8669/sono\\_motors\\_solar\\_bus\\_kit\\_info\\_sheet\\_en.pdf](https://sonomotors.com/site/assets/files/8669/sono_motors_solar_bus_kit_info_sheet_en.pdf)

<sup>157</sup> <https://doc.irasia.com/listco/hk/transport/annual/2023/ar2023.pdf>

<sup>158</sup> <https://www.trailar.co.uk/post/flixbus-saves-7-fuel-with-trailar>

<sup>159</sup> <https://sonomotors.com/en/press/press-releases/sono-motors-acquires-scania-and-llt-as-customers/>

<sup>160</sup> <https://www.pv-magazine.com/2023/08/02/sono-motors-equips-first-bus-with-its-photovoltaic-retrofit-solution/>; <https://newsroom.go-ahead.com/news/a-year-of-progress-go-ahead-advances-along-the-road-to-net-zero>;

and “Diesel bus + solar” configurations across different regions (London, Oulu, Hong Kong, and Granada). The key assumptions used are shown in Table 3 below.

Table 3: Key assumptions used for solar rooftop illustrative costing example - comparison between a diesel and BEB bus across 4 cities (London, Oulu, Hong Kong, and Granada)

| Parameter   | London   | Oulu  | Hong Kong | Granada | Source(s)   |
|---|--|-------|-----------|---------|---|
| System peak output (kW <sub>p</sub> )                   | 1.5 kW <sub>p</sub>  |       |           |         | TRAILAR system <sup>161</sup>   |
| System cost (€)   | €9000 (annualised to c. €1200/annum over a lifetime of 7-8 years) <sup>162</sup> |       |           |         | TRAILAR <sup>163</sup> array cost with a mark-up for labour, inflation and other costs applied                                  |
| Diesel bus alternator specific fuel consumption (l/kWh) | 0.4 l/kWh  |       |           |         | See link in footnote <sup>164</sup>   |
| Diesel (€/l ex VAT)                                     | €1.46  | €1.34 | €3.10     | €1.20   | Multiple sources for each of the UK, EU (Finland and Spain data), and Hong Kong <sup>165</sup>                                  |
| Depot charging (€/kWh ex VAT)                           | €0.33  | €0.09 | €0.17     | €0.14   | Commercial electricity prices for the UK, EU (Spain/Finland), and HK <sup>166</sup>   |
| Final average system output (kWh/year)                  | 1247   | 1016  | 1891      | 2161    | EU PVG tool <sup>167</sup> for a default CIS array with 0deg slope – assuming the bus is operated throughout all daylight hours |

<sup>161</sup> [https://www.trailar.co.uk/files/ugd/330fe1\\_f1a8ce91bc2d4ba19ab34d05e268d92c.pdf?index=true](https://www.trailar.co.uk/files/ugd/330fe1_f1a8ce91bc2d4ba19ab34d05e268d92c.pdf?index=true)

<sup>162</sup> OEMs of flexible solar arrays such as SONO guarantee >80% performance after 10 years ([https://sonomotors.com/site/assets/files/8669/sono\\_motors\\_solar\\_bus\\_kit\\_info\\_sheet\\_en.pdf](https://sonomotors.com/site/assets/files/8669/sono_motors_solar_bus_kit_info_sheet_en.pdf))

<sup>163</sup> <https://www.trailar.co.uk/post/bus-coach-buyer-magazine-article-featuring-trailar>

<sup>164</sup> <https://www.bluedm.com.au/blog/diesel-generator-fuel-consumption-guide/>

<sup>165</sup>

UK: [https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fassets.publishing.service.gov.uk%2Fmedia%2F67629f81e6ff7c8a1fde9a80%2Ftable\\_411\\_413\\_3\\_.xlsx&wdOrigin=BROWSELINK](https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fassets.publishing.service.gov.uk%2Fmedia%2F67629f81e6ff7c8a1fde9a80%2Ftable_411_413_3_.xlsx&wdOrigin=BROWSELINK);  
Spain & Finland: [https://energy.ec.europa.eu/data-and-analysis/weekly-oil-bulletin\\_en](https://energy.ec.europa.eu/data-and-analysis/weekly-oil-bulletin_en); HK: [https://www.globalpetrolprices.com/diesel\\_prices/](https://www.globalpetrolprices.com/diesel_prices/)

<sup>166</sup> UK: <https://www.gov.uk/government/statistical-data-sets/gas-and-electricity-prices-in-the-non-domestic-sector>; Spain & Finland: [https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity\\_price\\_statistics#:~:text=Non%2Dhousehold%20consumers%20are%20defined,average%20consumption%20in%20each%20band.;](https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics#:~:text=Non%2Dhousehold%20consumers%20are%20defined,average%20consumption%20in%20each%20band.;) HK: [https://www.globalpetrolprices.com/electricity\\_prices/#hl120](https://www.globalpetrolprices.com/electricity_prices/#hl120)

<sup>167</sup> [https://re.jrc.ec.europa.eu/pvg\\_tools/en/tools.html](https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html)

For the diesel configuration, savings were estimated as the amount of diesel fuel displaced to get the same amount of energy in kWh through the panels rather than combustion and through the alternator.<sup>168</sup> For BEB buses, the maximum average daily savings observed for the sunniest months were minimal and could not justify any potential downsizing of battery packs or infrastructure required. Therefore, the savings associated with deploying this system on a BEB were limited to electricity cost savings from charging the buses.

We found that across all 4 cities, annual savings were higher than the annualised system cost (particularly in Hong Kong where diesel prices are especially high). For BEBs, the savings were found to be negligible and lower than the annualised system costs. See Figure 48 for the full set of results.

**Annual fuel/energy cost savings from rooftop solar (€/annum)**

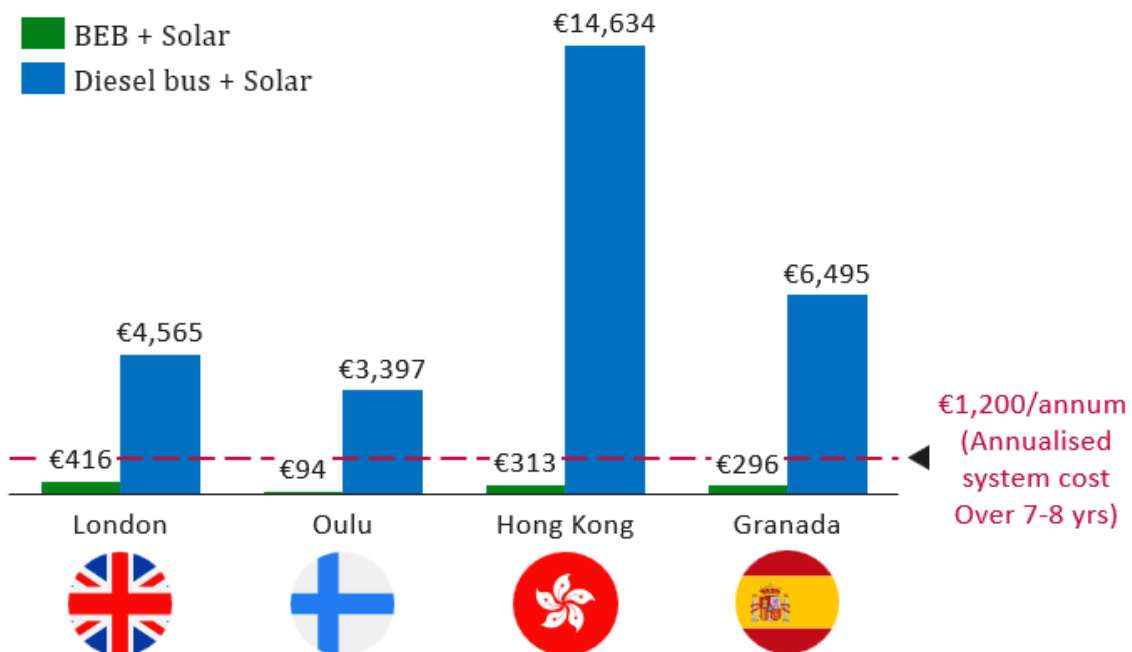


Figure 48: Results of rooftop solar costing for BEBs and diesel buses across 4 cities (London, Oulu, Hong Kong, and Granada)

<sup>168</sup> Some bus operators could be receiving subsidies on their fuel costs (e.g. bus operators eligible for the England’s Bus Service Operators Grant - <https://www.gov.uk/government/publications/bus-service-operators-grant-guidance-for-commercial-transport-operators/bus-service-operators-grant-guidance-for-commercial-transport-operators>), resulting in lower savings seen from such a system.

## Appendix: Interviewees

As part of this study, formal interviews were conducted with leading operator and agency practitioners. Interviewees were selected because they had experience of evaluating or implementing more than one solution to the problem this report focuses upon (for example, BEBs with enroute opportunity charging on one route and FCEB on another) and thus had an intuition for the relative merits and challenges of each solution. Interviews probed:

- Strategy adopted and why, including any in-process evolution of approach and lessons learnt for the future.
- Practical constraints and issues, related to both implementation and operation.

A reasonably representative mix of ten operators and agencies, geographically spread across Europe, was attained. Extra emphasis was placed on interviews in Germany, as our original report had identified Germany as the biggest single potential market for FCEBs. Interviews in Germany conducted by JIVE partner Sphera. All interviews were conducted between October 2024 and February 2025.

Organisations that agreed to be named were:

- Hansea, one of the largest bus operators in Belgium - Pieter Steurbaut (Chief Operating Officer): Hansea has a rapidly growing fleet of BEBs, operates a wide range of different route archetypes, and provided a large contractors' perspective on the strategic challenges of bus decarbonisation.
- Ruter, public transport agency for Oslo and surrounding Akershus in Norway - Pedram Nadim (Project Manager Vehicle Technology and Environment): Oslo provided insight into managing BEBs in extremes of cold weather, and the future challenges of decarbonising interurban routes.
- Transport for London (TfL), public transport agency for Greater London, United Kingdom - Lucy Arnold (Senior Zero-Emission Bus Development Manager) and Jane Wright (Senior Environment and Sustainability Engineer): TfL has implemented a wide range of solutions alongside its operator partners, including FCEBs, and depot, pantograph and wireless charged BEBs.
- Transports Metropolitans de Barcelona (TMB), municipal public transport operator in Barcelona, Spain - Mario Canet Sabaté (Engineer, Innovation and Projects): TMB operates FCEBs, and both opportunity and depot charged BEBs, and provided insight into the engineering optimisation of fuel cells and batteries.
- Wiener Linien, municipal public transport agency and operator in Vienna, Austria - Mohamed Abou El Enein (Project Manager for Hydrogen and E-Mobility): Vienna's network is especially challenging to decarbonise with BEBs, promoting both FCEBs and pantograph-charged BEBs, delivered in the context of a strong local municipal ethos.

In addition, further confidential discussions took place with two leading British bus companies and three Passenger Transport Operators in Germany, all with practical

experience of multiple decarbonisation technologies, including some with practical exposure to in-motion charging solutions.

The learnings from these interviews have been integrated into the wider text of this report and influenced our decisions on which options for hard-to-decarbonise routes to evaluate in the greatest detail.

## Appendix: TCO tool and inputs

This section summarises the structure of the bespoke ERM Total Cost of Ownership (TCO) tool (shown in Figure 49 below), and outlines key inputs and sources used to create the TCO evaluations between diesel, electric and hydrogen fuel cell buses for operations on hard-to-decarbonise local bus routes in Europe.

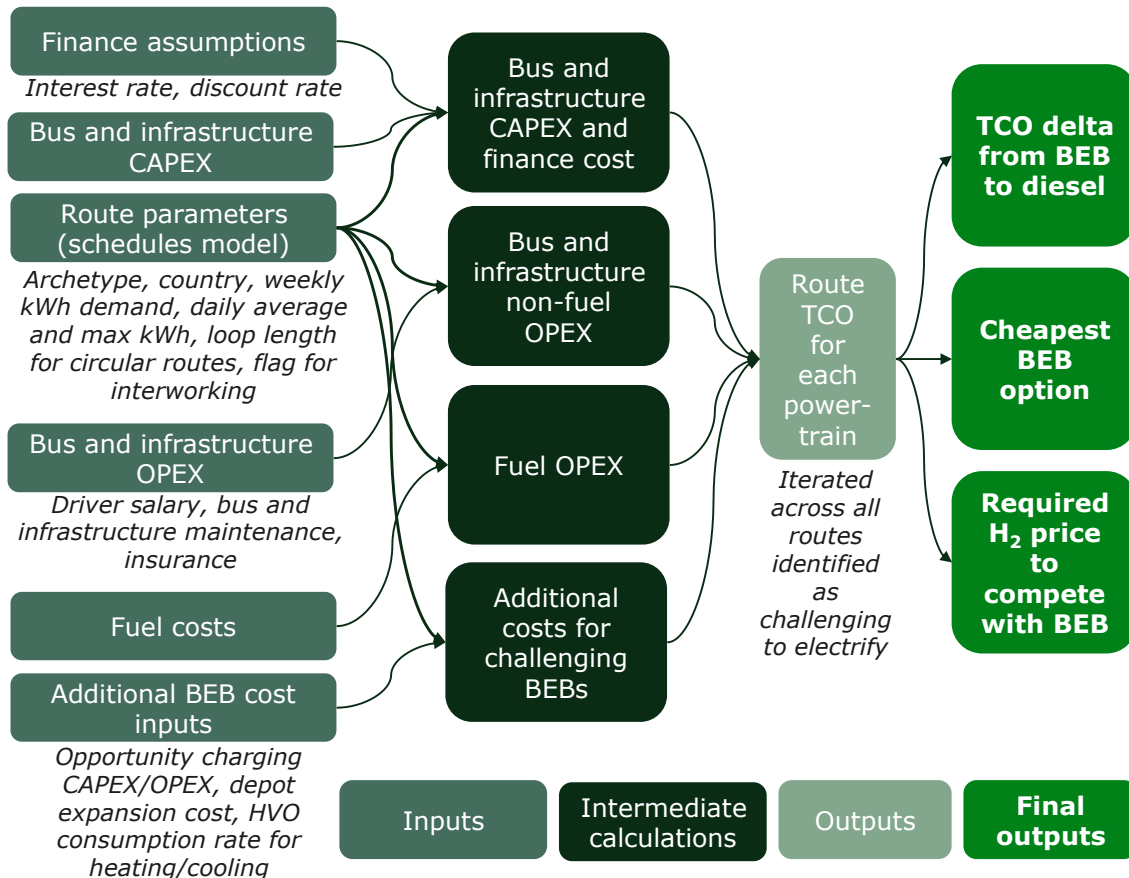


Figure 49: TCO model flow diagram

As discussed in the earlier TCO modelling approach subsection, the aim of is to differentiate between different strategic options across Europe. As outlined in the TCO sensitivity analysis, only a few factors make a tangible difference to the overall pattern of cheapest options, which means that the input assumptions made here need only be broadly typical to have validity within the wider model.

### Finance parameters

- Vehicle finance rate of 5% (ERM assumption)
- Real (excluding inflation) discount rate of 4% (ERM assumption). This is equivalent to a nominal discount rate of ~6% (with the average inflation rate assumed to be 2%).
- Average inflation rate of 2% (<https://www.ecb.europa.eu/mopo/strategy/pricestab/html/index.en.html>)

*Vehicle CAPEX (in 2024€)*

| Powertrain                                | Archetype  | Value in 2024 ('000s, 2024€) | Value over time  |
|---|------------|------------------------------|--|
| ICE powertrain                            | Suburban   | 250                          | Constant   |
|   | Interurban | 300                          |  |
|   | Rural      | 250                          |  |
|   | City       | 325                          |  |
|   | Long       | 350                          |  |
| BEB powertrain                            | Suburban   | 510                          | Reduces over time as battery price decreases, reducing by €60k in 2050. All other costs assumed constant (bus sector is insufficient size to see significant economies of scale savings) |
|   | Interurban | 610                          |  |
|   | Rural      | 510                          |  |
|   | City       | 630                          |  |
|   | Long       | 660                          |  |
| FCEB powertrain, central scenario         | Suburban   | 600                          | Constant (bus sector is insufficient size to see significant economies of scale savings).  |
|   | Interurban | 600                          |  |
|   | Rural      | 600                          |  |
|   | City       | 725                          |  |
|   | Long       | 700                          |  |
| FCEB powertrain, decreasing cost scenario | Suburban   | 600                          | Decreases by 1% per year between 2025-2035   |
|   | Interurban | 600                          |  |
|   | Rural      | 600                          |  |
|   | City       | 725                          |  |
|   | Long       | 700                          |  |

Sources: ERM estimations, based on Sphera data (including [https://www.now-gmbh.de/wp-content/uploads/2022/09/220823\\_BeFo\\_Bus\\_Abschluss\\_ENG\\_DIGITAL\\_EZ.pdf](https://www.now-gmbh.de/wp-content/uploads/2022/09/220823_BeFo_Bus_Abschluss_ENG_DIGITAL_EZ.pdf)), CATP data (<https://www.agir-transport.org/wp-content/uploads/2024/07/Etude-comparative-des-differentes-motorisations-de-bus-2024.pdf>), ZEBRA bid analysis (<https://www.gov.uk/government/publications/apply-for-zero-emission-bus-funding>).

*BEB maximum battery size (NMC/LFP, total capacity in kWh)*

| Year | Maximum battery size (kWh) |
|------|----------------------------|
| 2025 | 601                        |
| 2030 | 668                        |
| 2035 | 703                        |
| 2040 | 737                        |
| 2045 | 775                        |
| 2050 | 816                        |

Source: Potential for Hydrogen Buses JIVE report, Table 4 (<https://fuelcellbuses.eu/public-transport-hydrogen/d336-potential-hydrogen-buses-europe-results-bulk-analysis-passenger>).

*BEB % usable battery*

- 80% for all battery chemistries across all archetypes, constant over time (Potential for Hydrogen Buses JIVE report, Page 54)

<https://fuelcellbuses.eu/public-transport-hydrogen/d336-potential-hydrogen-buses-europe-results-bulk-analysis-passenger>)

#### *Battery cost per kWh (2024€/kWh)*

- LFP/NMC chemistry: €207/kWh in 2024 decreasing to €59/kWh in 2050 (Based on BNEF 2024 report stating ~\$200/kWh price, converges to an LDV forecast by 2035, which is based on ERM's analysis of BNEF projections)
- LTO chemistry prices are assumed to be double LFP/NMC: €415/kWh in 2024 decreasing to €138/kWh in 2035 (<https://www.sustainable-bus.com/news/nmc-lfp-lto-battery-explained/>).

#### *Additional CAPEX for opportunity charging in 2024€*

- Pantograph arm on charger: €2,000 for all archetypes (ERM assumption), constant over time.
- Pantograph arm on bus: €20,000 for all archetypes (based on interviews with operators), constant over time.

#### *Vehicle chassis residual value*

- 0% (ERM assumption) assuming a low residual value as the chassis is only sold as scrap after a 15 year/1.6 million kilometres lifetime. Accounting for this scrapping cost (e.g. a 5% residual value) will make a negligible difference to the TCO, as this value is still low and will be heavily discounted as it is at the end of the vehicle's life.

#### *Battery residual value and degradation rate*

- Base scenario: battery residual value is assumed to be zero. This is a conservative assumption consistent with assuming a 0% residual value for chassis components, and assumes the cost to repurpose/recycle the battery at end of life roughly balances the value of the end material.
- The following values were used for the "Battery residual value" sensitivity (page 68):
  - Battery degradation (LFP/NMC): 2.38% loss per year, plus 0.0023% per full-cycle equivalent (see the *Battery degradation* section, page 29, for data and sources).
  - Residual value of remaining capacity is half of the cost of a new battery in the given year (ERM assumption): €76/kWh in 2024 decreasing to €34/kWh in 2035.

#### *Ratio of electricity use to other fuel use*

The route analysis in the preceding report (Potential for Hydrogen Buses JIVE report, <https://fuelcellbuses.eu/public-transport-hydrogen/d336-potential-hydrogen-buses-europe-results-bulk-analysis-passenger>), calculates the electrical energy use for each route. For the TCO calculations, this has been converted to an equivalent fuel consumption for diesel and hydrogen buses with the following conversion factors:

- BEBs are assumed to use 2.85 times the equivalent quantity of diesel litres in battery kilowatt-hours. For example, if a diesel bus uses 29 L/100 km, an equivalent electric bus would use 82.6 kWh/100 km. This uses the ratio of

0.351 L diesel/kWh electricity from: <https://www.agir-transport.org/wp-content/uploads/2024/07/Etude-comparative-des-differentes-motorisations-de-bus-2024.pdf>). This ratio was used in the TCO. The ratio means that for every 1 kWh of electricity used, the equivalent energy content in diesel fuel would be 0.351 litres. The ratio takes into account the higher efficiency of electric buses compared to diesel buses. Electric drivetrains have an efficiency of 85-90% whereas diesel engines have an efficiency of 30-45%. This means that out of ~3.6 MJ of energy in 1 kWh of electricity, 3.1-3.3 MJ is converted into useful motion in an electric bus, and out of 12.6 MJ in 0.351 L of diesel, 3.8-5.7 MJ is converted into useful motion in a diesel bus.

- 0.075 kg hydrogen/kWh electricity (Potential for Hydrogen Buses JIVE report, <https://fuelcellbuses.eu/public-transport-hydrogen/d336-potential-hydrogen-buses-europe-results-bulk-analysis-passenger>. "Base (primarily traction) energy consumption has been assumed as 0.8 kWh/km for BEB and 0.06 kg/km for FCEB").

#### *Depot fuel costs*

- Diesel prices: Between 1.21 to 1.85 2024€/L per country in 2024, using the Weekly Oil Bulletin ([https://energy.ec.europa.eu/data-and-analysis/weekly-oil-bulletin\\_en](https://energy.ec.europa.eu/data-and-analysis/weekly-oil-bulletin_en)). Projected into the future using the UK Green Book projections (last updated in Nov 2023, Table 8: <https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal>).
- Electricity prices: Between 0.10 to 0.28 2024€/kWh per country in 2024, using Eurostat 2024 H1, non-household customers, including taxes and levies ([https://ec.europa.eu/eurostat/databrowser/view/nrg\\_pc\\_205\\_custom\\_1493\\_5879/default/table?lang=en](https://ec.europa.eu/eurostat/databrowser/view/nrg_pc_205_custom_1493_5879/default/table?lang=en)). Projected into the future using the UK Green Book projections of commercial electricity prices (last updated in Nov 2023, Table 4: <https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal>).
- HVO prices: Between 1.57 to 2.40 2024€/L per country in 2024, assuming a 30% premium on diesel prices (ERM experience with fleet operators estimates 20-40% increase).

#### *Opportunity charging electricity costs*

- From 0.176 to 0.513 €/kWh per country in 2024. This price has been calculated by taking the depot electricity price (above), increased by multiplying by the ratio of domestic versus commercial electricity price in each year from the UK Green Book (last updated in Nov 2023, Table 4: <https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal>).

#### *Maintenance cost by vehicle mileage and powertrain*

- 0.28 €/km for ICE buses and 0.22 €/km for BEBs and FCEBs in 2024 ([Etude-comparative-des-differentes-motorisations-de-bus-2024.pdf](https://www.agir-transport.org/wp-content/uploads/2024/07/Etude-comparative-des-differentes-motorisations-de-bus-2024.pdf)).

*Insurance cost by year of insurance (% of replacement cost)*

- 0.8% of replacement cost for all archetypes and powertrains (ERM experience from projects with private clients).

*Driver salary*

- 93,600 2024€/year for all countries (Assuming ~€40/hour, including employer costs (pensions, taxes etc). 45 hours/week, 52 hours/year).

*Infrastructure CAPEX and installation (in 2024€/charger)*

- 50 kW DC charger: €18 000
- 100 kW DC charger: €36 000
- 300 kW DC charger: €108 000
- 500 kW DC charger: €180 000

Source: Average of chargers 50-450kW in European sources from ERM research.

Note: Buses using opportunity charging still have a depot charger installed, to recharge to full when off duty.

*Infrastructure annual OPEX (in 2024€/year)*

- 50 kW DC charger: €1 005/year
- 100 kW DC charger: €2 010/year
- 300 kW DC charger: €6 030/year
- 500 kW DC charger: €10 050/year

Source: ERM analysis of industry data.

*Grid upgrades*

- Cost of grid upgrade per kW installed: €228/kW
- Grid upgrade lifetime: 15 years

Source: Confidential industry sources in UK.

*Floor space required per bus (for extra buses)*

- In general, assume 3m width \* (length of bus + 0.5m)
- Suburban and interurban bus: 31.5 sqm per bus (Average length = 10m)
- Rural bus: 25.5 sqm per bus (Average length = 8m)
- City bus: 46.5 sqm per bus (Average length = 15m (average of 12 and 18m))
- Long bus: 37.5 sqm per bus (Average length = 12m)

*Cost of land to increase bus depot (in 2024€/sqm)*

- €360/sqm for all countries (assumed same as UK: Average (Excluding London) of “2019 Defra land costs for appraisal” (<https://www.gov.uk/government/publications/land-value-estimates-for-policy-appraisal-2019>) for “Office - edge of CBD”, inflated and converted to EUR.

*Opportunity charging infrastructure CAPEX and installation*

- 300 kW charger:
  - Located on charger: €285 000

- Located on bus: €252 000
- 500 kW charger:
  - Located on charger: €475 000
  - Located on bus: €420 000
- 1 MW charger:
  - Located on charger: €950 000
  - Located on bus: €840 000

Source: ERM research.

*Infrastructure lifetime:*

- 15 years (ERM assumption, reflecting maximum industry warranty periods)

*Infrastructure annual OPEX*

- €14 978 /year

Source: Page 9 (section 3.1.1), summed costs to 2021 USD 13,200 per year for new 3-year contract, converted to 2024 Euros

(<https://www.nrel.gov/docs/fy21osti/80022.pdf>).

*Grid capacity required per charger*

- Grid capacity required is equal to charger power, assuming no diversity effect.

Project coordination:



Project dissemination:



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