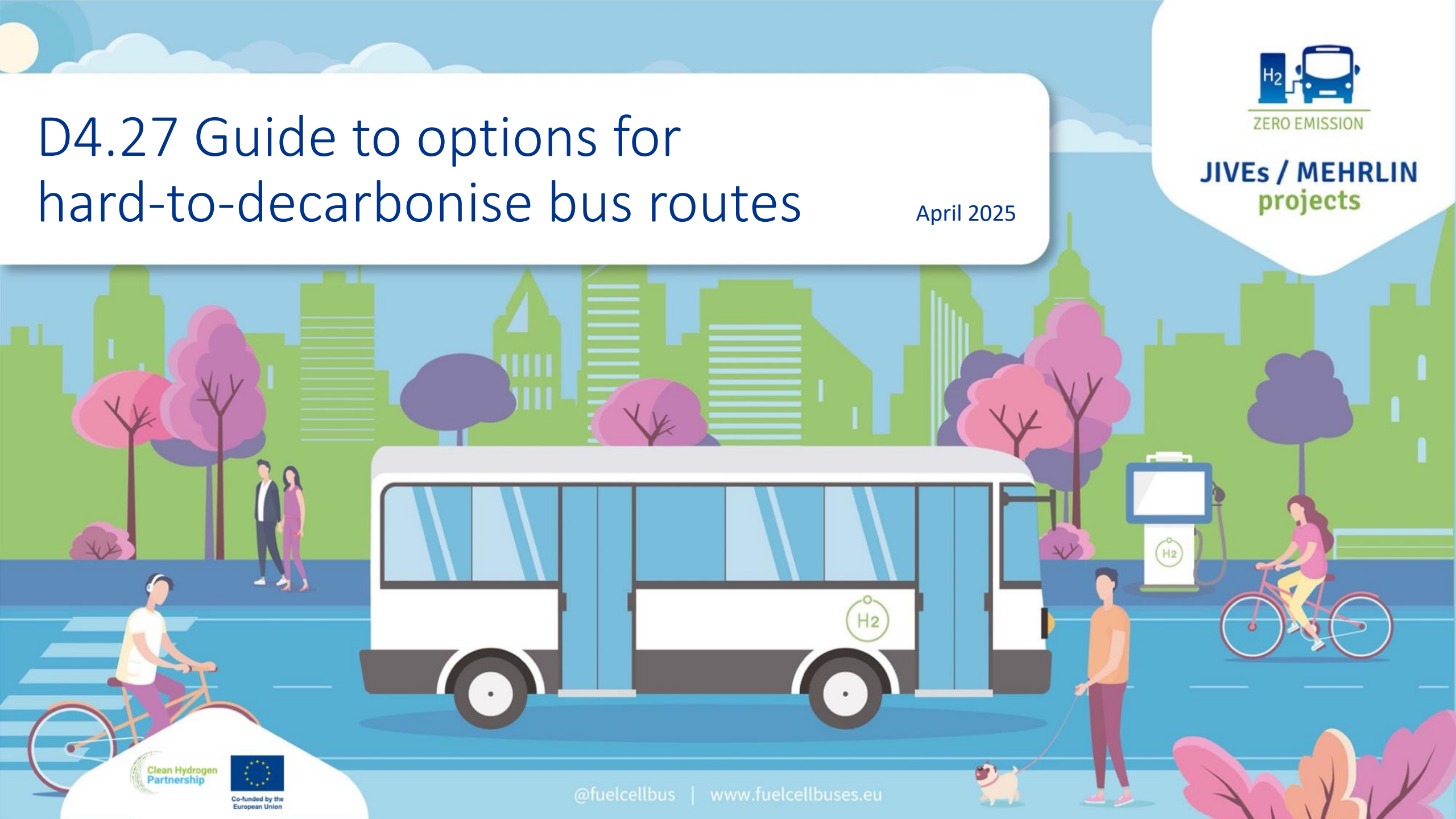
D4.27 Guide to options for hard-to-decarbonise bus routes

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ZERO EMISSION

JIVEs / MEHRLIN projects



Clean Hydrogen Partnership

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Why some local bus routes might be harder to decarbonise

All local bus decarbonisation means transitional change. Zero Emission Buses (ZEBs) typically double capital cost vs diesel buses, which is repaid over the vehicle's life as lower operating cost. Connecting and converting depots to new fuels adds time and complexity to initial ZEB deployment. Operators' organisational processes will need to evolve alongside their new ZEBs.

Battery Electric Bus (BEB) is the most common decarbonisation solution. However, BEB battery capacity is constrained by vehicle weight limits. This limits BEBs' effective range from a single charge, and thus which bus routes BEBs can be easily operated on. Battery energy density (storage per weight) will improve in future, but not fast enough to meet all Net Zero goals.

Meantime, local bus operators and agencies still have options to decarbonise these routes. These options tend to add further cost and complexity. Even well-resourced organisations can struggle to evaluate and justify the most suitable option. Specific ZEB investment decisions must consider local circumstances – detail we cannot provide here. However, we can:

- Suggest a strategic approach to solving these challenges, derived from both a detailed review of technologies and the experience of European bus sector practitioners.
- Indicate the decarbonisation option likely to be most cost-effective given a bus route's characteristics, derived from applying Total Cost of Ownership (TCO) modelling to ¾ of all European bus routes.



Hydrogen FCEB passes an opportunity-charging BEB in Barcelona, Spain. Which solution is best for each route?

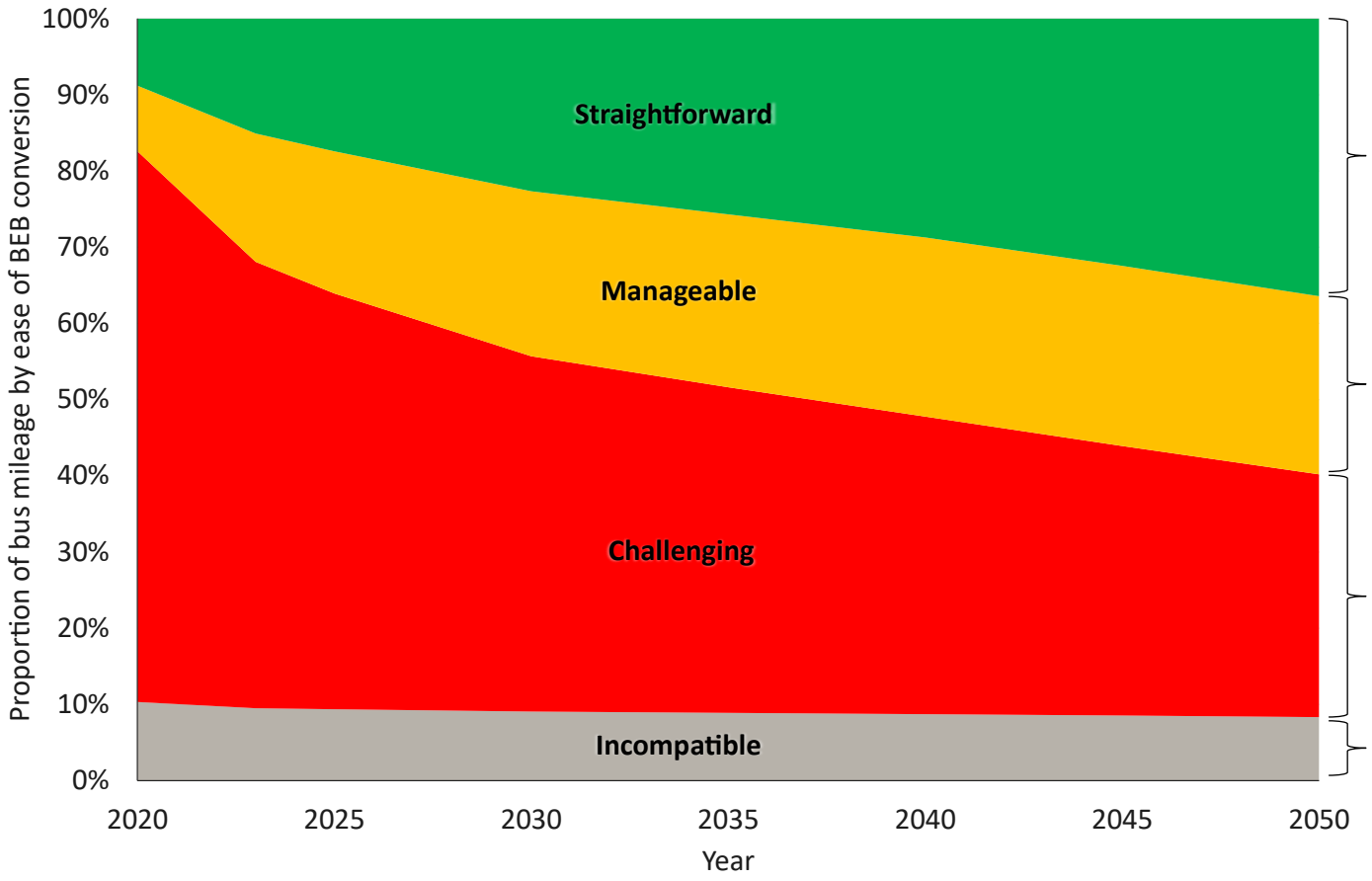
The three most common options are discussed in detail: Secondary non-battery-powered heaters, deployment of extra BEBs, and remote (non-depot) opportunity charging. We also outline several potential niche alternative technologies, which are either geographically situational solutions or early-stage technology.

Fuel Cell Electric Buses (FCEBs) are considered via the green hydrogen fuel price at which they become competitive with the main BEB options: FCEBs are as operationally flexible as diesel buses, but in the long term will need to compete on price, yet the green hydrogen sector is too nascent to reliably predict ultimate fuel price levels.

This guide is focused on hard-to-decarbonise scheduled local bus routes in Europe, not all bus and coach decarbonisation challenges.

Operational and schedule flexibility constrain BEB compatibility

We modelled the operations and energy of ¾ of Europe's local bus routes and analysed how compatible BEBs could be expected to be in the years to 2050. Our distribution of overall mileage is graphed below. This analysis assumes passenger schedules are fixed, but internal operations are more flexible. That will not be the case for all operators and agencies:



Modelled BEB local bus route compatibility by year, for Europe

BEBs can operate the route with a simple overnight at-depot charge. All operators should ultimately be able to deploy BEBs here, as there are few changes beyond initial depot conversion and plug-charging processes.

There is sufficient slack in the existing route Peak Vehicle Requirement to allow BEB operation, but only if BEBs can return to depot during slack periods to charge. In practice factors such as inflexible labour agreements or remote depots can force these routes into the hard-to-decarbonise category in the short-term. Longer term, decarbonisation strategy should evolve from purely technical to organisational.

Insufficient slack in the existing vehicle allocation for BEB operation, so BEBs are likely to require one of the solutions outlined in this guide. **Our TCO assessments are made against these routes.**

Long distance intercity coach routes where one out-and-back BEB trip could not return to home depot. The options in this guide are not optimised for such routes.

The method and analysis behind the graph can be read at:
https://fuelcellbuses.eu/public-transport-hydrogen/d336-potential-hydrogen-buses-europe-results-bulk-analysis-passenger

Emphasise in-service utilisation, not residual battery life

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 our interviewees[1] with long-term BEB operating experience reported battery degradation had been far less than originally expected.

Both main fully-Zero Emission BEB solutions to hard-to-decarbonise bus routes involve using batteries more extensively or charging them more rapidly, which will have some impact on degradation and life.

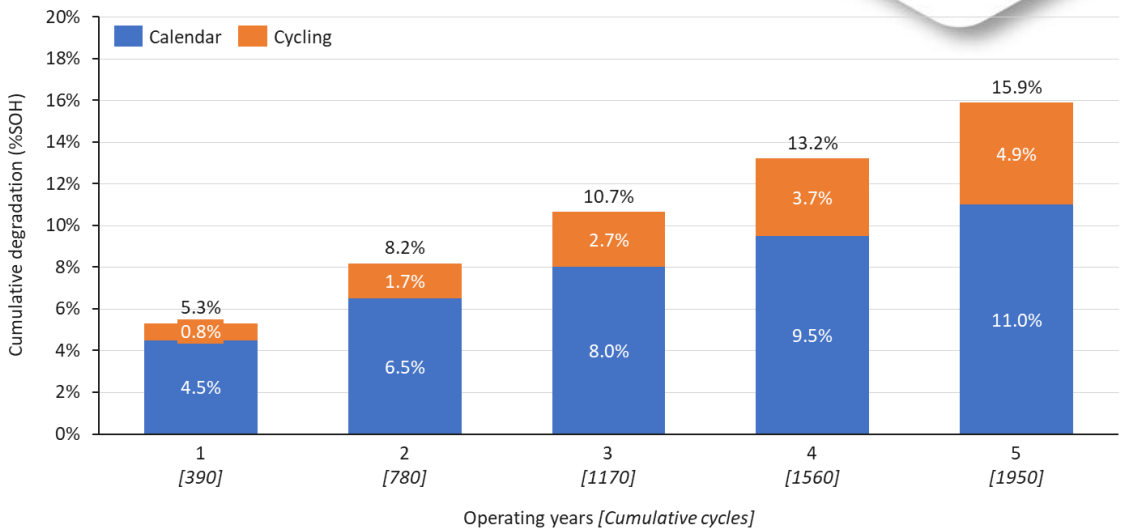
Battery degradation consists of both:

- Calendar, which occurs over time regardless of use.
- Cycle, which occurs when the battery is discharged and recharged.

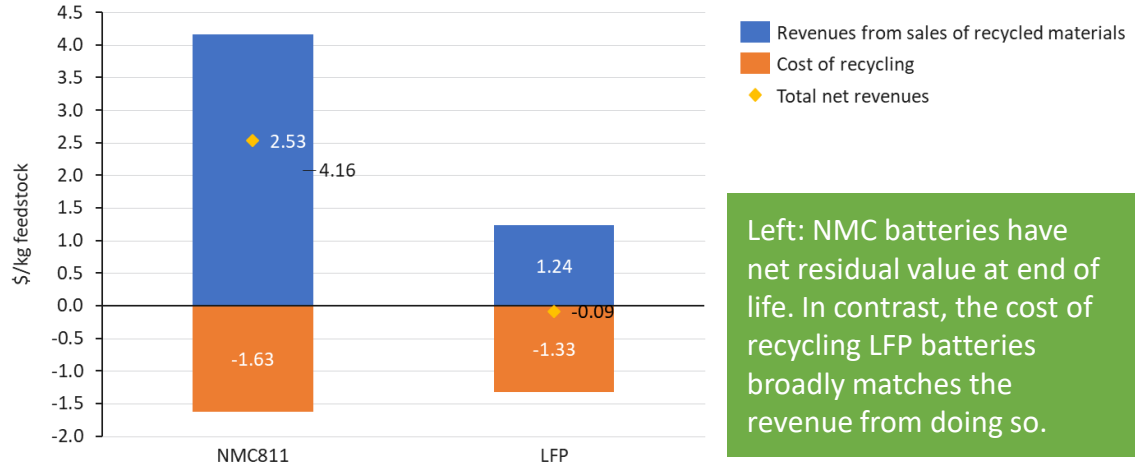
Adding extra cycles to a fixed calendar degradation (more cycles per year) will tend to give a better lifetime payback on investment than using the battery more sparingly over a potentially longer life, if those extra cycles are converted into in-service, revenue-earning, bus operation.

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.
- LFP tends to better suit route decarbonisation solutions which involve more than overnight charging, since LFP tends to degrade less per cycle than NMC.
- LFP has slightly lower energy density, so lowers maximum onboard battery capacity, and thus LFP-operated routes are slightly more likely to need the sort of solutions outlined in this guide.



Above: Calendar degradation is the main loss of battery State of Health when cycling roughly once per day. Overnight-only charged BEBs typically average less than 1/day.



Left: NMC batteries have net residual value at end of life. In contrast, the cost of recycling LFP batteries broadly matches the revenue from doing so.

[1] Ten operators/agencies were interviewed, detailed in the accompanying technical report's appendix.

Upper graph shows NMC, derived by ERM from Thingvad et al, 2021. Lower graph derived by ERM from Argonne National Laboratory's EverBatt, 2023.

Main option: Secondary heaters/coolers



How it works

Heating or cooling the passenger cabin can use up to half a BEB's daily energy in the worst climatic conditions, especially below freezing. This energy use varies with temperature, so on most days is far less. Battery-powered heating and cooling requires BEB capacity to be specified for the most extreme day. By focusing the battery on traction and using a higher energy density fuel to power heating/cooling, the BEB gains daily range.

Hydrogenated vegetable oil (HVO) is assumed as the future fuel for secondary heaters/coolers, although diesel is currently common, and synthetic e-fuels may emerge as an alternative. HVO is not strictly a Zero Emission solution. But when used marginally – primarily in the worst weather – overall vehicle tailpipe emissions savings vs diesel are still likely to reach 90%, depending on fuel source and climate.

Advantages and disadvantages

HVO and e-fuels are handled in a similar way to existing diesel fuelling, ultimately powering familiar internal combustion technology: No new depot processes or engineering complexity, and no tangible change to existing in-service operation.

Diesel heaters have become accepted practice for "ZEB" operation in some parts of Europe, but even with HVO, they are not truly Zero Emission, just a way of substantially reducing CO2 emissions vs a conventional diesel bus.

The United Kingdom, at least, already defines this option as non-Zero Emission in respect to government ZEB financial support. Other corporate, national or local policy may similarly dissuade this option as insufficient to meet climate targets.

TCO optimal routes

The HVO heaters/coolers option favours routes with relatively (to all challenging routes, which are above average) lower energy requirements, and is typically the cheapest option for vehicle duties under about 650 kWh in the worst climatic conditions (shown "max" right). This is equivalent to 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 and suburban operations.

If HVO price were to double, high frequency city routes would instead favour opportunity charging, with HVO heaters/coolers emphasising only the remaining *lowest* energy routes, where the marginal use of an expensive fuel is still cheaper than procuring and operating additional assets.

Risks

This option's key risks are typically outside the direct influence of operators/agencies:

- High HVO fuel price had the greatest impact on relative TCO of any factor tested. Biofuels, here HVO, are inherently supply constrained, and theoretically capped by e-fuel prices, so could rise significantly in future.
- Zero Emission policy on heaters/coolers is far more uncertain than traction decarbonisation policy. Pursuing this option risks not being able to access certain route contracts or ZEB financial support in future.

These risks can only be partly moderated by ensuring BEBs can be heated/cooled from both secondary and battery systems, allowing such BEBs to be redeployed to less challenging routes if policy or fuel cost changes.

Indicative Cheapest TCO:

Max kWh/bus
< 650

Peak vehicles
4-8

Route hours
< 21

Flexibility need
Minimal

Extra risk
External

Main option: Extra buses



How it works

Extra BEBs are procured for the route in comparison to prior diesel vehicle requirements. This creates enough slack downtime across the fleet to rotate BEBs in-and-out of service across the day for additional at-depot daytime charging. In summary, this option adds enough vehicle resource to make the route “manageable” to operate with BEBs.

In addition to the costs of the extra buses, each vehicle still needs to charge overnight, so requires extra depot space and chargers. Extra driver time and “dead mileage” to and from depot can potentially be moderated by greater use of out-stations or equivalent remotely located mid-power plug chargers. The added managerial complexity of operating such a route may naturally suit centralised operating hubs – or improved human management or related information technology systems.

Advantages and disadvantages

Extra BEBs can be seamlessly integrated into a much wider fleet, which shifts the decarbonisation challenge from vehicle to operations management.

Extra BEBs suit operators able to fundamentally rethink how they deliver services, both hour-to-hour, and from what base locations. Such process change can transpire to be much harder than mere vehicle decarbonisation.

In contrast operators that approach decarbonise with expectations of 1:1 battery-for-diesel replacement or are constrained in their ability to expand or move depot space, will struggle to adopt this option.

For those that can, this option is the most operationally resilient and future-proof investment of all the three options detailed here.

TCO optimal routes

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: Roughly hourly or less, Peak Vehicle Requirements of under 4, and, if choice is limited to only fully Zero Emission options, optimal for routes operated under 17 hours per day, respectively.

The longest routes and the highest energy requirements are more likely to favour extra BEBs. This option tends to be best suited to rural/small town services, despite the practical tendency for these routes to be operated relatively remote from home depot. This option tends to be favoured in TCO modelling where fleets are too small to make opportunity charging equipment viable, or energy requirements are too high to be moderated effectively by secondary heaters/coolers.

Risks

Extra BEBs are the lowest risk strategy of all the three options detailed here. All the main sensitivities we tested that might add cost to other options resulted in strong shifts towards extra BEB strategies. So, while pure TCO analysis frames extra BEBs as the least applicable solution for local bus routes across Europe, extra BEBs may be a much more attractive options once the risks of alternatives are priced into decisions.

This is equally true of the investment risk, which is much easier to manage over the BEB’s life: Not only can these extra BEBs be freely redeployed to other similar local routes, but the absolute European market for this style of operation is expected to be relatively constant between 2030 and 2050, unlike opportunity charging, which is expected to decline in relative attractiveness over the transition.

Indicative Cheapest TCO:

Max kWh/bus
> 950

Peak vehicles
< 4

Route hours
Lower

Flexibility need
High

Extra risk
Minimal

Main option: Opportunity charging



How it works

Additional rapid charging equipment is installed at one or more places along the route where buses idle, especially termini. This allows each in-service BEB's battery to be topped-up regularly over the day, extending effective range. Charger connections are typically by overhead pantograph, with bus-mounted "panto-up" considered most resilient and easiest to manage across a fleet.

BEBs using low capacity LTO (Lithium Titanate Oxide) batteries can be optimised to always recharge once or more per vehicle trip along the route. LTO batteries are heavier and more expensive but degrade much slower per cycle. They are cost-effective here because far smaller battery capacity is required.

Alternatively, BEBs using high capacity (typically LFP) batteries can top-up less across the day while gradually running down a much larger overnight-charged reserve.

Advantages and disadvantages

Opportunity charging can allow existing passenger schedules to be maintained without extra buses or drivers. Large-battery BEBs allow in-service charging when downtime happens to occur across the day. Small-battery variations are cheaper but less flexible – suited to routes with more predictable operation. Pantographs are also a space-efficient means of overnight depot charging.

Opportunity chargers are installed at fixed locations so only able to support one or a few routes, so are the least flexible of all the main options considered here – both operationally and as an investment. Installation, in addition to home depot, multiplies the number of sites where electrification needs to occur. Land ownership, planning processes, and grid constraints may limit locations in practice. These extended processes, combined with the inflexibility of charger compared to a BEB, may not suite shorter-term contractual regimes.

TCO optimal routes

Small-battery LTO BEBs tend to be cheapest, notably at higher service frequencies because charger utilisation is greater.

Larger-battery BEB opportunity charging was assumed in TCO modelling, as applicable to a wider range of routes. Here, high peak vehicle requirement is a good guide: 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 long days.

Opportunity charging favours the most intensive operational styles, especially interurban routes, but also higher-energy city routes. If options are limited to pure Zero Emission, opportunity charging emerges as the cheapest option for almost all city routes.

Risks

Opportunity charging adds significant implementation risk. Each remote site duplicates many of the issues encountered during depot electrification, but often at locations with unfamiliar ownership and planning processes. Historic vehicle-centric contractual or partnership mechanisms may need to evolve to reflect this option's longer lead times and relatively immobile assets.

Remote charging infrastructure adds points of potential technical and thus service failure, partly moderated by panto-up technology and higher than necessary charger redundancy.

Well established operators/agencies with stable route networks and long concession periods are best able to manage implementation risks over long payback periods. Operators whose baseline is simply procuring a bus may favour other options, regardless any arithmetic TCO advantage.

Indicative Cheapest TCO:



Max kWh/bus
650-950



Peak vehicles
> 8



Route hours
> 21



Flexibility need
Low



Extra risk
Multi-site

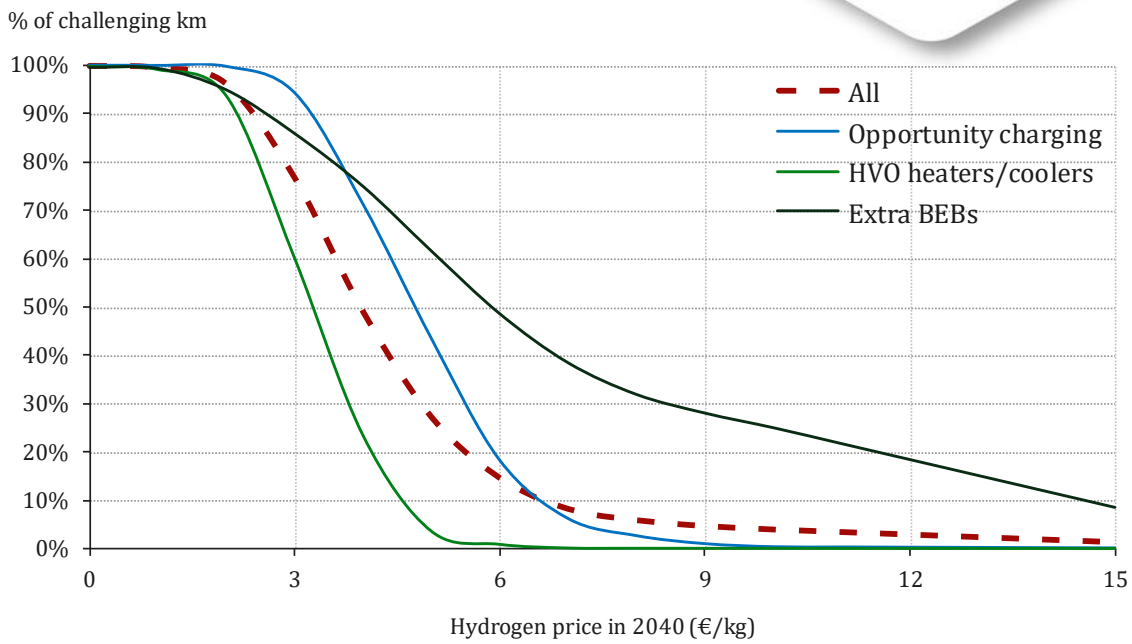
Comparative option: Hydrogen fuel cell buses

Hydrogen is a renewable Zero Emission fuel when produced by electrolysis (which splits hydrogen and oxygen from water) powered by renewable electricity. Hydrogen can be combusted much like diesel. Combustion can use impure hydrogen, but is relatively energy-inefficient and, unless pollutants are captured, negatively impacts local air quality.

ZEB technology has therefore emphasised hydrogen fuel cells. FCEBs take hydrogen stored on the bus and convert it to electricity, that then powers a BEB-like electric drive train. This allow FCEB technology to be integrated into BEBs, for example to extend their effective range on days with more extreme climatic conditions, or to provide a steady supply of energy for an urban bus that constantly brakes and accelerates into a small LTO battery.

Hydrogen is light (in the order of 25 kg per bus per day), so FCEBs can maintain prior diesel passenger capacity and daily range, even on small or well-loaded buses with relatively long daily duties. Hydrogen fuelling raises new safety-related challenges, especially for multi-tonne storage at urban depots, but is otherwise broadly comparable to diesel. Unlike opportunity charging and extra BEBs, the *extra* cost of FCEBs is operational, not capital, so FCEBs may suit operators with poor access to finance. Overall, hydrogen is technically well suited to decarbonising buses with minimal change to operations or size of fleet.

The key long-term disadvantage of hydrogen is fuel cost, and in turn small scale of supply chain. Energy loses during the process of converting electricity to hydrogen and back again mean more direct use of electricity to/from battery storage is more cost-effective. Hence TCO favours BEBs over FCEBs, potentially except where BEBs add cost or operational complexity.



Distribution of hydrogen price for FCEBs to compete against cheapest BEB-based option

Our TCO modelling shows (graph upper-right) the price point at which hydrogen could expect to become competitive with each for the 3 main BEB-based options for hard-to-decarbonise local bus routes. For context, the current price to bus operators of green hydrogen typically exceeds €10/kg, a value that would need to halve for FCEBs to become a common solution for challenging routes. The strongest market at higher prices is that in comparison to extra BEBs, which is the option 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.

Specific local operations will vary, while green hydrogen prices may drop in future, but it is likely that FCEBs will only provide the cheapest (on pure TCO) option for a minority of a local bus fleet. Operators/agencies will therefore need to consider whether such a fleet is of sufficient size to justify investment in refuelling equipment, storage and reliable fuel supply. Small daily hydrogen volumes (especially under 500 kg, about 20 active FCEBs) are more difficult to scale than BEB chargers, especially where at-depot electrolysis is envisaged.

Further in-depth guides to FCEBs, and their deployment and operation, can be found at: https://fuelcellbuses.eu/

Niche options: Situational and partial solutions

Energy management

Strategies to reduce in-service energy use, either while in-service or by better preparing the bus, are common but still evolving. These approaches can reduce energy bills and can help maintain services in unexpectedly extreme climatic conditions. But they are unlikely to be the whole solution to a challenging route decarbonisation, so should be considered as an enhancement to one of the three main options.

Driver training is a well-known means of reducing energy consumption. Further matching the most efficient drivers to the most challenging routes may test labour relations. Monitoring software that provides proactive feedback to drivers may offer an acceptable compromise. As with Extra BEBs, improving driver energy management emphasises the human/process aspects of decarbonisation and may not initially suit organisations focused on vehicle replacement.

The main secondary heater/cooler option illustrates the potential for thermal management strategies, especially where operating in relatively extreme climatic conditions.

Pre-heating of buses, sometimes occurs by storing buses in temperature-controlled sheds, but more commonly occurs by timing overnight charges to finish just before the BEB commences its duty. This both pre-warms the passenger cabin and ensures efficient brake regeneration. Software is increasingly important to optimise such charging.

Fewer options exist in warmer climates, where energy to cool the passenger cabin is primarily needed in the afternoon, not at the start of a BEB's duty. Optimisations may instead focus on cooling chargers to reduce charging times.

In-motion trolleybus

Trolleybus is a historic method of bus electrification, where electric buses draw power from overhead wires. We judged the financial, and sometimes local political, cost of wiring a new route to be excessive in almost all cases, with most capital cost estimates over a million Euros per route kilometre.

Where a city already has a trolleybus network, it may be possible to in-motion charge (IMC) BEBs whose routes partly operate under overhead wires.

Trolleybuses can be slightly more expensive than BEBs and typically use small-capacity LTO batteries. Charging is thus like small-battery opportunity charging, but with fewer time delays and potentially no extra infrastructure costs:

While no fixed opportunity chargers are required, the overhead system may require additional power. Trolleybus typically operates at 600 volts, so can be fed from the domestic grid, potentially simplifying the grid connection issues of conventional BEB opportunity chargers.



Instructions to trolleybus drivers in Lausanne, Switzerland, upon rejoining an overhead-wired section of route.

Niche options: Early-stage and limited use case technologies

Wireless charging

Wireless charging uses magnetic resonance to charge BEB 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.

Static WPT is like fixed opportunity charging but has no significant practical advantage over pantograph-based systems and is typically in the order of double the capital cost. The required ground clearance between road and bus tends to result in greater power loss than direct connection. Current WPT designs do not exceed 450 kW and thus lag the power capabilities of the fastest pantograph opportunity chargers.

Dynamic WPT is like in-motion trolleybus, but instead of drawing from an overhead power supply, wireless charging coils are installed under stretches of road to allow buses to charge as they drive. There is no pause to connect or disconnect, although in-motion BEBs do need to align precisely to the coils. There are none of the visual policy concerns which can arise for overhead solutions. The frequent oscillation of a finite fleet of buses along one stretch of highway is theoretically well suited to this technology.

However, prevailing capital costs tend to be higher than new trolleybus wiring, and thus likely to be prohibitively expensive as a solution for hard-to-decarbonise routes. The installation of large subterranean components raise similar risks as city centre tram construction, especially conflicts with utility pipes and cables. There are currently no standards for this technology, risking vendor lock-in.

Battery swapping

Battery swapping physically replaces a discharged battery with a charged battery, automated via machine at a fixed location on the route. Battery swapping is popular for small vehicles in some parts of Asia, primarily as a way of *financing batteries*: Much of the additional cost of an electric vehicle is effectively leased and managed via swaps.

We found no clear use case for swapping in local bus, nor evidence of extensive use of the technology in the sector:

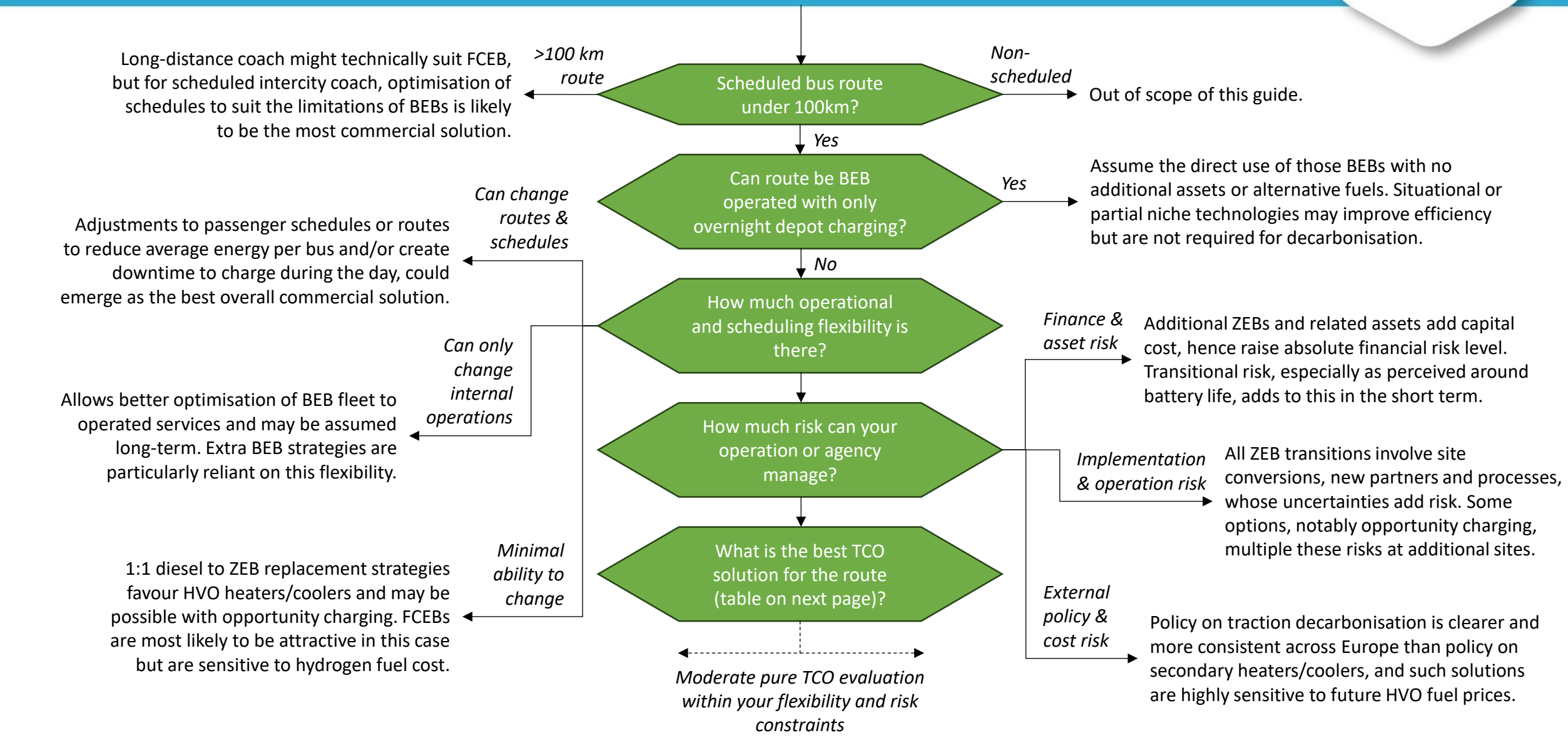
- Well-managed opportunity charging provides similar operational advantages.
- Costs tend to be higher, requiring many additional batteries and relatively expensive swapping stations.
- Modern BEB battery packaging and distribution within the chassis is increasingly incompatible with in-service battery swapping.

Rooftop solar

Rooftop solar involves the installation of solar panels onto the roofs of buses, typically to augment power to electrical systems. Panels typically utilise thin, light and flexible Copper Indium Gallium and Selenide (CIGS) module technology. While this technology offers lower efficiencies when compared to other solar products, their lower density adds relatively little weight.

Our analysis showed that rooftop solar could produce 3-6 kWh per bus per day, an insignificant contribution to a BEB's energy requirements on any one day. In contrast, for a conventional diesel bus, where electricity is generated onboard from diesel, rooftop solar could repay its installation cost in lifetime fuel savings. Rooftop solar may have a marginal role in reducing diesel emissions from non-ZEBs, while having no significant role on a BEB.

Strategic hard-to-decarbonise local bus route decision tree



Indicative summary of the cheapest lifetime BEB option for a route

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)	< 650	> 950	650-950	> 900	< 900
Peak vehicle requirement (buses)	4-8	< 4	> 8	< 4	> 4
Daily operating hours of route	< 21	Lower[1]	> 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

Footnote 1: Extra BEBs are not a dominant strategy at any specific number of operating hours, but skew towards 12, not 24, hour routes.

Thank you for your attention

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For a full explanation of how we reached our conclusions, and for a comprehensive evidence base, please see the companion report **"The potential for hydrogen buses in Europe: Analysis of alternatives"** which is freely available at https://fuelcellbuses.eu/publications

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