The potential for hydrogen buses in Europe: Results from the bulk analysis of passenger schedules

July 2024

ZERO EMISSION

JIVEs / MEHRLIN projects

Clean Hydrogen Partnership

Co-funded by the European Union

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Contents

Abbreviations

Term	Explanation
BEB	Battery electric bus
ºC	Celsius degrees
DRT	Demand responsive transport
EU	European Union
FCEB	Hydrogen fuel cell electric bus
GTFS	General Transit Feed Specification, a standard interchange format for passenger-facing public transport schedule data
kg	Kilogram
km	Kilometre
kWh	Kilowatt hour, a measure of energy storage and use
JIVE	Joint Initiative for hydrogen Vehicles across Europe
NUTS	Nomenclature of territorial units for statistics
OEM	Original equipment manufacturer, which in the bus sector can be an amalgam of separate chassis, bodywork, and battery suppliers
ZEB	Zero emission bus (at tailpipe), including BEB and FCEB, but excluding other gas buses

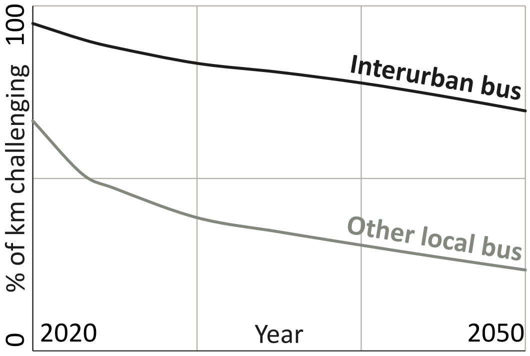
Summary

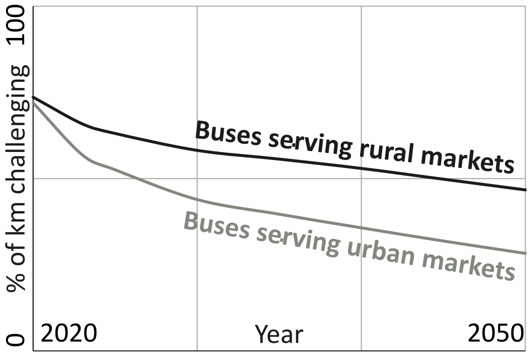
The JIVE project was established to help commercialise hydrogen Fuel Cell Electric Buses (FCEBs) across Europe. This report frames the European markets where FCEBs are most likely to be adopted in the long term. It is intended to help focus public transport agencies, policymakers, and vehicle manufacturers on markets where FCEB is most likely to succeed in future.

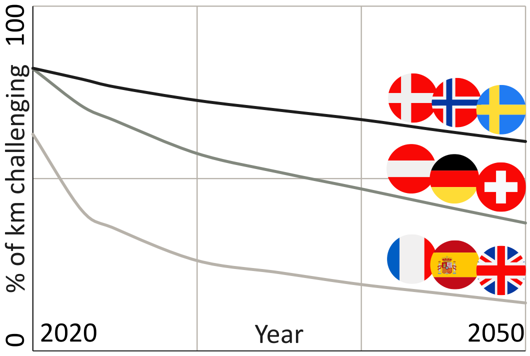
Given the inherently higher production costs of hydrogen fuel, it is reasonable to assume that where Battery Electric Buses (BEBs) can be operated with just depot charging infrastructure (and no additional investments such as opportunity charging), battery electric technology will be used to decarbonise bus routes. This frames FCEB as a niche solution for bus routes that will be more challenging to decarbonise – those where all options would add further cost.

This challenging-to-convert-to-BEB niche has been quantified by analysis of the operational requirements of individual local bus routes. We modelled the energy requirements of each route, across the three quarters of all scheduled bus operations in Europe for which open schedule data was available.

Interurban routes, buses serving rural markets, and certain parts of Europe such as Scandinavia, are more likely to be challenging to convert to BEB[1]







The modelling gave insight into three key factors defining the FCEB market niche – interurban routes, buses serving rural markets, and certain nations of Europe – summarised in the graphic above. BEB capabilities will primarily be limited by maximum legal vehicle weights. Expected future improvements in battery energy

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[1] Only headline patterns illustrated – more detailed analysis can be found later in the report.

density could still leave about a third of all European scheduled bus mileage challenging to convert to BEB in 2050.

The modelling allowed us to frame the potential European FCEB market as about 20% of Europe's scheduled bus fleet, roughly five thousand vehicle sales per year by 2050, peaking at a total fleet parc of about sixty thousand FCEBs.

In practice, hydrogen will not be the only solution to decarbonise buses in this market niche. Battery-based alternatives include opportunity charging infrastructure or sufficient extra BEBs to allow daytime depot charging. These may be judged more cost-effective than hydrogen, especially by urban operators. Our pragmatic assessment concluded that only about a quarter of the potential FCEB vehicle market might reasonably be expected to adopt FCEBs. However, the study did not analyse the alternatives in sufficient depth to draw firm conclusions, with no cost modelling or detailed assessment of local factors.

FCEBs will be most likely to be deployed on routes serving more rural markets, especially on interurban routes. Demand for longer-range models, including those with coach bodies, can be expected to surpass the current FCEB vehicle market trend for high-capacity city buses.

FCEBs may appeal financially, since bus operators tend to be revenue-rich but capital-poor: the additional cost of solving challenging routes – that cost beyond the initial investment in vehicle and fuelling infrastructure – would primarily add operating cost with FCEBs (as more expensive fuel), instead of extra capital cost for BEB-based solutions (typically extra infrastructure or vehicles).

If the whole potential FCEB market niche were to adopt FCEBs, total daily local hydrogen volumes should be expected to be viable to supply to the vast majority of local FCEB fleets. Hydrogen demand for FCEBs in Europe could reach 600 kilo-tonnes annually. However, with our more pragmatic assessment of FCEB adoption, the majority of FCEBs could be commercially unviable to supply without additional local demand from other modes of transport. Operators, contracting agencies, FCEB manufacturers, and hydrogen suppliers should all expect to plan far more strategically and holistically than has traditionally been the case when replacing fleets route-by-route.

This analysis has assumed no change to bus services, only to the bus powertrain. In deregulated markets we should rationally expect operators to avoid additional lifetime costs by attempting to design networks that can be operated within the limitations of BEBs. However, most European local bus operators have little geographic or commercial freedom to modify routes to suit BEBs, and so are more likely to have to adopt solutions with additional costs, such as FCEBs. The extent to which operational or service compromises might be acceptable to accommodate BEBs will vary by place, adding further uncertainty to long-term FCEB demand.

Many of the operators who are most advanced on bus decarbonisation are only now beginning to face the true challenges of battery electrification. Over the next two decades, as these challenges come to the fore across Europe, hydrogen should have genuine opportunities to be considered as a viable long-term option when decarbonising certain challenging routes – if it can demonstrate its commercial readiness and reliability.

Aims and context

European policy will require all new “urban” buses to be zero emission by 2035, with other categories requiring a 90% reduction in carbon dioxide emissions by 2040[2]. Many operators and local government agencies have set targets that imply fleet decarbonisation commences sooner. Zero Emission Buses (ZEBs) are on the verge of becoming the standard across Europe. Standardisation implies commercial and operational viability.

In simple terms, the halving of fuel costs typically associated with Battery Electric Bus (BEB) operation somewhat balances BEB’s substantial increase in capital cost relative to a diesel bus. Therefore, on purely commercial logic, BEB deployment is primarily inhibited by transitional risks, both financial and practical, which should dissipate in the long run.

In contrast, hydrogen Fuel Cell Electric Buses (FCEBs) are currently slightly more expensive to buy and offer no significant savings to fuel costs vs diesel. The inherent production inefficiency in converting energy into hydrogen, in comparison to electricity grid battery charging, means that FCEBs may be expected to cost more to operate than BEBs. FCEB capital cost is unlikely to fall significantly below that of a BEB while hydrogen fuel cells are manufactured only for niche markets such as bus.

So why and where might hydrogen have a role? The answer lies in the second aspect of standardisation, operational viability: not all bus routes can be efficiently operated with a BEB that is only charged at its home depot.

Conventional two-axle BEBs are especially constrained in their single-charge operating range by total vehicle weight. Without fundamental changes in battery chemistry, this constraint will diminish only gradually over time, and not soon enough to meet all Net Zero decarbonisation targets.

This battery weight constraint means that there will be a proportion of bus routes where all decarbonisation solutions add cost – cost in addition to the base cost of introducing the ZEB, primarily vehicle purchase and new fuelling or charging infrastructure at its home depot:

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[2] https://data.consilium.europa.eu/doc/document/PE-29-2024-INIT/en/pdf with further ICCT analysis - https://theicct.org/publication/revised-co2-standards-hdvs-eu-may24/ . In the context of this legislation, urban buses are M3 Class 1 – broadly those where most passenger capacity is standing, not seated, with more than one door for passenger use. In practice, many local bus operations outside of big cities can be adequately performed by low floor Class 2 (majority seated, single door) vehicles. Many OEM designs can be registered as either Class 1 or 2, depending on seating configuration and bodywork. This would seem to create considerable flexibility for OEMs struggling to meet the 2035 mandate for “urban” buses. This implies the broader bus and coach criteria could apply to most vehicles used on local bus services: 43% carbon dioxide reductions in the period 2030-2034, rising to 90% from 2040. Nations included in this study that are not part of the European Union, such as Norway, Switzerland, and the United Kingdom, are moving in a similar policy direction, so it is reasonable to generalise “European policy” to that of the European Commission and Parliament.

- Additional vehicles (beyond current Peak Vehicle Requirement) to allow extra downtime for at-depot charging during the day.
- Opportunity charging infrastructure to allow in-service charging, commonly ultra-rapid charging via a pantograph at a fixed location on the bus route, but potentially in-motion, including the use of trolleybus overhead or highway-embedded induction.
- Triaxle vehicles able to carry greater weight of battery.
- Or hydrogen FCEBs.

Whether each such route can bear these additional costs, and if so which of the above solutions is ultimately selected, are secondary questions. The first task is to identify the volume and geography of such routes, and in doing so identify the potential long-term market for FCEBs.

While the operational flexibility of FCEBs (which is like diesel), or potentially the ease of supplying hydrogen to a depot instead of obtaining a high voltage electricity grid connection, can ease the transition to ZEBs, these advantages are unlikely to be the basis of a strong long-term market for FCEBs, so have not been considered by this study.

This study focuses only on vehicles used to operate scheduled public passenger services in Europe. This definition of “bus” stresses how the vehicle is used. It includes a small proportion of routes which are operated with coach-bodied vehicles. Much of the European coach fleet is used for private groups or tours. Analysis of this coach fleet has been excluded from this study because it does not operate to a fixed, published schedule.

Strategic approach

As introduced in the previous section, the characteristics of individual bus routes are key to understanding the ease with which BEBs can be deployed upon them – and hence whether routes could be reasonable targets for FCEBs in future. Scheduled bus routes are associated to highly consistent patterns of vehicle operation. This consistency makes it possible to gauge key vehicle specifications from route schedules.

Public passenger-facing bus schedules are commonly published as open data[3]. This study assembled six hundred separate datasets, collectively estimated to represent about three quarters of all scheduled bus services in Europe – with a similar coverage proportion for each contemporary definition of Europe. Coverage was assessed by correlating bus services to population density of places served, and then applying that formula to all demographics in the country, as detailed in the technical method.

The type of bus service included in schedules (and thus subsequent analysis) varied slightly between data sources. For example, some countries operate dedicated school

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[3] Attributions can be found at the end of this report.

transport services which may not be available to the public, while others, such as Germany, integrate scholar transport into the wider public transport system. In practice these variations tend to relate to mid- or low-intensity vehicle duty cycles, those duties unlikely to be future targets for FCEBs.

The analysed data described bus services in a typical week, in most cases one week in the second half of April 2024, avoiding public or school holiday periods when lower service levels might apply. The technical method contains extensive data validation and comparison to other metrics.

Passenger schedules were then used as the basis for route-level modelling of distances and hourly vehicle requirements. As detailed in the technical method, while analysis was primarily conducted at route level, infrequent routes were modelled to allow vehicles to inter-work between routes in the same vicinity.

Data coverage may be imperfect, and modelling may simplify operational reality slightly, but the aim was not perfection, rather enough data volume to capture and explore the most important patterns. With almost a hundred thousand uniquely named routes processed[4], our method granted far more extensive coverage of European bus operations than any operator or route case study might, albeit in a slightly less accurate manner.

Range requirements

Potential demand for FCEBs is rooted primarily in each bus's daily duty cycle range requirement. Scheduled bus services imply extremely consistent vehicle duty cycles: Mileage, headway, and geographic character of route is effectively fixed from day to day, with local traffic and weather conditions being the main operational variables. The ability of hydrogen to match the "fuel and go" operational flexibility of diesel may make hydrogen an easier fuel to transition to, as overnight depot processes will be largely unchanged. But ultimately this flexibility is of marginal value to most local public bus operators, who operate fixed bus routes with predictable daily battery charging requirements.

Modelled vehicle range S-curves are shown on the graph below for Europe by operational archetype. Europe refers to all analysed data. Operational archetypes were defined mathematically, as described in the technical method's Table 2. These archetypes describe the style and geography of each bus route. Operational archetypes do not strictly align to vehicle classifications, although city archetypes will favour high-capacity urban buses, while long-distance routes are in practice highly likely to be operated with coaches. Services in rural markets are not only provided by the rural operational archetype – interurban routes often form the backbone of bus services in rural areas.

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[4] Unique combination of operator and route number. Within that, about half a million unique sequence of bus stops, commonly called route variations, were processed.

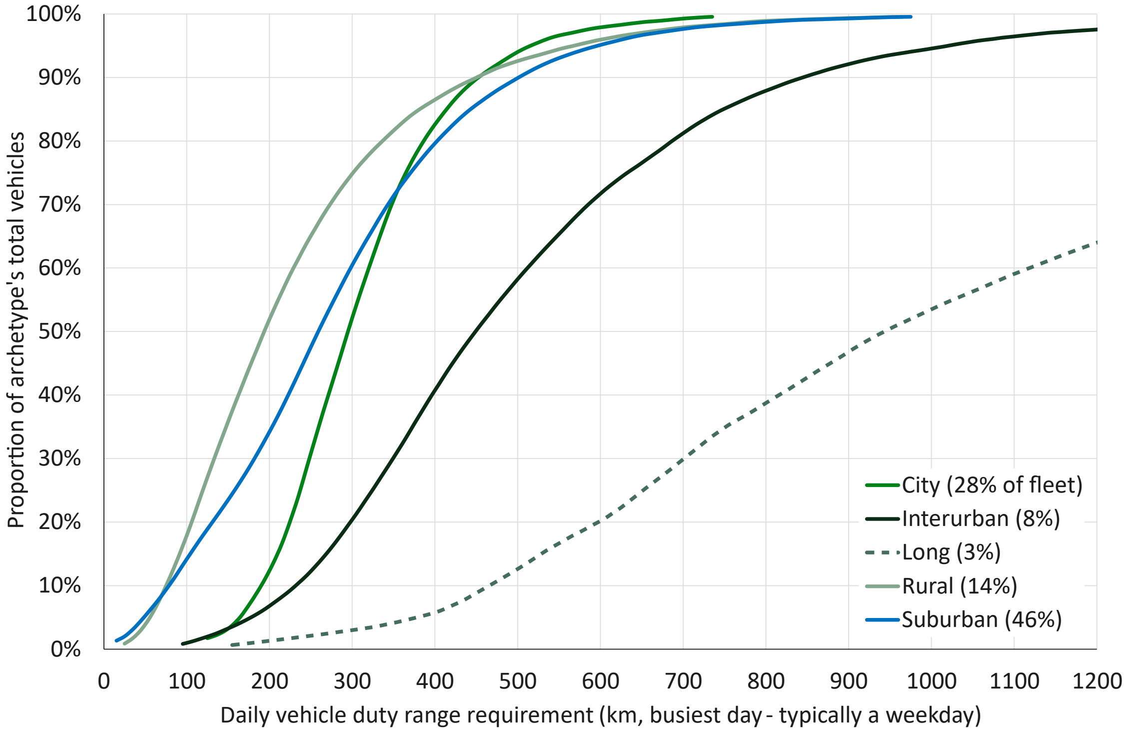

Figure 1: Bus duty distance requirements by operational archetype

City (core high frequency urban) routes have the greatest consistency of range requirement. Rural (local services in rural areas or small towns) and suburban (lower frequency urban) routes include a proportion of vehicles with low daily mileage, but also a longer tail with higher mileage requirements. City, rural and suburban profiles all coalesce at about the same upper range, while collectively account for 89% of the modelled fleet, both factors which naturally lead them to be generalised together to define a typical requirement for a local bus.

Interurban routes are those regularly operated to a regional centre from outside that centre. They are commonly considered part of local bus services yet have roughly double the range requirement of the previous three archetypes.

Scheduled long-distance (over 100 km) routes are more obviously in a class of their own. A “daily duty” is misleading in this context because the distance modelled is that between leaving and returning to home depot, which for a proportion of long-distance international services occurs over a period of more than one day: Indeed, the upper 15% of long-distance vehicles were modelled with duties over 2000 km, roughly the limit of travel in any one day. Long-distance operations are not the prime focus of this study and represent a small yet especially untypical segment of the analysed data. So, while included in the overall study, more focused analysis excludes them to clarify patterns most relevant to “bus”.

While there is a key difference between interurban and non-interurban local bus operational archetypes, European averages disguise tangible differences between nations, as summarised in the figure below. Nations with similar patterns have been grouped together. Ungrouped smaller nations, and those with poor coverage in the analysed data are included only in the comparative all-Europe curve.

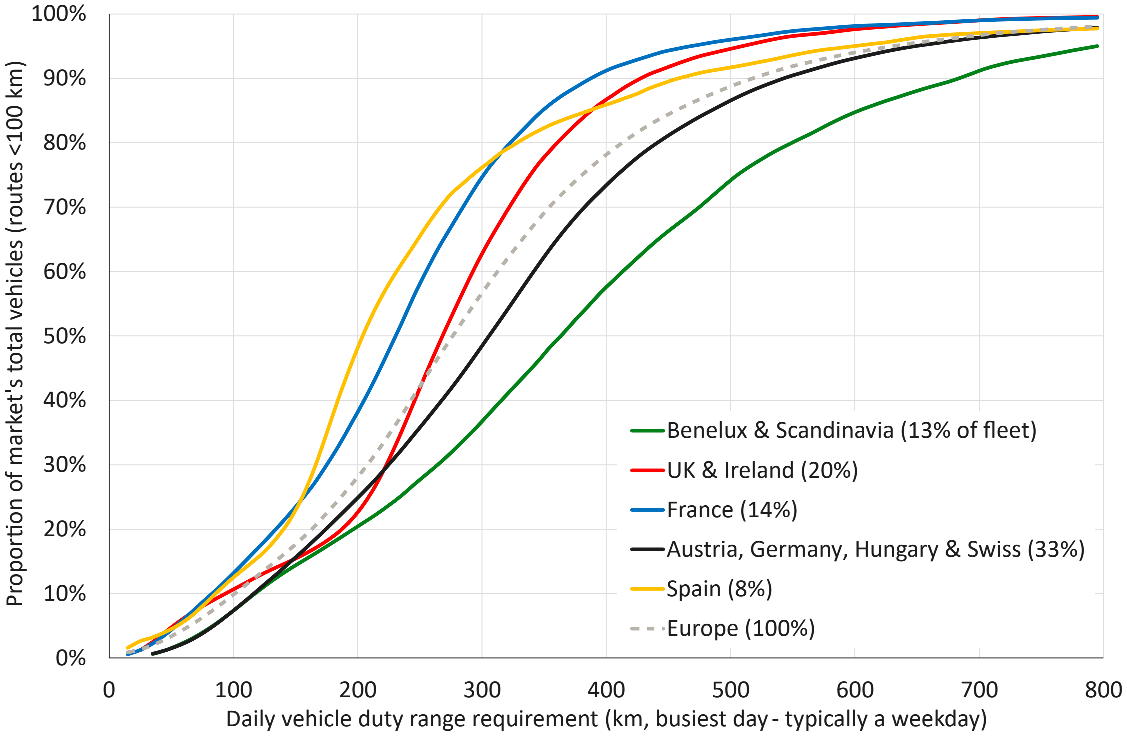

Figure 2: Bus duty distance requirements within selected territorial markets (routes under 100 km)

The spread of data is significant, in that an “average” bus in Spain travels about 40% fewer kilometres than an average bus in the grouping of Benelux and Scandinavian countries. However, the diversity of Spain can also be seen in the long tail of high mileage Spanish bus duties – a far less consistent pattern overall than, for example, France.

Some of the patterns echo biases in the distribution of operational archetypes shown in Figure 21 of the technical method, for example around 30% of bus mileage in Denmark and Sweden is Interurban, more than double the European average. However, both France and Germany have similar balances of operational archetypes, yet a typical bus in Germany can expect to travel up to 100 km further each day than a typical bus in France. As the technical method’s Figure 22 explains, the average operating speed of buses in Germany is higher than in France. This pattern largely explains why the Benelux and Scandinavia curve is so far to the right: For example, buses in Sweden tend to operate about 15% faster than buses of the same operational archetype across Europe as a whole.

While not the focus of this study, and thus not analysed in further detail, the evidence above points to the existence of quite different bus operations and network design in western-most Europe from those in central, eastern, and northern Europe.

Limitations of battery electric

The basic premise of this study's methodology is that because green hydrogen is expected to be a significantly more expensive fuel than electricity (due to its inherently poor production efficiency), bus operators will decarbonise with BEBs where possible to do so without needing additional assets such as extra vehicles or non-depot charging infrastructure. Possible means the BEB can either complete a full daily duty in the worst climatic conditions on a single overnight charge (hereafter called Straightforward) or can do so by using vehicle downtime in existing schedules to charge at depot during the day (referred to as Manageable).

In contrast, where BEBs cannot be so easily deployed, and thus would add further cost, there is a potential market for hydrogen FCEBs. Where a bus route is short enough to allow BEBs to return to their home depot after one out-and-back trip, these deployments are categorised as Challenging. Where not, which comprises exclusively long-distance coach, BEB is considered incompatible in practice. Analysis of BEB compatibility therefore frames the theoretical limits of hydrogen in local bus markets.

As detailed in the technical method, BEB vehicle battery capacity is constrained by vehicle axle weight. Capacity is expected to improve as research and development improves battery energy density, raising the amount of energy available per kilogram. However, the pace of recent technological development is expected to slow, and thus so will the rapid advances in BEB battery capacity and effective range the bus sector has seen over the last decade.

Operations

This study's analysis has assumed bus networks and operations remain unchanged. The gradual easing of BEB compatibility modelled in the graph below is due to improved vehicle range making it progressively easier to convert routes to BEB[5].

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[5] The technical method's Figure 24 helps explain the sensitivity of BEB compatibility analysis to future battery energy density assumptions. In very broad terms, battery energy densities 50% higher than modelled – a reasonable scenario only with as-yet-unproven solid-state battery technology – could halve the proportion of mileage assigned as Challenging while making minimal impact on mileage categorised Incompatible.

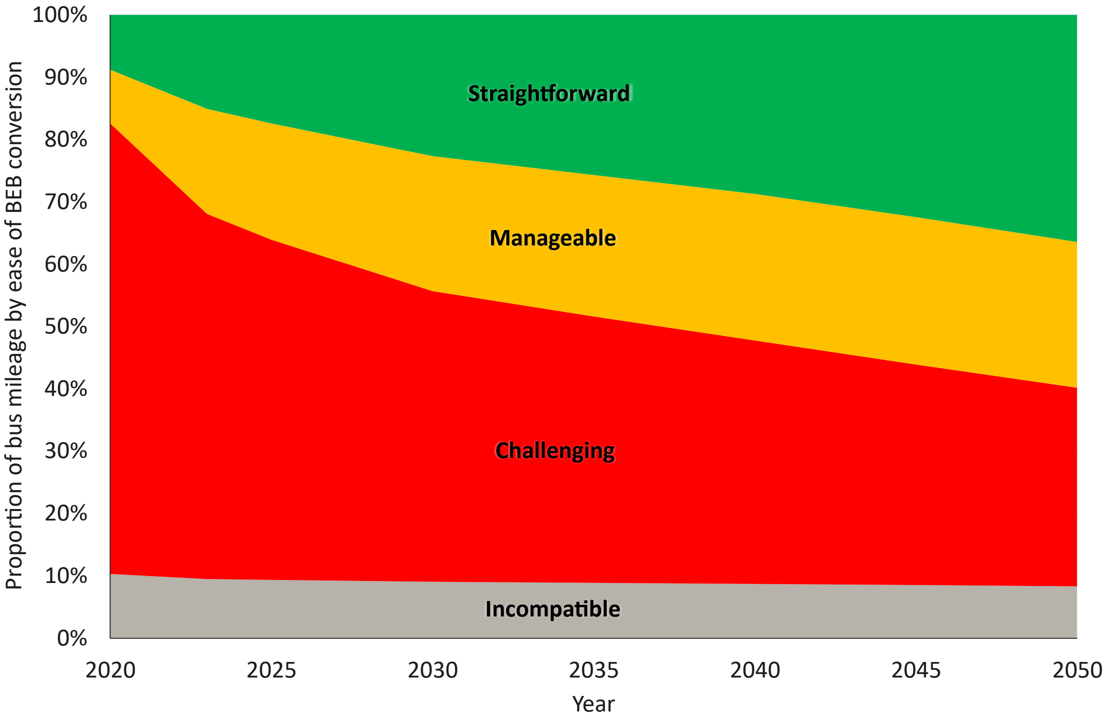

Figure 3: Modelled BEB compatibility with current European bus mileage (all analysed data, forecast 2020-2050)

Policymakers and operators expecting to decarbonise local bus networks with BEBs in the 2030s – or even by 2050 – will eventually need to reflect on the large red block marked Challenging: half of European scheduled bus mileage will be challenging to convert to BEB in the 2030, with a third still challenging in 2050.

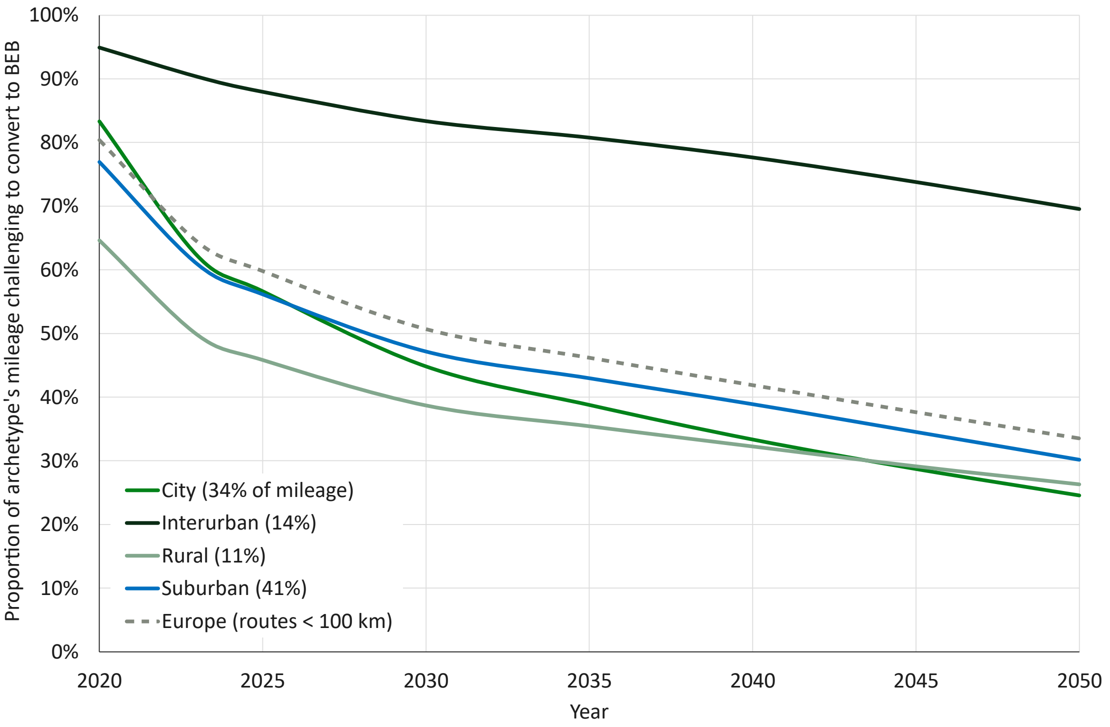

Figure 4: Proportion of mileage challenging to convert to BEB (routes under 100 km)

While challenges remain for all operational archetypes, the graph above shows interurban routes will be much more likely to be challenging than other forms of local bus operation. The proportion of city routes that are challenging should drop more quickly with time than other operational archetypes, reflecting the intense, but localised nature of city operations.

National

The distinction between interurban and other local bus is not the only determinant of routes that will be challenging to convert to BEB operation. There will be differences both within and between countries. The graph below summarises national trajectories for the proportion of mileage that will be challenging to convert to BEB. Each nation with representative coverage[6] has been grouped with others that share a similar trajectory. The dotted lines show the value of the highest and lowest nation within the grouping in each year.

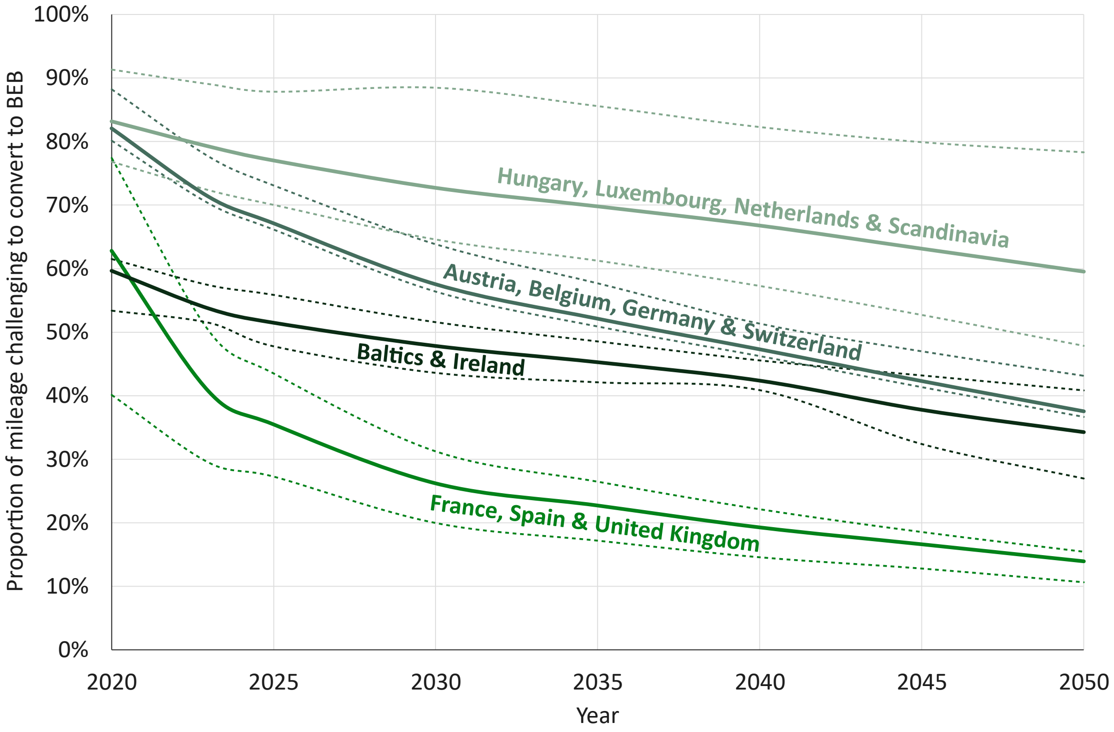

Figure 5: Proportion of mileage challenging to convert to BEB by national groups sharing similar trajectories (nation maxima and minima within group indicated by dotted lines)

The graph reveals two sets of trends: Two pairs of groups with different base 2020 proportions of challenging to convert to BEB miles, one broadly 20% higher than the other. And two pairs of groups, one where the ease of conversion to BEB improves rapidly in the 2020s and then improves more slowly, and one which just improves more slowly throughout.

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[6] Assessed by comparing actual coverage to that predicted by population density, as described in the technical method's Representativeness of coverage section.

These patterns might be expected to influence national policy towards bus decarbonisation. The current European leaders (relative to their fleet size) on BEB deployment, the Netherlands and Norway, sit in the most challenging group. However, only about 20-25% of these bus fleets have been estimated BEB[7], a sufficiently low proportion to have not yet had to deploy BEBs to the most challenging routes. The combination of both factors suggests these countries will increasingly have to work around the limitations of BEBs and adjust to the higher costs implied by decarbonising such challenging routes.

National patterns can disguise substantial differences within countries, as illustrated by the map below. This shows the proportion of mileage modelled as challenging to convert to BEB in 2040, by NUT3 area, for areas with representative data coverage. The year 2040 perhaps best describes the point in the Net Zero journey when most operators will no longer be able to defer decarbonisation decisions. Transport is often administered locally, typically allowing different approaches to decarbonisation to be adopted in different parts of each country.

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[7] Norway has introduced about a thousand BEBs since 2020s - https://www.sustainable-bus.com/news/uk-germany-norway-leader-electric-bus-market-2023-europe/ - against an estimated local bus fleet of about five thousand buses. The Netherlands has a similarly sized local bus fleet and had the highest proportion of new bus sales BEB in 2022 - https://www.transportenvironment.org/articles/netherlands-leads-the-way-on-new-electric-buses-analysis

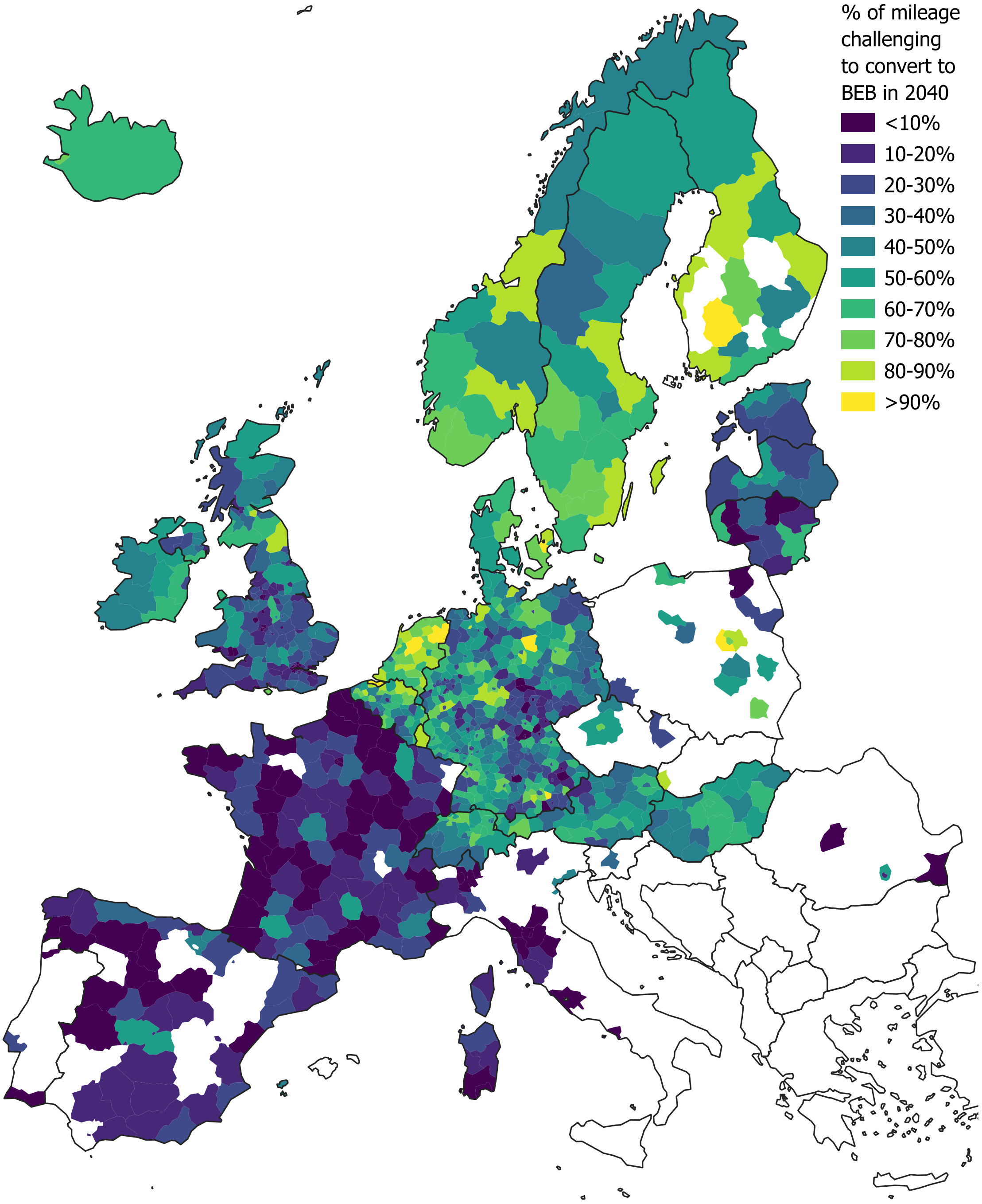

Figure 6: Proportion of all mileage challenging to convert to BEB in 2040 by NUTS3 area (blank areas are those assessed with inadequate data coverage to produce representative analysis)

Rural

Each bus route has been classified as urban or rural, based on the market territory it primarily serves, as detailed in the technical method. The definition of urban and rural approximates to that used by Eurostat.

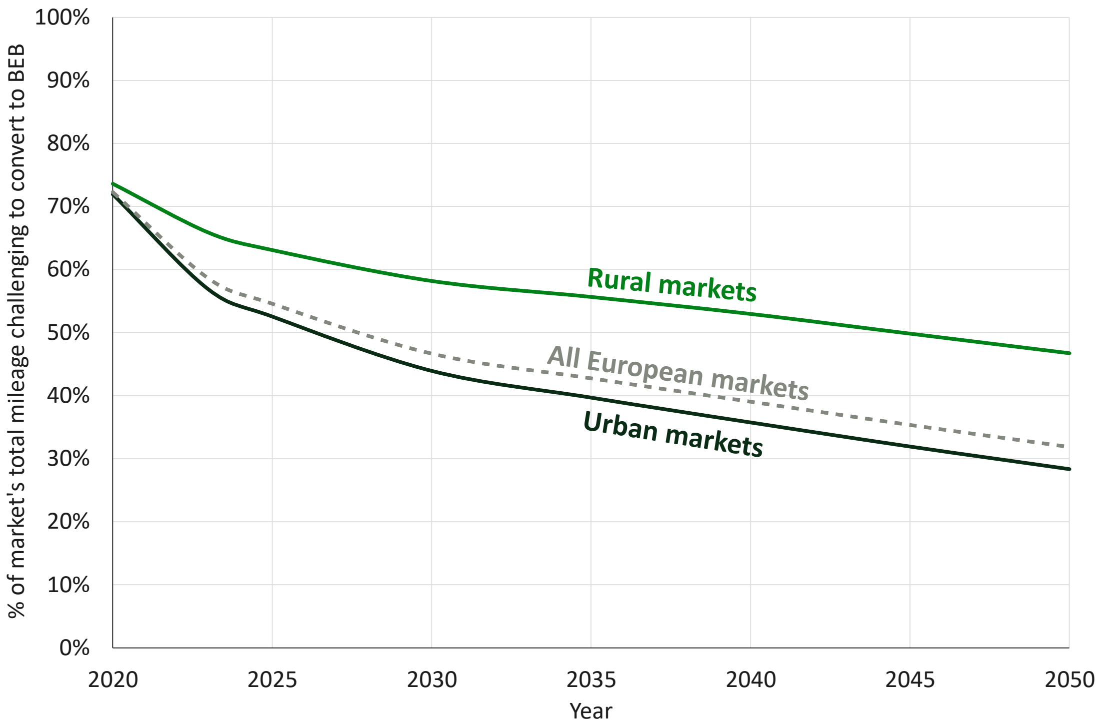

Figure 7: Proportion of all mileage serving rural or urban markets that will be challenging to convert to BEB (all analysed data, 2020-2040)

As clearly seen in the figure above, a higher proportion of all mileage serving rural markets will be challenging to convert to BEB than the comparative profile for urban markets. Further, urban markets will benefit disproportionately from improvements in BEB capability during the 2020s. In practice, electrification of rural routes will tend to be even more challenging than shown, since the depots used for such routes tend to be less likely to be near route termini (implying above average "dead mileage" and less operational flexibility) and may occupy geographically remote sites that are more difficult to connect to the electricity grid. European bus networks are dominated by urban, not rural: About 80% of all mileage serves primarily urban markets, although the balance varies between and within individual countries.

All these factors increase the risk that rural market services will be "left behind" as the wider European bus sector decarbonises, while ultimately tending to be served by a technology that is fundamentally more expensive to operate, implying either service reductions on increased fares or subsidy. Such rural concerns are most likely to promote what is otherwise just a bus industry decarbonisation problem into a broader socio-economic question. Consequently, state actors are most likely to become involved in these issues, which in turn may change the funding or regulation affecting these bus routes.

The figure below captures the likely extent of this policy risk for countries with reasonably representative data coverage. The first data bar shows the magnitude of the issue – the proportion of the country's challenging mileage that serves rural markets, as an average over the period 2020 to 2050. The second data bar shows the changing importance of the issue – the change in that proportion from 2020 to 2050.

Countries are ordered by the addition of the two, to give an indication of relative rural bus policy risk.

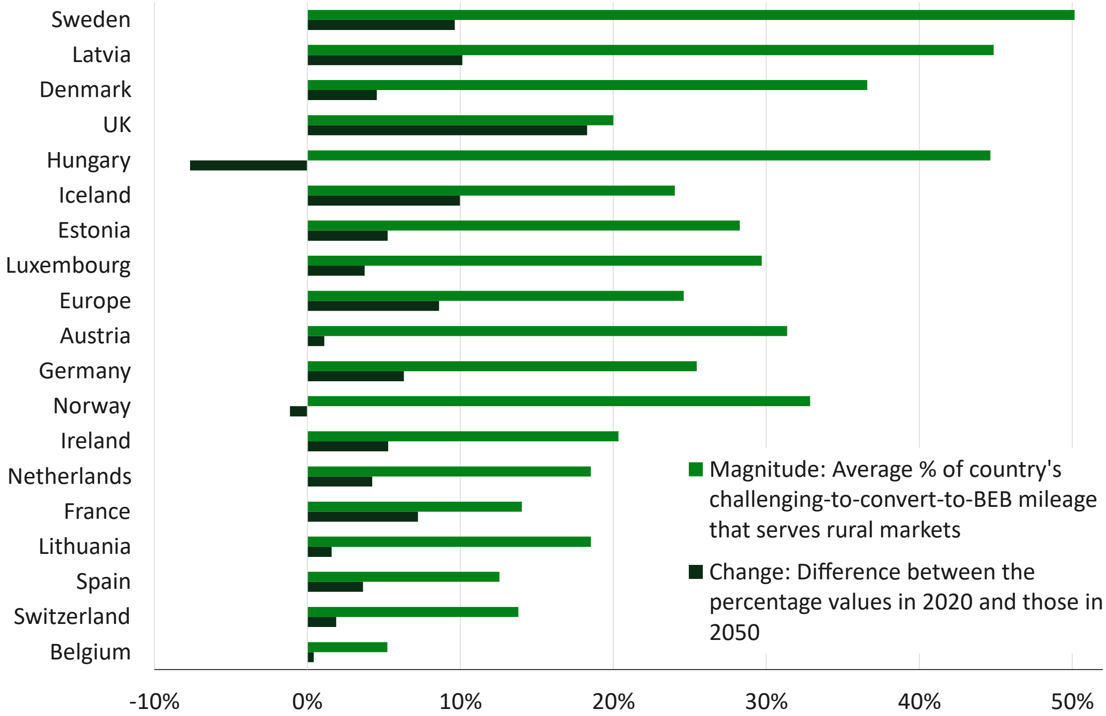

Figure 8: Rural bus policy risk (countries with representative data only[8], listed from highest to lowest rural risk)

Both magnitude of issue and the change in that magnitude over time may trigger public policy discussion. For example, Hungary averages a high proportion of challenging mileage serving rural markets, but the perception of this problem is likely to ease towards 2050. Hungary has been modelled with higher proportion of challenging mileage rural in 2020 than in 2050, hence the rate of change is shown as negative. In contrast, the magnitude of rural challenges in United Kingdom (shown UK) are just below average overall but grow rapidly in importance towards 2050.

Potential for hydrogen

If all the bus routes modelled as challenging to convert to BEB in 2050 were assumed to convert to FCEB instead, an average of 820 tonnes of hydrogen would be consumed per day across 36 thousand in-service FCEBs. Assuming the same patterns of bus operation apply in the quarter of Europe[9] that was not analysed due to lack of data,

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[8] Europe value describes all analysed data, including countries with partial data not listed separately. Note that data availability tends to skew towards the most heavily industrialised countries. So, while the overall pattern suggests rural policy risk tends to be greatest in Northern-most Europe, there is simply no data with which to judge, for example, the strength of issues in the Balkans.

[9] Europe defined as up to but not including Belarus, Russia, Türkiye, and Ukraine. The derivation of that quarter is discussed in the coverage subsection of the technical method. Long-distance networks have

and about 15% more buses are acquired than are needed in-service on the busiest day to provide maintenance cover[10], the total FCEB fleet parc would number about 55 thousand buses, and the total average daily hydrogen consumption would rise to about 1100 tonnes. Add routes modelled as “incompatible” with battery electric, which are entirely long-distance coach routes, and daily hydrogen consumption would reach 1700 tonnes across a parc of around sixty thousand FCEBs.

For context, the 600 kilo-tonne implied annually for FCEB is the equivalent of under a tenth of current (largely not “green”) European hydrogen production[11], with sixty thousand vehicles representing under a tenth of the current European bus and coach parc[12], but roughly a fifth of all vehicles used on scheduled public bus services.

Vehicle market

The figure below shows uptake of FCEBs if all routes that will be challenging or incompatible to convert to BEB opt for FCEB. As described in the technical method, uptake curves were modelled by presuming European bus buyers pre-empt EU vehicle mandates by 5 years on average. Long-distance vehicles were assumed to be replaced every five years, instead of 15 years for other operational archetypes. This means total long-distance vehicle sales, of which all would be coaches, would be three times greater than the proportion of the overall parc they represent.

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been scaled up for consistency, although this likely overestimates the European total for long-distance because the largest known networks were all included in the analysed data.

[10] Assumes FCEB attains the same fleet availability as modern BEB, biogas and hybrid fleets, which is not yet the case.

[11] https://observatory.clean-hydrogen.europa.eu/hydrogen-landscape/end-use/hydrogen-demand Cites current hydrogen production as 8.2 Mega-tonnes but has a slightly narrower geographic definition of Europe than that used to calculate FCEB demand.

[12] ACEA estimate just over 800 thousand bus and coach vehicles in use, https://www.acea.auto/files/ACEA-report-vehicles-in-use-europe-2023.pdf but this includes vehicles used on non-scheduled services, which have not been modelled here. Most of the vehicles not modelled are expected to have modest daily duty cycles suitable for battery electric, however there are niches, such as mid-distance group hire or coach tours, where FCEB may have a market.

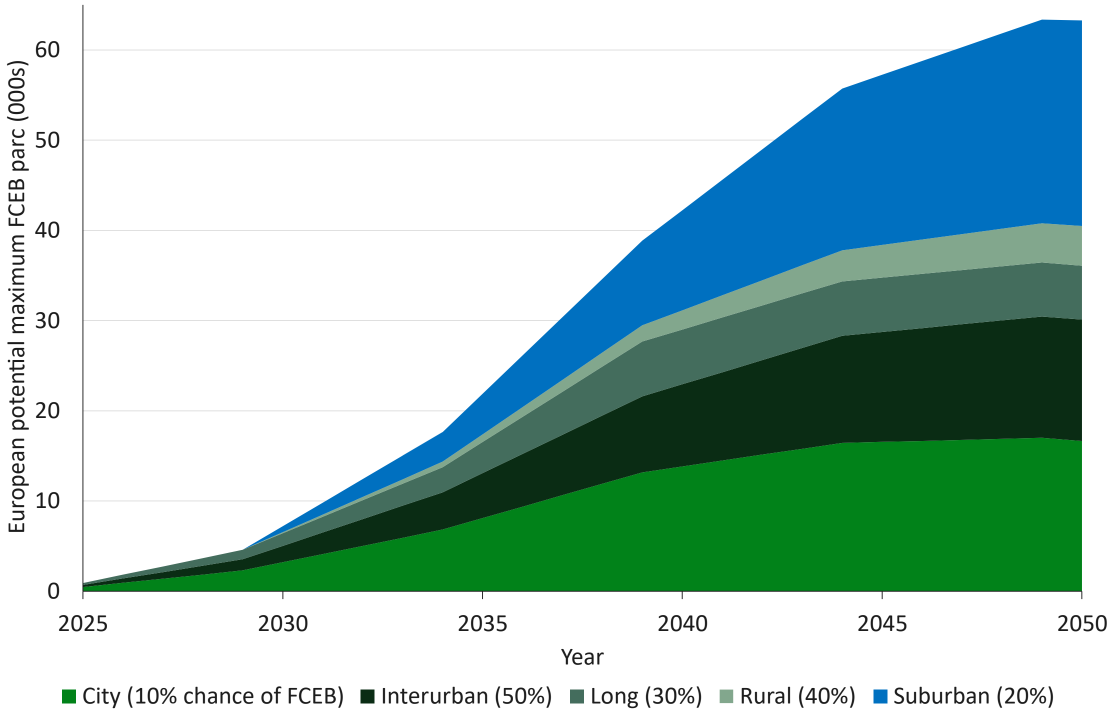

Figure 9: Estimated potential maximum FCEB parc by year (scheduled buses, whole of Europe, assuming all routes challenging or incompatible to convert to BEB opt for FCEB – the indicative chance of that happening is shown in brackets in the legend)

Modelling suggests the FCEB parc could start to decline after 2050, as the initial wave of conversion from non-ZEBs finishes and the dominant trend becomes improvement in BEB capability reducing the proportion of challenging or incompatible routes. BEB route compatibility in 2045 (which is modelled above as the basis for fleet investment decisions between 2045 and 2049) is thus the best single year-period guide for the high point of the potential FCEB market.

The indicative chance of each potential segment opting to convert to FCEBs is shown in brackets in the legend, and fully rationalised in the technical method's review of FCEB alternatives. These percentages are intended to guide a broad risk assessment, not imply a deterministic outcome: There is still considerable uncertainty as to the ultimate role of hydrogen. Likewise, any single value generalises a range of organisational and financing environments, some of which will better suit FCEB's skew to extra operational, rather than capital, cost.

If the chances assigned are assumed to represent a central future scenario, these chances equate directly to market share. In this case, the total FCEB parc would peak at around 16500 vehicles, or average European sales of about 1350 FCEBs each year. These sales would be distributed between operational archetypes as shown in the figure below.

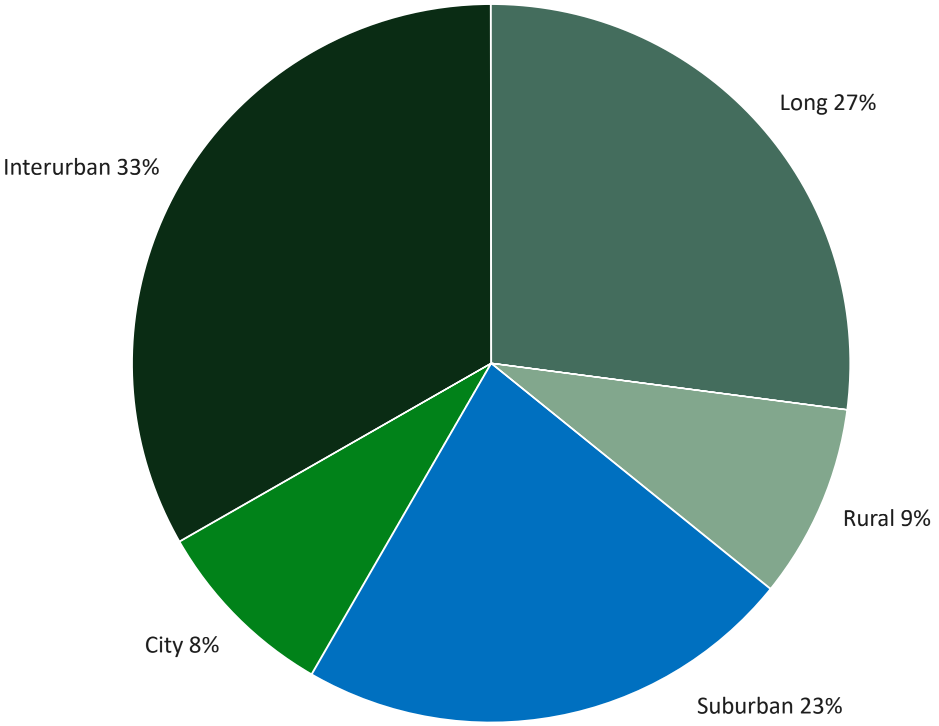

Figure 10: Balance of estimated FCEB annual sales at peak, central future estimate

Bus manufacturing is a specialist niche activity, so a market of this size is theoretically large enough to be commercially viable, in contrast to most other vehicle categories. Many of the manufactured parts of a FCEB can parallel those used in BEB designs, and thus FCEB models are theoretically sustainable with low overall market shares.

The sales in the chart above only count those to operators of scheduled bus services. It may be reasonably assumed that FCEB coaches deployed on long-distance scheduled routes could also be sold to operators providing private group hires and tours. Equally, a proportion of the interurban vehicle market either expects, or could accept, a coach-bodied vehicle. It follows that the strongest demand for FCEBs may emerge as for fuel cell electric *coaches*. It is less clear that the development of high-passenger capacity city FCEB models would be viable, given estimated annual sales of barely a hundred, and the relatively wide range of specifications commonly demanded, potentially including both articulated and double-deck models.

The graph below shows the proportion of each selected country's scheduled local bus fleet that could convert to FCEB. The green bars show the range from central future estimate to estimated maximum potential. There is no certainty of any long-term FCEB market, so in all cases the theoretical long-term minimum fleet share is 0%. The total proportion of all European FCEB hydrogen fuel demand is shown in brackets[13].

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[13] These proportions do not vary significantly between estimates, so only one percentage value is shown.

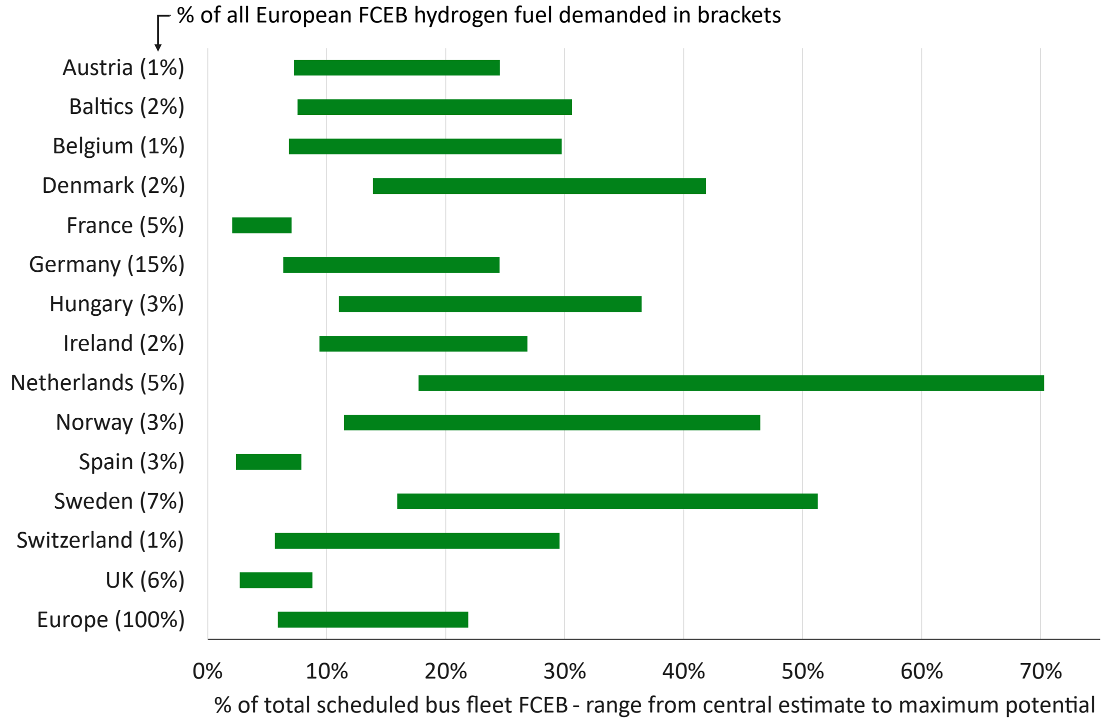

Figure 11: National FCEB scheduled bus market shares for selected countries (range from central estimate to estimated maximum potential)

FCEBs are likely to have the largest fleet shares in the Netherlands and Scandinavia. Germany could become the largest single market for FCEBs and associated hydrogen fuel in Europe. Three of the biggest European nations – France, Spain, and the United Kingdom – are expected to have low market shares for FCEB, which lower the European average.

Hydrogen supply

The graph below shows the ramp-up of FCEB hydrogen demand across Europe, for both estimation methods described above, ignoring any local supply constraints. Weekdays would use about 10% more than the overall daily average, with Sunday consumption only two thirds of average. The impact of climatic extremes on energy use for cabin heating and cooling was not modelled for FCEBs[14].

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[14] Observations suggest FCEBs tend to use more hydrogen below 5°C and above 20°C, which in practice makes FCEBs far more consistent than BEBs.

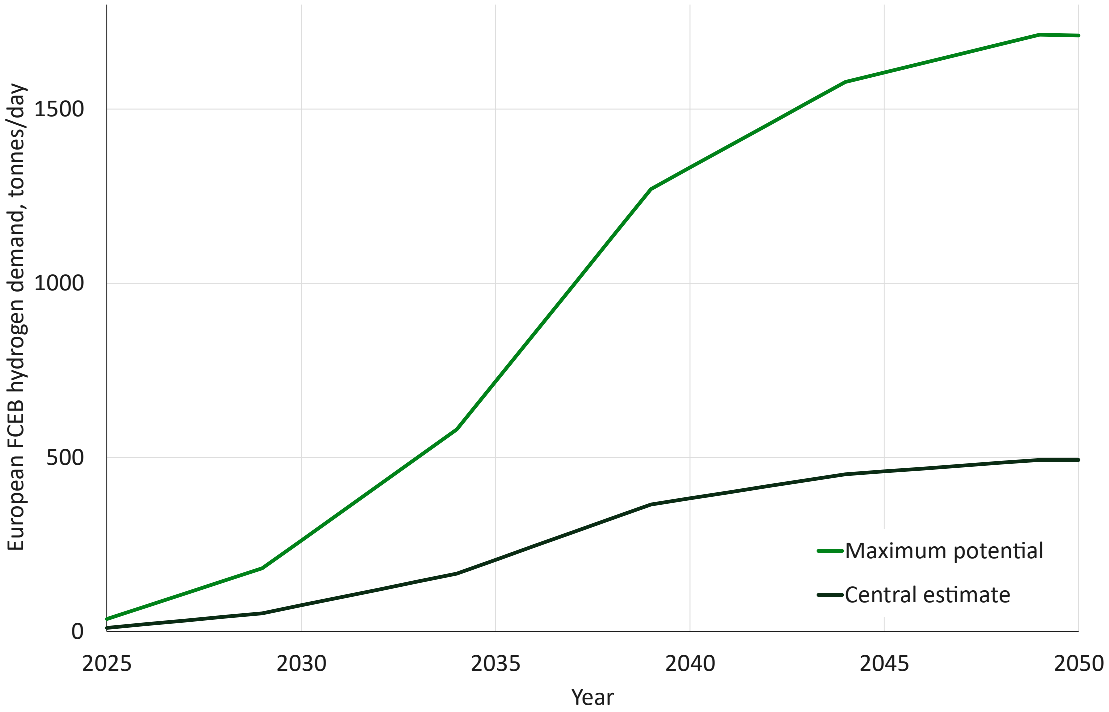

Figure 12: Total daily European FCEB hydrogen demand

Given the infrastructure required to produce, distribute, store, and dispense hydrogen, it is not generally cost-effective to supply in small quantities (especially with the need for redundancy in infrastructure designs to ensure high availability). Hubs should be expected to distribute a total of at least one tonne each day to be viable, with individual fuelling sites using hundreds of kilograms each day. FCEBs in the potential market, excluding those used on long-distance routes, would consume an average of 27 kg of hydrogen each day. So, in broad terms, a hydrogen supply hub dedicated to FCEB would need to support in the order of fifty FCEBs to be viable.

NUTS3 is a standard European nomenclature for territorial units, typically provinces or districts. NUTS3 geography varies in physical area and overall ease of transporting hydrogen, so cannot perfectly model efficient hydrogen distribution. In practice it could be much easier to share supplies across some neighbouring areas than others. However, by summing the total daily hydrogen demand by NUTS3 area, for all buses primarily operating in that area, we can start to gain insight into the magnitude of future FCEB hydrogen supply challenges, and to what extent these might inhibit deployment of FCEBs in local areas of Europe.

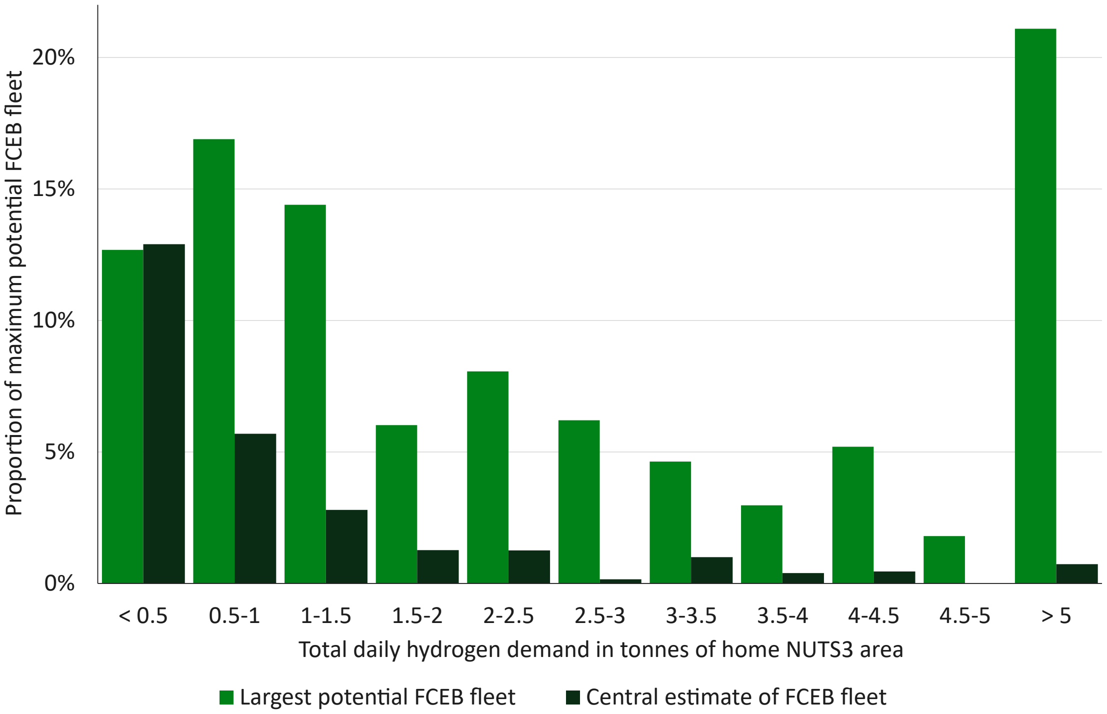

Figure 13: Distribution of total daily hydrogen demand by NUTS3 area (for FCEBs primarily operating in one area, for areas with representative coverage)

The graph above shows the balance of the maximum potential FCEB fleet that would be based within areas with different ranges of total hydrogen demand. Both the estimates outlined in the previous section are shown.

If the entire maximum FCEB potential market was achieved, roughly 70% of the fleet would fall within areas demanding over 1 tonne per day. A substantial portion of the remainder is marginal and could perhaps be made viable by supplying other modes of transport, alongside scheduled bus, or establishing local hydrogen partnerships, potentially including industry[15]. In contrast, the pragmatic central estimate reduces the proportion of the FCEB potential fleet that is clearly viable to supply to below 10%. That central estimate viable fleet would only use about 120 tonnes of hydrogen each day across Europe. Up to a further 150 tonnes per day could be required by vehicles that were not analysed above because they had no primary NUTS3 operating area (almost entirely long-distance coach).

While this analysis is approximate, it indicates how important local scaling of hydrogen supply could be to the FCEB *vehicle* market. It also points to the need to plan solutions to challenges across the local fleet, not one bus or route at a time. Where networks are contracted, this may require the contracting agencies to become much more engaged in overall fleet planning.

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[15] Many expected future industrial uses of hydrogen could use a lower purity of hydrogen than that required for fuel cells, which can limit the scope for jointly supplying hydrogen to both sectors.

The map below broadly summarises the viability of distributing or supplying hydrogen at NUTS3-level for potential FCEBs operating primary in one NUTS3 area. The four categories shown are assessed as follows:

- Green: Viable under central FCEB estimate – at least 1 tonne per day of hydrogen demanded if FCEB attains only the share of its potential market matched by the chance of conversion to FCEB assessed for each operational archetype.
- Yellow: Viable if all FCEB potential attained – at least 1 tonne per day of hydrogen demanded if the entire potential FCEB market converts to FCEBs.
- Orange: Marginal if all FCEB potential attained – between 500 and 1000 kg per day of hydrogen demanded if the entire potential FCEB market converts to FCEBs.
- Red: FCEB requires multi-modal demand – less than 500 kg per day of hydrogen demanded if the entire potential FCEB market converts to FCEBs.

This analysis excludes most potential long-distance coach demand, which is estimated to total roughly a third of all daily hydrogen tonnage. Long-distance coach could share fuelling facilities with local bus. However, coach could logically use future hydrogen refuelling stations intended for long-distance trucks, facilities unlikely to be well-placed for local buses.

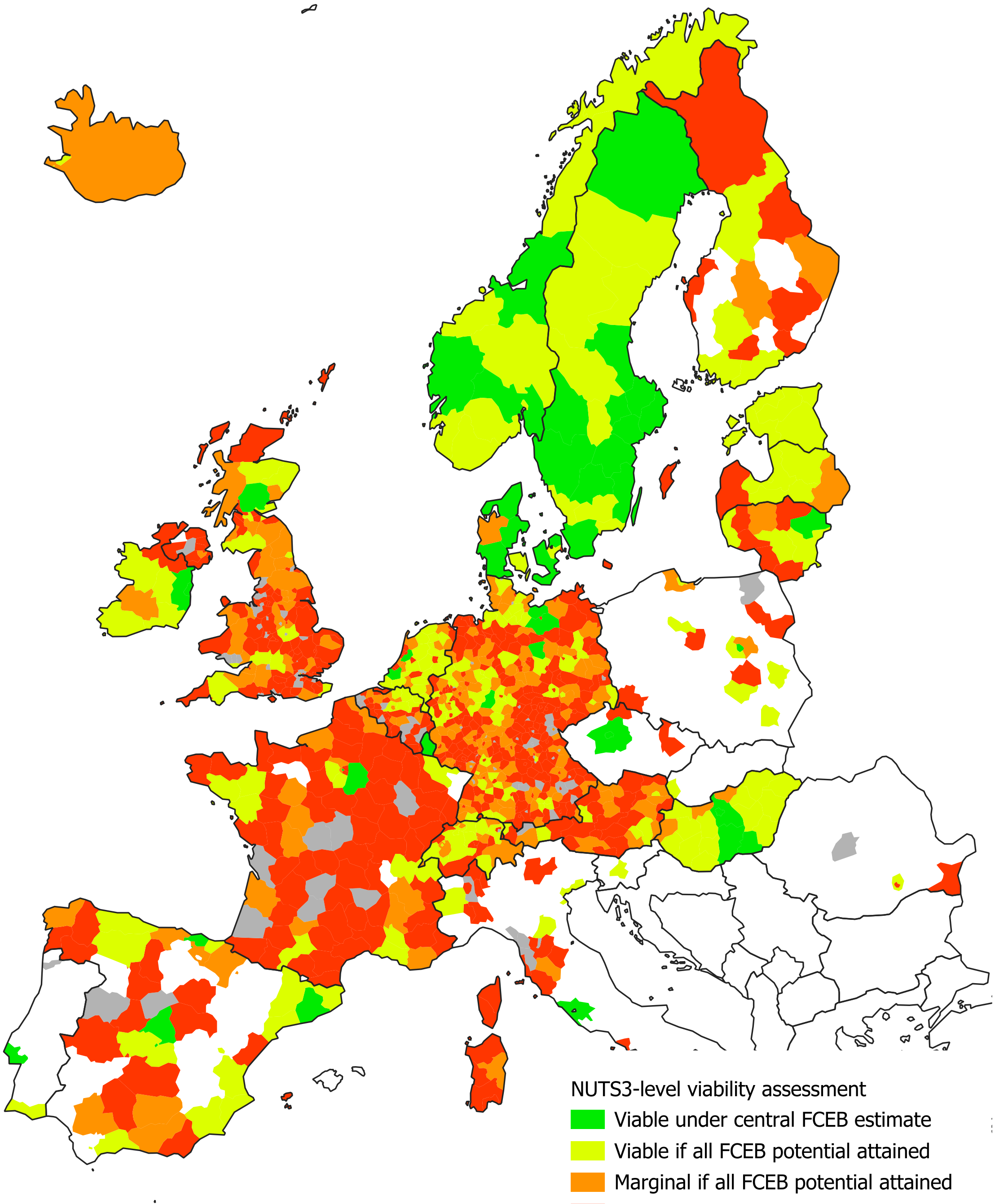

Figure 14: NUTS3-level indicative assessment of the viability of supplying FCEBs (blank areas are those assessed with inadequate data coverage to produce representative analysis)

The map confirms the strength of national markets for FCEBs, such as the Netherlands and Scandinavia. But it also highlights that potential exists within specific areas of almost every country.

Conclusions

The proportion of new European urban buses that are BEBs has grown year-on-year, with battery electric powertrains likely to account for most urban bus purchases by 2025[16]. With the help of JIVE, hydrogen FCEB has attained around 1% of that new urban bus market. From these patterns only, it would be reasonable to conclude that the future of bus decarbonisation is destined to be battery electric.

Yet such a conclusion overlooks the expected future difficulties of converting many bus routes to BEB operation. This study's analysis and modelling suggests that for about a third of European scheduled bus mileage, and about a fifth of the scheduled bus fleet, decarbonisation via battery electrification will be challenging based on the daily energy consumption.

All solutions in this challenging market niche would add cost, in addition to the base cost of buying BEBs and installing depot overnight chargers. Since all solutions add cost, the higher operating costs of FCEBs should not necessarily put FCEBs at a competitive disadvantage.

Operators will rationally first decarbonise within the limitations of BEB technology, avoiding extra costs but deferring challenging routes to later years. Early observations of successful BEB conversions will naturally tend to be on less challenging routes, creating a false sense of the ease of future bus decarbonisation.

This should ultimately present hydrogen fuel cell electric technology with a "second wind" in the bus market. FCEBs are unlikely to displace BEBs from their currently emerging market. But once only the challenging routes remain to be decarbonised, FCEBs should be more widely considered as a decarbonisation solution.

If FCEBs were to be adopted to decarbonise all challenging routes, daily hydrogen consumption for this market could reach approximately 1700 tonnes across Europe by 2050. Scandinavia and the Netherlands were identified as particularly strong potential markets, although Germany is likely to have the highest absolute demand of any one nation. France, Spain, and the United Kingdom emerged as weaker markets for FCEB, although local niches for FCEB could exist, especially for interurban buses.

The ultimate success of FCEBs in this challenging market niche is harder to predict than the overall size of the niche and would benefit from further evaluation of future alternatives. FCEBs are technically most likely to favour rural geography, especially interurban routes. FCEBs could also be easiest for bus operators to finance, relative to BEB solutions such as opportunity charging, as their *additional* cost is largely operational, not capital.

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[16] https://www.transportenvironment.org/articles/battery-electric-is-now-the-top-powertrain-type-for-new-city-buses-in-the-eu

Hydrogen cannot be efficiently supplied in very small quantities, so FCEBs will need to attain a reasonable proportion of their potential market niche in any one region to be commercially viable to supply. This may require a change in conventional fleet planning and procurement processes, away from route-by-route bus replacement, towards long-term local strategy and multi-modal partnership building.

The biggest uncertainty is not strictly technical but human. This study assumed that existing bus routes and operations would continue unchanged, except for vehicle decarbonisation. Yet it may be entirely rational to compromise existing operations to match BEB capabilities and avoid additional cost – for example by reducing frequencies at certain times of day, splitting longer routes into two, or attaching secondary heaters on the coldest days.

Any compromise would itself have a cost, be that passenger revenue or policy acceptability. It follows that the future success of hydrogen in the local bus sector may pivot on quite tangential agendas, such as the strength of campaigning to maintain existing rural bus connectivity.

Appendix: Technical method and data validation

The approach taken for data analysis and validation can be understood in four stages:

1. Source and acquire public GTFS (General Transit Feed Specification) passenger schedule feeds for bus services from across Europe.
2. Check GTFS quality, convert to network graph (an efficient way to manage and process large volumes of detailed schedule data), perform operational modelling, then analyse of battery electric compatibility.
3. Statistical pattern analysis, including the analysis of routes by geospatial demography to assess data gaps.
4. Report potential hydrogen demand by nation, operational archetype, and demography.

The flowchart below shows precisely how the different data sources and processes interact. Green shading shows automated (coded) processes, blue once-only manual, and dashed lines indicate limitations of method or data.

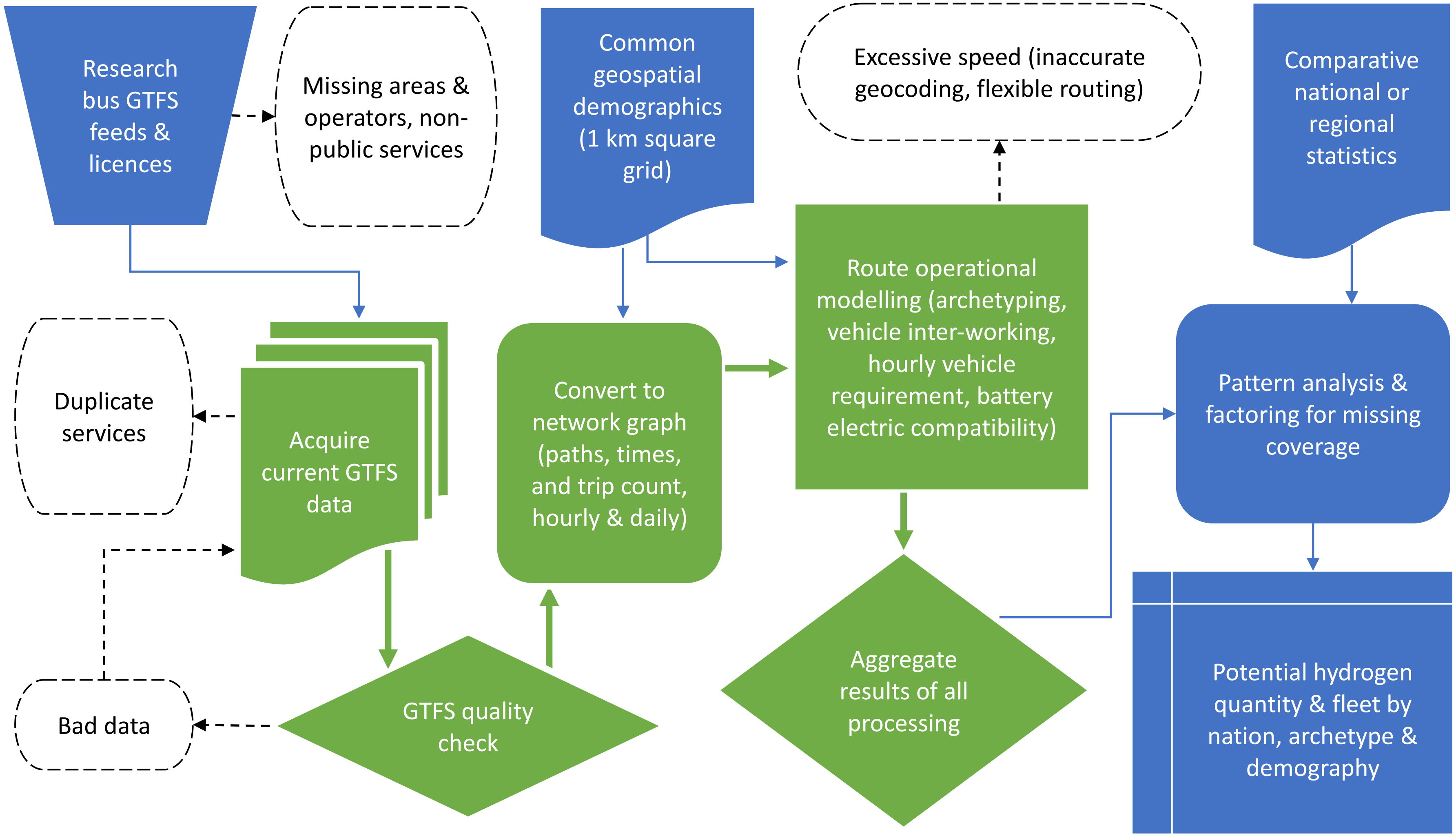

Figure 15: Data processing flowchart (green bulk automated, blue once-only, dashed indicate limitations)

Schedule data collection

Open data GTFS (General Transit Feed Specification) sources were identified across Europe from a mix of national data platforms, third party data aggregators, and local transport agencies. These sources are listed in the Attributions appendix. National or regional aggregations were used where possible, to reduce the risk of data duplication caused by multiple agencies publishing schedules for the same local operator. Care was taken to isolate a single source for operators routinely crossing national or regional boundaries, most notably international coach operator Flixbus.

Each GTFS source was validated using Mobility Data's gtfs-validator[17]. Minor problems affecting a very small proportion of the data were ignored as statistically insignificant. Where more fundamental problems were encountered with the latest GTFS source, an older version was used instead: Bus networks tend to be relatively stable from year to year, so the use of older data should not be unrepresentative. Six hundred sources were successfully acquired. These ranged from single sources for the whole of Germany or Britain, to over three hundred separate sources within France.

Analysis draws on bus schedule data for a representative week: 7 days in school term time, outside major holiday periods. Overall fleet and operational requirements are typically defined by the busiest regularly scheduled day, which for most local bus operators is normally a weekday. Where the current GTFS source was usable, this representative week was in the second half of April 2024, two weeks after Easter, but before any May Day public holiday.

Validated GTFS sources were processed into a simplified network graph: Each unique sequence of bus stops served by a scheduled bus service (commonly called a route variation) was assigned a count of bus vehicle trips (single timed vehicle journeys from origin to destination) and average duration of those trips (minutes from origin to destination), for each hour (timed at the midpoint of the journey) of each day (grouped into Weekday, Saturday and Sunday, with services operating only certain weekdays counted as 0.2 per day of operation). This approach allowed key differences in routes, frequencies, and operating speeds to be captured without retaining the large volumes of excess schedule data that would otherwise slow subsequent bulk processing.

Any non-local bus mode present in the GTFS source, notably trolleybus or tram, was excluded. Demand Responsive Transport was excluded where identified as such, with services with DRT characteristics further excluded during the operational modelling stage[18].

GTFS sources were processed by ignoring any "block" groupings in the data. Blocks allow GTFS data creators to express various operational features and complexities,

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[17] https://github.com/MobilityData/gtfs-validator

[18] A fully flexible Demand Response Transport services may be added to GTFS with every possible bus stop served on request, which when chained together as a bus route during operational modelling exceeds road speed limits and is thus excluded.

such as one trip that continues into another. Unfortunately, there is no consistency in the use of blocks. For example, a circular service may or may not be expressed as a block. Likewise, some operators use blocks to describe the continuation of all vehicles, while others only use blocks where that continuation is of benefit to passengers. Key operational features, such as circular routes or the inter-working of vehicles between infrequent routes were instead modelled, as described in the next section.

Each bus stop was allocated to the one-kilometre grid square[19] it lay within. This scale of geography approximates to the market catchment of local bus services, where passengers may expect to walk in the order of 500 metres to access a local bus service. The method is simplistic because a bus stop on the edge of one grid square may logically also serve a neighbouring grid square, but over a large network this approach adequately relates bus stops to the territories they serve and does so in a consistent manner across the whole of Europe. This method is least accurate for long-distance services, where market catchments tend to be whole towns or cities, not merely the place in that town or city the service stops at.

Validation of coverage

Any comparison of vehicle trip counts between different local bus operations is imperfect: For example, a network where all routes operate across a city centre, or where many routes are circular, might appear to have up to half the number of vehicle trips of a city where all route operates from suburb to city and back again as a separate trip. However, the measure is a reasonably efficient way of assessing any substantial difference in coverage between areas.

The map below shows the average daily (across the full week) number of bus vehicle trips (origin to destination) serving each NUTS3 region per thousand resident population. NUTS3 is a standard European nomenclature for territorial units, typically provinces or districts. A bus service is considered to serve a region if it stops at least once in that region to allow passengers to board. In this analysis, one cross-boundary service will be counted once in each NUTS3 region it serves. 2021 population data was used where available, but in some cases year 2018 was the most recent dataset published.

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[19] https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/grids

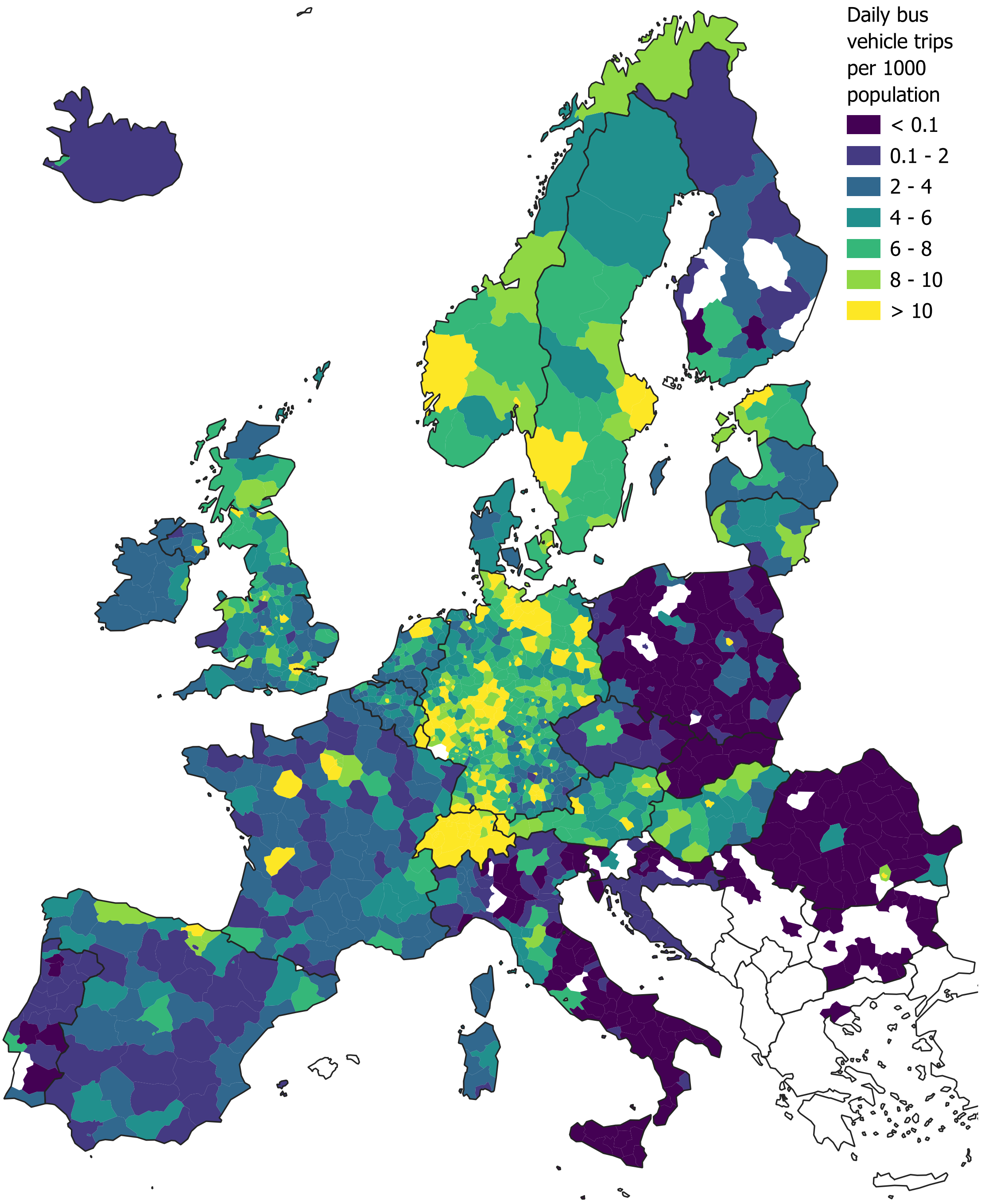

Figure 16: Average daily bus vehicle trips per thousand population by NUTS3 area (national borders in black)

NUTS3 regions shown in white contain no analysed local bus services, while those shaded dark purple have less than 1 daily service per 10 thousand people, which is indicative of only being analysed as served by long-distance routes, typically Flixbus. In these areas it is reasonable to conclude that all information on local bus services is missing. This applies to much of Eastern Europe and the Balkans (except Hungary and the Baltic states), Greece, much of Italy, and parts of Finland and Portugal.

In broad terms, western-most Europe appears to be much less intensively served by bus per head of population than Germanic and Scandinavian Europe. This applies to datasets known to be reliable and close to comprehensive, such as Britain and Germany.

The national equivalents of the data shown on the map above have been summed and sorted in the table below, excluding countries that appear to be missing data for all local bus services. Comparative data for bus mode share has been shown. There appears to be no correlation between bus provision and bus modal share: one might reasonably expect that the more bus services per head of population are available, the more likely those people are to make journeys by bus.

Table 1: Summary of country coverage metrics (sorted by daily bus vehicle trips per thousand population)

Country	**Average daily bus vehicle trips (000s)**	**Daily bus vehicle trips per 1000 population**	**Bus mode share of passenger journeys[20]**	**Peak hour as % of average daytime hour[21]**	**% of grid squares with 1000+ population served by any bus**
Luxembourg	11	16.8	10%	+32%	100%
Switzerland	109	12.5	6%	+16%	95%
Estonia	12	9.2	8%	+27%	97%
Sweden	89	8.5	8%	+26%	95%
Norway	42	7.8	4%	+50%	94%
Austria	66	7.3	8%	+44%	99%
Germany	588	7.0	5%	+27%	96%
Liechtenstein	0.3	6.8	6%	+60%	100%
Hungary	65	6.7	13%	+60%	87%
Lithuania	17	6.1	4%	+34%	83%
United Kingdom	362	5.4	5%	+10%	98%
Denmark	31	5.3	7%	+30%	97%
Iceland	2	4.9	11%	+21%	91%
Netherlands	80	4.5	2%	+10%	87%
France	279	4.1	5%	+28%	86%
Spain	194	4.1	6%	+12%	58%
Belgium	47	4.0	8%	+31%	95%
Ireland	19	3.8	12%	+21%	85%

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[20] 2019 (pre-Covid) bus and coach mode share as a proportion of all passenger transport via Eurostat https://doi.org/10.2908/TRAN_HV_MS_PSMOD with Liechtenstein assumed to mirror Switzerland, except for UK (as England) https://assets.publishing.service.gov.uk/media/5f27f7748fa8f57ac683d856/national-travel-survey-2019.pdf and Iceland https://www.statista.com/statistics/1359433/modal-split-passenger-transport-iceland/ The methods by which mode share is calculated may not be identical in all cases. Comparative mode share by distance has been summarised by https://erf.be/statistics/passenger-transport-2022/

[21] Weekdays, daytime defined as 12 hours from 07:00 to 19:00.

Country	Average daily bus vehicle trips (000s)	Daily bus vehicle trips per 1000 population	Bus mode share of passenger journeys[20]	Peak hour as % of average daytime hour[21]	% of grid squares with 1000+ population served by any bus
Finland	20	3.5	8%	+15%	41%
Latvia	6	3.4	9%	+35%	79%
Czechia	31	2.9	8%	+43%	34%
Portugal	23	2.2	5%	+31%	37%
Italy	92	1.6	12%	+24%	27%
Slovenia	3	1.3	8%	+27%	24%
Slovakia	7	1.2	9%	+21%	9%
Romania	22	1.2	12%	+19%	17%
Poland	41	1.1	8%	+11%	22%

The second column from the right indicates the peakiness of service patterns, by expressing the number of vehicle bus trips in the busiest hour against the average hour, for weekdays between 07:00 and 19:00 (a period indicative of daytime services). The average across all services analysed is 24% more bus services at peak than across the daytime. A few countries (notably Austria, Czechia, Hungary, and Norway) reveal well above average peaks, but as with mode share, there is no clear correlation to intensity of overall bus provision. It is likely that high levels of peakiness reflect a tendency to include school-related services within public bus schedules. Almost all countries peak in the morning between 07:00 and 09:00. The timing of the secondary afternoon peaks varies widely between countries: For example, early afternoon in Austria and Germany, and after 18:00 in France and Portugal. Some of these patterns will be validated further in the Validation of operations subsection.

The final column shows the proportion of all heavily populated (by a thousand or more people) grid squares that are served by at least one bus each week. It is reasonable to expect strong public transport provision to such areas, with bus the most likely mode to, at least in part, deliver that. Our bus stop assignment method makes it reasonable to expect a small proportion of highly populated grid squares to be only served by buses stopping in neighbouring squares, and hence few countries attain 100% coverage. In most cases this metric echoes patterns evident from the previous map. The obvious exception is Spain, where the coverage of heavily populated areas is relatively poor at just 58%. Spain's high level of decentralisation could explain why specific towns or operators might be more easily missed from data sources in Spain than in other countries with apparently good high-level geographic coverage.

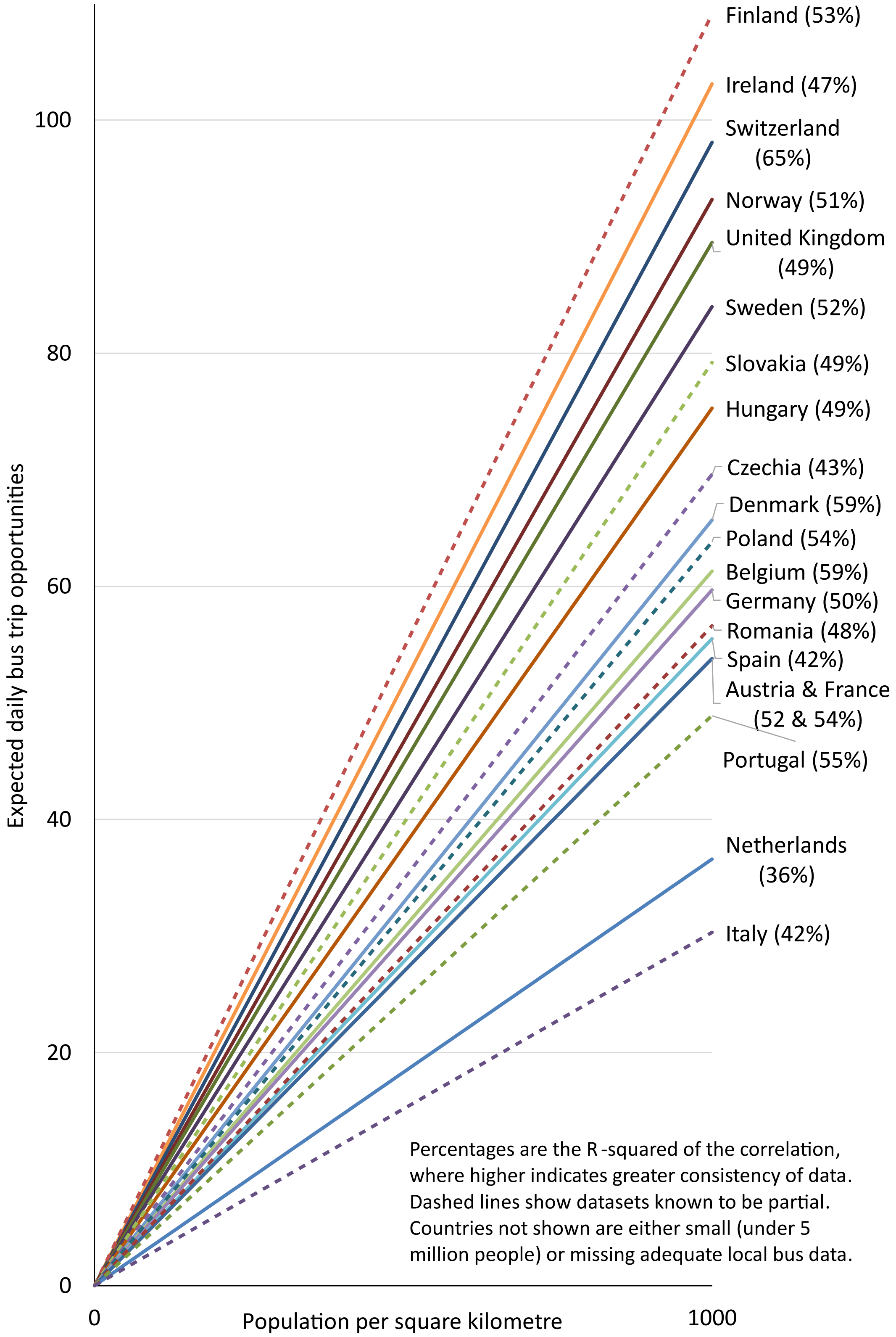
Representativeness of coverage

Strong public transport markets require strong geographic agglomerations of people. While not the only factor, population density is typically the main determinant of local bus service provision. For each kilometre grid square with at least one scheduled bus stopping each week, the square's average daily bus vehicle trips were correlated to the square's population. A linear correlation was assumed, with zero density equated to zero bus vehicle trips. The strength of the correlation was summarised by its R-squared value. Even with these simplistic assumptions, typically half the correlation is explained by population density – an R-Squared of 50%.

The graph below shows the best-fit correlations for larger European countries with at least some local bus schedule data available. All the smaller countries for which some local bus data is available exhibit relatively steeper curves with relatively strong correlations, except for Latvia.

The dashed lines show countries known from the earlier mapping to only be partly covered. The larger and more geographically or culturally diverse the country, the more caution should be applied when interpreting results. For example, all the local bus data in Italy was sourced from the north and centre, with the none from the south.

The bracketed percentage against each country is the R-squared of the correlation. R-squared should be interpreted as showing the degree of consistency of provision across the country. Inconsistency could reflect partial data – but could also be a genuine reflection on differences within the country.



Percentages are the R-squared of the correlation, where higher indicates greater consistency of data. Dashed lines show datasets known to be partial. Countries not shown are either small (under 5 million people) or missing adequate local bus data.

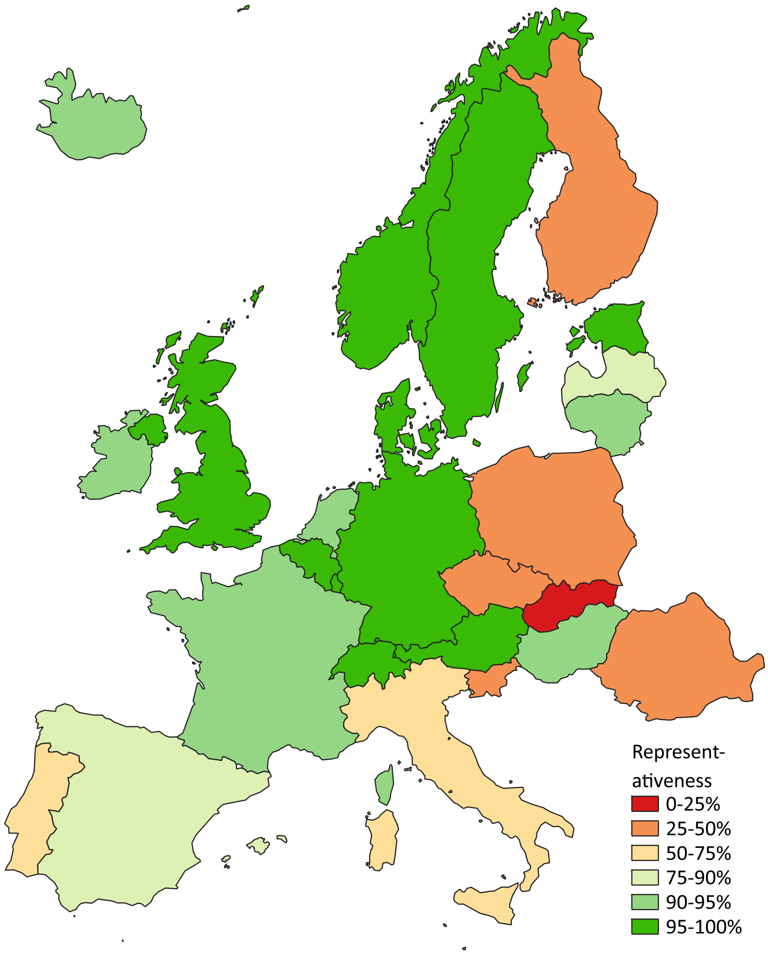
Figure 17: Linear correlations between local population density and bus service intensity (R-squared values in brackets)

The density-derived patterns shown above reflect how well bus operators serve their local operating territory. In contrast, prior counts of bus vehicle trips per head of population tend to be skewed by how well suited that local territory happens to be to bus operation. On this density-derived measure much of the heart of Europe (not least France and Germany) attain comparable levels of bus provision, while Britain and Ireland perform relatively well.

Ireland is particularly notable in delivering similarly high bus service levels per population density to Switzerland while deploying roughly a third of the operations and gaining double the modal share. The implication is that the Irish emphasise natural bus markets, while the Swiss emphasise geographic coverage. Likewise, it is apparent that the strength of German's bus network lay not primarily in its bus operations, but in a land use policy that has made it relatively easy to serve most Germans with buses. Those three countries start to provide an insight into the multi-facetted and differently conceived nature of bus policy as practiced by and within individual European states.

The Netherlands emerges as a statistical outlier, with not only a low level of bus provision relative to population density, but also a low R-squared. This may be a quirk of the Netherland's exceptionally high bicycle use (a tenth of all journeys) displacing short journeys that elsewhere might be by bus – a pattern also implied by the relatively low mode share of bus in the Netherlands.

To assess how representative each country's bus data coverage was, the equations describing the curves shown in the previous graph were applied to all kilometre grid squares within the respective country (with no regard for the presence of bus services). This was compared directly to actual bus coverage by multiplying the derived or actual average daily bus vehicle trips in the square by the population of the square and summing the results. This method intentionally biases the assessment of reliability to the most populated places, where bus services are in turn most likely to present. The proportion of the actual total contained within the modelled total indicates how representative of the country and actual values are expected to be. The result is shown in the figure below.



Austria	99%
Belgium	98%
Czechia	49%
Denmark	98%
Estonia	99%
Finland	41%
France	91%
Germany	98%
Hungary	94%
Iceland	95%
Ireland	94%
Italy	63%
Latvia	88%
Liechtenstein	100%
Lithuania	93%
Luxembourg	99%
Netherlands	95%
Norway	96%
Poland	36%
Portugal	61%
Romania	41%
Slovakia	21%
Slovenia	40%
Spain	82%
Sweden	98%
Switzerland	98%
United Kingdom	99%

Figure 18: Representativeness of bus schedule data by country

Representativeness should be read as the confidence we have in applying subsequent analysis for each country to that country. For example, the bus schedule data representing Austria almost perfectly fits Austria as an entire country, most likely because the data itself is comprehensive. In contrast, data for Czechia is focused on the region around Prague, which is not sufficiently typical of the demography of the whole country to score highly. Any conclusion this study might make about countries with low scores, such as Czechia, should be read with caution.

In summary, this study's analysis will be weakest in much of Eastern Europe, while caveats apply in the analysed parts of Southern Europe, most notably Italy. However, data in the north and centre is very representative. Weighting each country by population, and assigning any country not shown in the figure above a 0% representativeness score, the overall representativeness is:

- 75% for the whole of Europe (excluding Belarus, Russia, Türkiye, and Ukraine).
- 78% for the combination of European Union, European Free Trade Association, and United Kingdom.
- 74% for the 27-member European Union.

Operational modelling

The first stage of route analysis took the schedule-derived network graph, described above, and modelled the current operational characteristics of the bus routes therein:

- Calculation of route distances and vehicle mileage, including validation of operating speeds and assignment of "dead mileage" to and from depot.
- Assessment of the market territory and geography served by the route, including urban-rural classification.
- Categorisation of the route into one of five operational archetypes.
- Modelling the interworking of infrequent routes in the same locality to allow sets of vehicles to be shared between many such routes.
- Calculation of the vehicle requirement to operate each route or interworked group of routes.

Distances between bus stops were calculated using Haversine (direct line) distances, and then factored up by an extra 17% to account for the indirectness of roads. Each vehicle travels into service to and from a home depot, adding "dead mileage" which was assumed to add 6% to each vehicle's daily in-service mileage. Both factors were derived from analysis of Britain, where more detailed data was available to the authors, but have been assumed typical of the rest of Europe:

- The extra 17% indirectness factor was derived from analysis of a sample of over five thousand routes where precise road routes were available. The factor reflects the tendency of bus routes to travel along road corridors, and thus is lower than might be applied to any one origin-to-destination journey through a complex road network.
- The extra 6% dead mileage factor was derived from analysis of the average distance between depot (using vehicle allocations where known, or nearest depot belonging to the route's operator where not known) and nearest termini of the route operated. In practice this assumption varies tangibly between operators. For example, in Britain, the larger bus operating groups average about 5%, while smaller, especially independent operators average about 15%. In practice that difference can make electrification especially challenging for smaller operators, since their buses need around 10% greater daily range to meet current operational requirements, and their remote depots make any strategy involving extra vehicles with daytime at-depot charging far more difficult to manage.

Route variations (unique sequences of stops) containing any journey where modelled operating speed exceeded 90 km/hour were excluded. Express long-distance coach can average about 80 km/hour in parts of Europe, so the 90 km/h speed limit should have only excluded unreliable data. In the example of Germany, just 2% of all route variations were discarded for speeding over 90 km/hour, primarily affecting routes containing one or more very poorly geocoded bus stops. If the speed limit had been set at 50 km/hour, 7% of route variations would have been discarded, including almost all long-distance and many interurban routes.

Eurostat's urban-rural method[22] defines urban as “groups of contiguous grid cells of 1 km squared with a density of at least 300 inhabitants per km squared and a minimum population of 5000.” Unfortunately, Eurostat do not appear to publish their urban-rural classifications by grid square, so the only readily accessible metric would be to categorise grid squares with less than 300 population as rural.

Instead, a simple correlation was established between NUTS3 average densities, and their urban-rural classification. The best-fit power curve had an R-squared of 45% and cuts the urban-rural midpoint at 257 person per square km: Slightly lower than the 300 in the method used to create the urban-rural statistics, a difference which reflects both clustering of urban squares into settlement and the disproportionate number of lowly populated squares. The derived formula used was:

*28.885% * (density ^ 0.1552)*

Values below about 70% are rural. This creates considerably more nuance in degree of urbanity and rurality.

For each route variation, the urban-rural percentage of the grid square in which each bus stop served lay was averaged, each stop weighted by the proportion of total route mileage nearest to the stop. The method aimed to summarise the urban-rural character of the territory the route serves, and thus skips territory the bus does not stop within. The mileage weighting counters the tendency for urban parts of a route to be served by many more bus stops than rural parts of the same route. All subsequent analysis simply summarises the entire route as either urban or rural.

Operational archetypes were assigned to routes based on the characteristics shown in the table below. There are no universally agreed or legislated definitions[23] for these archetypes – these definitions simply try to reflect the language commonly used in the bus industry.

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[22] https://ec.europa.eu/eurostat/web/rural-development/methodology

[23] The closest legal definition of local bus is “regular passenger services on routes up to 50 kilometres”, but only in so far as it exempts drivers from European driving time regulations in favour of relevant domestic legislation - https://europa.eu/youreurope/citizens/work/work-abroad/rules-working-road-transport/index_en.htm . There are many scheduled routes that function as local bus services and exceed 50km, especially in less densely populated areas of Europe. To add further confusion, the 50km cut-off has led some bus operators to split intended through-routes into fragments to ensure compliance with only domestic legislation, while in practice vehicle, driver, and passengers all transition seamlessly from one “route” to the next.

Table 2: Operational archetype definitions

Archetype	**Description**	**Weekly vehicle trips**	**Mostly urban or rural**	**Route length[24] (km)**
City	Core high-frequency urban	>= 600	Urban	< 40
Interurban	To regional centre from outside that centre	>= 100	Rural	20-100
		Any	Urban	40-100
Long	Long-distance - inter-city/region	Any	Any	> 100
Rural	Local rural or small town	Any	Rural	< 20
		< 100	Rural	20-100
Suburban	Secondary urban - lower frequency	< 600	Urban	< 40

While technically any public passenger carrying vehicle could be deployed on any other of these route archetypes, the definitions provide an indication of the type of vehicle likely to be deployed: For example, coach-bodied vehicles on long distance routes, or high-capacity urban buses on city routes. Some categories require further local context before vehicle types can be assigned. For example, coach-bodied vehicles are often deployed on interurban routes in rural Scotland, but not on equivalent routes in England.

Higher frequency routes can be assumed to be operated by a set of buses dedicated to the same route throughout the day. While in practice, operators may inter-work the same vehicle between many such routes, this is commonly done to achieve minor schedule or staff rostering efficiencies – a minor error in the context of the strategic modelling undertaken in this study. In these cases, the route's minimum vehicle allocations were calculated hourly by dividing the time taken for each vehicle to return to the same point on the route into the service headway, both values specific to the hour.

A different approach was adopted for low frequency routes, where the allocation of vehicles is more likely to change from hour to hour and/or where the route is more likely to inter-work with others to attain a significant reduction in overall vehicle requirement. This study defined low frequency routes as less that 30 (one way) bus vehicle trips per day – roughly the equivalent of an hourly headway or less. For these routes:

- Vehicles were assigned based on the start and end hour of each bus vehicle trip, which allowed vehicles to be assigned more precisely to longer-duration journeys without consistent headways (which describes many long-distance coach routes). Calculations assigned proportions of vehicles for trips not operating the full hour, which were only rounded up to whole vehicles after applying the grouping logic below.
- Infrequent routes operated by the same operator, and sharing at least one terminus within 500 metres, were assumed to be part of an inter-worked

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[24] Length from origin to destination in one direction of travel.

group. The cumulative vehicle requirements of all routes in the group were summed for each hour and rounded up to whole vehicles. This total in each hour was then redistributed across all routes in the group in proportion to each route's initially calculated maximum vehicle requirement. These patterns were assessed separately for each day operated.

This model of interworking has limitations. For example, frequent and infrequent routes are assumed not to inter-work, which might overestimate actual vehicle requirements slightly. Similarly, where the GTFS source defines only the responsible agency, not individual operators, the potential for inter-working could be over-estimated: In the extreme case, the Spanish region of Galicia, the bus network is characterised by very many infrequent routes and all routes are assigned to the regional government.

Validation of operations

The graph below shows the distribution of bus vehicle trips by hour (in the middle of the journey) for a weekday, showing key differences in operating intensity for the four largest analysed countries, which collectively represent 62% of all trips analysed. The pattern for all analysed data is shown as a dotted "Europe" line. Weekend patterns are not shown because they are more consistent across the day (albeit with lower levels of service and a shorter period of core daytime operation, especially on Sunday).

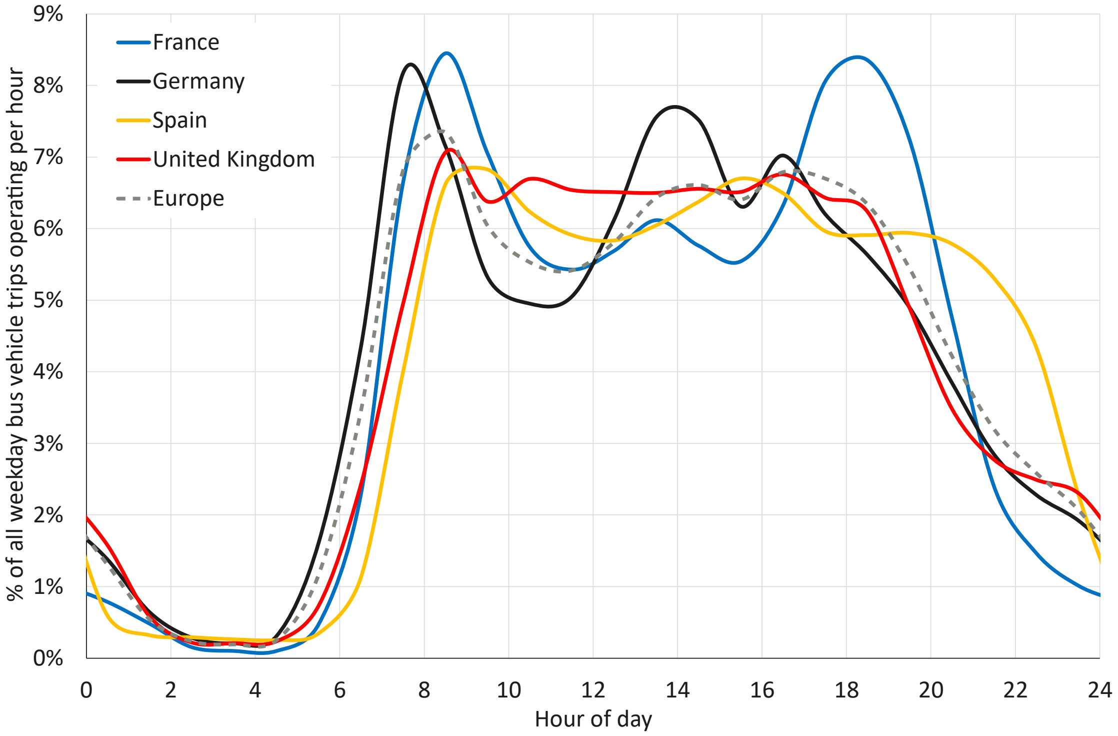

Figure 19: Weekday bus vehicle trips by hour

Several key differences in bus service patterns can be seen on the graph above, all of which were expected, and thus help validate the analysed datasets:

- Sunrise influences the timing of the morning peak, with the three countries in the same time zone peaking in longitudinal order: Germany, then France, and finally Spain.
- Germany's relatively short school day and high reliance on public local bus services for the transport of scholars can be clearly seen in its early afternoon peak. In contrast France's school day more closely mimics the adult working day, resulting in two equally intense morning and early evening peaks.
- The longer Spanish working day and tendency to conduct social activity into the late evening are clear from the way full daytime service levels continue until after 20:00.
- The United Kingdom's relatively flat daytime profile reflects the dominance of commercial considerations, both the difficulty of earning sufficient revenue from peak-only services to justify the vehicle asset, and the freedom to react to post-Covid declines in commuter traffic[25].

As previously noted, comparison of total bus vehicle trips can be skewed by the structure of the local network, for example cross-city routes vs routes that terminate in the city centre. For this reason, comparative analysis of results has been expressed in total mileage and vehicle requirement. Unless stated, mileage refers to total in-service mileage (excluding dead mileage to/from depot) and vehicles to the minimum theoretically requirement to operate those services (ignoring maintenance reserves).

The table below summarises metrics for routes with more than 50% of mileage in one country. This classification, adopted here and in the study's results, produces very slightly different totals to the earlier Validation of coverage, which counted each cross-border routes once against each country it served. Average metrics are weighted by proportion of total country mileage. Long-distance routes (over 100 km length) are excluded from the country-based numbers shown, and instead summarised in the final row.

The table includes countries where coverage has already been demonstrated unrepresentative and is not intended to be cited out of context. Prior coverage assessment suggested our analysed dataset represented about three quarters of Europe. This would, for example, suggest a total minimum European fleet requirement of about 250 thousand vehicles, plus a maintenance reserve, implying an active European public scheduled bus fleet in the order of 300 thousand vehicles.

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[25] Circumstantial evidence suggests the current UK daytime profile is flatter than that before the Covid pandemic. Any adjustment in service levels to match higher post-Covid tendencies to work from home is more likely to be seen in Britain's deregulated environment than in the contractual environments that tend to dominate European local bus, where may current local bus service patterns would have been agreed prior to the pandemic.

Table 3: National operational modelling metrics, excluding long-distance

Country	Average route length km	Primary serving rural markets	Average weekday operating speed km/h	Average weekday in-service km per vehicle[26]	Minimum vehicles required [27]	% of bus and coach fleet required [28]
Austria	21	34%	32	300	4320	43%
Belgium	21	5%	28	300	3620	22%
Czechia	24	21%	32	340	2060	9%
Denmark	30	39%	34	360	3120	35%
Estonia	30	42%	36	410	1060	20%
Finland	22	20%	31	370	1490	12%
France	20	9%	26	240	24040	26%
Germany	19	25%	31	340	43930	54%
Hungary	28	46%	35	330	5260	27%
Iceland	23	18%	31	330	140	7%
Ireland	37	14%	33	330	2080	19%
Italy	19	14%	26	260	7720	8%
Latvia	39	52%	37	390	700	18%
Lithuania	19	28%	30	300	1480	19%
Luxembourg	21	22%	34	420	490	25%
Netherlands	23	17%	34	430	4320	43%
Norway	27	39%	36	360	4030	26%
Poland	17	3%	26	340	2420	2%
Portugal	18	7%	25	290	1780	11%
Romania	15	3%	20	250	1640	3%
Slovakia	12	4%	29	370	110	1%
Slovenia	13	3%	24	230	220	8%
Spain	21	9%	25	310	15130	25%
Sweden	29	45%	37	390	7070	47%
Switzerland	12	15%	25	330	3670	27%
UK	22	9%	24	270	33620	41%
Europe[29]	*22*	*20%*	*29*	*320*	*181570*	*22%*
Long[30]	640	15%	65	1510	5070	

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[26] Excludes dead mileage to/from depot.

[27] Defined by each route's busiest day, not including maintenance reserves, which will add about 15% to fleet size in practice.

[28] Modelled vehicle requirement as a proportion of ACEA 2019 estimates of buses and coaches in use - https://www.acea.auto/files/ACEA-report-vehicles-in-use-europe-2023.pdf . ACEA's definition is much wider than just local bus because there is no legal distinction between a vehicle used on scheduled public service and one used for a private group.

[29] All analysed, except long-distance routes over 100 km.

[30] Routes over 100 km. Our method is insufficiently accurate to analysis many long-distance services and markets. For example, it is reasonable to expect that far higher average in-service mileages be associated with longer periods of downtime for maintenance (and hence above average numbers of reserve vehicles). Likewise stopping points tend to serve a larger hinterland than is within walking distance of the stop.

Average operating speed varies significantly between countries with buses in western-most Europe tending to be slower than those in central and north-east Europe. This in part reflects different balances of operating styles, assessed later in this section. For example, Switzerland and the United Kingdom have some of the lowest average speeds, but also the highest proportions of city bus-style operations.

Average route lengths are tangibly longer in the Baltic region, which is partly explained by a greater tendency to serve rural areas, and thus is likely to reflect differences in geospatial population density. The countries with the lowest proportion of rural routes are either those with partial data coverage (which is more likely to be skewed to major urban areas) or are heavily urbanised (such as Belgium and the UK).

Vehicle modelling matches broad expectations of daily bus vehicle mileage, although it is worth noting that Germany’s average is 100 km greater than France: Daily mileage is the main determinant of BEB compatibility, so we should expect France to emerge as significantly easier to battery-electrify than Germany.

A comparison of modelled vehicle requirements to known active fleets has been provided to demonstrate the plausibility of the modelling – not least, that the modelled result is substantially less than the active fleet. However, since the active fleet includes many bus and coach vehicles used in other roles, any comparison needs careful evaluation. Germany’s high proportion of total fleet echoes the use of scheduled local bus for school-related transport: Non-public bus niches for bus and coach vehicles that exist in some other countries do not exist in Germany.

Weight the Europe total up for unrepresented coverage, and add a modest margin for maintenance, and it is reasonable to conclude at least a third of all active bus and coach vehicles in Europe are dedicated to scheduled local bus services.

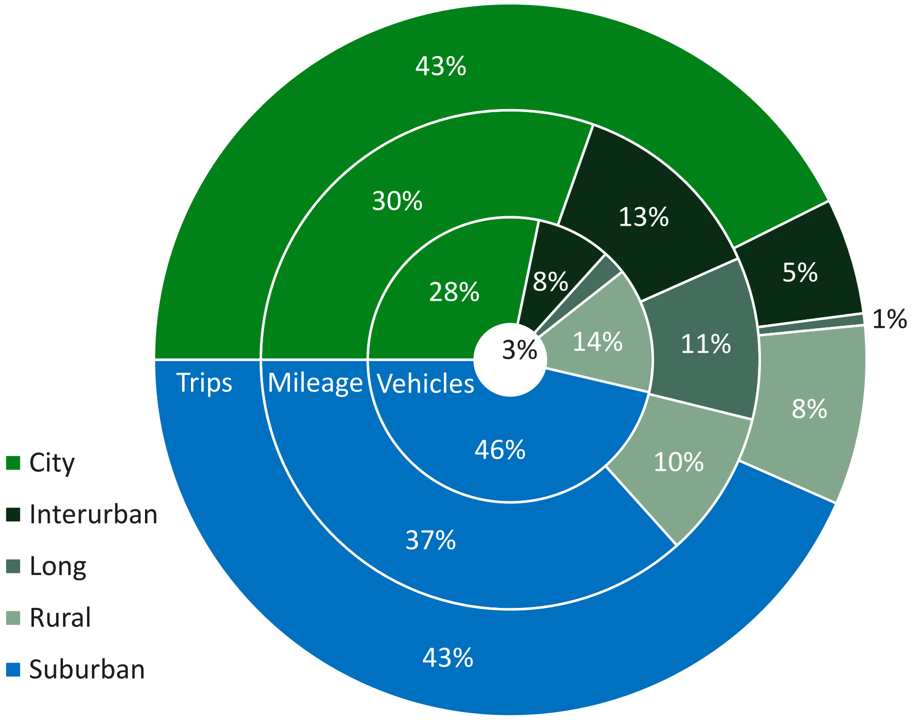

Figure 20: Distribution of archetypes by proportion of all trips (outer circle), mileage (middle) and vehicle requirement (inner), for Europe (all analysed data)

The figure above shows the distribution of operational archetypes. Urban (city and suburban) operations dominate the overall distribution, especially for trips because urban routes tend to be shorter. Urban operations tend to be slower, hence a lower proportion of overall mileage than trips. City routes tend to be more intensively operated than suburban routes, and hence require a lower proportion of vehicles than suburban routes. Patterns for longer-distance routes (interurban and long) naturally emphasise high mileage from a relatively smaller number of trips and vehicles.

The figure below shows the considerable variation in the balance of archetypes between countries. All countries with 75% or greater representativeness are listed, with all analysed data shown as Europe. In this analysis mileage has been assigned to countries as accurately as possible, so mileage includes that part of long-distance international routes estimated to operate within the country. Note that the Rural operational archetype is a different categorisation to Rural-Urban analysis – notably, many Interurban operations primarily serve rural markets.

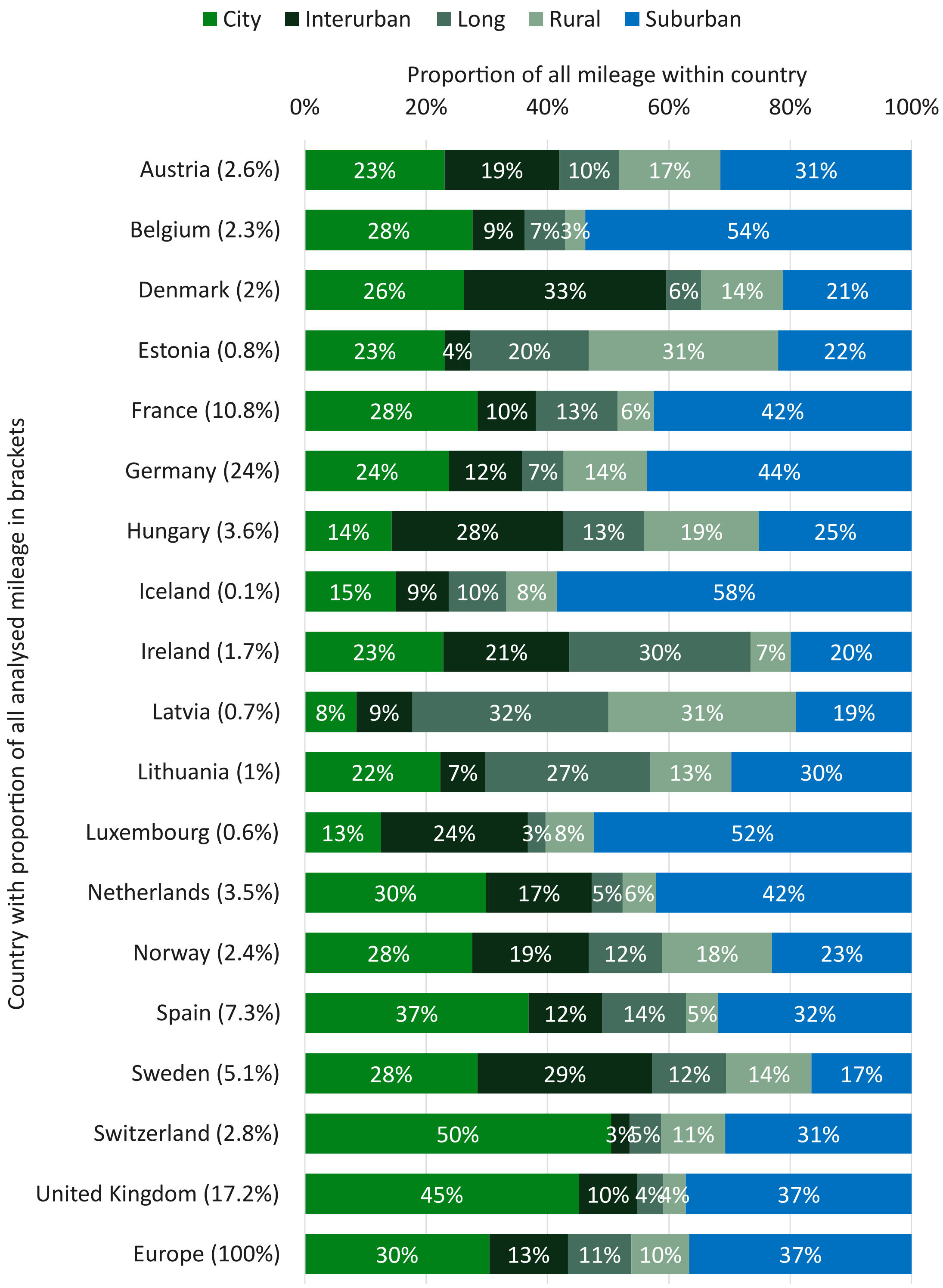

Figure 21: Distribution of archetypes by country, for the most representative countries

The demographic geography of countries is an important factor in the balance of operating archetypes, as perhaps is the differing role of rail in interurban markets: In some countries interurban bus routes have traditionally only been provided where there is no direct railway route. Among the larger nations, Spain and the United Kingdom are notably more heavily skewed to City operations, and less to Suburban, than France and Germany.

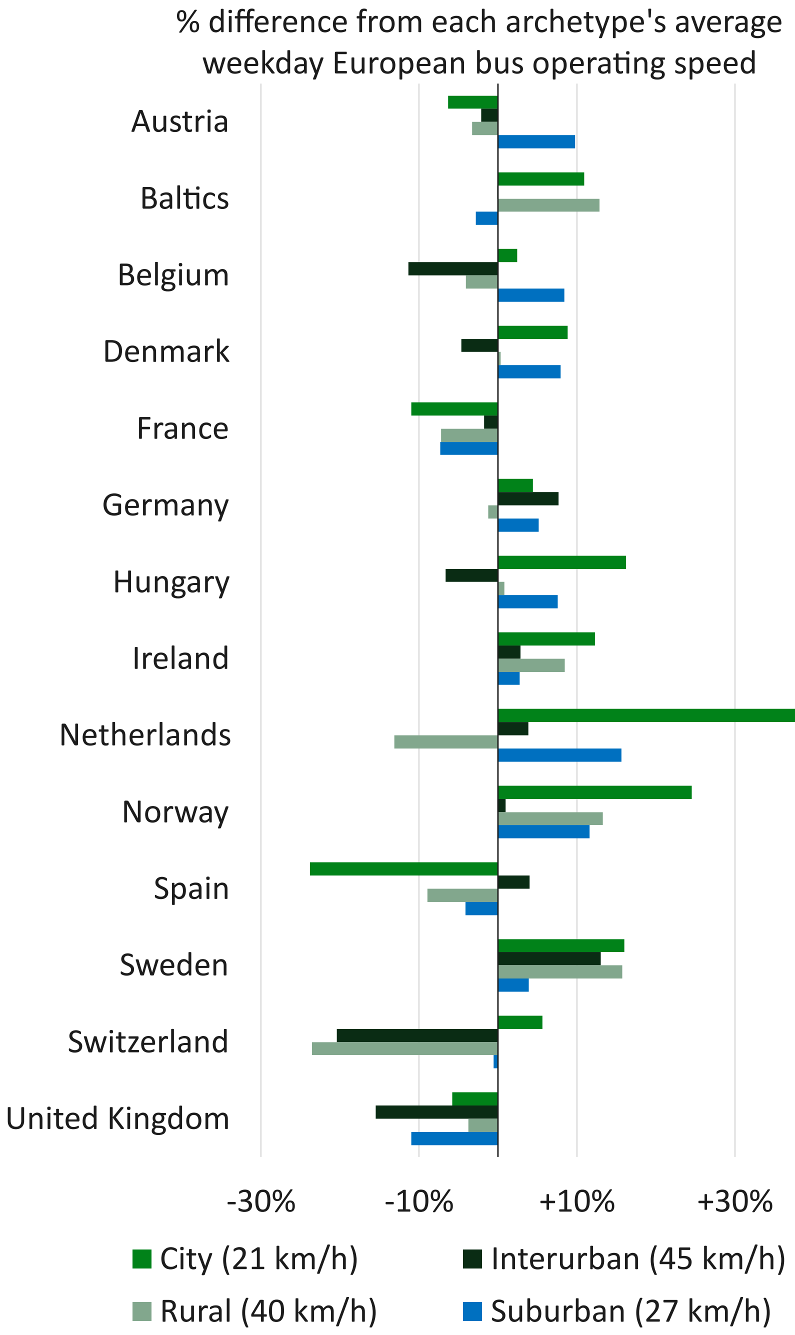

Figure 22: Weekday average operating speed relative to each archetype's European average (European average speed shown in legend brackets, selected larger countries with reasonably representative data, routes under 100 km)

Average bus operating speed differs by operational archetype. As discussed earlier, the different mix of archetypes between countries contributes to different average speeds. However, as shown in the figure above, there are also clear differences between nations in average speed within each archetype. The graph shows the percentage difference from the average across all analysed data.

Bus operating speeds in Norway and Sweden are faster than average across all archetypes, while speeds in France and the United Kingdom are slower for all. Patterns in other countries are more nuanced. For example, urban bus speeds in the Netherlands are well above average, unlike other styles of operation. One explanation for this quirk is the Netherland's high bicycle usage, which logically diminishes the need for short bus journeys, and skews the bus network accordingly. Strong public policy towards bus priority may also be a factor.

Spanish city operational archetype speeds are relatively slow, logically a reflection on the very high population density of many Spanish cities, while the speed of other archetypes in Spain is more typical of Europe. Spanish suburban routes are more typical of European operating speeds, and thus the average speed of all urban buses is more typical of Europe.

As outlined in the next section, energy modelling was not explicitly adjusted for average operating speed, just as it is not calibrated explicitly for elevation changes – both factors were considered relatively minor to the overall route energy consumption. Likewise, our method assumed no change to current operations.

A common policy intervention to bolster bus use and reduce operating cost is to increase bus operating speed. The higher the speed of the bus, the more kilometres it can cover each day, and thus the longer the duty requirement tends to be. Consequently, wider mode shift related bus policy might increase the range requirements of buses, which would make routes more challenging to battery electrify.

Energy modelling

The second stage of the route analysis assessed the capability of current and expected future ZEBs to meet the operational requirements modelled above. Our core method assumed operators and agencies would seek to maintain current service patterns, though they may need to reassess how ZEBs are deployed to deliver those services. This is a reasonable assumption for local buses, but not necessarily true in niche markets such as long-distance coach.

Although the study aimed to size the potential market for hydrogen, this market stems from the difficulty of deploying BEBs, and consequently the energy modelling presented here is focused primarily on batteries, not hydrogen.

Bus operators generally use vehicles consistently from day to day. This makes it relatively straightforward to specify each vehicle's engineering requirements. However, while the route and service level may be broadly fixed, the climatic conditions are not.

Truly zero emission BEBs require battery energy to maintain the temperature of the passenger cabin, in addition to smaller variations in energy requirement related primarily to the ambient temperature of the battery itself. BEBs thus need to be specified for the most extreme climatic condition likely to be experienced at any point in the year. BEB modelling thus produces two different energy metrics: The average daily energy use across the year, which is useful when annualising energy consumption and operating costs, and the extreme daily energy use that better specifies the energy storage needed on the vehicle itself.

In contrast, the fuel usage of hydrogen FCEBs has been reported by operators to be much more consistent when operating between about 5 and 20°C, as the heat generated by the fuel cell naturally counters the need to create energy to warm the cabin – what one FCEB operator has called "the blancmange effect". FCEBs will logically use extra hydrogen at extremes of heat and cold, but this difference will not significantly affect the specification of the vehicle in the way it does for BEBs[31].

Our method assumes that decarbonisation means deployment of true ZEBs. In practice, where climatic extremes occur rarely, operators might manage extremes by augmenting buses with non-Zero Emission heat sources[32].

Base (primarily traction) energy consumption has been assumed as 0.8 kWh/km for BEB and 0.06 kg/km for FCEB. Both figures reflect prevailing 2024-era technology in temperate operating conditions. Supporting data is biased to findings from Britain[33] (which has the largest BEB fleet in Europe) and to full-size bus models (which critically tend to be deployed on the routes which are harder to electrify).

The values used have been calibrated to reflect what a sample of BEB operators were observed to trust in practice. Calibrated to best match a sample of the 110 British bus routes where ZEBs provided at least 90% and 1000 km per week of all the route's mileage. Vehicle size was considered, but not found to be a significant factor. While a high-capacity (in Britain) double-deck city bus logically requires more energy than a lower-capacity single deck, that double deck is more likely to be deployed on routes where traffic conditions inhibit acceleration to higher speeds, such that energy consumption differences due to capacity and due to speed perhaps tend to cancel one another out. As discussed in the Ember section below, current BEB operations are overwhelmingly urban, providing insufficient evidence of interurban BEB energy consumption.

Elevation change has not been modelled. In the extreme case – a bus route to a ski station with half its mileage assumed either up or down a 1 in 10 gradient – only 15% more energy would be needed due to elevation changes, with the traction and braking system assumed able to regenerate much of the extra uphill energy over a round trip.

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[31] Implying only a marginal increase in fuel tank capacity, with minimal impact on overall vehicle weight.

[32] It is not yet clear how the CO_2 emissions of a *ZEB* which included a diesel heater for extreme weather only might be accounted for under European standards, since the use of the heater is inherently difficult to *average per kilometre* for the vehicle. While the use of non-battery electric heating could solve many BEB route compatibility challenges, it is not clear how acceptable this solution would be in places with strong political or owner commitments to fleet decarbonisation.

[33] British data has been favoured as the country currently has one of the largest BEB fleets in Europe. ZEMO certification provides an overview of BEB performance in test conditions - https://www.zemo.org.uk/work-with-us/buses-coaches/low-emission-buses/certificates-hub.htm . FCEB energy consumption derives from prior JIVE project monitoring.

In almost all practical local bus cases, which involve minimal elevation change, the extra energy due to elevation change may be assumed negligible.

Five different academic studies of the influence of temperature on BEB energy consumption have been compiled into a single indicative equation shown in the graph below[34]. The base assumption of 0.2 kWh/km provides a margin with which to manage the inherent variability in temperature within the day and month: For example, a day that averages 20°C may in practice require early morning trips to be heated and afternoon trips to be cooled. Studies suggest less than a fifth of the temperature factor is related to the lower performance of the battery itself, with the heating or cooling of the passenger cabin the critical factor. Modelling assumes the use of a heat pump, which is at least twice as efficient as traditional electrical heating[35].

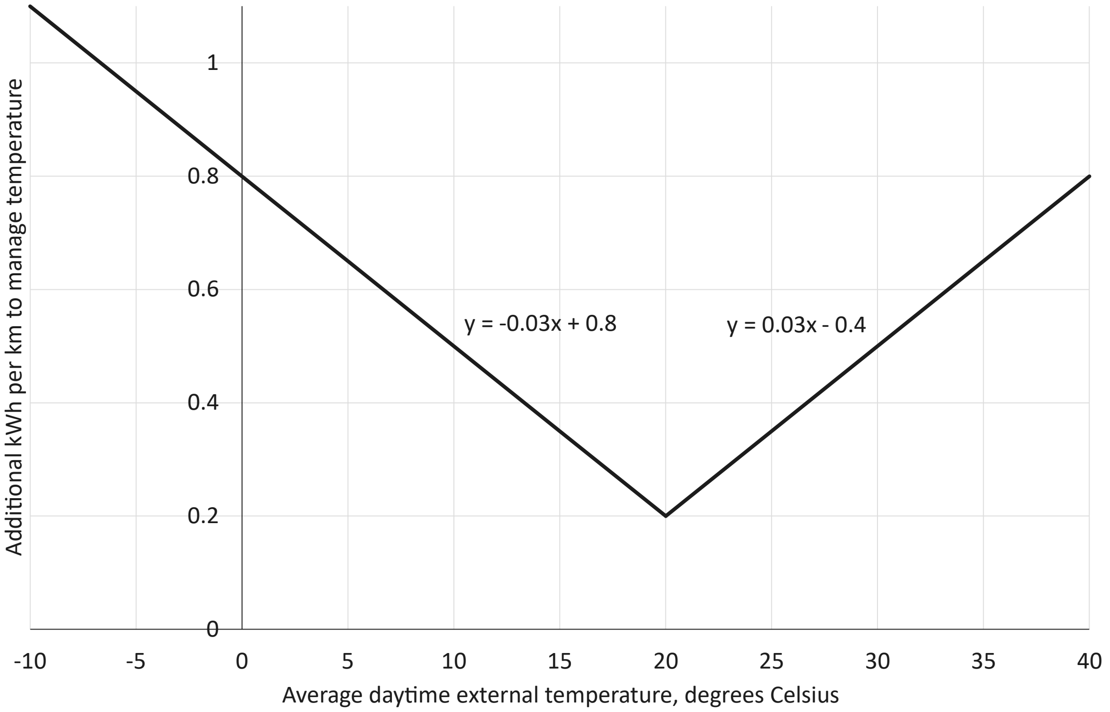

Figure 23: Additional BEB energy consumption due to temperature

The equation above is stated per kilometre. This does not adequately capture the frequency with which the doors open or the human load factor of the vehicle: It is reasonable to conclude that a city operation would require far more cabin-related

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[34] Comprehensive energy modeling methodology for battery electric buses - https://www.sciencedirect.com/science/article/abs/pii/S0360544220313487 , UK Low Emission Bus Scheme monitoring programme - https://assets.publishing.service.gov.uk/media/646f304c24315700136f4228/lebs-monitoring-report.pdf , Setting Up and Operating Electric City Buses in Harsh Winter Conditions - https://www.researchgate.net/publication/359100457_Setting_Up_and_Operating_Electric_City_Buses_in_Harsh_Winter_Conditions , Towards Efficient Battery Electric Bus Operations: A Novel Energy Forecasting Framework - https://www.mdpi.com/2032-6653/15/1/27 and Trip energy consumption estimation for electric buses - https://www.sciencedirect.com/science/article/pii/S2772424722000191

[35] https://r744.com/co2-heat-pumps-found-to-outperform-electric-heaters-in-electric-buses/

energy, especially if as cooling, than an interurban operation, but in the absence of clear analytic evidence for this, a single equation has been applied to all styles of operation.

Average temperatures for a sample of the largest city or cities in each country[36] by month were used to apply the equation above to each country. Temperatures were applied both as a factor for the month with the highest additional energy, and as an average for the whole year. Monthly extremes average the daily extremes that should define energy requirements, although it is expected operators will tolerate reducing service levels in exceptional climatic conditions[37]. Likewise, average daily temperatures understate the daytime temperature when day buses tend to operate, underestimating energy in hot climates and overestimating in cold climates. The bias towards city temperature data is intentional, as this is where most bus services tend to operate. However, some countries, for example Spain, contain a wide range of climatic environments even at city level. All these issues make the application of national factors to local buses imperfect.

The highest “worst month” factors in Europe were found to be in north-eastern Europe. In Finland an extra 1 kWh/km has been assumed for heating, broadly doubling the base energy requirement of operating the bus. The (population-weighted) average factor for Europe were an extra 0.66 kWh/km extreme and 0.41 kWh/km average, which were applied to international operations such as Flixbus. Operators were otherwise assigned the factors for their home country.

BEB battery sizing assumed the upper and lower 10% of battery capacity is unusable, which is a common condition of warranties or lease arrangements, and thus the vehicle is assumed to be specified with 25% more kWh of battery capacity than would ever be used. No battery degradation is assumed: Batteries or vehicles may be assumed to be cascaded to routes with lower energy requirements as vehicles age – degradation is not a hard limitation on route compatibility, rather a factor to be managed across the fleet.

Buses are limited by axle weight, and battery capacity is thus primarily limited by the weight of batteries. Modelling assumes the use of two-axle buses, and thus current battery energy density limits BEBs to just under 600 kWh of battery capacity. This value is lower for buses with higher passenger capacity because more of the weight limit needs to be allocated to passenger load. Triaxle, including articulated, buses allow greater weight to be carried. Current designs are not suitable for many local roads, while many existing triaxle deployments reflect high passenger loads which in practice yield relatively little extra capacity for additional batteries. In theory a short wheelbase triaxle bus could be built akin to a rigid truck – but doing so while maintaining low floor access and packaging potentially upwards of 700 kWh of batteries would represent a substantial engineering challenge.

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[36] https://en.wikipedia.org/wiki/List_of_cities_by_average_temperature#Europe

[37] In some places service reductions are already a logical consequence of the lower passenger demand associated with extreme conditions, for example the August frequency reductions seen in Madrid or Sevilla.

The last decade has seen substantial gains in battery cell energy density. Current (2024) battery technology attains about 0.2 kWh/kg, with a theoretical upper limit of about 0.35 kWh/kg and any further advance to 0.5 kWh/kg requiring yet-to-be-proven solid-state technology[38]. Recent battery research and development funding has been driven strongly by the needs of large mass markets – first mobile phones, later the range anxiety of small car owners – with heavy vehicles a marginal beneficiary. Given the difficulty of developing ever-higher density batteries, and the lack of an obvious mass market for them, it is reasonable to conclude the pace of density evolution will slow.

In contrast, contemporary battery market challenges tend to emphasise issues such as uncertainty of lifetime residual value, battery management software, rate and associated degradation of rapid charging, and recyclability – for example, the current difficulty recycling the LFP (Lithium Ferro Phosphate) batteries best suited to frequent rapid recharge. It is a reasonable hypothesis that market-driven research will advance primarily in these areas, ultimately making it easier for bus operators to manage (both technically and financially) BEBs that may not have substantially greater range than current models.

The battery energy density assumptions made in our modelling are shown in the table below. These assumptions are one of the most sensitive, yet hardest to accurately predict, part of our modelling method. A significant proportion of bus routes modelled as challenging to battery-electrify on these assumptions could become much easier to battery-electrify if an unexpected break-through in solid state technology delivered a doubling in battery density by the 2030s.

Table 4: Assumed maximum bus battery capacity by year

Year	Density (kWh/l)	Density (kWh/kg)	Largest battery size (kWh)[39]
2025	0.234	0.207	601
2030	0.306	0.230	668
2035	0.321	0.242	703
2040	0.338	0.254	737
2045	0.355	0.267	775
2050	0.372	0.281	816

The BEB compatibility in each year was modelled against each route's day of greatest energy need – the schedule day with the highest mileage and calendar month with the most extreme climatic conditions. Each combination of route and year was categorised as one of:

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[38] https://cnevpost.com/2024/04/29/catl-to-produce-solid-state-batteries-2027/

[39] Assumed maximum installed capacity per two-axle bus. Value includes "unusable" lower and upper 10%.

- **Straightforward**: Required energy of the maximum daily duty, multiplied by 106% to account for dead mileage to and from depot, less 20% unusable battery capacity, is less than the capability of the best available BEB. At least 3 hours[40] of slack exists in the schedule per vehicle per day to charge. These routes were assumed straightforward to operate with a single overnight at-depot charge. While these routes would technically be the easiest to convert to BEB operation, they also tend to be associated with low mileage or short operating days, and in future may be better suited to older BEBs with degraded batteries than to new vehicles.
- **Manageable**: Not straightforward, but the energy requirement of the average daily duty on the route, including a margin for two returns to depot (one to allow charging during the day), is within the capability of the best available BEB. There is therefore enough capability within the route's existing vehicle allocation and single home depot charging infrastructure to deliver the service with BEBs, but conversion to BEB may imply changes to the way each vehicle is utilised to maintain existing service patterns. Manageable routes imply relatively high vehicle utilisation with minimal charging infrastructure, so tend to represent the best return on BEB investment, so will tend to be the most likely to attract new BEBs.
- **Challenging**: Not manageable, but the energy requirement of an out-and-back round trip (plus dead mileage) is less than the capability of the best available BEB. This implies the route would be possible to operate with a single set of infrastructure, but not without additional investment – typically enough extra BEBs to make the route manageable, or rapid charging infrastructure sited on the route. Since all BEB solutions add cost, a FCEB solution (which also adds cost) could be a viable competitor to BEBs.
- **Incompatible**: Beyond challenging, meaning cannot complete a single out-and-back round trip and return to depot for charging. While not strictly "incompatible", since a BEB can in theory be recharged multiple times enroute, the practicalities and additional infrastructure costs of that make BEB an unattractive solution operationally.

Compatibility was assessed per route, with vehicles only shared between routes if modelled as inter-workable. Only infrequent routes were considered for inter-working. In practice, where overall service patterns are peaky, but specific routes either peak or do not peak, it is possible that a local operator could use vehicles from peaky routes to make challenging routes merely manageable. This has not been modelled because of the likelihood of different vehicle types being needed on routes with such different characteristics.

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[40] Three hours is indicative of a minimum period to recharge a BEB in a carefully managed way – in practice most bus fleets have far greater overnight downtime, as broadly indicated by Figure 19, so this criterion is rarely relevant to the assessment of BEB route compatibility.

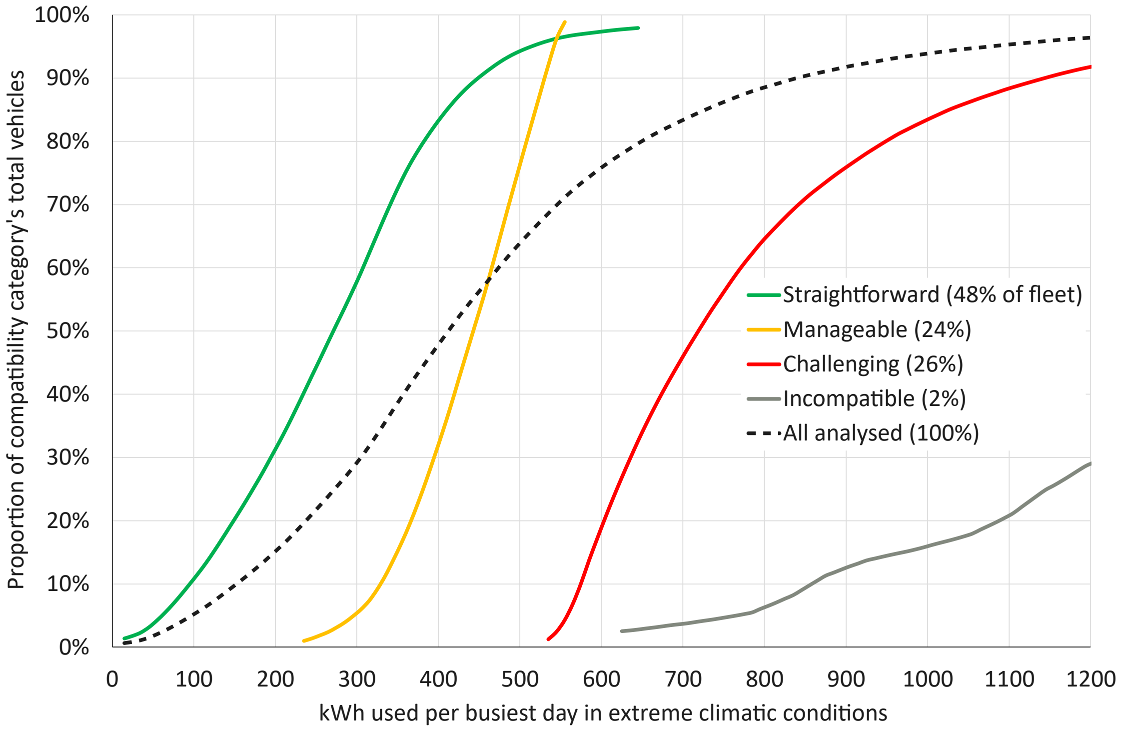

Figure 24: Modelled bus energy usage by BEB compatibility category in 2040, busiest day in extreme climatic conditions

The graph above shows the modelled distribution of daily power requirements on the worst day (busiest schedule and most extreme climatic month) for 2040, by category of BEB compatibility, expressed as proportion of vehicle fleet in each category. These figures do not include unusable battery capacity, so in practice BEBs would need to be specified with about 25% more installed capacity than shown.

Modelling has assigned a lower proportion of the total fleet (than to total mileage) to the least compatible categories because buses in these categories tend to be associated with higher mileage. The proportion of the fleet that operates, for example, challenging routes, is lower than the proportion of overall mileage that is challenging to operate.

The Manageable curve occurs wholly within the kWh range covered by the Straightforward because Manageable routes rely on utilising existing vehicle allocations, not necessarily on vehicles with fundamentally greater battery capacity. In contrast, the Manageable and Challenging curves do not overlap, as routes were only assigned Challenging where existing service patterns could not be delivered by managing charging across each route’s existing vehicle allocation.

Ember - a counterpoint

The pioneering Scottish mid-distance battery electric coach operator, Ember, challenges two key assumptions made within our modelling method:

1. That interurban and long-distance buses will have similar per-kilometre energy profiles as more local buses.
2. That bus operators will continue to deliver existing service patterns, not re-optimise those patterns to fit the limitations of BEBs.

As modelled, Ember's Dundee-Glasgow route requires 395 kWh per out-and-back trip in extreme climatic conditions. Ember launched the service with Yutong TCe12s, a model whose maximum battery capacity is specified as 350 kWh[41], implying under 300 kWh usable in practice. That suggests Ember's BEBs are using at least a quarter less energy than that modelled. Ember's vehicles have a single door and average about one stop every 10 km, so can be expected to lose far less heat than a city route where multiple doors can open several times per kilometre. Ember's BEBs also operate predominantly on relatively fast and direct inter-city roads, implying less active energy recovery due to braking and acceleration.

Almost all BEBs in Britain are currently deployed on city or suburban routes[42], and circumstantially similar patterns appear to dominate elsewhere in Europe. This bias means empirical research and calibration naturally skews to measure BEB performance in city and suburban operations. Figure 20 (the distribution of archetypes) shows that most European bus operations are city or suburban. However, many of the most challenging routes for BEBs – and those that are therefore potential candidates for FCEB – are in other categories, and this is where differences in energy utilisation between operating styles could become critical.

As a BEB-only startup, not an established diesel bus and coach operator, Ember's intuitive ethos has been to build service patterns and operations around the limitations of BEBs, not to simply replace diesel with battery electric. For example, on launch, Ember's Dundee-Glasgow route was operated by fully charging a BEB at Dundee, operating to Glasgow and straight back, then leaving service for at least two hours to fully recharge. This resulted in a tangibly lower vehicle utilisation than competing diesel coach routes, which Ember balanced by operating its services for around 22 hours each day. That meant that an individual BEB could still travel up to 900 kilometres daily. In the year since, Ember has continued to evolve and optimise BEB duties, including opening a new charging hub in Dundee and reaching an agreement with First Group to use bus charging facilities in Glasgow.

Our modelling assumes no substantial change to existing local bus service patterns. Yet in practice many of these have been optimised around vehicles that only need to be fuelled once per day. Where a route has been modelled as challenging to convert to BEB operation, there may be a strong business case for reducing service intensity at certain times of day when passenger demand is lower, and thus convert the route to one that is manageable with BEBs. Likewise, agencies with sharp school-related peaks

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[41] https://pelicanyutong.co.uk/coaches/tce12-electric-coach/ - the specification of Ember's TCe12s may have initially been even lower, at the default 281 kWh.

[42] A sample of real time data collated by bustimes.org and made available through their API was analysed to identify which routes BEBs had been deployed on. 70% of BEB mileage was on city routes and 22% on suburban routes, with Ember's mileage accounting for most of the remainder.

might seek to increase the amount of interworking of vehicles between routes to enable charging between peaks.

FCEB modelling

The inherent production inefficiency of the green hydrogen required to meet Zero Emission targets means that BEBs will be cheaper than FCEBs to operate in the long term. FCEBs are currently no cheaper to purchase than high battery capacity BEBs – indeed are typically slightly more expensive – so there is no clear Total Cost of Ownership business case for FCEBs. While a variety of transitional advantages may exist locally for FCEBs – typically related to the ease of securing electricity grid connections, or the similarity of FCEB fuelling processes to diesel – these are unlikely to shape the long-term market for FCEBs. The focus of this study has thus been on bus routes that cannot be converted to BEB operation without inflating cost beyond that of a BEB with at-depot charging.

However, FCEBs cannot be simply assumed to fill the BEB compatibility gaps modelled in 2050:

1. Many operators will, because of a mix of local policy and European regulation, seek to decarbonise routes well before 2050, when BEB compatibility will tend to be less favourable.
2. Hydrogen is only one of a range of possible solutions: Challenging-to-battery-electrify routes imply greater cost, but that could equally pay for solutions such as extra BEBs or non-depot opportunity charging infrastructure. The attractiveness of hydrogen vs other solutions will vary with geography and nature of bus operation, underpinned by relative costs. These options will be assessed further in the Alternatives to FCEBs section below. As discussed in the context of Ember above, there may be certain markets where the best business case involves changing operations to match the limitations of BEBs.
3. Hydrogen supply and fuelling infrastructure requires greater local scale than battery electric: Operations requiring only a handful of FCEBs, or regions demanding less than around one tonne of hydrogen per day to fuel them, may not be practical to deploy FCEBs to.

Prior ERM analysis of ZEB uptake in Great Britain found actual ZEB adoption rates mid-way between those implied by owners’ stated targets, and those implied by expected laws limiting the purchase of new non-ZEBs. Britain is one of the most advanced on bus decarbonisation of the large European countries with almost 10% of its local bus parc converted by mid-2024. The two curves were ten years apart. We therefore estimated an actual trajectory five years ahead of any legal limit. In the absence of a detailed assessment of often quite local ZEB fleet targets across Europe[43], we have

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[43] ICCT’s list of targets in selected major European cities - https://theicct.org/publication/the-rapid-deployment-of-zero-emission-buses-in-europe/ - reveals how locally nuanced many are, with differing ideals on exactly which fuels constitute Zero Emission, and inconsistent tolerances for partially non-ZEB fleets in later years. But critically the cities setting ZEB fleet targets are almost by definition the early adopters, and therefore not representative of wider European bus decarbonisation.

assumed the same patterns in Europe: that buyers will adopt ZEBs five years before that implied by the European regulation[44]. European Union regulations do not apply to all the countries of Europe, however policy in the main exceptions modelled is broadly similar[45].

European emission standards for heavy-duty vehicles set two relevant criteria:

- Vehicles modelled as serving City operational archetype routes adopt the more rapidly decarbonising "urban bus" criteria.
- All other operational archetypes adopt the later "coach and interurban" criteria because of the flexibility operators may have to deploy low-floor class II (single door, majority seated) vehicles on Suburban and Rural routes.

We expect a "grey area" to emerge between policy intention and pragmatic application, in which many buses operating in urban areas match the second "coach and interurban" criteria. That led us to make a more pessimistic assumption of ZEB trajectories than policy intended.

To avoid unnecessarily complex emission-centric micro-modelling, mandates for lower carbon dioxide emissions were transposed directly into the equivalent ZEB sales, while the residual 10% of carbon dioxide emissions allowed for this category after 2040 was assumed sold to non-scheduled bus and coach operators with stronger requirements for both range and operational flexibility (for example, mid-distance group and tour coach markets). Sales to non-scheduled bus markets were otherwise assumed to mimic the patterns of scheduled bus.

Buses average a 15-year working life. Traditionally this tends to be slightly longer in eastern than western Europe. Just 5 years are expected of a scheduled long-distance coach[46]. Long-distance routes were modelled as certain to require a new vehicle in each 5-year period. Other route operational archetypes were modelled with a one third chance of vehicle replacement in each 5-year period. Modelling initially assumed that vehicle buyers would first deploy ZEBs to routes which were either straightforward or manageable to convert to BEB, and thus initial demand for vehicles capable of operating challenging (or incompatible) routes would only occur in the final stages of decarbonisation. The example graphed below demonstrates this for city buses.

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[44] https://data.consilium.europa.eu/doc/document/PE-29-2024-INIT/en/pdf

[45] The biggest exception, the United Kingdom had no equivalent regulations in law by mid-2024, although policy intentions had been to cease the same of new non-Zero Emission buses by 2032 at the latest, and 2040 for coaches, both targets like those laid down in Europe.

[46] UITP concluded the average age of a bus to be 6.9 years, although noted ages were skewed down by non-European countries - https://cms.uitp.org/wp/wp-content/uploads/2020/07/Statistics-Brief_Global-bus-survey-003.pdf Analysis of the second-hand bus market in Scotland - https://www.climatexchange.org.uk/projects/the-impact-of-electric-buses-on-the-scottish-second-hand-bus-market/ - concluded 15 years for mainstream commercial bus operation, with specific operators favouring between 12 and 18 years. The biggest operator of long-distance coach services used new coaches for just five years.

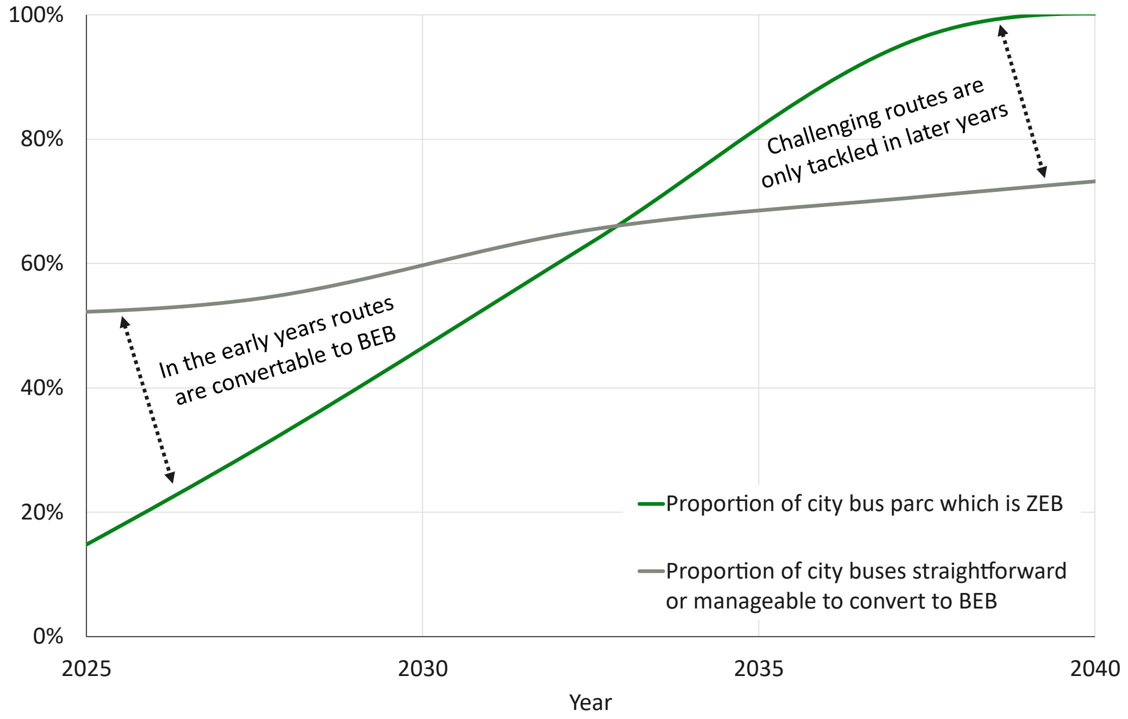

Figure 25: City bus ZEB uptake and BEB compatibility curves, showing how solutions for routes which are challenging to convert might logically only be demanded in the final years of decarbonisation

The implication of this pattern is a stop-start cycle of demand for vehicles capable of operating challenging routes, in which demand occurs for one 5-year period in every 15. Long-distance vehicles would be the exception because of their assumed 5-year vehicle replacement cycles. However, the European regulatory trajectory interacts with different local, regional, or national policy objectives, while individual operators will face BEB compatibility curves with different shapes and gradients to the European average. The final modelling was therefore smoothed across the 15-year life cycle of the bus. This logic was then used to decide the year in which FCEBs would be purchased.

Alternatives to FCEBs

FCEBs will be one of several possible technologies that could be deployed to decarbonise bus routes which will be challenging to convert to BEB. A basic assessment of the likely suitability of these options was used to evaluate the chance of hydrogen being selected for each operational archetype. This evaluation was intended to guide a broad assessment of risks. It has not drawn on detailed cost modelling or full consideration of local factors.

Opportunity charged BEBs typically require investment in rapid charging infrastructure that tops up the BEB's batteries at one or more places the bus was already scheduled to stop or pass through. Prevailing technology uses a pantograph at a fixed location (with the mechanical element either attached to the overhead charger or to the roof of the bus). Trolleybus-based in-motion solutions are already in operation and induction technology is mooted. Where trolleybus overhead cabling exists over part of the route (most common in cities within Austria, Switzerland and much of Eastern Europe), power for in-motion charging can potentially be drawn from low voltage domestic electricity grid connections, avoiding the need for expensive new electricity grid connections[47]. Likewise, rapidly reducing battery prices are expected to promote greater use of trickle-charged stationary batteries attached to opportunity charging infrastructure[48].

While likely to become easier to implement, opportunity charging infrastructure is expected to remain a more expensive, and a considerably less flexible, investment than simply buying an extra BEB, so opportunity charging will tend to suit long-established high-frequency routes. In some countries planning, land ownership and safety considerations greatly limit the locations in which opportunity infrastructure can be installed, so opportunity charging will not always be an option. Opportunity charging strategy is closely linked to battery strategy, as regular rapid charging implies at least the risk of faster battery degradation, but also potentially much smaller installed battery capacity. All this makes the assessment of opportunity charging potential locally complex, and hence difficult to generalise across Europe.

Extra BEBs with daytime at-depot charging means the use of existing depot charging equipment during the day by extra BEBs, which are rotated in-and-out of services to charge, while overall maintaining route service levels. Extra buses both increase capital expenditure and fixed costs, such as insurance and depot space. Staff costs rise slightly due to the need to drive buses to and from depot. Where routes are less frequent, the extra buses may be inter-worked between routes. The lack of additional fixed infrastructure makes this approach more operationally flexible than opportunity charging. This approach generally scales better to lower frequency routes operated in reasonably close geographic proximity to a depot.

This approach relies on depots being reasonably close to route termini, to minimise time lost bringing buses in and out of service. This limitation can be moderated by creating additional “out-stations”, potentially consisting of no more than a dedicated parking bay and a charger. This might naturally occur as part of a BEB optimisation strategy, since BEBs generally require less maintenance than diesel buses, and thus have less need to return to a maintenance depot each evening.

Triaxle BEBs can carry more weight and thus more batteries – potentially enough to meet the duty cycle requirements on a single overnight charge. Increasing battery capacity and chassis size raises capital cost. The main limitation on the use of triaxle vehicles is their length and increased difficulty manoeuvring, which makes them unsuitable for many local roads, especially in suburbs, town centres, and on rural roads. Short wheelbase triaxle high battery capacity BEBs would in practice be difficult to engineer while maintaining low floor access. Routes already using triaxle buses

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[47] https://www.sustainable-bus.com/news/tallinn-revives-trolleybus-technology-procurement-40-vehicles/
[48] https://cleantechnica.com/2024/05/19/dirt-cheap-batteries-enable-megawatt-scale-charging-without-big-grid-upgrades-right-away/

typically do so to accommodate high passenger (or luggage) loads, which imply relatively little spare axle load for extra batteries.

Battery swapping was not considered a relevant technology for local buses, not least because of the inaccessible parts of the chassis on which batteries are packaged on modern BEBs – mounted in the floor or stacked around wheel arches.

Biofuels were not considered long term solutions for bus decarbonisation because theoretical supplies of fuel will be highly constrained. Hydrogenated Vegetable Oil is already a significantly more expensive fuel than diesel, and as aviation demand for Sustainable Aviation Fuel grows over the 2030s, terrestrial transport users can expect to be priced out of biofuels market. A caveat is that the strong affiliation of bus operators to their localities can make buses a natural off-taker of highly local sources of biofuel, including approaches which are not solely governed by global prices, such as involvement in local municipal circular economies. Biogas is low, but not zero emission (a charge reasonably levelled at most current hydrogen production) and has raised concerns over excess methane emissions[49]. Synthetic fuels, by dint of being made from hydrogen, have no obvious cost advantage where hydrogen can be used directly[50].

FECBs are currently no cheaper to purchase than BEBs, yet their fuel costs are, and will be, significantly greater than electricity. This cost assessment applies to north-western Europe, where the levelised cost of hydrogen production is expected to be cheapest[51]. This means FCEBs are likely to be priced off routes that can be operated efficiently with one of the alternative solutions above, even after the added costs of the previous options have been considered.

In assessing the chance of adopting FCEBs vs alternatives, the dominant characteristics of European local bus organisation and objectives have been considered – often municipally focused, with strong ethos of social benefit. European policy has emphasised commercial competition in at least service contract procurement. This increasingly brings multinationals, with access to non-local capital, into the structure. There will inevitably be parts of Europe where such a broad assessment might not apply. The generally lower levels of liberalisation in Eastern Europe may make long-term capital investment harder to secure[52], potentially favouring FCEB where much of the additional cost is operational. The more commercial market structure of much of the British bus and international long-distance coach is more likely to lead to routes being restructured to work within the limitations of BEBs.

Ultimately any assessment of such an under-developed market is a judgement intended to give a relative sense of what is reasonable to expect given current

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[49] https://www.imperial.ac.uk/news/222213/biogas-emissions-could-risk-net-zero/

[50] https://www.iea.org/reports/the-role-of-e-fuels-in-decarbonising-transport

[51] https://www.iea.org/data-and-statistics/data-tools/levelised-cost-of-hydrogen-maps Parallel analysis of green hydrogen production by ERM suggests both higher overall unit costs, and relatively higher costs in Switzerland and the Balkans due to very limited wind power potential.

[52] UITP's member survey - https://www.uitp.org/news/the-future-of-buses-in-europe-results-of-europe-bus-fleet-survey-2023/ - supports the tendency for the finance elements of bus decarbonisation to be more challenging in south, central and eastern Europe, than in the north and west.

evidence. In referring to the “chance” of FCEBs being adopted, it is important that the reader adopt a risk-based mentality, not a deterministic one. Even in operational archetypes where the prognosis for FCEBs is relatively good, it is still possible that the long-term market for FCEBs is zero. The table below outlines the rationale for the chances assigned.

Table 5: Rationale for chance of FCEB adoption by operational archetypes

Operational archetype	Chance of FCEB	Rationale
City	10%	High frequency and historic stability of route makes these best suited to opportunity or in-motion charging. Alternatively, depots tend to be nearby which makes extra BEB strategies viable. However, passenger load-related weight concerns may promote FCEB ahead of triaxle BEBs. Generally high revenue earning potential makes hydrogen cost less of a blocker to FCEB adoption.
Interurban	50%	Intensive operations to dispersed, sometimes relatively rural termini, can make any solution that relies on infrastructure in a fixed location challenging (be that opportunity charging or return to depot). While interurban routes are most likely to use wider roads suitable for triaxle buses, many also need to access constrained rural settlements or small towns. Interurban routes tend to have reasonable revenue-earning potential, so may be able to sustain the higher operating costs of hydrogen.
Long	30%	Current operational requirements tend to be very well suited to hydrogen fuel cell electric vehicles. However, most long-distance coach *markets* are time-rich and cash-poor, suggesting passengers will be unwilling to pay for the continuity of journey allowed by a more expensive fuel[53]. No state intervention can be expected in such a liberalised market. However, European policy requirements for a minimal network of long-distance road hydrogen refuelling stations, with set minimum daily fuel availability, may promote a scenario where long-distance coach is the only consistent user, and thus able to negotiate favourable terms with station operators.

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[53] This assessment applies specifically to scheduled long-distance coach. A much more favourable case can be made for mid-distance group hire and coach tours, which are both more likely to be time-sensitive, and value the operational flexibility of hydrogen.

Operational archetype	**Chance of FCEB**	**Rationale**
Rural	40%	Low frequencies, dispersed networks, remote depots, and sometimes narrow roads or undulating terrain collectively offer no good BEB-based options to maintain existing service patterns. The relatively marginal business case for this style of operation increases the chance that BEB compatibility issues will be managed by altering operating patterns or routes. Supply scaling is most likely to limit hydrogen in this niche because vehicles are more likely to be based in more sparsely populated (and thus bused) territory.
Suburban	20%	Lower frequencies and potentially greater tendency for routes to evolve as urban areas expand, may make opportunity or in-motion charging unattractive. Triaxle buses tend to be unsuitable for suburban roads. However, routes within the same urban area may be able to share charging infrastructure, especially for depot-based options involving extra BEBs. FCEBs will therefore be best suited to operations serving dispersed or sprawling suburban areas, the occurrence of which varies substantially between countries.

Appendix: Attributions

As described above, six hundred different open data GTFS sources have been distilled and processed to produce much of the analysis presented in this study. These GTFS sources were all published as open data, some as part of compliance with EU regulation 2017/1926[54], but many to promote local bus networks within third party applications. Most data sources have been published under a licence that requires attribution. The following data aggregators and providers are acknowledged:

- Austria:
  - https://mobilitaetsverbuende.at/mobility-association-austria/ - Mobilitätsverbünde Österreich
- Belgium:
  - https://data.gov.be/en/ - Belgian government
  - https://data.stib-mivb.be/pages/home/ - STIB-MIVB - Brussels Intercommunal Transport Company
- Croatia:
  - http://hzpp.hr/ - HŽ Putnički Prijevoz
- Czechia:
  - http://www.dpmlj.cz/ - Dopravni Podnik Mest
  - https://www.dpmo.cz/ - Olomouc transport company
  - https://pid.cz/ - Prazska Integrovana Doprava
- Denmark:
  - https://help.rejseplanen.dk/ - Rejseplanen
- Estonia:
  - https://web.peatus.ee/ - Peatus journey planner
- Finland:
  - https://www.hsl.fi/hsl/avoin-data - Helsinki public transport authority
  - https://developer.matka.fi/[55]
  - https://gtfs.pro/ - GTFS.pro global database[56]
- France:
  - https://transport.data.gouv.fr/ - French national access point to transport data
- Germany:
  - https://gtfs.de/en/ - Germany's dedicated GTFS provision platform
- Hungary:
  - https://go.bkk.hu/ - BudapestGO
  - https://gtfs.kti.hu/public-gtfs/ - KTI Research Institute
  - https://gtfsapi.mvkzrt.hu/ - MVK bus and tram operator
  - https://mobilitas.biokom.hu/ - Biokom mobility centre
  - https://szegedimenetrend.hu/ - City of Szeged

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[54] https://eur-lex.europa.eu/eli/reg_del/2017/1926/oj

[55] Distribution and re-use of public transport database open data is allowed.

[56] Here and where used for other countries, as a reference for sourcing original datasets.

- Iceland:
    - https://straeto.is/en/about-straeto/open-data - Iceland's open data platform for route systems
- Ireland:
    - https://www.transportforireland.ie/ - Ireland's transport authority
- Italy:
    - https://gtfs.pro/ - GTFS.pro global database[56]
- Latvia:
    - https://gtfs.pro/ - GTFS.pro global database
    - https://www.atd.lv/ - Latvia's Road Transport Directorate
- Lithuania:
    - https://gtfs.pro/ - GTFS.pro global database
- Luxembourg:
    - https://data.public.lu/ - Luxembourg's open data platform[57]
- Netherlands:
    - https://mobilitydatabase.org/ - Mobility Database
- Norway:
    - https://nordicopenmobilitydata.eu/implementation-details-nordic-public-transport-network-visualization/ - the open data platform for the Nordics[58]
- Poland:
    - https://mkuran.pl/gtfs/ - a Polish GTFS aggregator[59]
- Portugal:
    - https://gtfs.pro/ - GTFS.pro global database
    - https://www.transit.land/ - GTFS aggregator[60]
- Romania:
    - https://gtfs.tpbi.ro/ - Intercommunity Development Association for Public Transport Bucharest-Ilfov
    - https://www.ctbus.ro/ - CT bus company
    - https://www.tursib.ro/ - TURSIB S.A. transport company
- Slovakia:
    - https://gtfs.pro/ - GTFS.pro global database
- Slovenia:
    - https://gtfs.pro/ - GTFS.pro global database
- Spain:
    - https://nap.transportes.gob.es/ - Ministry of Transport and Sustainable Mobility[61]
- Sweden:
    - https://www.trafiklab.se/ - Sweden's open data platform for mobility data

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[57] Licenced as Universal Transfer in the Public Domain Creative Commons CC0 1.0 - https://data.public.lu/en/pages/legal/terms/

[58] Under a Norwegian Licence for Open Government Data (NLOD) 2.0 - https://data.norge.no/nlod/en/2.0

[59] Integrates data from Miasto Stołeczne Warszawa, Koleje Mazowieckie-KM Sp. z o.o., Zarząd Dróg i Zieleni w Gdyni, ZTM Rzeszów, and Urząd Miasta Kielce - Zarząd Transportu Miejskiego.

[60] Terms of use - https://www.transit.land/terms

[61] Under a custom open data licence - https://nap.transportes.gob.es/licencia-datos

- Switzerland:
  - https://opentransportdata.swiss/en/ - Open data platform on mobility in Switzerland
- United Kingdom:
  - https://data.bus-data.dft.gov.uk/downloads/ - Department for Transport[62]
  - https://admin.opendatani.gov.uk/ - OpenDataNI

NUTS boundary mapping, kilometre grid square mapping, and related demographic data[63] © European Union, 1995-2023.

GTFS validation utilised Mobility Data's "gtfs-validator" package[64] under an Apache 2.0 licence.

Bus network graph building used the author's "Aquius" codebase[65] under an MIT licence.

The bus route energy modelling method and supporting codebase remains the property of The ERM International Group Limited (ERM). All rights reserved.

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[62] Under an Open Government Licence - https://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/

[63] https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/grids

[64] https://github.com/MobilityData/gtfs-validator

[65] https://github.com/timhowgego/Aquius

Project coordination:

ERM

Project dissemination:

Hydrogen Europe

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