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Hydrogen for long-haul road freight: A realist retroductive assessment

P. Churchman [a,*], T. Dekker [a], K. Pangbourne [a], V. Sanchez Rodrigues [b]

[a] *Institute for Transport Studies, University of Leeds, Leeds, LS2 9JT, United Kingdom*
[b] *Logistics & Operations Management Section, Cardiff Business School, United Kingdom*

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ABSTRACT

This study focuses on arguably the most contentious choice of energy supply option available for decarbonizing general-purpose long-haul road freight: hydrogen. For operators, infrastructure providers, energy providers and vehicle manufacturers to make the investments necessary to enable this transition, it is essential to evaluate the feasibility of individual energy supply choices. A literature review is conducted identifying ten requirements for an energy supply choice to be feasible, which are then translated into "what would need to be true" conditions for hydrogen to meet these requirements. Considering these, evidence from literature is used to assess the likelihood of each condition becoming true within the lifespan of a vehicle bought today. It is concluded that it is unlikely that hydrogen will become feasible in this time frame, meaning it can be disregarded as a current vehicle purchase consideration, as it will not undermine the competitiveness or resale value of a vehicle using a different energy source bought today. There are two principal innovations in the study approach: the consideration of socio-technical and political as well as techno-economic factors; and the application of realist retroductive option assessment. While not necessary to address the research question regarding hydrogen, a realist retroductive assessment is also presented for other prominent low carbon energy source options: battery electric, electric road systems (ERS) and biofuels; and the conditions under which these options could be feasible are considered.

1. Introduction

One of the most prominent debates in road freight decarbonization is whether hydrogen is a feasible fuel for long-haul freight, and if it should be developed in parallel with other low carbon options. There is broad consensus that hydrogen is not a feasible solution today, and that several unaddressed challenges would need to be resolved for it to become feasible [1]. Some suggest that hydrogen cannot be feasible for reasons including high energy losses and that, while hydrogen remains on the table, deployment of other decarbonization solutions will be slower [2]. However, others argue that all options are required and operators should make their own choices on the technology to adopt [3]. While these challenges remain, some analyses conclude that the rational choice is for operators to defer the transition to other low carbon energy sources [4]. This conclusion inevitably leads to further delay in the low carbon transition of this sector.

This paper focuses on the specific case of hydrogen as the choice of energy supply option in the context of general-purpose long-haul road freight within the United Kingdom (UK). General purpose long-haul road freight requires a comprehensive charging/fueling network and interoperability across thousands of operators [5]. Small operators are an important part of road freight [6], with operators with fewer than 50 employees representing 99 % of total UK operators; and 35 % of UK heavy goods vehicles (HGVs) in fleets of fewer than 10 vehicles [7]. Many smaller operators will not be able to deploy mixed technology fleets because of operational and resource constraints [8]. The cost for decarbonizing UK road freight is estimated at circa £20bn based on either an electric or hydrogen-based network [9], and these costs will be substantially higher if both networks are implemented nationally [10].

Hydrogen trucks come in two varieties, hydrogen internal combustion engine (ICE) and hydrogen fuel cell. These both require a hydrogen fuel supply but have different vehicle technologies. Hydrogen ICE trucks use modified diesel engines whereas hydrogen fuel cell trucks are battery electric trucks with the addition of hydrogen storage and a fuel cell to convert hydrogen to electricity, and a reduced battery size. Hydrogen ICEs incur a 75–80 % energy loss [11] and fuel cells incur 40–60 % energy loss in addition to a 10–15 % energy loss in the electric drive train [12,13]. While ICE technology is well developed, fuel cells remain expensive and challenging to manufacture and have unresolved reliability issues [14]. Both types of hydrogen truck can carry hydrogen either in liquid or compressed gaseous form. The former increases the

* Corresponding author.
E-mail address: p.d.churchman@leeds.ac.uk (P. Churchman).

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List of abbreviations and units:

DMDU	Decision Making under Deep Uncertainty
ERS	Electric road system
EU	European Union
ICE	Internal combustion engine
HGV	Heavy goods vehicle
NGO	Non-Governmental Organization
R&D	Research and development
RROA	Realist Retroductive Option Assessment
RTFO	Renewable Transport Fuel Obligation
TCO	Total cost of ownership
UK:	United Kingdom
km	kilometer
kWh/kg	kilowatt-hour per kilogram

range of vehicles but requires the hydrogen to be liquefied and maintained at minus 253 Celsius [15], incurring a substantial additional energy loss and cost penalty [16]. Based on a hydrogen energy density of 33 kWh/kg [17] and a liquefaction energy requirement of 13 kWh/kg [18], the energy loss through liquefaction is 13/(33 + 13) or c. 30 %.

There are four principal sources of low carbon hydrogen currently identified: 1) "Green" hydrogen produced by the electrolysis of water using electricity generated from low carbon sources; 2) "Blue" hydrogen produced from steam reforming of methane with carbon capture and storage (CCS); 3) "By-product" hydrogen produced from the chlor-alkali process [19]; and 4) "White" hydrogen that is naturally trapped in geological formations [20,21]. The last of these, while possibly providing an abundant, clean and cheap source of hydrogen, is also highly speculative and subject to widely varying estimates of production potential and environmental risks [21]. A further possible source of "orange" hydrogen is also proposed, which artificially provokes the natural processes that result in the generation of white hydrogen [22]. However, this is more costly and speculative than white hydrogen and is not considered further in this paper.

Alternative options to hydrogen include battery electric vehicles (BEVs) and Electric Road Systems (ERSs). BEVs appear certain to be part of the road freight mix for short-medium distances, and the range of applications is likely to grow as the charging network and battery technology further develop [23]. ERSs provide another electricity-based solution where electricity is supplied directly to the vehicle while in motion via an overhead catenary or other means [2]. Large scale battery electric and ERS deployment both share a requirement for an increase in low carbon electricity generation, storage and distribution capacity [24]. Battery electric and ERS trucks are technologically identical apart from the addition of equipment to connect to the external power supply and a reduced battery size for ERS trucks. Both offer high end-to-end energy efficiency [25,26]. However, ERS requires major investment in physical infrastructure before a single ERS vehicle can be deployed [27].

It is understandable that operators and infrastructure providers are hesitant to commit to a certain technology when facing such a complex option landscape. When operators purchase a vehicle, they are not doing so only based on the economics and capabilities of the vehicle today, but also on the expected performance and operating cost of the vehicle versus other technologies during its lifespan. This is because the latter will determine the operator's competitiveness while using the vehicle, and the value of the vehicle when it is resold to the next owner. If there is a high degree of uncertainty regarding future vehicle economics and capabilities, operators are likely to stick with tried and tested diesel vehicles for as long as possible.

Based on UK DfT [28] data, 82 % of HGVs registered in Great Britain at the end of 2023 were thirteen years or younger since first registration. A separate analysis based on the volume of HGVs deregistered per year versus the total number of licenced vehicles results in an estimated average HGV lifespan of twelve years, which reduces to 9.75 years for HGVs over 18 tonnes. Based on these analyses, a thirteen-year lifespan is taken as a conservative assumption for vehicles used for general-purpose long-haul road freight.

We propose that if the deployment of hydrogen for general-purpose long-haul road freight is unlikely within the thirteen-year lifespan of vehicles being purchased today, it can be disregarded by organizations buying vehicles at this time, as it will not undermine the competitiveness or resale value of a purchased vehicle that uses a different energy source. If this conclusion is generally accepted by road freight actors, this may increase the adoption of vehicles using other low carbon energy sources. This would not rule out the possibility that dedicated fleets with an economic supply of low carbon hydrogen could adopt hydrogen in the near term, or that hydrogen could play a wider long-term role in future vehicle renewal cycles.

However, there is substantial resistance to reaching this conclusion. There are powerful lobbyists and economic vested interests for all options, and policymakers are reluctant to back specific vehicle technologies [29].

Two core research questions are considered:

1. What systemic conditions would need to be true for hydrogen to be feasible for general-purpose long-haul road freight?
2. How likely is it that these conditions will be met within the lifespan of vehicles being bought today?

A realist retroductive option assessment is conducted to assess the research questions. The theoretical basis of this approach is described in Appendix A. The presented assessment evaluates whether the option itself is feasible for general-purpose long-haul freight within the lifespan of vehicles being bought today. Eliminating options that are infeasible in isolation is helpful as it simplifies the choice between remaining options. It also highlights conditions for which more information is required to determine feasibility, and where an option may be feasible for certain applications but not others.

While not required to reach a conclusion on hydrogen feasibility, an assessment is also presented for other principal low carbon energy source options: battery electric, Electric Road Systems (ERS), biomethane and Hydrogenated Vegetable Oil (HVO).

The remainder of the paper is organized as follows: section 2 presents the multi-perspective framework developed for the assessment; section 3 applies this framework to address the two research questions regarding hydrogen feasibility; section 4 undertakes an equivalent assessment for other vehicle energy source options; and section 5 presents principal findings, research contributions, study limitations and opportunities for further research.

2. Multi-perspective framework

Cherp and Vinichenko [30] identify techno-economic, socio-technical and political perspectives, shown in Fig. 1, as all being important for national energy transitions. The techno-economic perspective considers the technical and economic benefits, limitations, and costs of different technology solutions; the socio-technical perspective considers how innovations emerge and ultimately displace incumbent socio-technical systems; and the political perspective considers how policy processes, networks, vested interests and the state interact to enable or hinder sustainability transitions [31]. Most research into road freight decarbonization is techno-economic [32]. However, political and socio-technical aspects are also identified as important for this transition and are starting to receive greater attention [33,34]. The lack of research considering all three perspectives in combination is a significant research gap.

Building on this framework, Table 1 proposes ten conditions that all need to be fulfilled for a vehicle energy source option to be feasible.

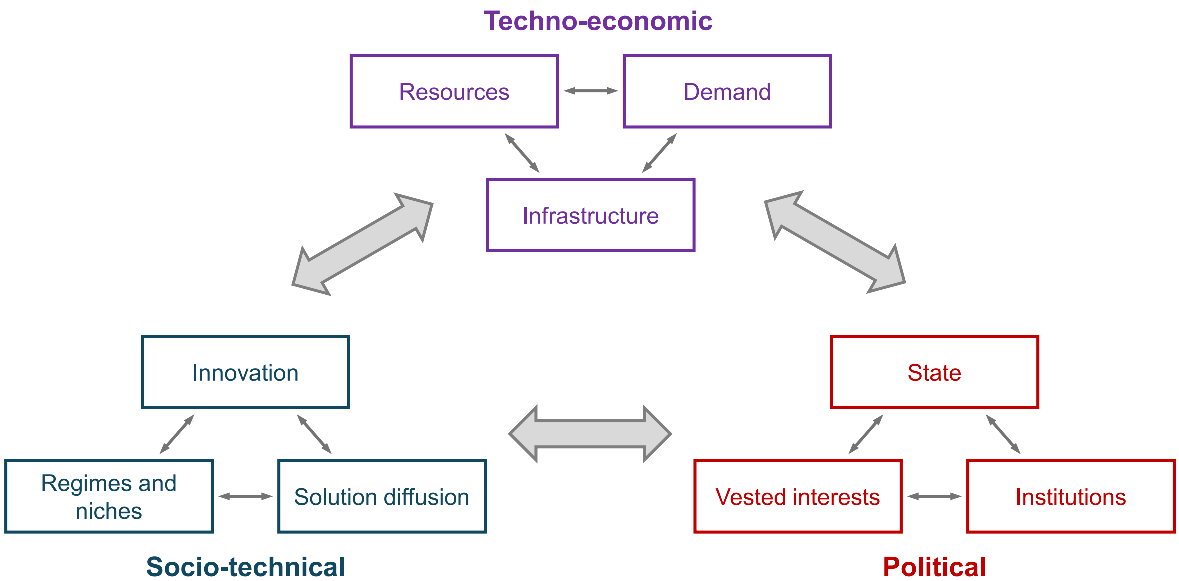

Fig. 1. Techno-economic, socio-technical and political perspectives of national energy transitions.
(Source: Reproduced from Cherp et al. [35]).

Table 1
Systemic conditions for an energy source option to be a feasible road freight decarbonization solution.

Condition	References
A: Techno-economic – Energy	
A1 Projected energy supply capacity satisfies projected demand at acceptable per-unit cost	[43–47]
A2 Total "well-to-wheel" emissions[a] of carbon, other greenhouse gases (GHGs) and non-GHG pollutants are a substantial reduction compared to diesel	[48–50]
B: Techno-economic - Vehicles	
B1 An acceptable return on capital on vehicles can be achieved	[51–53]
B2 Vehicle capabilities allow operators to meet customer requirements	[54–57]
B3 Emission increases from vehicle manufacture do not outweigh energy emission reductions	[58]
C: Techno-economic - Infrastructure	
C1 Emisvsions from infrastructure build do not outweigh net energy and vehicle emission reductions	[58,59]
D: Socio-technical	
D1 Energy, infrastructure and vehicle timelines can be aligned	[60,61]
D2 The risk of backtracking is minimized	[62,63]
E: Political	
E1 The solution provides energy and freight transport security	[64,65]
E2 The solution aligns with economic and strategic interests of actors required for its implementation	[66–68]

[a] Well-to-wheel emissions are the total emissions resulting from the extraction/generation, processing, storage and distribution of energy; and the consumption of energy in the vehicle.

These conditions are derived from the literature referenced in Table 1; and interviews and workshops from previous studies with policymakers, industry participants and experts [34,36,37]. These conditions are framed to be as mutually independent as possible. However, they are not exhaustive, for example "Vehicle and infrastructure reliability, performance, longevity and safety are adequately proven" [38,39,40], and "Sufficient vehicles can be produced" [14,41,42] could also have been added. In addition, broader political and social conditions could have been included, for example: "public acceptance of solution" and "a supportive policy framework". However, these other conditions are moot if one or more of the ten conditions are assessed as unlikely to be fulfilled. In addition, the wider conditions are to at least some extent dependent on the ten conditions. It was therefore decided to focus on the ten conditions only.

3. Assessment of hydrogen against conditions

This section considers the research question "How likely is it that these conditions will be met within the lifespan of vehicles being bought today?" for each of the ten conditions by means of evaluating peer reviewed and grey literature. Specific "what would need to be true" requirements for each condition are proposed, and the likelihood of the condition being fulfilled within the lifespan of vehicles bought today is classified as follows:

- GREEN: Likely to be feasible based on identified evidence
- AMBER: Feasibility unclear – more information required
- RED: Likely not to be feasible based on identified evidence

3.1. Condition assessments

3.1.1. A1: Projected energy supply capacity satisfies projected demand at acceptable per-unit cost – RED

What would be considered an "acceptable" per-unit cost is a subjective judgement. However, a relevant objective reference is the current cost of diesel per 100 km travelled for a given vehicle type, as it is a comparison against this reference that operators would make if they were considering switching to hydrogen today. Basma and Rodríguez [69] provide the estimates in Table 2 for a 2023 model long haul truck based on weighted average 2023 fuel prices in the European Union (EU). These estimates make the favorable assumption that that the minimum level of taxation as proposed in the Revision of the Energy Taxation Directive in Europe [70] is applied.

One reason for the high cost of green hydrogen is the 40–50 % energy loss incurred in the electrolysis of water [71]. A 2030 estimated fuel cost for green hydrogen of €7.77 [69] reduces the cost for the two hydrogen

Table 2
Comparison of green hydrogen and diesel fuel cost per 100 km (Source: [69]).

Long-haul truck fuel type	2023 fuel cost (EU weighted average)	Consumption per 100 km	Fuel cost per 100 km
Diesel	€1.22	30.7 L	€37.5
H_2 ICE	€10.30[a]	10.23 kg	€105.7
H_2 fuel cell	€10.30[a]	8.32 kg	€85.7

[a] Green hydrogen cost.

options to €64.6 per 100 km for H_2 fuel cell and €79.5 per 100 km for H_2 ICE. We suggest that this is still unlikely to meet the requirement of being an acceptable per-unit cost compared to diesel. Based on this, we propose that a "what would need to be true" requirement for this condition is:

> A sufficient supply of low carbon hydrogen that is substantially cheaper than green hydrogen produced via current methods is secured.

It is possible that "blue" or "white" hydrogen could fulfil this requirement. Green hydrogen would only meet the requirement if substantial advances were made in electrolyzer efficiency [71]. By-product hydrogen only makes up 3.5 % of hydrogen produced in the EU today and 85 % of this is already used for other purposes [19]. Neither blue nor white hydrogen have been realized or proven at scale and are subject to several development uncertainties [72–74]. Favorable assumptions are therefore necessary regarding the rapid proving and development of blue or white hydrogen and the subsequent deployment of large-scale production and distribution capacity for this requirement to be fulfilled. While this cannot be ruled out, we believe that this is unlikely and have assessed this condition as RED.

3.1.2. A2: Total "well-to-wheel" emissions of carbon, other greenhouse gases (GHGs) and non-GHG pollutants are a substantial reduction compared to diesel - AMBER

Hydrogen is the smallest molecule that exists and has a high propensity to leakage. While hydrogen is not a direct greenhouse gas, it has been found to have negative indirect climate impacts via its chemical interactions with atmospheric methane, ozone and water vapor, resulting in a global warming potential (GWP) of 6–16 times that of CO_2 for the same mass of gas [75,76]. Hydrogen is however a much lighter molecule than CO_2, meaning that hydrogen leakage is estimated as only partially offsetting rather than eliminating the benefits of decarbonization at a 20 % leakage rate [75]. However, there is a high uncertainty range in hydrogen's GWP and in the total "well-to-wheel" leakage that will occur. Based on this, we propose that a "what would need to be true" requirement for this condition is:

> It is confirmed that hydrogen leakage can be contained to a level at which its negative climate effects do not substantially offset benefits from carbon emission reduction.

Considering the impact of hydrogen adoption on carbon and methane emissions, these are dependent on how the hydrogen is produced:

- Green hydrogen is as low carbon as the electricity used to produce it.
- "Grey" hydrogen produced from methane without CCS represents most of the hydrogen produced today and can result in higher GHG emissions than diesel engines [77]. This should therefore be ruled out as a transportation fuel.
- Blue hydrogen produced from methane with CCS can capture 60–85 % of CO_2 emissions from the production process, but this results in an additional energy loss [46,78]. The undersea or geological storage of captured CO_2 entails a risk of further CO_2 leakage [79]. There is also a risk of methane leakage, which is itself a strong greenhouse gas, from blue hydrogen production [46]. As a result, there are question marks on whether blue hydrogen reduces global warming impact compared to the direct use of fossil fuels [80].
- By-product hydrogen, to be low carbon, needs to be produced using green electricity. Also, as discussed above, by-product hydrogen volumes are only a small proportion of hydrogen produced in the EU today and most is already used for other purposes [19]. By-product hydrogen can only therefore make a small contribution to the quantity of hydrogen required if hydrogen is to be used for large scale road freight decarbonization.
- White hydrogen reserves can also contain methane, creating the risk that methane could be released as well as hydrogen in its extraction [21].

Based on this, we propose that a further "what would need to be true" requirement for this condition is:

> Blue or white hydrogen are proven to offer substantial well-to-wheel carbon equivalent emissions reductions compared to diesel if these are to be used as alternatives to green hydrogen.

The use of the term "carbon equivalent" includes the impact of methane emissions in addition to carbon. Because of substantial open questions regarding both "needs to be true" requirements, this condition is assessed as AMBER.

3.1.3. B1: An acceptable return on capital on vehicles can be achieved – RED

Return on capital on vehicles purchased is determined by the total cost of ownership/operation (TCO) of vehicles and revenues for freight services minus non-vehicle costs over the lifespan of vehicles. If the TCO increases, revenues minus other costs also need to increase if return on capital is to be maintained. Based on this, we propose that a "what would need to be true" requirement for this condition is:

> Any increases in vehicle total cost of ownership/operation are compensated by increased freight service prices and/or subsidies.

Xie et al. [81] predict the cost of a long-haul diesel truck in the US to remain roughly constant at c. $180k in the period to 2040. By contrast, they predict the cost of a fuel cell truck to decrease dramatically from c. $550k in 2022 to c. $260k in 2030 and c. $210 in 2040. Based on this analysis, Basma and Rodríguez [69] predict hydrogen fuel cell long-haul trucks will not achieve TCO parity with diesel until close to 2040, with higher vehicle purchase price and fuel costs being offset by lower road tolls/charges and maintenance costs. Road toll reductions are based on the favorable assumption that no road tolls are applied to zero emission trucks. Fuel cost assumptions are those shown in section 3.1.1, including the favorable assumption that the minimum level of taxation as proposed in the Revision of the Energy Taxation Directive in Europe [70] is applied.

Lower fuel efficiency means that hydrogen ICE trucks, despite lower purchase costs, are projected to not achieve TCO parity within the modelled period.

The projected reduction in the cost of a fuel cell truck is principally driven by large projected cost reductions for fuel cells and hydrogen storage systems. Xie et al. [81] identify an order of magnitude (factor of 10) variation in cost estimates of fuel cells and a factor of 4 variation in cost estimates of hydrogen storage systems across all modelled time periods. This implies a high degree of uncertainty in hydrogen fuel cell truck purchase costs and TCO.

Even with the large assumed TCO reduction estimated by Basma and Rodríguez [69], hydrogen fuel cell trucks do not achieve TCO parity with diesel until close to 2040, and marginally less optimistic assumptions would push the point at which parity is achieved to beyond 2040. Until parity is achieved, hydrogen trucks will either require subsidy or increased freight service prices to provide an acceptable return on capital. The current UK political and economic climate suggests that large scale subsidies are unlikely. There is also currently very little evidence that freight customers are willing to accept substantially higher freight prices for low carbon transport. While it cannot be ruled out based on the evidence reviewed that this condition could be met within the lifespan of trucks bought today, we consider this unlikely. On this basis, the condition is assessed as RED.

3.1.4. B2: Vehicle capabilities allow operators to meet shipper requirements – GREEN

Road freight customers expect both speed and flexibility in service delivery. Operators' ability to meet these requirements are determined by the operational capabilities of vehicles including range, payload and refueling time. This must equal or exceed the service delivery capability of diesel vehicles, or customer service requirements must adjust to accommodate reduced capabilities. Based on this, we propose that a "what would need to be true" requirement for this condition is:

> Vehicle range, payload and fueling time are comparable to or better than diesel vehicles, or customer requirements adjust to compensate.

The ability of hydrogen trucks to match the range, payload and refueling times of diesel trucks provides one of the strongest techno-economic arguments for hydrogen, as little or no adjustment to customer requirements is needed if a minimum necessary hydrogen fueling network is available. Compressed hydrogen powered trucks can achieve a 250–350 mile range [12] and can be fueled in a similar time to diesel vehicles. Liquid hydrogen trucks can achieve a c.750-mile range although, as noted in section 1, the liquefaction process and liquid hydrogen storage incur substantial additional energy losses. Nevertheless, based on operational vehicle capabilities, this condition is assessed as GREEN.

3.1.5. B3: Emission increases from vehicle manufacture do not outweigh energy emission reductions – GREEN

Manufacturing vehicles generates carbon emissions. This means that when comparing new technology vehicles with diesel trucks, lifetime carbon emissions for the vehicle should include emissions from vehicle manufacture. Based on this, we propose that a "what would need to be true" requirement for this condition is:

> Any increase in the embedded carbon cost of vehicles is more than offset by carbon reductions from energy consumption over the lifespan of the vehicle.

O'Connell et al. [58] estimate that the carbon emitted when producing a diesel truck is less than 5 % of the carbon released from the production and consumption of fuel by the vehicle during its lifetime. While they find that the manufacture of a hydrogen fuel cell truck may result in c.30 % more carbon emissions than the manufacture of a diesel vehicle, this increase is small in absolute terms compared to the impact of emissions from fuel. As result, this condition is assessed to be GREEN.

3.1.6. C1: Emissions from infrastructure build do not outweigh net energy and vehicle emission reductions – AMBER

The building of new infrastructure generates a large amount of carbon emissions, particularly if this requires large quantities of cement, concrete or steel. Cement, concrete, iron and steel together account for over 15 % of global carbon emissions [82,83]. As a result, Marsden et al. [59] argue that infrastructure must be taken into account in transport projects. Based on this, we propose that a "what would need to be true" requirement for this condition is:

> The embedded carbon cost of infrastructure is substantially lower than net carbon reductions from vehicle production and energy consumption over the lifespan of the infrastructure.

No estimate of the total carbon emissions from building hydrogen production, distribution and fueling infrastructure has been found. However, research suggests that large scale geographic storage facilities will be needed [47]. In addition, a pipe distribution network is likely to be required as transporting gaseous hydrogen in trailers over long distances is costly and raises practical challenges due to the large volume of gas required [84]. The storage and transport of liquid hydrogen raises different challenges due to the very low temperatures that need to be maintained [85]. The construction of this infrastructure will result in large carbon emissions, but the inability to quantify this based on available information means this condition is assessed as AMBER.

3.1.7. D1: Energy, infrastructure and vehicle timelines can be aligned – RED

Operators will only buy hydrogen vehicles if they are confident that sufficient vehicles, hydrogen supply and distribution/fueling infrastructure are available. Conversely, energy providers, infrastructure providers and vehicle manufacturers will only build required delivery capacity when they believe that the demand from operators will be there. This means that, in addition to fulfilling the other requirements in this list, energy, infrastructure and vehicle timelines need to be aligned. This alignment will need to happen in phases when existing diesel vehicles are due for replacement. Based on this, we propose that a "what would need to be true" requirement for this condition is:

> Energy supply, infrastructure and vehicles can be progressively made available to align with vehicle replacement cycles.

To meet this requirement, energy, infrastructure, and vehicle suppliers need to plan and invest ahead of demand, so that required energy, infrastructure and vehicle capacity is available as demand materializes. This will require well-coordinated industrial planning, and a demand forecast in which providers are confident. Hydrogen investments are currently focused on trials in the UK and other countries [86,87] and, to our knowledge, no large-scale implementation and roll out plans are currently in place. While it is possible such plans could be established within the lifecycle of vehicles being bought today, this is uncertain. If plans were established, the subsequent construction of required hydrogen production, distribution and fueling infrastructure would require multiple coordinated projects, each of which represents a major investment over a multi-year timeframe. As a result, we consider it unlikely that alignment between energy, infrastructure and vehicle timeframes will happen within the lifespan of vehicles being bought today, and assess this condition as RED.

3.1.8. D2: The risk of backtracking is minimized – RED

Edmondson et al. [63] make a strong theoretical argument that negative policy mix feedback undermines the achievement of policy outcomes. A real-world demonstration of this is provided by backtracking on decarbonization goals when these run contrary to political or economic objectives [88,89]. If hydrogen production cost can be reduced by relaxing carbon reductions, ongoing robust regulation and monitoring is required to protect against emissions backtracking. However, there will also be a political incentive to relax regulations, as countries with more relaxed controls will have an economic competitive advantage over those with more stringent ones. Based on this, we propose that a "what would need to be true" requirement for this condition is:

> There is not an easy path and clear incentives to backtrack on emissions reduction.
>
> Considering each potential source of low carbon hydrogen:

- Green hydrogen requires low carbon electricity from renewable or nuclear sources for the electrolysis of water. If fossil fuel demand reduces, market economics suggests that fossil fuel prices will also reduce unless measures are taken to substantially reduce fossil fuel supply. Governments and oil companies have so far shown little sign of doing this and fossil fuels continue to be extracted at record rates [90,91]. If electricity produced from fossil fuels becomes cheaper than low carbon electricity, there will be an economic incentive for hydrogen producers to use this rather than low carbon electricity to produce hydrogen.
- Blue hydrogen produced from methane with CCS may or may not be cheaper than green hydrogen, but it will always be more expensive than grey hydrogen produced without CCS. It also only achieves 60–85 % CO_2 capture, with energy losses increasing with the

percentage of CO_2 captured [46]. There will therefore be an ongoing incentive for energy producers to relax CCS requirements for carbon capture.

- Producers of by-product hydrogen will, like green-hydrogen producers, have an economic incentive to use the cheapest source of electricity available, which may be from fossil fuels if fossil fuel supply is not restricted.
- If white hydrogen meets more optimistic predictions, it could be a "game changer" for energy production [92]. In this case, if it was also as inexpensive as these predictions suggest it could be, there would be little chance of backtracking. However, its exploitation is at a very early stage and there are many uncertainties regarding its extraction and distribution [93–95].

Overall, we suggest that fulfillment of this requirement would be only achieved if:

- Plentiful low-cost white hydrogen can be practically extracted and transported to where it is required; and/or
- Fossil fuel supply is substantially reduced.

If either one of these statements does not become true, substantial cost incentives will remain to backtrack on carbon reduction. Given white hydrogen is early in the exploration cycle, we believe the first statement is unlikely to be true within the lifespan of trucks bought today. As discussed above, there is also no evidence of governments and oil companies acting to substantially reduce fossil fuel supply. We therefore assess this condition as RED.

3.1.9. *E1: The technology provides energy and freight transport security – AMBER*

Freight transport security depends on factors independent of the vehicle technology including the attractiveness of the industry to drivers and the regulatory environment that influences whether operators can generate a profit [65]. Vehicle technology could also have an impact on the ability of operators to generate a profit via the other requirements considered in this assessment, but to avoid duplication, these arguments are not repeated here.

However, another important political requirement is the maintenance of energy security. Many countries are seeking to increase energy security in the face of geopolitical risks [64,96]. Any new vehicle technology that increases reliance on scarce or uncertain energy sources, or on energy provided by countries considered unfriendly, is likely to be politically unattractive. Based on this, we propose that a "what would need to be true" requirement for this condition is:

> Dependence on unsure energy sources is not increased.

The extent to which hydrogen would increase dependence on unsure sources depends on how the hydrogen is produced. Green hydrogen produced from electricity generated by local renewable sources potentially increases energy security [97]. On the other hand, blue hydrogen is produced from natural gas and, at the time of writing, countries supporting Ukraine that import natural gas from Russia are likely to wish to reduce rather than increase their natural gas consumption [96]. White hydrogen could increase or reduce energy security depending on the relationship with countries with exploitable naturally occurring hydrogen reserves. By-product hydrogen could reduce dependence on unsure sources if nationally produced green energy is used for its production. Given the multiple factors determining whether dependence on unsure energy sources would increase, reduce or remain unchanged, this condition is assessed as AMBER.

3.1.10. *E2: The solution aligns with economic and strategic interests of actors required for its delivery – GREEN*

Within a liberal market economy, companies will only invest in a given transition path if it is in their economic and strategic interest to do so [98]. A principal determinant of this for private sector companies is if a viable business case exists. Based on this, we propose that a "what would need to be true" requirement for this condition is:

> Viable business cases exist for energy, infrastructure and vehicle providers.

It is possible that, if existing energy companies are more prepared to invest in a hydrogen transition that leverages established fossil-fuel assets, this could reduce dependency on public funding. There is substantial interest and R&D investment from both established and new entrant energy companies, energy suppliers and vehicle manufacturers to develop and promote a hydrogen transition [99,100]. This suggests that these companies see viable business cases and strategic potential for hydrogen in general and for hydrogen road freight as part of this. For this reason, this requirement is assessed as GREEN.

3.2. *Summary findings*

Table 3 summarizes the assessments from sections 3.1. The overall finding is that it is very unlikely that all requirements for hydrogen to be a feasible energy source for general-purpose long-haul road freight will be met within the lifespan of vehicles that are bought today. Over a longer-term horizon, "learning by doing" may result in technological developments that would increase the likelihood of the conditions being met. However, the high energy losses of hydrogen are a result of the physics of the required energy conversions, and it is hard to see how these will be resolved even in the long term.

3.3. *Implications for policy and practice*

3.3.1. *Vehicle purchasers*

If vehicle purchasers' views align with the above assessment, it means that hydrogen can be removed as a consideration for current new vehicle purchases for general-purpose long-haul freight, as the operational competitiveness and resale value of vehicles purchased today are very unlikely be undermined by hydrogen vehicles within their lifespan. This means decarbonization effort should focus on other potential solutions at this time, recognizing that these also need to fulfil the feasibility conditions in Table 1.

As hydrogen technology develops, it may reach a point where assessments against the above conditions become predominantly green. Should this occur, operators should at that point assess new purchase decisions on this basis. It is also possible that, while hydrogen may not be suitable for general-purpose long-haul freight, it is suitable for specific freight applications with dedicated vehicles. An assessment for such applications could be made against the above conditions on a case-by-case basis to determine if hydrogen should be considered.

3.3.2. *Energy and infrastructure providers*

While energy and infrastructure providers need to consider demand through the whole infrastructure lifespan, they will also not wish to build large-scale assets a long time in advance of demand. If providers agree with the above assessment, they may choose to defer major investments in building hydrogen infrastructure until there is a greater probability of the above conditions being met and demand as a result being present for that infrastructure.

In the meantime, energy and infrastructure providers have a critical role to play in developing and testing hydrogen production, storage and distribution solutions, as proving these is necessary if the assessments in Table 3 are to become green.

3.3.3. *Vehicle manufacturers*

Vehicle manufacturers have made great strides in developing hydrogen, battery electric, ERS and biofuel trucks. This work is essential for creating the foundation for road freight decarbonization. As discussed above, hydrogen fuel cells remain expensive and challenging to

Table 3
Assessment summary.

Condition	Needs to be true within lifespan of vehicles bought today	Assessment
Techno-economic - Energy		
A1 Projected energy supply capacity satisfies projected demand at acceptable per-unit cost	• A sufficient supply of low carbon hydrogen that is substantially cheaper than green hydrogen produced via current methods is secured.	RED
A2 Total "well-to-wheel" emissions of carbon, other greenhouse gases (GHGs) and non-GHG pollutants are a substantial reduction compared to diesel	• It is confirmed that hydrogen leakage can be contained to a level at which its negative climate effects do not substantially offset benefits from carbon emission reduction. • Blue or white hydrogen are proven to offer substantial well-to-wheel carbon equivalent emissions reductions compared to diesel if these are to be used as alternatives to green hydrogen.	AMBER
Techno-economic - Vehicles		
B1 An acceptable return on capital on vehicles can be achieved	• Any increases in vehicle total cost of ownership/operation are compensated by increased freight service prices and/or subsidies.	RED
B2 Vehicle capabilities allow operators to meet customer requirements	• Vehicle range, payload and fueling time are comparable to or better than diesel vehicles, or customer requirements adjust to compensate.	GREEN
B3 Emission increases from vehicle manufacture do not outweigh energy emission reductions	• Any increase in the embedded carbon cost of vehicles is more than offset by carbon reductions from energy consumption over the lifespan of the vehicle.	GREEN
Techno-economic - Infrastructure		
C1 Emissions from infrastructure build do not outweigh net energy and vehicle emission reductions	• The embedded carbon cost of infrastructure is substantially lower than net carbon reductions from vehicle production and energy consumption over the lifespan of the infrastructure.	AMBER
Socio-technical		
D1 Energy, infrastructure and vehicle timelines can be aligned	• Hydrogen supply, infrastructure and vehicles can be progressively deployed to provide a feasible transition path for operators, vehicle manufacturers and infrastructure providers.	RED
D2 The risk of backtracking is minimized	• There is not an easy path and clear incentives to backtrack on emissions reduction.	RED
Political		
E1 The solution provides energy and freight transport security	• Dependence on unsure energy sources is not increased.	AMBER
E2 The solution aligns with economic and strategic interests of actors required for its implementation	• Viable business cases exist for energy, infrastructure and vehicle providers.	GREEN

manufacture and have unresolved reliability issues, so some manufacturers are focusing instead on hydrogen ICE vehicles. If vehicle manufacturers apply a similar assessment approach to the one used in this study for each of the vehicle technologies they are exploring, this may help them prioritize R&D investment and strategic planning.

3.3.4. Policymakers

Should policymakers agree with the above assessment, hydrogen development focus should be on supporting research and development, running pilots and potentially deploying hydrogen for specific use-cases where the feasibility conditions in Table 1 can be met. The focus for general-purpose long-haul freight should instead be on low carbon solutions that can be deployed in a shorter timeframe such as battery electric and biofuels, where these solutions fulfil feasibility conditions. As with vehicle purchasers, energy/infrastructure providers and vehicle manufacturers, a longer-term consideration of hydrogen can also be maintained provided this does not inhibit the shorter-term deployment of other energy source options.

A further implication for policymakers is that, in all decarbonization scenarios that reduce the use of fossil fuels, if fossil fuel supply is not reduced, simple market economics means that the resulting reduction in fossil fuel prices will create strong economic incentives to backtrack on emission reductions unless these are counteracted by increasingly large taxes on fossil fuels or subsidies on green alternatives: *"Even if countries were to enact policies that raised the cost of fossil fuels, like a carbon tax or a cap-and-trade system for carbon emissions, history suggests that technology will work in the opposite direction by reducing the costs of extracting fossil fuels and shifting their supply curves out"* [101, p.126]. For this reason, we propose that a critical role of policymakers is to create regulations that result in the reduction of fossil fuel supply.

3.3.5. Hydrogen system developers and investors

There are many established and start-up companies committed to the establishment of a hydrogen energy system to replace the direct use of fossil fuels in transport, building heating and various industrial processes. Hydrogen can be produced from fossil fuel sources and, as a gas, it shares some of the physical storage and distribution characteristics of natural gas. It therefore provides a transition path that better leverages established energy system capabilities and avoids early retirement of existing infrastructure and assets to a greater degree than an electricity-based transition. For many stakeholders, this is both economically and politically attractive.

This study specifically assesses the likelihood of hydrogen becoming feasible for general-purpose long-haul road freight in the UK within the lifespan of a vehicle bought today. It does not comment on the feasibility of hydrogen for other applications, over a longer timeframe, or in other regions. On this basis, we would recommend to hydrogen system developers and investors seeking to make the case for hydrogen that they: 1) adopt a realist retroductive approach to assess and prioritize other potential hydrogen applications; and 2) focus R&D effort for long-haul road freight in the UK on establishing if the conditions assessed as red or amber in this study could be turned green in the medium to long term.

4. Assessment of other energy source options

4.1. Overview

The central goal of this study is to assess the feasibility of hydrogen as potentially the most uncertain of the energy source options for long-haul road freight currently under widespread consideration. If vehicle purchasers agree with the finding from section 3 that hydrogen is very unlikely to be feasible within the lifespan of a vehicle bought today, this simplifies their energy source selection decision for the reasons described in section 3.3.1.

However, having conducted a realist retroductive assessment of hydrogen for this application, it is natural to ask how other low carbon vehicle options would fare if assessed using the same approach. Table 4 summarizes an assessment of the principal low carbon energy source alternatives to hydrogen for long-haul road freight. The basis of this assessment is presented in section 4.2.

4.2. Basis of assessment for other energy source options

This section provides the basis of the assessments of other energy source options presented in Table 4. In all cases apart from requirements A1 and A2, the same "what would need to be true" requirements as those

Table 4
Assessment of low carbon alternatives to hydrogen for long-haul road freight.

Condition	Hydrogen (from Table 3)	Battery electric	Electric Road System (ERS)	Biomethane	Hydrogenated Vegetable Oil (HVO)
Techno-economic - Energy					
A1 Projected energy supply capacity satisfies projected demand at acceptable per-unit cost	RED	AMBER	AMBER	AMBER	AMBER
A2 Total "well-to-wheel" emissions of carbon, other greenhouse gases (GHGs) and non-GHG pollutants are a substantial reduction compared to diesel	AMBER	AMBER	AMBER	AMBER	AMBER
Techno-economic - Vehicles					
B1 An acceptable return on capital on vehicles can be achieved	RED	AMBER	AMBER	AMBER	AMBER
B2 Vehicle capabilities allow operators to meet customer requirements	GREEN	AMBER	AMBER	GREEN	GREEN
B3 Emission increases from vehicle manufacture do not outweigh energy emission reductions	GREEN	GREEN	GREEN	GREEN	GREEN
Techno-economic - Infrastructure					
C1 Emissions from infrastructure build do not outweigh net energy and vehicle emission reductions	AMBER	AMBER	AMBER	GREEN	GREEN
Socio-technical					
D1 Energy, infrastructure and vehicle timelines can be aligned	RED	AMBER	AMBER	GREEN	GREEN
D2 The risk of backtracking is minimized	RED	AMBER	GREEN	AMBER	AMBER
Political					
E1 The solution provides energy and freight transport security	AMBER	GREEN	AMBER	AMBER	AMBER
E2 The solution aligns with economic and strategic interests of actors required for its implementation	GREEN	GREEN	AMBER	AMBER	AMBER

used for the assessment of hydrogen in section 3 are applied. For A1 and A2, the condition statements in Table 4 are used directly as what would need to be true requirements.

4.2.1. A1: Projected energy supply capacity satisfies projected demand at acceptable per-unit cost

4.2.1.1. Battery electric and ERS. Milence, a joint venture between Dailmer Truck, TRATON and Volvo, is planning to implement a network of truck charging points across the EU. They identify sufficient grid capacity and timely grid connections as two issues demanding urgent political attention [102]. These are also identified as critical issues for battery electric truck roll out in the UK [103]. Gaete-Morales et al. [104] confirm the substantial energy sector implications for battery electric and ERS truck deployment, although they note that, even if deployment is sub-optimal, the implications are less than for hydrogen and e-fuels. AMBER.

4.2.1.2. Biomethane and HVO. RAC Foundation [105] highlights the higher cost of biodiesel compared to fossil fuels in the UK. Biomethane is also higher cost than natural gas, although the price differential is projected to reduce over time [106]. Policies have been put in place to incentivize increased biofuel production in the EU and UK [107,108]. In 2023 in the UK, 0.8 % of arable crop land was used to produce 153 million liters of biofuel for transport [109]. However, total truck and van fuel consumption in the UK was 14 billion liters in 2023 [110]. This means 73 % of total UK arable land would be required to produce enough biofuels to meet all UK truck and van demand, which is evidently infeasible. In addition, there will be a competing demand for biofuels from sectors such as aviation for which electrification is not a feasible option. AMBER.

4.2.2. A2: Total "well-to-wheel" emissions of carbon, other greenhouse gases (GHGs) and non-GHG pollutants are a substantial reduction compared to diesel

4.2.2.1. Battery electric and ERS. While battery electric and ERS are highly efficient on a well-to-wheel basis, greenhouse gas (GHG) emissions are determined by how the source electricity is generated. If the electricity is generated from fully renewable sources, GHG emissions are low. However, in a carbon intensive energy system, GHG emissions could be as high or higher than for diesel trucks [111]. AMBER.

4.2.2.2. Biomethane and HVO. If biofuels are produced from sustainable sources, well-to-wheel emissions can be 78 % less than for diesel trucks [112]. However, there are concerns regarding the certification of fuel sources, particularly if fuel is imported from third countries [113]. In addition, there can be adverse environmental consequences if the growth of biofuel reduces biodiversity or changes the capacity of land to act as a carbon sink [114]. AMBER.

4.2.3. B1: An acceptable return on capital on vehicles can be achieved

4.2.3.1. Battery electric and ERS. In addition to the cost of energy considered in condition A1, return on capital is determined by the capital cost of vehicles, non-energy operating costs, and the revenue that can be earned from the vehicle. Electricity costs can be substantially lower than diesel or petrol per 100 km driven [69]. However, the capital cost of battery electric vehicles are currently substantially higher than diesel trucks [69]. While the capital cost of an ERS truck is lower than a battery electric truck due to the smaller battery size, this will be offset by ERS usage charges [2,25]. The revenue impact for a battery electric truck will be determined by the payload reduction due to weight and size of the battery, and the extent to which the time spent charging reduces vehicle and driver utilization and operational flexibility. The revenue impact for an ERS truck will depend on the coverage of the ERS network and the ability that this provides to operate with the same flexibility as a diesel truck. AMBER.

4.2.3.2. Biomethane and HVO. The cost of biofuel is typically higher than for fossil fuels. The impact of this will depend on subsidies and other regulatory incentives to use biofuels. The capital and operating cost of trucks running on biofuels is comparable to trucks running on diesel or natural gas [69,112]. AMBER.

4.2.4. B2: Vehicle capabilities allow operators to meet customer requirements

4.2.4.1. Battery electric. Truck manufacturers provide a range of battery configuration options that represent a tradeoff of vehicle cost and payload loss due to vehicle size and weight versus range [115]. In addition, battery electric truck operating cycles need to accommodate charging times. The extent to which the latter affects the ability to meet customer requirements depends on the opportunity to align charging to times when the vehicle would be stationary for other reasons, such as loading and unloading, and driver rest breaks. AMBER.

4.2.4.2. ERS. The ability of ERS trucks to meet customer requirements is dependent on the coverage of the road system provided by the ERS and the distance of loading and delivery locations from the ERS network [25]. There is also a tradeoff between the size of battery required in the ERS truck and the coverage the network [116]. AMBER.

4.2.4.3. Biomethane and HVO. Biomethane and HVO can be used interchangeably with natural gas and diesel respectively, meaning that they have comparable range and fueling times [117,118]. It also means that the fossil fuel alternatives can be used as a backup if biofuel is not available. GREEN.

4.2.5. B3: Emission increases from vehicle manufacture do not outweigh energy emission reductions

4.2.5.1. All energy sources. Although energy consumption and emissions from vehicle manufacture vary according to vehicle energy source, in all cases this is a small percentage of total lifetime energy consumption and emissions, which for long-haul trucks is dominated by fuel consumed in vehicle operation [59]. GREEN.

4.2.6. C1: Emissions from infrastructure build do not outweigh net energy and vehicle emission reductions

4.2.6.1. Battery electric and ERS. The required development of electricity generation and distribution capacity, including high power charging for battery electric and electric road infrastructure for ERS, represents a large infrastructure build requirement [10,119]. However, no estimate was found in peer reviewed or grey literature of the emissions associated with this. Steel and cement production is energy and carbon intensive [120]. The scale of emissions will in part be influenced by the success of efforts to mitigate emissions from steel and cement production. AMBER.

4.2.6.2. Biomethane and HVO. As biomethane and HVO are interchangeable with natural gas and diesel, they can use existing fossil fuel distribution infrastructure [117,118]. GREEN.

4.2.7. D1: Energy, infrastructure and vehicle timelines can be aligned

4.2.7.1. Battery electric. Milence is planning to roll out truck charging infrastructure in the EU [121]. The UK government is also supporting the roll out of truck charging as part of the Zero Emission HGV and Infrastructure Demonstrator (ZEHID) Programme [122]. However, the rate of public charging deployment is uncertain, and this may limit the adoption of battery electric trucks for applications where depot charging is not sufficient [123]. AMBER.

4.2.7.2. ERS. Unlike battery electric, ERS requires the deployment of a minimum viable network before a single ERS truck can be deployed [25, 116]. This means that the requirement for upfront infrastructure investment and the corresponding financial risk are higher. It seems unlikely that private sector actors would undertake this risk without some form of government guarantee or risk sharing. AMBER.

4.2.7.3. Biomethane and HVO. As biofuels can use the same infrastructure as their fossil-fuel equivalents [117,118] and vehicles are either standard diesel (HVO) or modified petrol (biomethane) trucks, aligning energy, infrastructure and vehicle timelines should be comparatively straightforward. GREEN.

4.2.8. D2: The risk of backtracking is minimized

4.2.8.1. Battery electric. No peer reviewed or grey literature has been identified for this condition. Speculatively for battery electric, the risk of backtracking will be low once operators have invested in battery electric trucks and operations have been aligned to the capabilities of these, provide electricity continues to be significantly cheaper than diesel per 100 km travelled. However, this could change if a reduction in fossil fuel demand leads to a substantial reduction in fossil fuel cost and/or taxation differentials on electricity versus fossil fuels is insufficient maintain the cost advantage of electricity. AMBER.

4.2.8.2. ERS. Again, no literature was identified that considers the risk of backtracking once an ERS system has been established. Speculatively, the biggest barrier to ERS deployment is the infrastructure build. Once this is in place, it seems likely that government and/or infrastructure providers would set usage charges at a level that would incentivize operators to use it. GREEN.

4.2.8.3. Biomethane and HVO. As biomethane and HVO are interchangeable with their fossil fuel equivalents, it seems likely that their ongoing use will be directly influenced by biofuel cost and availability versus fossil fuels. Regulation and taxation will therefore need to be maintained by government to ensure that there continues to be an incentive for the ongoing supply and usage of biofuels. AMBER.

4.2.9. E1: The solution provides energy and freight transport security

4.2.9.1. Battery electric. Once again, no literature was identified that considers the question of energy and freight security in relation to the adoption of battery electric road freight. However, once sufficient electricity distribution capacity is in place, there is flexibility in the electricity supply mix that feeds this. It seems reasonable to assume that this could provide a higher degree of energy and freight security than the current high dependence on diesel supply, which is vulnerable to geopolitical factors, and market volatility and manipulation. GREEN.

4.2.9.2. ERS. Similar to battery electric, the fact that the there are multiple options for supplying the electricity to an ERS might suggest that an ERS could provide greater energy security. However, there are some additional questions regarding the technical reliability of ERS systems, which vary according to the ERS technology adopted [124]. Speculatively, ERS may also be more vulnerable to deliberate or accidental damage, although no research was found that considers this specific vulnerability aspect. AMBER.

4.2.9.3. Biomethane and HVO. As discussed above for requirement A1, there is insufficient arable land available to produce the quantity of biofuel that would be necessary to meet the energy needs of a large proportion of road freight in addition to continuing to meet food supply and other requirements [109,110]. As biofuels can therefore only be a partial solution, the extent to which they affect energy and freight security is likely to be marginal. AMBER.

4.2.10. E2: The solution aligns with economic and strategic interests of actors required for its implementation

4.2.10.1. Battery electric. Battery electric trucks covering a full range of vehicle categories are now available from manufacturers [125,126]. In addition, vehicle manufacturers and energy infrastructure providers are actively engaged in the deployment of charging infrastructure [121, 127]. In the UK, the government is supporting the deployment of an initial charging network as part of the Zero Emission HGV and Infrastructure Demonstrator (ZEHID) program [122]. Based on this there is judged to be good support from critical actors for the deployment of battery electric for road freight. GREEN.

4.2.10.2. ERS. The large upfront infrastructure investment required before a single ERS vehicle can be deployed represents a financial risk that would most likely need to be underwritten by government [128]. The willingness of the UK and other governments to do this remains uncertain. AMBER.

4.2.10.3. Biomethane and HVO. The higher price of biofuels compared to their fossil fuel equivalents is likely to mean that financial and/or regulatory incentives will be required to incentivize their uptake [129,130]. In the UK, the Renewable Transport Fuel Obligation, the principal regulation to incentivize the uptake of biofuels in transport is, at the time of writing, under review [131]. AMBER.

4.3. Implications for policy and practice

The first observation on this assessment is that, for all options excluding hydrogen, none of the conditions are assessed as red. However, more than half of the conditions are assessed as amber for each option. In addition to dependencies on specific operational requirements, this reflects uncertainty in future capital and operating costs; and in the ability to execute the necessary coordinated deployment of energy supply infrastructure. A key policy-making goal should therefore be to reduce these uncertainties to the extent possible.

It is once again important to note that, as for the assessment of hydrogen in section 3, the conditions assessed for other energy sources are necessary but not exhaustive. For example, the environmental and human health impacts of battery production and materials mining [132] and the environmental sustainability of biofuel production [133,134] are not considered. This means that the assessment cannot be used to definitively rule a given energy source in. However, the absence of red assessments against the criteria also means that, unlike for hydrogen within the lifespan of a vehicle bought today, none of these energy sources can be ruled out.

ERS offers the best energy efficiency of all options, addresses the range limitations of battery electric and would substantially reduce the size of batteries requires in vehicles, and thereby address the cost and payload penalties of large batteries [116]. However, it requires a phased roll out of major infrastructure, the financial risk of which would almost certainly need to be underwritten by government [135]. This requirement, together with potential public resistance to the building large scale ERS infrastructure [136], may present a barrier to ERS implementation in the UK and other countries. However, in any region where there is a credible government commitment to build an ERS that covers a vehicle's operating cycle, this will become the clear first choice for vehicles once that ERS is available.

If ERS is not an available option, the next consideration is whether a battery electric vehicle can work operationally and economically. Where this is the case, this should be the next first choice for operators. There is the possibility of a more gradual roll out path for battery electric than for ERS, and the feasibility of battery electric for individual freight operations can be assessed on a case-by-case basis. Back-to-base operations where vehicles are not in use for a full 24-h period provide clear "low hanging fruit" opportunities for battery electric deployment, followed by operations with defined sources and destinations where destination charging is an option. Further adoption of battery electric is dependent on 1) the deployment of a sufficient number of "megawatt" chargers at locations that allow charging and driver rest breaks to be coordinated; or 2) swappable battery solutions.

For any freight operation for which there is not a feasible ERS or battery electric option, biofuels should be considered as an interim solution. Supply limitations and environmental impacts mean that biofuels cannot be the long-term answer for all road freight, but they provide a short-term opportunity to reduce emissions for a proportion of freight while ERS and/or battery charging networks are being deployed.

5. Conclusions

5.1. Main findings

The principal finding from this assessment is that, based on the evidence identified, hydrogen can be ruled out as a purchase consideration for current purchasers of general-purpose long-haul road freight vehicles. This is because, not only is it not a feasible solution now, it is very unlikely to become feasible within the lifespan of a vehicle using a different energy source purchased today, meaning hydrogen will not undermine that vehicle's competitiveness or resale value. The main reasons for this are:

- the current high cost and restricted supply of hydrogen, and early development stage of low carbon hydrogen production and distribution;
- the large energy losses due to the physics of the energy conversions required to produce low carbon hydrogen, and to then convert this to motive power in the vehicle;
- the large capital costs that further contribute to the total cost of ownership of hydrogen vehicles and the several favorable assumptions that are required for these to reduce to a level that would support an acceptable return on investment;
- the high degree of industrial coordination that would be required to align hydrogen energy, infrastructure and vehicle timelines, and the time it would take to execute a plan that would deliver this; and
- the high and ongoing risk of emissions backtracking that would exist if hydrogen was adopted as a vehicle energy source.

An assessment of other energy source options concludes that, while no option currently meets the needs of all general-purpose long-haul freight, there are circumstances where each could be feasible. This means that these options should be considered by vehicle purchasers where feasibility conditions can be met today. Where they are not feasible today, operators, energy and infrastructure providers, vehicle manufacturers and policymakers should collaborate to determine the actions required to address feasibility barriers.

5.2. Contribution to research

The study makes two original research contributions. The first is specific findings regarding the feasibility of hydrogen and other energy source options for general-purpose long-haul road freight in the UK. While studies on the feasibility of hydrogen for road freight exist, e.g. Refs. [1,2,60,47], no other identified studies have considered feasibility conditions spanning techno-economic, socio-technical and political transition dimensions. Furthermore, the assessment of whether conditions will be met within the lifespan of vehicles bought today is, to our knowledge, novel and provides a focus on current transition choices rather than on how technology may evolve over a longer time horizon, which is even more uncertain and of limited relevance to current vehicle purchase decisions.

The second contribution is the application of a realist retroductive assessment approach to identify "what would need to be true" conditions for a defined transition option to be feasible; and to assess the likelihood of these conditions being fulfilled within a defined timeframe. While the application of retroductive methods exists in research, e.g. Refs. [137,138,139], this is principally within ontologically relativist or constructionist rather than realist research. Mukumbang et al. [140]

identify that its use in realist studies remains “minimal and inadequate”. This study applied realist retroductive assessment to the feasibility of hydrogen and other energy sources for general-purpose long-haul road freight drawing on secondary research data. However, the realist retroductive assessment approach would be equally applicable for studies considering:

- Other complex system transitions
- Other transition choices and options
- Other time horizons
- Primary data

Given the inherent uncertainties and conflicting vested interests associated with complex system transitions, we believe that the realist retroductive approach can provide a more practically helpful approach than either deductive or inductive methods for actors seeking to make system-level transition choices.

5.3. Study limitations

The debate regarding the feasibility of hydrogen is highly polarized and politically charged. While we argue that this assessment is logically founded, objective and evidence-based, others making the same claim may reach different conclusions. Primary research engaging a cross section of transition stakeholders would be valuable. In gaining this input, we propose that the retroductive “what needs to be true” approach is helpful in engaging with the widely differing viewpoints and in separating objective assessment from subjective opinions and vested interests.

This paper has focused on requirements for energy source options to be feasible decarbonization solutions for general-purpose long-haul road freight in the UK, assuming that the current economic and political order is not radically altered. A subjective argument that is used against the adoption of hydrogen is that it is a means for the oil and gas industry, which is argued to be either a principal culprit for or willing enabler of the climate crisis, to remain relevant and that this industry cannot be trusted to act in the interests of sustainability [141]. A broader argument still is that all approaches that rely on large scale deployment of technology and engineered solutions or require top-down “technocratic” governance processes will lead humanity further down the path of unsustainability [142]. A further deconstructionist argument is that it is ultimately global capitalism and consumerism that are responsible for the climate crisis, and that any approach that does not renounce these will never achieve decarbonization goals [143]. While we are sympathetic to these arguments, this analysis has not considered these, partly because their subjectivity means they do not fit well into the realist framing of this assessment. Moreover, it is our view that if radical deconstruction of the political and economic order is necessary for decarbonization, in the absence of a catastrophic scenario that would itself bring extreme human suffering, this will not be achieved within the timeframes required to materially mitigate climate change. We understand however that others may hold a different view.

We believe that the ten conditions identified in section 2 are applicable irrespective of region or economic environment. However, the assessments against these conditions have focused on general-purpose long-haul road freight in the UK. This means that the assessment may differ for other regions. The UK characteristics that we are conscious of that have influenced the assessment are a liberal market economy in which private sector actors make their own operational and investment choices; insufficient public funds or political will to support extensive long-term subsidies to vehicle purchasers and infrastructure providers; and the lack of a low-cost, abundant and environmentally sustainable white hydrogen supply.

5.4. Opportunities for future research

There are substantial opportunities for further research stemming from each of the two contributions described in Section 5.2:

5.4.1. Assessment of road freight decarbonization options

While energy supply selection is a rather tangible and hotly debated topic, other important transition choices exist for road freight decarbonization related to areas including public and private sector capability development; energy, infrastructure and vehicle supply; funding, incentives and risk sharing; realignment of supply chains; and the prioritization of different road freight segments. All these transition choices could also be assessed using a realist retroductive approach if classical deductive and inductive approaches are found to be lacking in their ability to support actor decision making.

5.4.2. Consideration of road freight decarbonization in other regions

This assessment has focused on general-purpose long-haul road freight in the UK. While we believe that the findings are likely to be similar in other regions that share the characteristics summarized in section 5.3, further work would be required to confirm this.

5.4.3. Wider application of realist retroductive assessment

Beyond road freight decarbonization, the realist retroductive approach can in principle be applied to the assessment of any option for any system transition. It provides the greatest benefit over other assessment approaches when there is a need for decision making clarity on transition choices and feasibility criteria; and at least some feasibility criteria are subject to substantial uncertainty. The benefits over other more widely used approaches are potentially less if there is not a need for such clarity or when there are fewer feasibility criteria that need to be considered and/or these are subject to lower uncertainty.

To apply the realistic retroductive approach, it is necessary to identify a specific transition choice and a specific option to be assessed. It is also helpful to identify the actors who will make the decision, as this enables the “what needs to be true” conditions and assessment timeframe to be defined so that, in addition being relevant to the achievement of transition goals, they are also relevant to the specific decisions that need to be made by these actors. The choice of primary and/or secondary data on which to base the assessment will be influenced by the transition choice and feasibility criteria being assessed; and on the data and resources available to conduct the assessment.

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CRediT authorship contribution statement

P. Churchman: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Project administration. **T. Dekker:** Conceptualization, Methodology, Formal analysis, Writing – review & editing. **K. Pangbourne:** Conceptualization, Methodology, Formal analysis, Writing – review & editing. **V. Sanchez Rodrigues:** Formal analysis, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

APPENDIX A. THEORETICAL BASIS OF REALIST RETRODUCTIVE OPTION ASSESSMENT APPROACH

The ontologically realist assessment presented in this paper adopts a retroductive analysis approach. The significance of adopting a realist ontology is that, unlike relativist ontology, it assumes that reality and truth are independent of context and the individual values, norms and beliefs of humans. We propose that this is a necessary assumption if actors are to codesign system transitions as, to do this, actors need to reach a common view of the system to be transitioned, the choices required, and the options available for these choices.

Retroduction is a methodological alternative to more commonly used deductive and inductive research methods. The "retro" in retroduction implies a form of backcasting in which analysis considers a predefined theory, in this case that a certain energy source option could be feasible; identifies the conditions under which this theory would be true; and assesses the likelihood of these conditions being met [137,144]. Retroduction allows an ontologically realist view of the future to be taken while at the same time recognizing that complex and emergent causal mechanisms of systems are very hard to "prove" deductively using traditional positivist methods [145]. Both qualitative and quantitative approaches can be relevant for retroductive analysis [144,138]. Realist retroductive analysis aligns with the "answer first" approach used by management consultancies to efficiently assess strategic options, which is also known as the "pyramid principle" of problem structuring and communication [146]. The realist retroductive approach is to our knowledge novel for the assessment of sustainability solutions; and Mukumbang et al. [140] specifically identify the use of retroduction in realist studies to be "minimal and inadequate". Retroduction is more widely, although still not extensively, used in ontologically relativist (rather than realist) social science research [137,138,139]. Realist retroduction is a powerful and, we would argue, under-exploited tool for research seeking to inform policy and decision-making in the context of high systemic complexity and uncertainty.

A relevant body of academic work is Decision Making under Deep Uncertainty (DMDU). Under the banner of DMDU, a suite of approaches has been developed to increase the robustness and adaptability of decision-making regarding systems that are subject to high uncertainty [147,148]. Of these, the method that is conceptually closest to realist retroductive option assessment (RROA) is Robust Decision Making (RDM), as this seeks to identify decision options that are valid across a range of contextual and systemic input variable assumptions. However, an important distinction is that, while RDM applies quantitative modelling to identify the range of potential system outcomes that result from adjusting contextual and system variables, RROA applies logical argumentation supported by available quantitative and qualitative evidence.

The hybrid quantitative/qualitative approach adopted by RROA is aligned with the "broad critical scrutiny" advocated by critical realism [145], and contrasts with the principally quantitative approaches typically used for techno-economic analyses. As well as permitting consideration of qualitative evidence in the assessment of techno-economic requirements, it allows socio-technical and political requirements, which are often inherently qualitative in nature and as a result not readily amenable to quantitative analysis, to be evaluated.

Data availability

No data was used for the research described in the article.

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Phil Churchman is a PhD student with the Institute for Transport Studies at the University of Leeds, with a background in senior management and consulting in business strategy, technology and supply chain management. His PhD research focuses on social, political and organizational aspects of road freight decarbonization.

Thijs Dekker is Professor of Transport Economics with the Institute for Transport Studies at the University of Leeds. His research interests are in the areas of transport and environmental economics. Specifically, he uses choice modelling techniques to analyze and derive the welfare implications of changes in transport policy and infrastructure on travel demand.

Kate Pangbourne is Professor of Transport Transitions with the Institute for Transport Studies (ITS) at the University of Leeds. Her research focuses on sustainable travel, persuasive technology, and the implications of socio-technical change at the interface of transport, governance, sustainability and energy demand. She is Governance theme lead for the Energy Demand Research Centre, Deputy Director of the Leeds Social Sciences Institute and co-leads the ITS Social and Political Sciences Research Group.

Vasco Sanchez Rodrigues is Professor of Sustainable Supply Chain Management at Cardiff University with established expertise on NetZero and circular economy in supply chain and logistics contexts. Vasco has published over 50 papers in prime international academic journals and has successfully secured £4 million of external funding. Vasco holds several senior management roles including Chair of the CILT-sponsored Logistics Research Network Forum and Head of Logistics & Operations Management Section at Cardiff.