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Electrification versus hydrogen for UK road freight: Conclusions from a systems analysis of transport energy transitions

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ABSTRACT

Collectively the UK investment in transport decarbonisation is greater than £27B from government for incentivising zero-emission vehicles as part of an urgent response to decarbonise the transport sector. The investments made must facilitate a transition to a long-term solution. The success relies on coordinating and testing the evolution of both the energy and transport systems, this avoids the risk of unforeseen consequences in both systems and therefore de-risks investment Here, we present a semiquantitative energy and transport system analysis for UK road freight focusing on two primary investment areas for nation-wide decarbonisation, namely electrification and hydrogen propulsion. Our study assembles and assesses the potential roadblocks of these energy systems into a concise record and considers the infrastructure in relation to all other components within the energy system. It highlights that for system-wide success and resilience, a hydrogen system must overcome hydrogen production and distribution barriers, whereas an electric system needs to optimise storage solutions and charging facilities. Without cohesive, co-evolving energy networks, the planning and operational modelling of transport decarbonisation may fall short of meaningful real-world results. A developed understanding of the dependencies between the energy and transport systems is a necessary step in the development of meaningful operational transport models that could de-risk investment in both the energy and transport systems.

Introduction

The predominant transport energy vector in the United Kingdom (UK) is liquid fuels for transport (Department for Business, E., & I. S, 2020). Energy demand for heavy-good vehicles (HGVs) was reported as 6 Mtoe (70 TWh) in 2019. The UK government has hastened the transition away from internal combustion engine (ICE), becoming one of the first nations to ban ICE sales by 2030 starting with cars and small vans. This strategy is aligned with their greenhouse gas (GHG) emission reduction targets in accordance with the Paris Agreement (UK Government, 2020). To achieve these decarbonisation goals, the UK government has developed a Whole Systems Policy, which aims to integrate and aggregate the decarbonisation initiatives across critical sectors and energy infrastructure (UK Council for Science and Technology, 2020). Without a coordinated plan, that provides clarity on energy network capacity, adaptive capacity, technology readiness and energy demand forecasts for transport, there is a risk that infrastructure developments will be insufficient, incompatible or underutilised. Therefore, a robust strategy to reach intermediate carbon targets needs to be developed.

The two leading options for a nationwide reduction in GHGs from on-road emissions are electric and hydrogen vehicles for HGVs, both of which must have overall energy systems that are in line with the UK's Ten Point Plan for the Green Industrial Revolution (HM Government, 2020). The preferred solutions and transitions to a net-zero future are disputed, in part due to individual components of the energy system being optimised, rather than considering the entire energy system. Although beneficial, system-wide analyses are lacking in the literature, as it requires deep dives into independent barriers that often involve further assessments to understand how the components can be integrated together to produce an optimum energy system.

Abbreviations: CCS, carbon capture and storage; CESI, National Centre for Energy Systems Integration; CO_2, carbon dioxide; DfT, Department for Transport; eHGV, all-electric heavy-goods vehicles; ERS, electric road system; GHG, greenhouse gas; GJ, gigajoules; GW, gigawatt; H_2, hydrogen; HGV, heavy goods vehicles; HRS, hydrogen refuelling stations; Kg, kilogram; km, kilometre; kWh, kilowatt hour; MW, megawatt; PEM, polymer electrolyte membrane; SMR, steam methane reformation; SRN, Strategic Road Network; TW, terawatt; TWh, terawatt hour; vkm, vehicle kilometre.

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Commissioned by the Department for Transport's Chief Scientific Adviser, the UK Centre for Sustainable Road Freight Centre has worked in conjunction with the Department for Transport London (DfT) and the National Centre for Energy Systems Integration (CESI) to assess the system wide, transport-energy network interdependencies, challenges and opportunities for HGV energy strategies. It was evident that condensing the abundance of information into a concise document would be advantageous to the scientific community, as well as rationalising the interdependences between infrastructure components. This work examined the essential infrastructure in both electric and hydrogen energy systems for long-haul heavy-goods vehicles, diagrammed in Fig. 1. Individual key unknowns and potential barriers that could prevent success of individual components were assessed first. However, the collective value and novelty of this analysis is from assembling the individual factors to give an inclusive overall system assessment. By providing this information, individual advancements can be placed into a larger system view for transitioning to a decarbonised energy system within the transport sector that is currently absent from the literature.

Methods

This analysis extracts pertinent information from primary data using a systematic review process that has been used throughout the literature (Antonopoulos et al., 2020; Wilson et al., 2021). SCOPUS was used as the central database for literature searches and the reporting was guided by the Preferred Reporting Items for Systematic Review and Meta-Analysis Statement (PRISMA) (Page et al., 2021). Table S1 details the SCOPUS results using the PRISMA framework to systematically filter the literature. Primary research was searched, and results were triangulated against similar reports to find commonalities and overlaps to provide a semi-quantitative metric. However, due to both hydrogen and electric HGV energy systems being in their initial stages, most outputs are the results of models, placing a high dependency on the boundary conditions of the work assessed. This prohibits real-world results from being obtained, and places large uncertainties on any quantifiable information that is accessible.

This analysis includes conclusions from numerous literature sources and is individually detailed in the Supporting Information. A variety of resource types were used including academic papers, government reports, industrial and commercial information to gather a consensus, or identify disputed conclusions, on opportunities and challenges within each energy system. Sources from the UK were the focus, but information from the US, Europe and Asia was also incorporated when literature from the UK was not available. Fig. 1 shows the input flow diagram for how these resources were used. Table S2 details the rubric used to assess the literature. The technology analysed included the energy production, distribution, transportation, and dispensing. The boundaries also included technology that has a readiness level of 7, where working systems have been demonstrated. Therefore, boundary conditions of the analysis excludes the societal and macroeconomic implications and focuses on the technological opportunities and challenges as this allows the analysis to be used in a more universal context. A whole-system analysis of the technology provides a foundation for future assessment of both social and economic metrics.

The individual literature sources determine the likelihood that the component will prevent downstream components from succeeding in an energy system. Some resources were used for multiple infrastructure elements, while others focused on one barrier within the infrastructure component. These are detailed in Tables S3–S13. Low barrier areas are denoted with a green chevron, areas with moderate barriers are yellow, and high barriers are red. Areas that have literature concluding mixed risks are symbolized with multicoloured chevrons. There were also areas that do not currently have accessible literature, or in cases where the technology is so new there may not be information publicly available. These evidence gaps and new technology areas are coloured with red and black stripes. The analysis is performed on a semi-quantitative basis as individual assessments of infrastructure components is often evaluated individually rather than on a system-wide basis, thus giving inconsistent boundary conditions between studies, and prohibits a quantitative calculation of all the literature. However, a semi-quantitative result provides valuable insight for a variety of constituents that are interested in system-wide change, as well as companies that need to consider entire energy supply chains, such co-locating energy production with energy generation, storage or use.

The terms used for the barriers are defined in the following way: Technology readiness refers to the developmental stage of the technology, scalability is the ability for the infrastructure component to scale up with large increases in energy demand. Scalability refers to energy flexibility over long timescales and the ease of adding infrastructure that is needed. Geographical barriers refer to how geography influences the component. This would include topographical dependences for energy storage systems (i.e. pumped hydro), putting renewable energy sources in beneficial locations, or how pipelines are fixed in one location, reducing geographical freedom. System dependence refers to how interconnected the component is to other infrastructure components. Consumer acceptance relates to consumer facing infrastructure, which could potentially include more infrastructure elements as the energy system decentralises. Resource requirements refer to the reliance on rare, raw materials. Resilience looks at the ability of the infrastructure mechanism to adjust to changes in energy demand on a shorter time

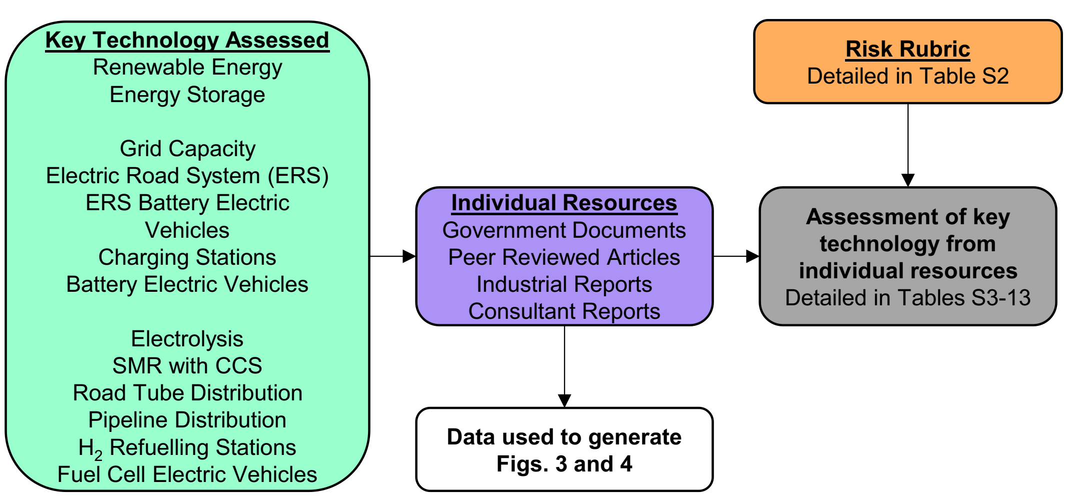

Fig. 1. Flow diagram of how literature resources were used in analysis.

scale than scalability. This mainly pertains to the fluctuation of energy demand on a day-to-day level rather than the increased requirements year over year. The Reduce CO_2 barrier addresses whether the infrastructure component reduces CO_2 levels from current operations with a timescale variable built in. For example, SMR with CCS has an unknown timescale, the ability to reduce CO_2 may not be met at its full potential prior to 2050. It also addresses whether CO_2 is being eliminated or if it is being relocated. Consumer cost is at the end use of the energy. Industrial cost is the capital, operating and maintenance costs. National costs reflect both how much a national investment would be relied upon going forward.

For on-road calculations, it was assumed that electric vehicles consume 1.6–2.17 kWh/km at the wheel (Earl et al., 2018; Tesla, 2017).

Results and discussion

There are limitations to bounding the study to the components in Fig. 2, such as political and international influences, where events such as Brexit and Covid-19 could either bolster or hinder net-zero efforts (European Commission, 2021). Our present analysis, however, focuses on the physical infrastructure required for future energy systems, as it can be applied to infrastructure and energy systems regardless of political situations.

Tables 1 and 2 summarise the restrictions or barriers (horizontal) that may prevent individual components (vertical) from being successful in hydrogen and electric energy systems, respectively. The unknowns highlight evidence gaps or discrepancies in the literature, whereas the colours represent literature results that are in agreement with how difficult the barrier is to overcome.

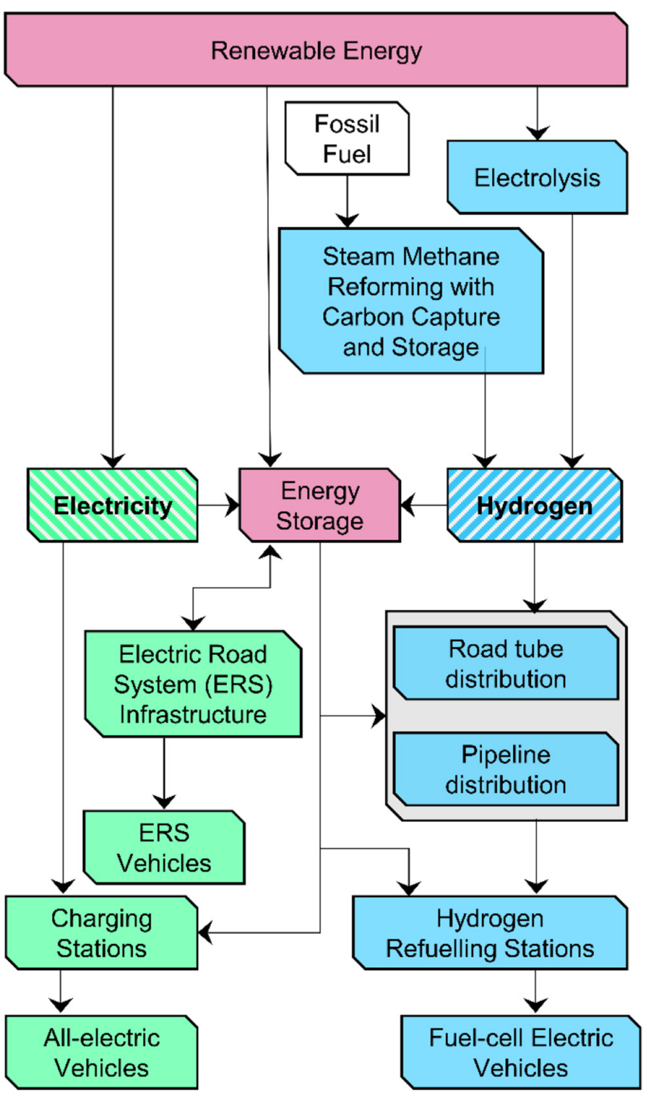

Fig. 2. Flow diagram of the assessed infrastructure for electric (green), hydrogen (blue) and either (purple) energy system. The energy carriers are denoted with patterned boxes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Hydrogen energy system barriers.

Key Technology	Tech. Readiness	Scalability	Geographical	System Dependence	Consumer Acceptance	Resource Requirements	Resilience	Reduce CO_2	Consumer Cost	Industrial Cost	National Cost
Renewable Energy	Low	Low	Moderate/High	Low/Moderate		Moderate	Moderate/High	Low	Unknown/inconclusive	Moderate	Unknown/inconclusive
Electrolysis	Moderate	Moderate	Moderate/High	Moderate/High		Moderate	Low/Moderate	Low/Moderate	Unknown/inconclusive	Unknown/inconclusive	Unknown/inconclusive
SMR with CCS	Unknown/inconclusive	Unknown/inconclusive	High	Moderate		Moderate	Low	Moderate	Unknown/inconclusive	Unknown/inconclusive	Unknown/inconclusive
Energy Storage	Low/Moderate	Moderate/High	Low/Moderate/High	Moderate/High	Unknown/inconclusive	Moderate/High	Low/Moderate			Low/Moderate/High	Unknown/inconclusive
Road Tube Distribution	Low/Moderate	Moderate/High	Low	Moderate		Moderate/High	Moderate/High	Moderate	Unknown/inconclusive	Moderate/High	Unknown/inconclusive
Pipeline Distribution	Unknown/inconclusive	Unknown/inconclusive	High	Moderate/High		Unknown/inconclusive	Moderate		Unknown/inconclusive	Unknown/inconclusive	Unknown/inconclusive
H_2 Refuelling Stations	Moderate/High	Unknown/inconclusive	Moderate/High	Moderate/High	Low	Moderate/High	Moderate		Unknown/inconclusive	Low	Unknown/inconclusive
Fuel Cell Electric Vehicles	Moderate/High	Unknown/inconclusive	Moderate	Moderate/High	Low/Moderate	Unknown/inconclusive		Low	Moderate/High	Unknown/inconclusive	Unknown/inconclusive

Key: Low; Moderate; High; Low/Moderate; Moderate/High; Low/Moderate/High (Storage options); Unknown/inconclusive

Table 2
Electric energy system barriers.

Key Technology	Tech. Readiness	Scalability	Geographical	System Dependence	Consumer Acceptance	Resource Requirements	Resilience	Reduce CO_2	Consumer Cost	Industrial Cost	National Cost
Renewable Energy	Low	Low	Moderate/High	Low/Moderate		Moderate	Moderate/High	Low	Unknown/inconclusive	Low/Moderate	Unknown/inconclusive
Energy Storage	Low/Moderate	Moderate/High	Low/Moderate/High	Moderate/High	Unknown/inconclusive	Moderate/High	Low/Moderate			Low/Moderate/High	Unknown/inconclusive
Grid Capacity	Low	Low/Moderate	Moderate	Moderate/High	Moderate	Unknown/inconclusive	Unknown/inconclusive	Low	Unknown/inconclusive	Unknown/inconclusive	Unknown/inconclusive
Electric Road System (ERS)	Low/Moderate	Low/Moderate	Moderate/High	High	Low/Moderate	Moderate	Low/Moderate	Low	Low/Moderate	Moderate/High	Unknown/inconclusive
ERS Battery Electric Vehicles	Low/Moderate	Low/Moderate	Moderate	High	Low	Low/Moderate		Low	Low	Moderate/High	Unknown/inconclusive
Charging Stations	Low/Moderate	Unknown/inconclusive	Moderate/High	Moderate/High	Moderate/High	Unknown/inconclusive	Unknown/inconclusive		Moderate/High	Unknown/inconclusive	Unknown/inconclusive
Battery Electric Vehicles	Low/Moderate	Unknown/inconclusive	Moderate	Moderate	Moderate/High	Moderate/High		Low	Low/Moderate	Unknown/inconclusive	Unknown/inconclusive

Key: Low; Moderate; High; Low/Moderate; Moderate/High; Low/Moderate/High (Storage options); Unknown/inconclusive

Infrastructure in both energy systems

With renewable energy comprising nearly 40% of the electricity generation in the UK (gov.uk, 2020), renewable energy has proved its foothold in future energy systems. It has readily available technology that is scalable as the demand for renewable electricity increases towards 2050, and thus a low barrier in Tables 1 and 2. The location of energy generation will influence costs downstream, but capital costs are consistently decreasing (Nguyen et al., 2019). Time of day and seasonality will also influence the consumer cost and the ability to meet consumer demand and will promote energy storage during times when renewable production is greater than demand in a compatible energy form (Ofgem, 2020).

Storing energy, including central, distributed and responsive (vehicle to grid or vehicle to warehouse), are vital to the resilience of any energy system. It provides the necessary support and flexibility for demand to be met, and there are a variety of storage options available with diverse retention times and geographical dependence to suit the needs of the market (Koohi-Fayegh & Rosen, 2020). Here, the importance of whole-system analysis is evident as the overall energy system dictates the success of the individual energy storage system; it determines which markets are available for the stored energy to participate in, and thus the economic return (Andoni et al., 2021).

Energy generation and storage must work in concert to meet on-road demand. Using data from DfT, Fig. 3a shows the actual freight vehicle km (vkm) travelled in 2019 and projections for 2030 and 2050 for the Strategic Road Network (SRN) and all UK freight vkm. Of the 27.8 billion vkm travelled in 2019, 16.5 billion vkm were on the SRN. This distance is forecasted to increase up to 3% in 2030 and 5–12% in 2050 (Department for Transport, 2020). Fig. 3b and c translates the vkm to energy required at the "tank" level, or the amount of energy required on-board the HGV assuming 1.6–2.17 kWh/km was consumed for electric vehicles (Earl et al., 2018; Tesla, 2017) and 0.06–0.09 kg H_2/km for hydrogen vehicles. The dark band incorporates DfT vkm projection uncertainties and the shaded area includes vehicle energy consumption uncertainties. An average of 27 TWh would be needed to meet the 2019 demand using electric HGVs (eHGVs) on the SRN and 45 TWh for all eHGV vkm driven in the UK. For fuel-cell HGVs, 41 and 69 TWh worth of hydrogen would be needed to fuel HGVs on the SRN and the entirety of the UK, respectively.

Fuel cell electric vehicle pathway infrastructure

While all major infrastructure components have been analysed in detail (see SI), the examination of the hydrogen electrolysis is illustrative of the barrier analysis performed for all components. Literature projections use electrolysis as a short-term solution for hydrogen production until steam methane reformation with carbon capture and storage (SMR/CCS) comes online and can produce the quantity of hydrogen required (Energy Network Association, 2020). Other sources deem electrolysis as the long-term solution for sustainable hydrogen production as this production method has a significantly lower carbon footprint using renewable primary energy compared to SMR/CCS (LowCVP, 2015). Although conflicting, these types of assumptions rely on electrolysis to provide hydrogen economically and at scale. Alkaline electrolysers are commercially available with 10 MW capacity, on average, yet they are not suitable for the intermittent nature of renewable energy in coupled operation with variable renewable energy sources. Therefore, to produce renewable hydrogen and use the projected CO_2 emission savings from green-hydrogen production, polymer electrolyte membrane (PEM) electrolysis is needed. Current PEM electrolyser projects average ~0.6 MW with commercial interest for much larger stations (2 MW–1 GW) (International Energy Agency, 2020a). Recent research shows a significant reduction in capital cost for electrolysers as capacity increases (capital cost of ~£200/kW at 1 TW of installed capacity and decaying further as capacity increases) (IRENA, 2020). However, a 1 TW electrolysis factory is 3 orders of magnitude larger than the largest planned electrolyser facility in the world (1 GW), which ITM Power plans to build within the UK by 2025 (ITM Power, 2020). This type of hydrogen production is also indicative of a highly centralised energy system where cost effective hydrogen distribution is mandatory. Therefore, technology readiness and scalability for electrolysis are classed as moderate (yellow) barriers in Table 1.

To demonstrate the scalability of electrolysis on a more decentralised energy system, the on-road fuel demand (shown in Fig. 3c) is assumed to be supplied from hydrogen produced via electrolysis where electrolysers are co-located with the hydrogen refuelling stations (HRSs), eliminating transportation inefficiencies. The load factor of an electrolyser is an important part of maintaining a resilient hydrogen energy system. Operating at 90% of their rated capacity achieves optimal cost and maintenance schedules (Guerra et al., 2019). If a fuelling facility installs enough capacity to meet the demand in 2030 with a 90% load factor, maximizing short-term profits, there is little scalability as demand increases beyond this and additional electrolysers will need to be installed to keep up with demand. However, if a facility anticipates the demand increase so that it will reach a 90% load factor when a higher percentage of vehicles have transitioned to hydrogen fuel, such as in 2050, the initial cost of hydrogen during the years the electrolyser is operating at lower loads, such as 10–50%, will be a significant barrier for the entire energy system to overcome.

With a load factor of 40–90%, a 1 MW PEM electrolysers can produce 200–400 kg H_2/day, whereas 2.5 MW electrolysers are anticipated to produce ~1000 kg H_2/day (Nguyen et al., 2019). Fig. 4a shows that 13,500–20,300 1 MW units producing 200 kg H_2/day (left-axis) are needed to meet the SRN vkm demand in 2019, which expands to

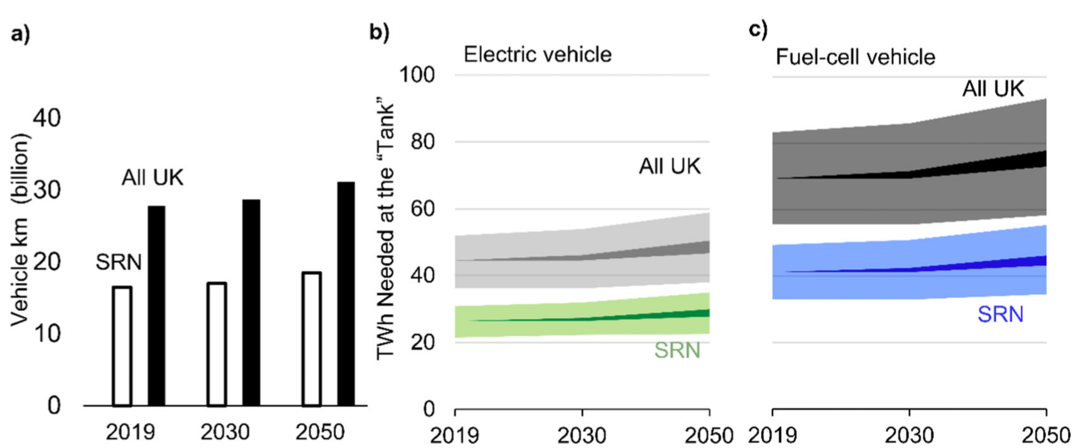

Fig. 3. a) Distance travelled by on-road, freight vehicles on the Strategic Road Network (SRN, open bars) and throughout the UK (black bars) using historical data for 2019 and UK government projections for 2030 and 2050, and the at-tank energy needed for b) an electric or c) fuel-cell HGV when considering vehicle energy efficiency.

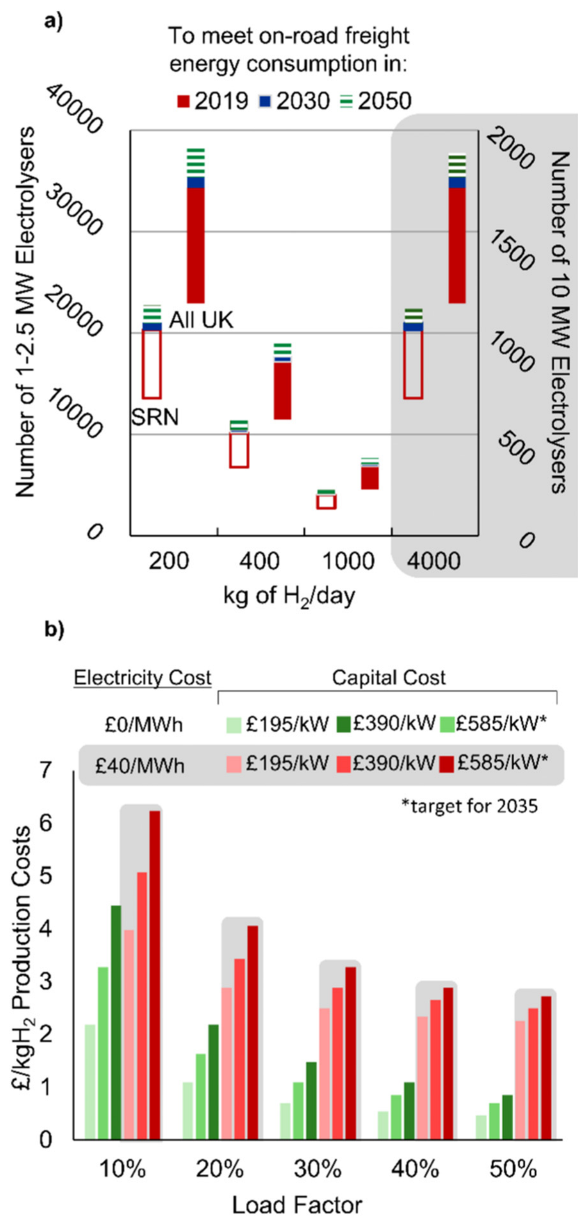

Fig. 4. a) Number of 1–2.5 MW electrolysers (left axis) or 10 MW electrolysers (right axis) needed to meet the SRN or the UK on-road, freight energy demand, and b) the hydrogen production cost as a function of the electrolysers' load factor, capital cost and cost of electricity.

22,900–34,300 to meet the entire UK network. This accounts for vehicle efficiency and drive cycle variability (0.06–0.09 kg H_2/km). The number of electrolysers reduces 50% if units double their load factor and produce 400 kg H_2/day. The largest electrolyser in operation (10 MW) can produce ~4000 kg H_2/day (Shell & ITM Power, 2018). A total of 700–1000 10 MW electrolysers (right-axis) would be needed to meet the fuel demand in 2019 on the SRN and 1100–1700 for UK wide vkm (Ricardo Energy & Environment, 2020). This aligns with the DfT funded Teesside Hydrogen Transport Hub calculations, where electrolysis was determined to limited applicability due to the vast number required to meet energy demand (H21 Leeds City Gate Team, 2016). The primary cost of operating electrolysers is the cost of electricity, which models must assume what type of primary energy the electricity is coming from (renewable or carbon-based). The values of wholesale price, electrolyser load factor, and the efficiency of the electrolyser (International Energy Agency, 2015). Differences in these boundary conditions limit the comparability between studies as the research shows production prices ranging from £1.50 to 10.40/kg H_2 (Guerra et al., 2019). The development of more efficient electrolyser technologies that minimise rare resource requirements is an opportunity for the academic and industrial sectors. From this analysis, the scalability of currently available electrolysers is proven to have a high barrier for the overall energy system, shown in red in Table 1.

Cost for hydrogen produced via electrolysis is known to decrease as the infrastructure scales up. However, the extent of this decrease is unknown (patterned black and red in Table 1). To demonstrate the uncertainty associated with production costs, an economic analysis by McKinsey that highlights the variables influencing hydrogen production cost is shown in Fig. 4b. It shows how the cost of hydrogen (£/kgH_2 produced) decreases as the capital and electricity costs decreases and as the load factor increases (Hydrogen Council, 2020). Using £0/kWh energy (green) results in production costs of £1–4.50/kg in 2035, not including distribution or storage. However, an electricity price of £0/kWh is highly unlikely in any resilient, renewable energy future scenario (International Energy Agency, 2020b). The hydrogen price range shown in Fig. 4b emphasises why this barrier is unknown in Table 1; the variables that must be considered are hard to predict on their own, future capital costs, electricity pricing and infrastructure load factors, and when considered together, the uncertainty aggregates.

Deemed as either the predecessor or long-term replacement of electrolysis for hydrogen production is steam methane reforming (SMR), which is currently available but requires carbon capture and storage (CCS) to adhere to carbon reduction initiatives. Additionally, the infrastructure needed in an SMR/CCS energy system compared to an electrolysis-based system is not directly interchangeable, with a transition that would require further planning. The commercial availability timeline for SMR/CCS capabilities varies widely from 2035 to 2050 (Catapult Energy Systems, 2019; Committee on Climate Change, 2019; Moreno-Benito et al., 2017), resulting in an unknown barrier in Table 1. The cost for hydrogen produced via SMR/CCS is anticipated to be less expensive than hydrogen from electrolysis. The Department for Business, Energy & Industrial Strategy has projected a cost of £1.65–2.62/kg H_2 including carbon transmission and storage (BEIS, 2021). Although the cost is not a barrier, the ability to adequately reduce CO_2 remains a challenge. Without CCS, SMR becomes a hindrance to net-zero initiatives as the average carbon intensity is 9.3 kg CO_2/kg H_2 produced (H21 Leeds City Gate Team, 2016), whereas with CCS, the carbon intensity is 0.9–3.3 kg CO_2/kg H_2 (Malerød-Fjeld et al., 2017). Current CCS technology captures CO_2 generated from the methane to hydrogen chemical reaction but does not include the CO_2 from providing heat required for the endothermic reaction. Purpose built SMR/CCS plants have a CO_2 capture efficiency of 65–75%, with aspirations to achieve a 90% capture efficiency (Malerød-Fjeld et al., 2017). Retrofit CCS plants have a 60% capture efficiency (3.7 kg CO_2/kg H_2) (Roussanaly et al., 2020). Therefore, even with purpose built or retrofit CCS, SMR pathways will continue to have a carbon footprint. This causes SMR with CCS to be a moderate barrier to reducing CO_2, shown in Table 1.

Hydrogen can be compressed to gas for pipeline distribution or distributed via road tube trailers as either liquid or gas. Pipelines require individual assessment and are currently being evaluated as part of the H21 Leeds City Gate project to discern what retrofit or replacement resources are needed, causing cost, time and scalability unknowns in Table 1, including possible long-term effects such as embrittlement (Energy Network Association, 2020; H21 Leeds City Gate Team, 2016; Moreno-Benito et al., 2017). Depending on the evaluation, pipes would either need to be retrofit or replaced to distribute hydrogen and must consider future energy demand to establish size requirements. A recent analysis reports a cost comparison for either repurposing or building new pipelines. A range of £0.04 to 0.75/kg/1000 km was determined depending on the diameter of the pipe and retrofit capabilities (Wang et al., 2021). Currently, road tubes are used for distributing hydrogen and can adapt to changing hydrogen demands. When comparing compressed and liquified hydrogen transport via road tubes, liquified hydrogen is about 20% less expensive than compressed on-road transportation (Reuß et al., 2021). Along with being less expensive, liquid hydrogen tankers have up to six times the hydrogen capacity than gaseous tankers (~450 GJ vs. ~75 GJ, respectively), but are still being developed (Shell Global, 2017). Road distribution is therefore a low to moderate technological barrier in Table 1.

HRSs have the most similar consumer experience to current refuelling operations, and due to on-site storage, would have a degree of resilience embedded within them. However, HRSs contribute ~70% of the consumer cost of hydrogen, with cost reductions coming primarily from increased utilisation rate and larger stations (Hydrogen Council, 2020). Table 1 shows an unknown scalability and cost barriers for HRS as there is not a consensus on where hydrogen is needed, which also leads to utilisation rate and subsequent cost projections being disputed (Hall & Lutsey, 2019; National Academy of Engineering, 2004).

The cost of hydrogen fuel is dependent on HRS utilisation rate, and thus the number of fuel-cell HGVs on the road nation-wide, causing a moderate to high barrier for system dependence in Table 1. There may be exceptions to this at specific ports within the UK, but this is outside the scope of the study. Similar to HRSs, the reduction in fuel-cell HGV cost is dependent on the mass production of vehicles, and therefore is anticipated to reach cost parity with current vehicles by 2040–2050 (Committee on Climate Change, 2019; Transport and Environment, 2020). Because of this timeline, Table 1 shows the cost parity results to be a moderate to high barrier in the hydrogen energy system. Fuel-cell HGVs have increased geographical freedom compared to eHGVs. They also require a battery ranging from 12 to 250 kWh for auxiliary purposes, and with fuel-cell sizes unpublished, the raw material requirements are unknown (Nikola Motor Company, 2019; Ricardo Energy & Environment, 2020).

Battery electric vehicle pathway infrastructure

The electric grid capacity is one of the most highlighted barriers in a future electric system, as the requirements are largely unknown. An even higher uncertainty is associated with grid expansion for urban HGV applications and industrial fleet depots (International Energy Agency, 2019). Here, the cost, resource requirements and resilience barriers in Table 2 are consequentially unknown. Beyond physical reinforcements within the grid, implementing energy demand-side response into the electric network has been shown to improve energy system resilience and flexibility and could serve as a buffer for projected uncertainties (Antonopoulos et al., 2020). The increase in peak demand and network costs have been projected for light-duty electrification within the UK, reporting that the level of centralisation and the 'smartness' of the charging infrastructure contribute large uncertainties (Hill et al., 2019; National Grid ESO, 2020). However, the on-road HGV sector continues to be excluded from these models. Because energy distribution is the bottleneck within the electric grid (Nicholas & Hall, 2018), energy storage co-located with charging stations would help maintain functionality and will be relied upon for resilience within the overall system.

All-electric system

Charging stations play an important role for eHGVs as the fleet operations will dictate when and how these vehicles are able to charge. Overnight and mid-route charging are currently available, but at a higher cost compared to overnight charging that is likely to be the preferred, cheapest option when operations allow. Fast chargers, which would reduce wait times with mid-route charging, are not currently available for HGVs (Furnari et al., 2020). These barriers are subsequently classed as low and moderate, respectively, in Table 2. Additionally, the industrial costs remain unknown as the cost per charger, in either a slow or rapid charge point, is dependent on the number of charge points frequency of use. It is shown that chargers could increase lifetime costs for long-haul vehicles by 20% during an initial uptake in eHGVs and drop to a 10% increase in high eHGV volume scenarios (Nicholas & Hall, 2018). The uncertainty for resource requirement and scalability barriers is due to the unknown number of chargers required for an electric energy system, which is highly dependent on the level of decentralisation, available grid capacity and individual vehicle operations.

The moderate to high barriers attributed to individual eHGVs in Table 2 come from the required resources for the 575–1150 kWh on-board battery and the payload trade off due to the battery weight (Earl et al., 2018; Transport and Environment, 2020). However, battery technology continues to evolve, and has meet or outperformed energy density and cost projections due to ongoing battery material advancements, but with more improvements needed in decreasing battery weight (Duffner et al., 2020; International Energy Agency, 2019). These innovations have led eHGVs to have lower life-cycle CO_2 emissions than current internal combustion engines and are on par with modelled fuel-cell HGV life-cycle emissions (Hall & Lutsey, 2018). While the geographical barrier in Table 2 remains a moderate barrier, urban operations are conducive to eHGVs, maintaining operation functionality with smaller batteries and intermittent charging, while decreasing the need for geographical independence. Regional eHGVs will reach cost parity to current vehicles by 2025 and long-haul eHGV by 2030, albeit local differences in efficiency, due to temperature and terrain, will have to be further considered (Buholtz et al., 2020; Committee on Climate Change, 2019).

Electric-road system

Electric road systems (ERSs), using overhead catenary and an on-board pickup system, could alleviate electricity demand from overnight charging needs from eHGVs, but this infrastructure cannot be built incrementally and therefore remains a high barrier for system dependence in Table 2. ERS infrastructure has on-road data for trials in Germany, Sweden, and the United States (Siemens, 2020). These long-haul and port demonstrations have been developed in conjunction with ERS vehicle manufactures and have shown that peak electric grid load increases by 2–3% with HGV use on the ERS (Jelica et al., 2018; Taljegard et al., 2017).

The economic feasibility of the ERS relies on stepwise transformation within HGV fleets. Taljegard, et al. reported that in 2016, the cost for an ERS pick-up system and battery was less than £20,000 per vehicle. For vehicles driving more than 60,000 km/year while operating on an ERS, the cost per km becomes almost exclusively determined by the electricity price, and remains well below current diesel pricing (£0.18–0.42/vkm for ERS HGVs compared to £0.52/vkm for diesel vehicles in Sweden) (Taljegard et al., 2020). The pick-up systems are ready for commercialisation, but are limited to roads that have ERSs and would require on-board energy storage systems, such as batteries, for the fraction of the delivery route not on an ERS. The on-board storage could be tailorable to final delivery destinations (100–200 kWh typically), which would reduce resource requirements from batteries (Cambridge Econometrics, 2018; Ricardo Energy & Environment, 2020). The majority of the barriers for an ERS equipped HGV, shown in Table 2, are low to moderate, but with a high barriers with system dependence and upfront infrastructure costs.

Conclusion

Decarbonizing integrated components within an energy system is a monumental task that has been considered for decades. Previous literature has presented analyses for one barrier (columns in Tables 1 and 2) or one component (rows in Tables 1 and 2) within an energy system. However, these single point analyses have the potential to conclude very different courses of action due to optimising only one variable in the complex energy system equation. Whole system thinking is mandatory to successfully implement future energy systems yet is relatively absent from energy decisions. This gap in literature motivated the Chief Scientific Advisor at the Department for Transport London (DfT) to commission this work to inform DfT policy and provide a system-wide analysis on both electric and hydrogen energy systems. This discussion helps to coalesce the abundance of independent analyses and emphasise their broader implications.

In an electric energy pathway, the barriers stem from the system-wide resilience and resource uncertainties. Grid capacity needs upgrading to account for increased peak demand, and electricity usage optimisation and efficient energy storage would be necessary for system resilience. Fully electrifying all HGVs in the UK would stress resources due to battery production, but outfitting HGVs with ERS technological capabilities and automation, primarily those travelling on the SRN, the resource (and payload) barrier is significantly reduced, with on-board batteries needed only for final delivery requirements. This could reduce battery sizes by an order of magnitude. The barrier with implementing ERS nationally is the large upfront cost of a stepwise change in infrastructure that requires national financial support.

The main barriers for a hydrogen system are economically producing low-carbon hydrogen. The CCS technology, a prerequisite to make SMR a viable option, must be universally adopted to be impactful in a relevant timeframe. Additionally, this pathway will continue to have a carbon footprint associated with on-road freight, due to CCS not being able to capture CO_2 with a 100% capture efficiency. The alternative hydrogen production method, electrolysis, has commercially available options for steady-state operations (alkaline electrolysis), but would need to adapt to the intermittent nature of renewables (PEM electrolysis) to produce green hydrogen necessary for the anticipated CO_2 reductions from using hydrogen. The degree of incentivisation required for electrolysis to become a universal, low-cost hydrogen production method is unknown. Without a clear and distinctive path forward on how hydrogen will be produced on a national level, downstream infrastructure is at risk, and the ultimate cost of hydrogen for the consumer cannot be determined.

When considering the whole-system on a national scale, a hydrogen pathway requires more unknowns to be further researched and high barriers to be overcome than an electric system, in part due to a decade lag in government investments into the hydrogen energy system compared to electrical system components. However, a realistic, unified timeline to implement these components is key to a successful decarbonisation strategy, to which this work has actively contributed to within the UK. This work has influenced the view of hydrogen within DfT, the pathway to enable its use and the funding of the Teesside Hydrogen Hub. Here, it has been determined that to help achieve net-zero by 2050, accessible research is needed in the following areas: 1) zero-emitting vehicle specifications such as battery, fuel-cell and tank size based on various duty-cycles, 2) on-road measurements for energy consumptions of eHGVs and hydrogen HGVs under various drive cycles and ambient conditions, 3) determination of the number and location of hydrogen fuelling or electric recharging stations based on different levels of decentralisation, 4) the grid requirements needed based on recharging station locations or electrolysis locations that use grid energy, and 5) an understanding of national incentivisation required for each system and the duration of the incentivisation to promote fleet uptake to reach decarbonisation goals. Quantification in these areas would contribute to a more concrete direction for HGV decarbonisation when integrated into the whole-system analysis and would provide further targets for development.

Declaration of competing interest

The authors declare no competing interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esd.2022.03.011.

References

Andoni, M., et al. (2021). Analysis of strategic renewable energy, grid and storage capacity investments via Stackelberg-cournot modelling. *IEEE Access*, *9*, 37752–37771.

Antonopoulos, I., et al. (2020). Artificial intelligence and machine learning approaches to energy demand-side response: A systematic review. *Renewable and Sustainable Energy Reviews*, *130*, Article 109899.

BEIS (2021). *Hydrogen production costs 2021*.

Buholtz, T., et al. (2020). Electrifying freight: Pathways to accelerating the transition. https://media.daimler.com/marsMediaSite/pic/en/30010495.

Cambridge Econometrics (2018). European Climate Foundation trucking into a greener future: The economic impact of decarbonizing goods vehicles in Europe. www.camecon.com.

Catapult Energy Systems (2019). *Innovating to net zero*.

Committee on Climate Change (2019). Net zero technical report. www.theccc.org.uk/publications.

Department for Business, E. & I. S (2020). Road fuel consumption and the UK motor vehicle fleet. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/729420/DUKES_1.1-.

Department for Transport (2020). Statistical release minor road traffic estimates revisions. https://www.gov.uk/government/.

Duffner, F., Wentker, M., Greenwood, M., & Leker, J. (2020). Battery cost modeling: a review and directions for future research. *Renewable and Sustainable Energy Reviews*, *127*, Article 109872.

Earl, T., et al. (2018). Analysis of long haul battery electric trucks in EU. https://ec.europa.eu/inea/en/ten-t/ten-t-projects.

Energy Network Association (2020). *Gas goes green*.

European Commission (2021). *Brexit and the UK's decarbonisation efforts: A hit or a miss?* .

Furnari, E., Johnnes, L., Pfeiffer, A., & Sahdev, S. (2020). Why most electric trucks will choose overnight charging. McKinseyhttps://www.mckinsey.com/industries/automotive-and-assembly/our-insights/why-most-etrucks-will-choose-overnight-charging.

gov.uk (2020). *Digest of UK Energy Statistics (DUKES): Electricity*.

Guerra, O. J., Eichman, J., Kurtz, J., & Hodge, B. M. (2019). Cost competitiveness of electrolytic hydrogen. *Joule*, *3*, 2425–2443.

H21 Leeds City Gate Team (2016). Leeds city gate. https://www.northerngasnetworks.co.uk/wp-content/uploads/2017/04/H21-Report-Interactive-PDF-July-2016.compressed.pdf.

Hall, D., & Lutsey, N. (2018). *Effects of battery manufacturing on electric vehicle life-cycle greenhouse gas emissionsROMAN]*. *https://doi.org/10.1088/1748-9326/11/5/054010*.

Hall, D., & Lutsey, N. (2019). Estimating the infrastructure needs and costs for the launch of zero-emission trucks. *International Council on Clean Transportation*, 1–31.

Hill, G., Heidrich, O., Creutzig, F., & Blythe, P. (2019). The role of electric vehicles in near-term mitigation pathways and achieving the UK's carbon budget. *Applied Energy*, *251*, Article 113111.

HM Government (2020). *The ten point plan for a green industrial revolution*.

Hydrogen Council (2020). Path to hydrogen competitiveness; a cost perspective. www.hydrogencouncil.com.

International Energy Agency (2015). Technology roadmap hydrogen and fuel cells. www.iea.org/t&c/.

International Energy Agency (2019). How much carbon dioxide is produced when different fuels are burned? https://www.eia.gov/tools/faqs/faq.php?id=73&t=11.

International Energy Agency (2020a). Average installed size of electrolyser projects, 2000–2019. https://www.iea.org/data-and-statistics/charts/average-installed-size-of-electrolyser-projects-2000-2019.

International Energy Agency (2020b). Projected costs of generating electricity 2020. https://www.iea.org/reports/projected-costs-of-generating-electricity-2020.

IRENA (2020). Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5C climate goal. www.irena.org/publications.

ITM Power (2020). The world's largest electrolysis factory. https://www.itm-power.com/.

Jelica, D., Taljegard, M., Thorson, L., & Johnsson, F. (2018). Hourly electricity demand from an electric road system – A Swedish case study. *Applied Energy*, *228*, 141–148.

Koohi-Fayegh, S., & Rosen, M. A. (2020). A review of energy storage types, applications and recent developments. *Journal of Energy Storage*, *27*, Article 101047.

LowCVP (2015). *Transport energy infrastructure roadmap to 2050*.

Malerød-Fjeld, H., et al. (2017). Thermo-electrochemical production of compressed hydrogen from methane with near-zero energy loss. *Nature Energy*, *2*, 923–931.

Moreno-Benito, M., Agnolucci, P., & Papageorgiou, L. G. (2017). Towards a sustainable hydrogen economy: Optimisation-based framework for hydrogen infrastructure development. *Computers and Chemical Engineering*, *102*, 110–127.

National Academy of Engineering (2004). The hydrogen economy. *The Hydrogen Economy*. National Academies Press. https://doi.org/10.17226/10922.

National Grid ESO (2020). *Future energy scenarios*.

Nguyen, T., Abdin, Z., Holm, T., & Mérida, W. (2019). Grid-connected hydrogen production via large-scale water electrolysis. *Energy Conversion and Management*, *200*, Article 112108.

Nicholas, M., & Hall, D. (2018). Lessons learned on early electric vehicles fast-charging deployments. www.theicct.org.

Nikola Motor Company (2019). Nikola products. https://nikolamotor.com/one.

Ofgem (2020). Wholesale electricity charts and indicators. https://www.ofgem.gov.uk/data-portal/all-charts/policy-area/electricity-wholesale-markets.

Page, M. J., et al. (2021). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *Systematic Reviews*, *10*, 1–11.

Reuß, M., et al. (2021). Hydrogen road transport analysis in the energy system: A case study for Germany through 2050. *Energies*, *14*, 1–17.

Ricardo Energy & Environment (2020). Zero emission HGV infrastructure requirements, *111*.

Roussanaly, S., Anantharaman, R., & Fu, C. (2020). Low-carbon footprint hydrogen production from natural gas: A techno-economic analysis of carbon capture and storage from steam-methane reforming. *Chemical Engineering Transactions*, *81*, 2020.

Shell Global (2017). Energy of the future? Sustainable mobility through fuel cells and H2. www.shell.de.

Shell, & ITM Power (2018). European consortium with Shell and ITM Power announce agreement to build electrolysis at Rhineland Refinery. www.shell.de/rheinlandraffinerie.

Siemens (2020). eHighway – Solutions for electrified road freight transport. https://press.siemens.com/global/en/feature/ehighway-solutions-electrified-road-freight-transport.

Taljegard, M., Göransson, L., Odenberger, M., & Johnsson, F. (2017). Spacial and dynamic energy demand of the E39 highway – Implications on electrification options. *Applied Energy*, *195*, 681–692.

Taljegard, M., Thorson, L., Odenberger, M., & Johnsson, F. (2020). Large-scale implementation of electric road systems: Associated costs and the impact on CO_2 emissions. *International Journal of Sustainable Transportation*, *14*, 606–619.

Tesla (2017). Tesla Semi. https://www.tesla.com/en_GB/semi.

Transport and Environment (2020). *Comparison of hydrogen and battery electric trucks.*

UK Council for Science and Technology (2020). A systems approach to delivering net zero: Recommendations from the Prime Minister's council for science and technology. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/910446/cst-net-zero-report-30-january-2020.pdf.

UK Government (2020). Government takes historic step towards net-zero with end of sale of new petrol and diesel cars by 2030. https://www.gov.uk/government/news/government-takes-historic-step-towards-net-zero-with-end-of-sale-of-new-petrol-and-diesel-cars-by-2030.

Wang, A., et al. (2021). *Analysing future demand, supply, and transport of hydrogen, European Hydrogen Backbone.* Available at:https://transparency.entsog.eu/.

Wilson, J., et al. (2021). Are medical procedures that induce coughing or involve respiratory suctioning associated with increased generation of aerosols and risk of SARS-CoV-2 infection? A rapid systematic review. *The Journal of Hospital Infection*, *116*, 37–46.