Decarbonising UK Transport

Final report and technology roadmaps

March 2021

Mott MacDonald
10 Fleet Place
London
EC4M 7RB
United Kingdom

T +44 (0)20 7651 0300
mottmac.com

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Prepared for the Department for Transport

Mott MacDonald Limited. Registered in
England and Wales no. 1243967.
Registered office: Mott MacDonald House,
8-10 Sydenham Road, Croydon CR0 2EE,
United Kingdom

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Glossary of abbreviations

Abbreviation	Description
BECCS	Bioenergy with Carbon Capture and Storage
BEV	Battery electric vehicle
CCC	Committee on Climate Change
CCS	Carbon capture and storage
CO_2	Carbon dioxide
DACCS	Direct Air Capture and Carbon Storage
DfT	Department for Transport
ERS	Electronic Road System
FCEV	Fuel cell electric vehicle
GHG	Greenhouse gas
HFCs	Hydrofluorocarbons
HGV	Heavy goods vehicle
HRS	Hydrogen refuelling stations
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ICE	Internal combustion engine
IMO	International Maritime Organization
LGV	Light goods vehicle
LNG	Liquid natural gas
N_2O	Nitrous oxide
NH_4	Methane
OLEV	Office for Low Emission Vehicles
PFCs	Perfluorocarbons
PHEV	Plug-in hybrid electric vehicle
PtL	Power to Liquid
RFNBO	Renewable fuel of non-biological origin
RSSB	Rail Safety and Standards Board
SAF	Sustainable aviation fuels
SF_6	Sulphur hexafluoride
SMR	Steam methane reforming
SRN	Strategic Road Network

TCO	Total Cost of Ownership
TDNS	Traction Decarbonisation Network Strategy
TDP	Transport Decarbonisation Plan
TRL	Technology Readiness Level

Executive summary

This is an independent report commissioned by the Department for Transport to inform its Transport Decarbonisation Plan. It considers what needs to be achieved over the next 30 years, in terms of technological solutions, to reduce and remove direct emissions from the UK's domestic transport sector across modes by 2050. It represents the view of Mott MacDonald and partners and is not government policy.

A pillar for ambitious plans to decarbonise transport

In June 2019 the Government amended the *Climate Change Act* committing the UK to a net-zero contribution to global greenhouse gas emissions by 2050. Direct (tailpipe) emissions from domestic transport represent over a quarter of UK greenhouse gas emissions, making it the largest single source, 99% of which is comprised of CO_2. In October 2019, the Government announced the development of the first *Transport Decarbonisation Plan* (TDP). To support the development of the TDP, the Department for Transport (DfT) asked Mott MacDonald and its partners, as part of the future resilience support they provide, to examine **technological solutions for reducing and removing CO_2 at point of use across all modes for *domestic* transport**. In March 2020 the DfT published *Decarbonising Transport: Setting the Challenge* which confirmed the role of this study to "*give advice on the support we need to provide in the near and medium term in order to de-risk, and have in place, the technologies which will help us deliver a decarbonised transport system by 2050*"[1]. The study's purpose has not included consideration of the role of changing travel behaviour in reducing CO_2 emissions from transport.

Pathways for reducing and removing direct emissions across modes

This report sets out a series of seven roadmaps for **decarbonising domestic transport in the UK**. These roadmaps address: cars and light goods vehicles; buses; coaches; heavy goods vehicles; rail; domestic shipping; and domestic aviation. International aviation and shipping are not included within the scope of this study. These have been recognised by the Government as important to address through international co-operation and action, to which some of the solutions discussed in this report will contribute. It should be noted that in its *Sixth Carbon Budget* report published on 9 December 2020, the Committee on

[1] DfT (2020). Decarbonising Transport: Setting the Challenge. Department for Transport, March.

Climate Change (CCC) recommends that the legal limit for UK net emissions of greenhouse gases "*should cover all greenhouse gas emissions, including those from international aviation and shipping*"[2]. The implications of this recommendation are not within scope of the roadmaps in this report.

Each roadmap considers the progression of relevant candidate technology solutions. The roadmaps work backwards from an achievable 2050 end state aligned to the goal of decarbonisation, identifying developments and milestones over the period between 2050 and 2020 that would enable the 2050 end state to be reached. Developments are centred – especially for road transport - upon fleet turnover (the replacement of CO_2-emitting vehicles with zero-emission vehicles) and the supporting infrastructure (for refuelling/recharging those zero-emission vehicles). Underpinning the developments, **the roadmaps set out recommended research and innovation interventions that need to be progressed in the coming five to ten years.** The roadmaps also consider the recommended role of policymaking and fiscal/regulatory measures in helping to enable progress.

The roadmaps are the result of a process that originally ran from October 2019 to March 2020. This began with an extensive review of literature published prior to November 2019 to examine and develop a synthesis of understanding concerning the progress and potential of different technology solutions for decarbonising transport across different modes. A roadmapping exercise then followed involving a series of 'sprints' in which the set of roadmaps was evolved in conjunction with engaging policymakers and experts. Internal reporting of the work within DfT has helped inform preparations of the TDP from April 2020 onwards. To help ensure this published final report of the work is as up to date as possible, ahead of the TDP's publication, an additional round of review and revision was undertaken during November and December 2020. The roadmapping study and resulting report help provide a whole-sector view of the challenges, opportunities and requirements facing transport, and the key actors and agents of change, on the road to decarbonisation.

The mix of solutions for decarbonising transport

The technology solution for decarbonising road transport by 2050 (which represents 91% of direct emissions from domestic transport as at 2019[3]) is

[2] Committee on Climate Change (2020). *The Sixth Carbon Budget: The UK's path to Net Zero*. December.

[3] Department for Business, Energy & Industrial Strategy (2021). Final UK greenhouse gas emissions national statistics, 1990-2019. February.

principally electrification with electric motors driven from either a battery or hydrogen fuel cell with a potential supporting role from route electrification, whereby vehicles can receive dynamic or static charging between their origin and destination. Rail (which represents 1% of direct emissions from domestic transport) is much more strongly dependent upon continuous route electrification, but there may be a complementary role for hydrogen and battery-electric powertrains to cover non-electrified routes. It may not be desirable (even if technically feasible) to decarbonise all rail locomotives moving heavy freight by 2050, because of the need to balance multiple (conflicting) policy outcomes and trade-offs. Therefore, a small proportion of locomotives may require modification to diesel-hybrid propulsion to reduce emissions. Battery-electric and hydrogen propulsion could also be contributory solutions for addressing direct emissions from some components of domestic shipping and aviation (representing 5% and 1% of direct emissions from *domestic* transport, respectively). However, in terms of heavy and/or energy intensive vehicles, these modes will involve a more mixed economy of solutions to reduce emissions including the development of low carbon fuels, including biofuels. In line with the view of the CCC, biofuels – while not zero-emission at point of use – have a part to play for vehicles in the domestic transport sector most difficult to decarbonise (including aircraft).

The extent of decarbonisation achievable by 2050

The roadmaps have been drawn up to reflect *credible* pathways towards decarbonisation of direct (tailpipe) emissions. Given uncertainty in both the balance of solutions and speed of progress, along with very demanding timescales, achieving this across the domestic transport sector by 2050 is not certain and indeed in some respects is not likely in full. Each roadmap gives a sense of the nature and extent of decarbonisation that is achievable by 2050 (in terms of the available technical solutions and the extent they penetrate the market(s) concerned by that time). Broadly speaking, a descending order of the extent of modal decarbonisation (proportion of a mode’s 2020 *domestic* emissions removed by 2050) can be seen as:

- cars and light goods vehicles (full removal of direct emissions achievable);
- buses (full removal of direct emissions achievable);
- coaches (near full, if not full, removal of direct emissions achievable);
- rail (near-full removal of direct emissions achievable);

- heavy goods vehicles (near full, if not full, removal of direct emissions achievable)[4];
- shipping (significant removal of direct emissions achievable)[5]; and
- aviation (partial removal of direct emissions achievable)[6].

Alongside uncertainty in the makeup of actual change to the transport sector over the next 30 years, a defining feature of this piece of work is that the overall timescale for change is largely non-negotiable. **The roadmaps depict what *needs* to be addressed within a fixed timescale but what is *actually* addressed is in the hands of the key players in the public and private sector. The time criticality of action and progress cannot be overstated.**

Since the work covered in this report commenced, the COVID-19 pandemic has caused a global shock with economic and social repercussions that cannot yet be fully understood. During 2020, unprecedented issues have affected the transport sector with dramatic suppression of passenger demand, notably for bus, coach, rail and air travel. Public sector financial aid has been necessary to support services whose commercial viability has been compromised. This may or may not lead to new challenges in terms of investment requirements for transport decarbonisation. However, as the CCC noted in June 2020 "*[t]he fundamental requirements to achieve Net Zero … are largely unchanged by COVID-19*"[7]. It went on to say that "*[t]he most effective and decisive action to secure our recovery from COVID-19 will also accelerate the transition to Net Zero and strengthen our resilience to the changing climate*." Allied to this, in

[4] Rail appears more likely to have a residual of CO_2 than HGVs but this residual could be smaller than for HGVs, if currently anticipated developments fall short in their realisation. It can be said that there are more known knowns, and fewer known unknowns for rail than for HGVs.

[5] By 2050, UK domestic shipping could have zero direct CO_2 emissions. However, this is subject to overcoming several significant uncertainties in technology development, deployment and scaling.

[6] It should be noted that the Committee on Climate Change (as at December 2020) is recommending full decarbonisation of both domestic and international UK aviation emissions no later than 2050. See Table 8.1 in Committee on Climate Change (2020). *Policies for the Sixth Carbon Budget and Net Zero*. December.

[7] Committee on Climate Change (2020). *Reducing UK emissions Progress Report to Parliament*. June.

November 2020 the Prime Minister announced the Government's *10-point plan for a green industrial revolution*[8].

Battery technology

Battery technology for propelling vehicles has advanced considerably over time and this is expected to continue. It is a key solution for the removal of tailpipe emissions (especially for road transport) and is further ahead of other technologies such as hydrogen propulsion in terms of market readiness and adoption. The weight of the battery affects a vehicle's performance and can also have implications for the amount of goods that can be carried in terms of fully laden weight. Developments continue in terms of increasing the energy density of batteries with the prospect of improving energy carrying capacity and/or lowering the battery weight. Such developments offer benefits in terms of improving vehicle range (the distance that can be covered between recharging) and spillover opportunities for using battery technology across different domestic transport modes. Batteries are able to offer high energy efficiency, and their unit cost (per kilowatt-hour) has fallen significantly in tandem with growing demand (particularly for cars[9] and light goods vehicles). However, there are risks in relying on battery technology to the exclusion of other solutions. Global supply of precious metals used in the manufacture of batteries may or may not become a challenge in future as batteries need replacing and fleet turnover towards battery-electric propulsion accelerates internationally. **Considerable investment has been made by the private sector in advancing battery technology (and (rapid) re-charging technology). This is expected to continue such that public sector investment in research and innovation is less warranted**, especially as a short-term priority, and this is reflected in the roadmaps.

The role of hydrogen

Like batteries, hydrogen offers a form of on-board energy storage with no *direct* CO_2 emissions in use. While it is not the dominant solution across the transport sector, it could have some significance for particular use cases within and across modes. Moreover, the importance of hydrogen could increase if: (i) other solutions fail to fully deliver decarbonisation; and/or (ii) the wider economy's dependence on hydrogen leads to scaling up of availability and falling prices. As

[8] UK Government (2020). *PM outlines his Ten Point Plan for a Green Industrial Revolution for 250,000 jobs*. Press Release, 18 November.

[9] Given further impetus with the Government's announcement in November 2020 that sale of new petrol and diesel cars will be phased out by 2030 in the UK (10 years earlier than previously planned) – See link.

such, **it is judged that development of hydrogen-fuelled transport could be integral to achieving full transport decarbonisation. Accordingly, urgent steps are needed to advance hydrogen's technology readiness and the scaling of its availability, particularly for maritime applications**[10]. At the same time, from a whole economy perspective, hydrogen production must be net-zero in terms of CO_2. While advances in electrolysis and Carbon Capture and Storage (CCS) are not centrally addressed in the roadmaps, they are fundamental considerations as part of advancing hydrogen's technology readiness and use. Since the provisional reporting on this roadmapping work in Spring 2020, the Secretary of State for Transport announced on 30 September 2020[11] the development of a vision and masterplan for a Multi-modal Transport Hydrogen Hub in Tees Valley (TVTHH)[12]. This centres upon supporting **a series of operational trials in the second half of this decade, powered by green hydrogen**. Green hydrogen is produced by electrolysis that draws upon electricity generated from renewable energy. In July 2020, the European Commission set out its *Hydrogen Strategy* with ambitions for 40-gigawatt green hydrogen production capacity by 2030, noting that "*[h]ydrogen is enjoying a renewed and rapidly growing attention in Europe and around the world*"[13].

Fleet turnover will determine the pace for decarbonisation

The roadmaps concern reducing and removing direct (tailpipe) emissions of CO_2 from vehicles. **Decarbonising the vehicle fleet involves some shorter-term retrofit or changes to fuel mix but principally concerns replacing, over time, vehicles that produce emissions with those that do not.** This relies upon technological advancements and breakthroughs, it relies upon manufacturers to take advantage of such developments in their product lines, and it relies upon consumer or business demand for the vehicles. Rate of change is also dependent upon the service life of a vehicle and this can vary

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[10] The Government has announced a £20 million investment into the Clean Maritime Demonstration Programme to develop clean maritime technology, see HM Government (2020). *The Ten Point Plan for a Green Industrial Revolution*. November.

[11] UK Government (2020). *UK embraces hydrogen-fuelled future as transport hub and train announced*. September.

[12] Mott MacDonald (2021). Tees Valley Multi-Modal Transport Hydrogen Hub - Vision, Requirements and Options; and Masterplan. Reports to the Department for Transport, January.

[13] European Commission (2020). *A hydrogen strategy for a climate-neutral Europe*. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, July.

significantly – for example, from a few years for intensively used HGVs (which may then be sold on to smaller operators) to decades for rail locomotives. **Those responsible for producing and purchasing vehicles are looking for certainty over the return on their investment and assured fitness for purpose of the vehicle**. This calls for timely signals from Government regarding regulatory changes affecting the market over the period out to 2050 as well as for fiscal measures to promote appropriate market dynamics regarding the vehicle fleet. Significantly, the nature and pace of change in the vehicle fleet is influenced by the availability of infrastructure to support low or zero-emission vehicles. In November 2020 the Government confirmed the phasing out of the sale of new petrol and diesel cars by 2030 (10 years earlier than previously planned) and funding to provide grants to incentivise vehicle purchase and funding to accelerate the rollout of charge points[14].

The pressing need for infrastructure development

Dominant across the set of roadmaps is the need for infrastructure solutions to be further developed and better understood, followed by prioritisation of solutions and scaling up of these solutions across the country. As was the case when the regime transition from horse-drawn transport to the motor car unfolded, the process of change now before us involves concurrent developments in vehicle production, infrastructure development and consumer and business demand[15]. Given the significant dependence in some vehicle use cases upon recharging or refuelling infrastructure being in place, and noting potential timescales of fleet turnover, there is an urgency for infrastructure development. In some cases, infrastructure to support decarbonisation is already well advanced, for example in relation to route electrification on the rail network. In other cases, the infrastructure is more embryonic in nature. **There is a pressing short-term need to understand what is achievable, what constitutes the most appropriate infrastructure solutions, and in turn to inform the identification of a suitable programme of work to deliver those solutions at scale.**

Urgent short-term research and innovation interventions

Research and innovation are precursors to market readiness and scaling. They are therefore a priority for the earlier part of the 30-year period ahead across all the roadmaps. Most notably, for road-based transport, **the recommended**

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[14] UK Government (2020). *PM outlines his Ten Point Plan for a Green Industrial Revolution for 250,000 jobs*. Press Release, 18 November.

[15] Dudley, G., (2014). *The Motorcar and the Construction of a New World*. Prepared for the New Zealand Ministry of Transport, July.

research and innovation interventions are all to start, if not have been undertaken, within the next five years. These include highly challenging trials – spanning different forms of solutions - for infrastructure development and use that in turn must inform forward developments in infrastructure roll-out. Research and innovation interventions recommended for rail, shipping and aviation extend into the rest of this decade, and in some cases beyond. Subsequent progress towards decarbonisation across the roadmaps is dependent upon these innovations being taken forward and upon their outcomes. While hydrogen features across the roadmaps, there is a fundamental dependence upon batteries to deliver decarbonisation of domestic transport. Battery technology has relevance to all modes and there are prospects of spillovers from research and innovation from one use case to another. While significant advances have been made in battery energy density and with developments continuing concerning rapid recharging capability, there is a need for such research and innovation to continue. It is assumed that the private sector will continue to have an important role here.

Moving forwards

This study has informed the UK Government's TDP and the decisions therein. By drawing together a picture across the transport sector, the intention has been to help the co-ordination of understanding, and subsequent prioritisation and action, in order to progress towards decarbonising domestic transport.

As noted earlier, this report has been written at a time when the world faces an unprecedented shock in the form of the COVID-19 pandemic. Systemic change that may emerge as a consequence could fundamentally affect the actors, processes and resources which determine the direction and speed of change towards decarbonisation that is achievable and achieved over the years and decades ahead. Yet as governments take action to support the global economy, the requirements for research and innovation, infrastructure development and vehicle fleet turnover set out in the roadmaps could generate overall long-run returns, economically, socially, and environmentally.

Throughout this study, it is apparent that consensus is often lacking across stakeholders and expert opinion. This reflects, in part, the lack of certainty over future developments and prospects. However, the roadmapping exercise has seen a convergence, through successive iterations, in relation to inter-related elements that guard against single point of failure for decarbonisation. It has highlighted **the importance of a co-operative and collaborative approach between government and industry and the dependence on each other for mutual success. Stewardship over decarbonising transport will need to be clear, strong and sustained**. This includes a need to recognise that this roadmapping exercise should not be seen as finalised, but rather as a platform for periodic future review and revision. It should be, informed by an ongoing programme of monitoring to assess progress within and beyond the priorities, actions and milestones set out within the roadmaps.

1 Introduction

As part of the UK's first Transport Decarbonisation Plan (TDP) this report addresses the role of technology across domestic transport modes to reduce and remove direct carbon emissions. Through a series of roadmaps, it considers the direction and speed of development in vehicles and infrastructure and the associated short-term research and innovation requirements.

Mott MacDonald and its partners have been providing 'futures support' to the Department for Transport (DfT) since January 2019 with the aim of helping to improve the resilience of decision making in the face of uncertainty. In September 2019 the team was asked to undertake a study to examine technological solutions for reducing and removing direct carbon emissions across domestic transport modes. **This report sets out a series of technology roadmaps for the decarbonisation of domestic transport in the UK by 2050, in terms of direct emissions. It contributes to the Government's first *Transport Decarbonisation Plan* (TDP).** The development of this Plan was announced by the Government in October 2019. It is intended "*to bring together a bold and ambitious programme of coordinated action needed to end the UK's transport emissions by 2050…**it will consider how UK technology and innovation can be implemented** to encourage major changes to the way people and goods move across the UK*" (emphasis added) [16]. In March 2020 the DfT published *Decarbonising Transport: Setting the Challenge.* This set out the approach to developing the TDP and confirmed the role of this study to "*give advice on the support we need to provide in the near and medium term in order to de-risk, and have in place, the technologies which will help us deliver a decarbonised transport system by 2050*"[17].

The roadmaps and their accompanying commentaries consider the products (vehicles and infrastructure) and underlying technology required to reduce and remove direct CO_2 emissions across domestic transport modes. **They recommend short-term research and innovation priorities to develop these products and underlying technologies**. The roadmapping exercise has

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[16] DEFRA, BEIS and DfT (2019). *UK to go further and faster to tackle climate change*. Press Release, 15 October.

[17] DfT (2020). *Decarbonising Transport: Setting the Challenge*. Department for Transport, March.

focused upon reduction and removal of direct (tailpipe) carbon emissions at the vehicles' point of use, while recognising that this does not *fully* address carbon emissions associated with the transport sector. Individual roadmaps have been produced for: cars and light goods vehicles (LGVs); buses; coaches; heavy goods vehicles (HGVs); rail; domestic shipping; and domestic aviation.

1.1 Background

In 2019, 27% of UK emissions of greenhouse gases (GHGs) were from domestic transport[18]. **Figure 1.1** shows the direct GHG emissions for UK transport across different modes for 2019. GHGs reflected in the figures include carbon dioxide (CO_2), methane (NH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6)[19]. However, **CO_2 represents 99% of total direct domestic transport emissions – hence the priority to 'decarbonise' transport**.

On 12 June 2019 the UK Government announced an amendment to the *Climate Change Act 2008* to reflect a new legally binding commitment to "*eradicate [the UK's] net contribution to climate change by 2050*"[20]. This followed a May 2019 recommendation from the Committee on Climate Change (CCC). In its report '*Net Zero - The UK's contribution to stopping global warming*' it concluded that "*net-zero is necessary, feasible and cost-effective*"[21].The amendment came into force on 27 June 2019. While the CCC recommended that this target should be achieved through domestic action, the amended Act retains the ability to use international carbon credits. The target introduced into legislation is for "*at least a 100% reduction of GHG emissions (compared to 1990 levels) in the UK by 2050. This is otherwise* ***known as a net-zero target because some emissions can remain if they are offset by removal from the atmosphere and/or by trading in carbon units***" (emphasis added)[22].

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[18] BEIS (2021). *Final UK greenhouse gas emissions national statistics 1990-2019*.

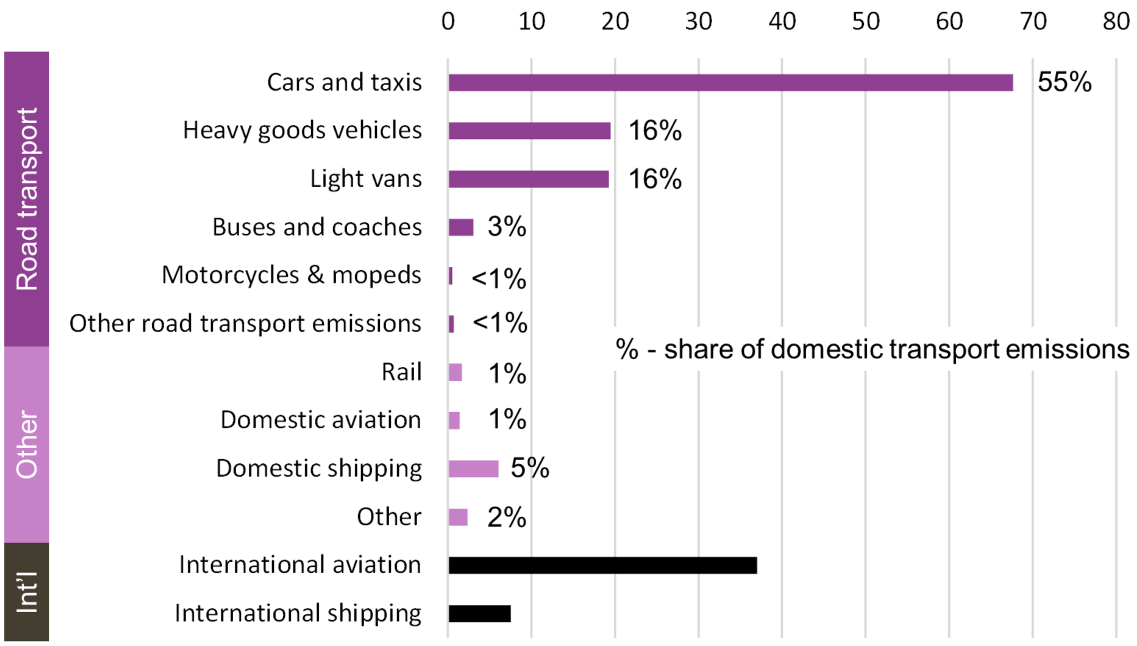
[19] BEIS (2021). *Final UK greenhouse gas emissions national statistics 1990-2019*.

[20] Prime Minister's Office (2019). *PM Theresa May: we will end UK contribution to climate change by 2050*. Press Release, 12 June.

[21] CCC (2019). *Net Zero - The UK's contribution to stopping global warming*. Committee on Climate Change, May.

[22] Priestley, S. (2019). *Net zero in the UK*. Briefing paper CBP8590, House of Commons Library, 16 December.

Figure 1.1: Greenhouse gas emissions by mode of transport (millions of tonnes), UK - 2019



Source: Mott MacDonald. Data, by source, from Department for Business, Energy & Industrial Strategy (2021). *Final UK greenhouse gas emissions national statistics, 1990-2019.* February. [23]

1.2 Aim and objectives

This report reflects a requirement to consider all modes of domestic transport and the candidate products and underlying technologies that have a credible prospect of making a significant contribution to decarbonisation by 2050 for a given mode and across modes. This study has set out to:

- produce a synthesis of progress and potential across different modes and products/technologies;
- undertake a roadmapping exercise to address the change that is required and is feasible over the next 30 years;
- engage with policymakers within the DfT and experts beyond the DfT to inform this roadmapping exercise; and

[23] Emissions from international aviation and shipping are estimated from refuelling from bunkers at UK airports and ports.

- produce a set of roadmaps that provide an informative representation of the decarbonisation considerations and requirements relating to fleet turnover, infrastructure development and underlying research and innovation priorities.

The report is intended to provide a ‘whole sector’ assessment that can help the DfT and its stakeholders better appreciate requirements associated with particular modes, and interdependencies and spillovers between modes in terms of technology solutions for decarbonising.

1.3 Clarifications

Decarbonisation is a complex topic and it is important at the outset of this report to clarify several points that contextualise its contents.

Interpreting ‘zero-emission’ – As already explained above, **this report centres upon the removal of direct emissions from domestic transport** – emissions at point of use. This is not the same as the removal of *all* emissions associated with the transport sector. There is a distinction between production emissions and consumption emissions. The former includes the emissions generated by other countries in the production of goods (known as offshoring or outsourcing) that are then consumed in the UK – for example the manufacture of vehicles and their components; or the production of vehicle fuels. There is embodied carbon - the carbon generated in the ‘cradle to grave’ creation, maintenance and disposal of a product such as a vehicle or transport infrastructure. There is a carbon footprint in the ‘well to wheel’ production and distribution of energy to then be used in propelling vehicles. For example, hydrogen is a zero-emission fuel at point of use, but the production of hydrogen can generate significant CO_2 emissions[24]. **Such considerations are significant in terms of the *overall* challenge to reduce domestic and global CO_2 emissions. However, they are not within the scope of this study**.

Domestic transport – As **Figure 1.1** shows, significant GHGs are attributable to the UK’s contribution to *international* aviation and shipping. The Government notes that international “*[a]viation and shipping emissions are global issues that require global solutions. The exclusion of international aviation and shipping emissions in the UK’s carbon budgets and 2050 emissions target is consistent with the Paris Agreement, which looks to the International Civil Aviation Organization (ICAO) and the International Maritime Organization (IMO) to*

[24] Green hydrogen refers to hydrogen produced through electrolysis that itself uses renewable electricity. Meanwhile grey hydrogen refers, for example, to hydrogen produced through steam methane reforming (SMR) that itself produces CO_2 emissions. Where CO_2 resulting from grey hydrogen is captured and stored then this becomes known as blue hydrogen.

develop targets. No practice for allocating such emissions to individual states has yet been agreed internationally, and we will continue to account for international aviation and shipping emissions via "headroom" within our existing carbon budgets"[25]. Accordingly, **this study was tasked with addressing domestic transport emissions and not international transport emissions**. In terms of technological solutions to reducing and removing tailpipe emissions, the boundary between the needs for domestic versus international aviation and shipping are not absolute. For example, the flight time from London to Paris – and the associated zero-emission propulsion challenge - is comparable with London to Edinburgh (though clearly not with London to New York or to Sydney). However, **the focus upon *domestic* nevertheless strongly orientates how candidate technological solutions for decarbonisation are examined**. Nevertheless, it is noted that in December 2020, the CCC published its *Sixth Carbon Budget* report[26]. In this it recommends that the legal limit for UK net emissions of green gases "*should cover all greenhouse gas emissions, including those from international aviation and shipping*". The implications of this recommendation are not within scope of the roadmaps in this report.

Behaviour – Direct carbon emissions from transport are a product of the emissions per unit of travel by a given vehicle and the amount of travel undertaken. The characteristics of the supply of vehicles and transport options, and the demand for travel are therefore both important. Reducing demand for a given carbon-emitting mode in favour of other lower or zero-carbon-emitting modes has the potential to significantly support decarbonisation. More efficient use of carbon-emitting vehicles could also be important. Reducing, or limiting growth in, the number of vehicles needed can help in relation to embodied carbon. **Changing travel behaviour is viewed within transport planning as a key part of the decarbonisation agenda. This is recognised as important but is not part of the scope of this report**. This said, behaviour change (vehicle purchasing decisions of consumers and businesses) will also form an important part of technology take-up (and this point is discussed in the report). Moreover, the behaviour of key actors in government and industry is key to unlocking the potential for technological solutions to address direct emissions from transport and is a matter that has influenced the roadmapping exercise undertaken. Lastly, it should be noted that the changing distribution of travel

[25] BEIS (2019). *Leading on Clean Growth - The Government Response to the Committee on Climate Change's 2019 Progress Report to Parliament – Reducing UK emissions*. Department for Business, Energy and Industrial Strategy, October.

[26] Committee on Climate Change (2020). *The Sixth Carbon Budget: The UK's path to Net Zero*. December.

demand across different modes, vehicle types and use cases has implications for the relative importance of different technology solutions for reducing and removing tailpipe emissions.

Offsetting – Allied to trading carbon credits as a means of a country buying or selling the entitlement to produce additional tonnes of CO_2, is the concept of offsetting, whereby activity is undertaken or invested in to remove CO_2 from the atmosphere. This holds the prospect of supporting net-zero emissions if the CO_2 emissions from one activity are countered by removal of CO_2 by another. **Offsetting may well be significant for the decarbonisation of transport where it proves impossible by 2050 to remove *all* direct CO_2 emissions. In the roadmapping exercise, care has been taken to acknowledge where such impossibility or limited likelihood may apply**.

Low Carbon Fuels - The term ‘low carbon fuels’ refers to fuels whose life cycle emissions are significantly lower than those from fossil fuels. It includes sustainable aviation fuels (SAF) and biofuels which are derived from biological materials (biomass) as well as fuels produced from non-biological materials (referred to as renewable fuels of non-biological origin or RFNBOs), such as hydrogen. Low carbon fuels currently deployed are mainly biofuels, hence both the terms low carbon fuels and biofuels are referred to in this document. Availability of sustainable biomass is limited, and while biofuels can reduce GHG emissions significantly compared to fossil fuels as the biological material has removed CO_2 from the atmosphere, they are still associated with direct emissions at the tailpipe. It is therefore important to use this resource where it can deliver the most cost-effective carbon savings, i.e. the sectors most difficult to decarbonise by any alternative means. In its 2018 report *Biomass in a low carbon economy* [27], the CCC suggested that for transport the most effective use of biomass by 2050 will be aviation biofuel (with Carbon Capture and Storage – see below) and that the use of biofuels will need to transition during the 2020s and 2030s from its current use in road transport to aviation. Indeed, the CCC notes more recently that “*[u]se of biofuels in surface transport should be phased out during the 2030s*”[28]. **Low carbon fuels have provided an interim solution to helping address CO_2 emissions from road transport. In the long-term, their use within the transport sector is expected to shift to modes such as aviation, combined with carbon capture and storage. They have been treated accordingly in the roadmapping undertaken**.

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[27] CCC (2018). *Biomass in a low-carbon economy*. Committee on Climate Change, November.

[28] CCC (2019). *Net Zero – Technical Report*. Committee on Climate Change, May.

Carbon Capture and Storage (CCS) – CCS involves capturing CO_2 that is produced in the process of, for example, energy generation (or biofuel production– see reference to aviation above) and then transporting and storing the CO_2 such that it does not re-enter the atmosphere – which could be deep underground in depleted oil and gas fields. CCS is especially relevant to the case for hydrogen as a means of decarbonising transport. Green hydrogen can be produced through electrolysis using electricity generated from renewable energy, and technological development continues in relation to the efficiency and scale of such production. However, today some 96% of hydrogen produced globally is from fossil fuels, with electrolysis accounting for only 4%[29] (though see reference below to the recently announced UK government plans for operational trials of vehicles powered by green hydrogen). As such, in the short-term at least, hydrogen production for transport could be dependent upon fossil fuels and existing industrial production facilities. **In this case, CCS would be highly significant to the part that can be played by hydrogen in decarbonising the UK economy, even if hydrogen itself appears highly promising in removing *direct* emissions of CO_2 from transport**. **While this is important to recognise, it has not been the role of this study to focus upon the resolution of this upstream challenge associated with hydrogen production**. Nevertheless, it should not be ignored in the steps that are taken by Government and industry in light of the roadmapping exercise, which itself recognises the role CCS must play. According to the Global CCS Institute, the number of CCS facilities in the pipeline of development showed a continuous decrease from 2010 to 2017 following the global financial crisis. Momentum appears to have been regained subsequently. In 2019 there were 19 large scale CCS facilities operational globally (none in the UK), with a further four in construction and 28 in development stages (including six in the UK at the early development stage with estimated eventual capture capacity *if fully realised and operational* in the region of 10-40 million tonnes per annum). Facilities that are operational and under construction globally have a combined "*capacity to capture and permanently store around 40 million tonnes of CO_2 every year*"[30]. In November 2020 the UK Government announced "*[a]n extra £200 million of new*

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[29] Hanley, E.S., Deane, J.P. and Ó Gallachóir, B.P. (2018). The role of hydrogen in low carbon energy futures–A review of existing perspectives. *Renewal and Sustainable Energy Reviews*, 82, 3027-3045.

[30] Global CCS Institute (2019). *Global Status of CCS 2019 – Targeting Climate Change*. November.

funding to create two carbon capture clusters by the mid-2020s, with another two set to be created by 2030"[31].

Vehicle types and use cases – Across domestic transport there are a considerable number of individual classes of vehicles as well as different use cases for those vehicles in operation. In short, the decarbonisation picture becomes more complex the more one zooms in to the detail. **This study has sought to strike a balance between breadth and depth. Several different vehicle types and use cases are acknowledged and accounted for but not systematically.** For example, HGVs span 15 categories ranging from 3.5 tonnes to 44 tonnes gross weight and from 2 to 6 axles[32] - the roadmapping exercise acknowledges this range and distinguishes between urban/regional use and long-haul but goes no further. Cars and LGVs (representing 55% of domestic transport's direct GHG emissions) are considered together on one roadmap. Motorcycles and mopeds (representing less than 1% of emissions) are not explicitly addressed. There are also specialist vehicles in operation across the transport sector, for example cranes, gritters, tractors and tunnelling machines. These tend to be expensive and low mileage. It is recognised that while specialist, there is clearly a commercial basis for their production while they have relied on fossil fuels. It would be reasonable to suppose that such a commercial basis could be maintained in a move to their decarbonisation. However, it may be the case that **unless specialist vehicles are decommissioned or regulatory measures are put in place to prevent new vehicles that are not zero-emission, they may remain in service as a source of CO_2 emissions by 2050**. While this should be highlighted, such vehicles have not been given direct consideration in the roadmaps.

Optimism bias – There are significant uncertainties facing the decarbonisation of domestic transport. These existed prior to the COVID-19 pandemic, which may now have introduced an amplifying effect. Past roadmapping exercises can sometimes, in hindsight, be seen to have been overly optimistic regarding the nature and pace of change over time. This reflects in part both the inertia in the current systems of production and consumption as well as uncertainties regarding technology breakthroughs and the diffusion of innovation. **The challenge for this study has been to try and offer a *realistic* portrayal of pathways forward while addressing a largely non-negotiable time-limited goal, namely to fully or at least largely remove direct CO_2 emissions from**

[31] UK Government (2020). *PM outlines his Ten Point Plan for a Green Industrial Revolution for 250,000 jobs*. Press Release, 18 November.

[32] Department for Transport (2003). *A Simplified Guide to Lorry Types and Weights*.

transport by 2050. Development of the roadmaps has acknowledged the uncertainties involved and the roadmaps are intended to represent an *achievable* approach for decarbonising transport. It is important to distinguish *certainty* of meeting the goal from *plausibility* or *probability* of meeting the goal. For each roadmap, the degree of confidence in fully (or largely) decarbonising is signalled in accompanying text. **The purpose of the roadmaps is to challenge, and to inform and mobilise action, rather than to assure achievement of the goal**.

Interim Carbon Budgets – The report's focus is on identifying realistic, albeit challenging, pathways to 2050. However, the roadmaps also recognise the UK's interim carbon budgets. "*Under the Climate Change Act 2008 (the 2008 Act), the Government must set five-yearly carbon budgets, twelve years in advance, from 2008 to 2050*"[33]. The first and second Carbon Budgets have been met (2008-2012: outperformed by 1%; and 2013-2017: outperformed by 14%) and the third is projected to be met (2018-2022: predicted, prior to COVID-19, to be outperformed by 3%). As the CCC notes[34], the UK "*is not on track to meet the fourth (2023 to 2027) or the fifth (2028-2032). To meet future carbon budgets and the Net Zero target for 2050 will require governments to introduce more challenging measures*". Transport is now the largest single source of emissions in the UK and with a backdrop of its emissions having *increased* from 2013 to 2017 (with decreases from 2017 to 2019)[35]. **For transport to positively, if not strongly, contribute to addressing Interim Carbon Budgets four and five there would need to be a significant penetration of low or zero-emission vehicles into road transport fleets – particularly for cars and LGVs.** The bringing forward of the ban on new petrol and diesel vehicles entering the car fleet from 2040 to 2030 is to be noted in this regard. The first five carbon budgets have been put into law. On 9 December 2020 the CCC published its advice on the *Sixth Carbon Budget*[36]. Government is expected to legislate for this by June 2021. The CCC advises Government "*to require a reduction in UK emissions of 78% by 2035 relative to 1990, a 63% reduction from 2019*"[37].

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[33] Priestly, S. (2019). *UK Carbon Budgets*. Briefing Paper CBP7555, House of Commons Library, 9 July.

[34] Climate Change Committee (2020). *Advice on reducing the UK's emissions*.

[35] BEIS (2021). *Final UK greenhouse gas emissions national statistics 1990-2019*.

[36] Climate Change Committee (2020). *Sixth Carbon Budget*. December.

[37] Committee on Climate Change (2020). *The Sixth Carbon Budget: The UK's path to Net Zero*. December.

Partnership – Decarbonising transport will involve a process of change that relies on the interplay between industry, government and consumers. Private sector businesses need to remain financially viable and their actions will reflect this. Their willingness to invest in decarbonising transport rests significantly upon a reasonable degree of assurance that such investment is commercially sound. Government meanwhile faces the challenge of how to support and stimulate the market without excessive or inappropriate intervention. It too needs to understand how to make resilient investment decisions. **Both industry and government are confronted by uncertainty. Overcoming this uncertainty will involve partnership. This report is intended to offer a framework within which public and private investment decisions can be made – especially over the short-term**.

Battery technology - Battery technology for propelling vehicles has advanced considerably over time and this is expected to continue. It is a key solution for removal of tailpipe emissions (especially for road transport) and is further ahead of other technologies such as hydrogen propulsion in terms of market readiness and adoption. The weight of the battery affects a vehicle's performance and can also have implications for the amount of goods that can be carried in terms of fully laden weight. Developments continue in terms of increasing the energy density of batteries with the prospect of improving energy carrying capacity and/or lowering the battery weight. Such developments offer benefits in terms of improving vehicle range (the distance that can be covered between recharging) and spillover opportunities for using battery technology to decarbonise other domestic transport modes. Batteries are able to offer high energy efficiency, and their unit cost (per kilowatt-hour) has fallen significantly in tandem with growing demand (particularly for cars and light goods vehicles). However, there are risks in relying on battery technology to the exclusion of other solutions. Global supply of precious metals used in the manufacture of batteries may or may not become a challenge in future as batteries need replacing and fleet turnover towards battery-electric propulsion accelerates[38]. **Considerable investment has been made by the private sector in advancing battery technology (and (rapid) re-charging technology). This is expected to continue such that public sector investment in research and innovation is less warranted**, especially as a short-term priority and this is reflected in the roadmaps.

Hydrogen - It is possible that hydrogen *may* not – for the transport sector as a whole – be a *substantial* contributor to decarbonisation, but that its potential across a range of use cases where there are limited alternatives, means **it is**

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[38] Joint Research Centre (2019). *The Future of Road Transport*.

more likely – as things currently stand - that hydrogen will be a *significant* contributor to full transport decarbonisation. This is borne out across the set of roadmaps. For some use cases, while hydrogen is technically feasible it is less energy efficient and/or more costly than other solutions (especially at existing levels of technology readiness and market development). In other use cases, other solutions are lacking or inadequate and this is where hydrogen may be able to make an especially important contribution. Given uncertainties and prospects for future technology breakthroughs (and barriers) across the set of candidate solutions to decarbonising transport, questions of scaling, and the huge challenges presented by the need to decarbonise, **the relative merits of hydrogen could change over time**. There is unavoidable uncertainty in this regard. Therefore, if a resilient approach to decarbonising transport is sought, then *resolute* rather than tentative support of hydrogen is important. On 30 September, the Secretary of State announced[39] the development of a vision and masterplan for a Multi-modal Transport Hydrogen Hub in Tees Valley (TVTHH) centred upon operational trials of vehicles, in the second half of this decade, powered by green hydrogen[40]. Hydrogen propulsion of vehicles could be in the form of Fuel Cell Electric Vehicles (FCEVs) or hydrogen Internal Combustion Engine (ICE) vehicles. In FCEVs, hydrogen is turned into electricity that drives an electric motor (and/or which is stored in an on-board battery). With hydrogen ICE vehicles, the hydrogen is combusted in the engine to create propulsion. Staffell et al. (2019: 465) note that "*[c]onventional internal combustion engines can be modified to run on pure hydrogen ('HICEs') and could see early deployment as they are substantially cheaper than fuel cells. However,* ***hydrogen combustion is less efficient than a fuel cell and releases NOx, hence is not expected to play a significant long-term role in transport***" (emphasis added)[41]. **The roadmapping mostly addresses FCEVs**. The exception is for domestic shipping where, in the short to medium term,

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39 UK Government (2020). *UK embraces hydrogen-fuelled future as transport hub and train announced*. News Story, 30 September.

40 Mott MacDonald (2021). Tees Valley Multi-Modal Transport Hydrogen Hub - Vision, Requirements and Options; and Masterplan. Reports to the Department for Transport, January.

41 Staffell, I., Scamman, D., Valazquez Abad, A., Balcombe, P., Dodds, P.E., Ekins, P., Shad, N. and Ward, K.R. (2019). The role of hydrogen and fuel cells in the global energy system. *Energy & Environmental Science*, 12, 463-491.

ICE's may remain the preferred engine of use with increasingly decarbonised low emission fuels[42].

COVID-19 - Since the work covered in this report commenced, the COVID-19 pandemic has caused a global shock with economic and social repercussions that cannot yet be fully understood. During 2020, unprecedented issues have affected the transport sector with dramatic suppression of passenger demand, notably for bus, coach, rail and air travel. Public sector financial aid has been necessary to support services whose commercial viability has been compromised. This may or may not lead to new challenges in terms of investment requirements for transport decarbonisation. However, as the CCC noted in June 2020 "*[t]he fundamental requirements to achieve Net Zero … are largely unchanged by COVID-19*"[43]. It went on to say that "*[t]he most effective and decisive action to secure our recovery from COVID-19 will also accelerate the transition to Net Zero and strengthen our resilience to the changing climate*." Allied to this, in November 2020 the Prime Minister announced the Government's *10-point plan for a green industrial revolution*[44]. Systemic change that may emerge as a consequence of COVID-19 could fundamentally affect the actors, processes and resources which determine the direction and speed of change towards decarbonisation that is achievable and achieved over the years and decades ahead. Yet as governments take action to support the global economy, the requirements for research and innovation, infrastructure development and vehicle fleet turnover set out in the roadmaps could generate overall long-run returns, economically, socially, and environmentally.

1.4 Report outline

The report is structured as follows.

Section 2 summarises the methodology that was followed, including desk-study work, stakeholder engagement and a series of roadmapping sprints iterating towards the final set of roadmaps.

Sections 3-8 set out the seven individual roadmaps and their accompanying narrative commentary for: cars and LGVs; buses and coaches; HGVs; rail; domestic shipping; and domestic aviation. The inter-dependencies between the

[42] Smith, T., O'Keeffe, E., Hauerhof, E., Raucci, C., Bell, M., Deyes, K., Faber, J. and 't Hoen, M. (2019). *Reducing the maritime sector's contribution to climate change and air pollution*. Report for the UK Department for Transport.

[43] Committee on Climate Change (2020). *Reducing UK emissions Progress Report to Parliament*. June.

[44] UK Government (2020). *PM outlines his Ten Point Plan for a Green Industrial Revolution for 250,000 jobs*. Press Release, 18 November.

roadmaps are signalled where appropriate for each roadmap. However, each roadmap and its narrative has been prepared such that it can be examined independently of the other roadmaps. This does have the consequence of some repetition across the set (notably in relation to road transport modes, and buses and coaches (**Section 4**) and HGVs (**Section 5**) in particular).

Conclusions are set out in **Section 9**.

2 Methodology

The methodology followed for this study has involved a combination of examination of relevant literature and engagement with key stakeholders to synthesise understanding and iteratively develop a series of roadmaps.

The study has been undertaken in two phases as part of the ‘futures support’ being provided to the DfT’s Office for Science. The internal client is the DfT’s Head of Environment Strategy, although the study has necessarily engaged more widely with several teams across the DfT with responsibility for different modes, addressing environment and climate change, and developments in vehicle technology. A three-phase approach was taken. The purpose of the first phase was to develop – through a literature review – a cross-modal understanding of progress and potential of technology solutions to reduce and remove direct CO_2 emissions. The second phase was a roadmapping exercise intended to develop a roadmap to 2050 for each domestic transport mode which highlights recommended research and innovation interventions needed in the shorter-term. It should be noted that quantitative modelling was not within the study scope. Reporting on the first and second phase to DfT concluded in April 2020. Preparatory work on the Transport Decarbonisation Plan (TDP) has taken place in the months that followed, drawing upon this reporting. The third phase involved an update to the work in November and December 2020 in readiness for final publication of this report in parallel with publication of the TDP.

2.1 Phase 1: Literature review

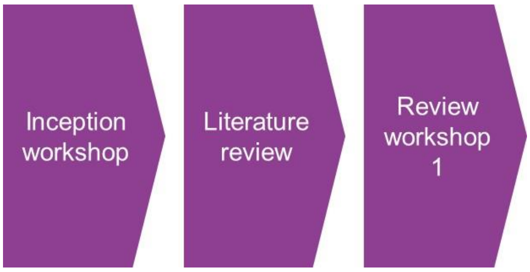
The first phase (outlined in **Figure 2.1**) began in September 2019 with an inception workshop with DfT staff to explore a number of issues pertinent to clarifying the scope of this study. The scope, as agreed at the inception workshop, has been to take a cross-modal look at domestic transport and determine pathways for the reduction and removal of direct (tailpipe) emissions by 2050. The focus has been on technology solutions as opposed to the potential effects from travel behaviour change, and on point of use emissions as opposed to other emissions associated with the production of vehicles, energy and infrastructure.

The principal activity was then a literature review. Its objectives were to:

- draw together a synthesis of progress and potential across modes regarding candidate technological solutions to reducing and removing direct CO_2 emissions;

- selectively examine material regarding approaches to developing roadmaps; and
- identify key issues of significance to inform a decision on whether and how to proceed with the second phase of this study.

Figure 2.1: Phase 1 approach



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The Mott MacDonald team conducted a search for available literature relevant to decarbonising transport and roadmapping. Specific literature searches were undertaken (using Google and Google Scholar) for each mode, focussing on technologies for decarbonisation and roadmapping in general. For each candidate item of literature, bibliographic details and an indicative overview of the article's coverage was recorded. This produced a bibliography containing around 300 items of literature. Based upon the overview of each article, the article was scored high/medium/low priority by the study team for closer examination – mindful of a need to ensure appropriate representation across the review's scope. In consultation with the DfT, 80 items were shortlisted for review. A template was developed and used to guide the review of each article and collate information from that review. Alongside developing a set of completed templates and in order to support development of a review report, an Excel spreadsheet was also prepared to transpose information from the review summaries into a cumulative representation defined by mode and decarbonisation technology. The reviewing was completed during October and November 2019. A review report was written in the first part of December 2019. **Annex A** reproduces summary material from this study's interim deliverable which examined progress and potential across modes and technological solutions in terms of decarbonising transport and which formed the basis for the subsequent roadmapping exercise[45].

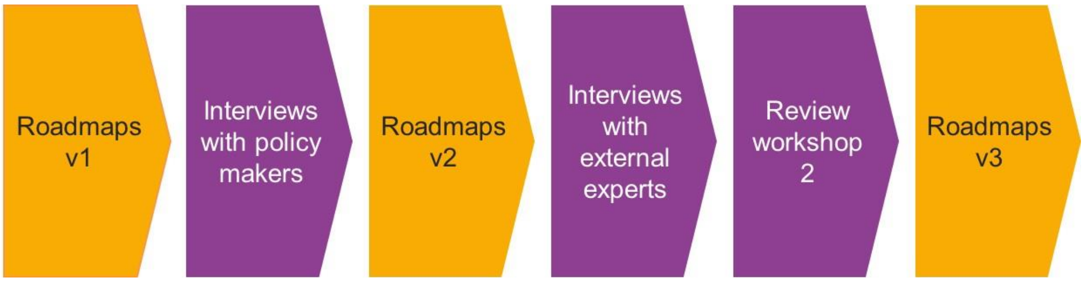
A workshop took place on 18 December 2019 involving several DfT staff to assess the synthesis of understanding from the review and in turn undertake an informed discussion regarding the second phase of this study. Further to the workshop, the review report was finalised[46].

It should be noted that the period of purdah for the 12 December General Election began on 6 November. The phase 1 work was unaffected.

2.2 Phase 2: Roadmapping

Phase 2 was planned and approved by mid-January 2020 and the work (outlined in **Figure 2.2**) then proceeded to completion at the end of March 2020. It involved a number of stages constituting three roadmapping sprints (short, time-limited periods when the core team worked to complete a set amount of work).

Figure 2.2: Phase 2 approach



[45] The Annex should not therefore be taken to reflect fully the more up to date and further detailed picture that has evolved during the course of the rest of the study, accounting also for further ongoing announcements and developments.

[46] Mott MacDonald and partners (2020). *FS05 Decarbonising Transport - Phase 1 Literature Review Report*. Internal deliverable to the Department for Transport, 30 January.

2.2.1 Sprint 1

Box 2.1: Template questions to guide revisiting the phase 1 review report

1. Does the development of this technology need further research and innovation?
2. If yes: What ongoing research and innovation is already identified in the literature review? Is this UK, European, or international?
3. If yes, what types of research and innovation, how complex is this research and innovation and how long could it take to get to prototype/initial market-readiness? (Give a range of timeframes)
4. Is this technology already in the market? If so, early market (<3%), early adopter (>3% <14%), early mainstream (>14%, <50%)? What are the main uses at present? If so, at what penetration level?
5. If in the market, is it currently in use in a market niche? (e.g. who are the specific users and use cases). How significant is it in this niche? (use judgement – high/medium/low)
6. Are there credible forecasts for future market penetration levels over time? If so, identify timeframe, data, source)
7. Are there factors cited that could accelerate diffusion? (e.g. social trends, falls in underlying costs, failure of existing business models, VC investment, etc.)
8. Are there factors that could slow diffusion? (e.g. adverse social trends, existing investment/ 'lock-in'/sunk costs, investor sentiment)
9. Are there specific hurdles that need to be overcome to enable diffusion (now or in the future)? (Check against: propulsion/ fuel production/ distribution)
10. Are possible regulatory interventions mentioned in the review?
11. Are there non-tailpipe issues that need resolving? (e.g. hydrogen production may be dependent on CCS)
12. What are our overall confidence levels in the prospects of diffusion? (scale of 1-5, to be defined by team)
13. In summary: Given the objective of the roadmap, how important is this technology (high/medium/low)? Why?
14. What else is helpful to note that has not been covered above?

The Mott MacDonald team developed a template of questions (see **Box 2.1**) pertinent to informing roadmap development. This was used by specialist members of the team to revisit the phase 1 review report for individual mode-technology pairs. The resulting summaries were used to produce a technology radar plot[47] (and accompanying notes) depicting key decarbonisation

[47] Thought Works (2016). *Build Your Own Technology Radar*.

technologies for each mode. The radar plot indicated the stage of development for each technology, categorised as: Hold, Assess, Trial, Adopt, and Market, allied to Technology Readiness Levels (TRLs). This enabled an ‘at a glance’ depiction of the current status of candidate technology solutions for reducing and removing direct CO_2 emissions as the basis for the roadmap development. Market readiness is taken to represent in excess of 3% adoption within the market[48]. In using the technology radar plot to inform the initial drafting of roadmaps, it was considered that **a product or technology that was not set to be in excess of 3% market penetration by around 2035 would have little or limited potential to significantly contribute to decarbonisation by 2050**.

Drawing on the radar plot and literature review material and an accumulated understanding to date in this study, the core study team co-created a set of initial roadmaps, aiming to track back from 2050 end states along a timeline to 2020 thereby identifying critical milestones, challenges and – in the shorter-term – research and innovation requirements.

2.2.2 **Sprint 2**

The DfT client team then shared the version 1 roadmaps (and progress note) with key internal colleagues spanning areas being addressed by the roadmapping. Twelve interviews involving these policy makers were undertaken with detailed notes recorded of their reactions to, and insights concerning, one or more of the version 1 roadmaps. All interviews were treated anonymously in terms of their content. General insights were discussed with the DfT client team.

Version 2 of each roadmap was then prepared, incorporating new insights and building up a clearer and common representation across the roadmaps. Linkages between the roadmaps were also considered at this stage. The revised roadmaps were circulated within the DfT (along with an accompanying progress note).

2.2.3 **Sprint 3**

As part of the internal DfT interviews, interviewees had been asked to identify external experts who could be approached to contribute their insights to the roadmapping. Eleven telephone interviews were undertaken with these external experts (associated with trade bodies and infrastructure and vehicle operators/manufacturers) – selected to provide the best representation of insight across the set of roadmaps. While the version 2 roadmaps were not

[48] When the diffusion of an innovation moves from ‘innovators’ (up to 2.5%) to ‘early adopters’ according to Rogers, E. M. (2003). *Diffusion of Innovations* (5th ed.) New York: Free Press, p.281.

directly shared with interviewees, they were walked through one or more of these roadmaps accompanied by questions to frame the interview discussion. Detailed notes were recorded. All interviews were again treated anonymously in terms of their content.

The interviews took place over a two-week period. The following week, a review workshop was held in London involving the interviewees or, in some cases, their nominated replacement from their organisation. Ten experts participated in the workshop (with three of these dialling in). The purpose of the workshop was to play back to attendees, insights from the interviews in the form of questions that have cross-modal relevance to the roadmapping. These were as follows and framed the workshop discussions:

End-states and trade-offs

- To what extent are low carbon fuels part of the 2050 mix and how do we decide who lays claim to them?
- Are specialist (expensive, low-mileage, long-life) vehicles receiving enough attention?
- How do we decide trade-offs between the cost of decarbonising ‘the last 5%’ and competition for offsetting?
- What criteria do we have for emissions exceptions?

Fleet turnover, progress towards end states

- Is the transport industry showing agency in determining pace of transition away from an ICE fleet?
- Which modes/use cases have greatest prospect of decarbonising furthest/fastest and leading others?
- How do we set ‘last date of sale’ criteria for fossil-fuelled vehicles/powertrains without damaging balance sheets/creating stranded assets?
- To what extent is progress here going to be dependent on global players and international or extra-national regulation?

Establishing minimum viable infrastructure

- Is the barrier: who pays, how much it costs, deciding on which infrastructure - or something else?
- In the infrastructure transition, is there a clear distinction between ‘low hanging’ solutions and those that are harder to reach in terms of change across the sector?
- How compatible are the recharging/refuelling infrastructure solutions across modes and use cases?
- What do we need to do to make hydrogen work?

- What form(s) of route electrification, if any, is/are deliverable at scale in this timeframe?
- Which market changes that help us hit interim carbon budgets could damage long-term drive to net-zero?

Velocity, key challenges, indicators

- Without assuming there will be behaviour change, to what extent can we ‘design out’ emissions?
- Are interim solutions (retrofit, hybrid) a catalyst or suppressant to decarbonisation?
- Is total cost of ownership (TCO) for FCEV solutions a key challenge for the transport sector as a whole?
- Is ‘let the market decide’ versus ‘tell the market what to do’ impeding progress?
- Is decarbonising business as usual assumed, or must players in the industry adapt business practices to the low carbon solutions emerging?

Research and innovation priorities

- Is the distinction between invention and innovation important in terms of setting near-term priorities?
- Should intermediate/partial solutions that can help address carbon reduction in the shorter-term receive more priority?
- How much of the innovation focus needs to be on the challenges of establishing new infrastructure?
- What criteria do we set to balance between being a ‘fast follower’ of low emissions technology proven elsewhere, and using UK research and innovation funding to create sector leadership?

It should be noted that the COVID-19 crisis was at the early stages of unfolding at the time of the workshop[49].

A debt of thanks is owed to the external experts who willingly contributed their time to participate in being interviewed and/or the workshop.

It was emphasised at the workshop that the process being followed was seeking to achieve *convergence* rather than consensus. It has indeed been the case through the process that the key issues across the roadmaps have become progressively clearer and reinforced, giving confidence that the final version of the set of roadmaps is well-grounded and representative of the

[49] The Prime Minister announced the UK’s first lockdown in response to the pandemic on 23 March 2020, 11 days after this workshop.

important issues that now require attention. Based upon the external interviews and workshop insights, the Mott MacDonald team then prepared Version 3 of the roadmaps. These were included in a draft of this report submitted to the DfT in April 2020.

2.3 Phase 3: Updating

The draft report (including revisions made in response to DfT feedback to its initial circulation internally) has served as a point of reference and influence within the DfT over the course of 2020 as it has consulted on, and made progress with, development of the TDP. Given the turbulence of 2020 and elapsed time before eventual publication of this report in advance of the TDP's publication, a third phase of work was undertaken. The purpose of this was to update the work and its reporting. This phase took place during November and December 2020. It involved: (i) invited input from DfT's modal teams on any significant further developments since the draft report was produced; (ii) an online scan of literature of potential relevance that had emerged since the previous literature review was undertaken; (iii) examination of new material and insights from (i) and (ii); and (iv) review and revision of the report and its roadmaps, in liaison with the DfT. Notably, even within the period for phase 3, significant new developments have included the publication in November of the Government's *Ten Point Plan for a Green Industrial Revolution*[50] and the CCC's publication in December of its *Sixth Carbon Budget* report[51]. During January and February 2021, the revised report was peer reviewed, with a final round of revisions.

2.4 The roadmaps

The roadmaps' design that has been prepared is rather unconventional. It is common for roadmaps to be landscape in orientation, encouraging the reader to move across the page from the present into the future. **This set of roadmaps adopts a portrait orientation that encourages the reader to move down the page, backwards from the 'end' state in 2050 to 2020. As such, the reader arrives at the short(er) term research and innovation interventions that are recommended in order to underpin the developments that should follow**. Timescale is especially important to these roadmaps since the 30-year period within which change must happen is, to a significant extent, non-negotiable.

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[50] HM Government (2020). *The ten point plan for a green industrial revolution*. November. https://www.gov.uk/government/publications/the-ten-point-plan-for-a-green-industrial-revolution

[51] Committee on Climate Change (2020). *The Sixth Carbon Budget: The UK's path to Net Zero*. December.

Each roadmap is structured according to a series of 'lanes' representing the different relevant solutions to decarbonisation (principally hydrogen, battery-electric, route electrification and fuel mix)[52]. The elements of each roadmap are then positioned across the relevant lane(s).

Six types of element are included in each roadmap: (i) *achievable end state* (the 2050 state which is considered deliverable in relation to the requirement to have removed as much direct CO_2 emissions as possible); (ii) *information that could lead to a route change* (milestones along the timeline which if not achieved have an associated consequence or action); (iii) *policy assumption/intervention* (measures that are needed to influence the dynamics required in terms of the direction and pace of change towards decarbonisation)[53]; (iv) *key information / point of fact* (notable markers of insight of particular significance to the developments set out in the roadmap); (v) *recommended research and innovation intervention* (a recommended undertaking that is seen to underpin the developments that follow); and (vi) *Interim Carbon Budget* (a reminder of how the developments set out on the roadmap relate to the 5-year periods for which (legally bound) CO_2 reduction targets apply).

Each roadmap has been designed to be read in a standalone manner. However, a critical aspect of this study overall is the need to be able to examine the totality of domestic transport and understand where the synergies lie and how the requirements for the different modes are inter-related. Accordingly, the annotation on each map seeks to identify this aspect of 'joining up' between and across the maps as a set. **An overarching observation that emerges by considering the roadmaps as a set is the matter of timescale and the extent of combined change that is required. Decarbonising transport amounts to a series of regime changes affecting all actors involved: from policymakers to private industry, from producers to operators to consumers. Timescales for research and innovation are urgent.**

In **Sections 3-8** of the report, each of the roadmaps and its accompanying commentary is set out in turn. The roadmaps are also reproduced as a set in **Annex B** for ease of viewing, comparison and (if desired) printing.

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[52] The shipping roadmap varies slightly in that it includes: low emission fuels more generally (including hydrogen), battery electric, route electrification, wind and exhaust treatment technologies. The aviation roadmap includes a design lane.

[53] It should be noted that such policy assumptions/interventions do not necessarily reflect Government policy – they reflect the judgements offered by this report.

3 Roadmap: Cars and LGVs

Cars and light goods vehicles (LGVs) are well placed to reach zero tailpipe emissions of CO_2 by 2050. Battery electric vehicles (BEVs) offer a credible pathway for full decarbonisation. Hydrogen fuel cell electric vehicles (FCEVs) could also play a role in the pathway, particularly for specific use cases. FCEVs can also offer robustness by mitigating unexpected risks in take-up of BEVs, for example in the case of material constraints, but will rely on technology developments for other modes.

3.1 Overview

BEVs are currently available in car and LGV markets but market take-up has remained low, although substantial increases in BEV market share have been observed between 2019 and 2020[54]. According to vehicle registration data to the end of December in 2020, the market share for BEVs over the year was 6.6%, nearly double from 2019, although new car sales in 2020 dropped by nearly a third as a result of the COVID-19 pandemic meaning that the total number of BEVs sold was lower than in 2019[55].

To date, consumer concerns about driving range, charging opportunities, the additional cost of purchase relative to cars with internal combustion engines (ICEs) and lack of BEV options in the market are challenges that have influenced the take-up of BEVs. Therefore, in the short to medium term, battery improvements to increase vehicle range, provision of more charging infrastructure, lower battery and car purchase costs as well as more BEV options in the market are needed to drive take-up of BEVs (it is noteworthy that the number of new BEV models in the market are expected to increase substantially in the next few years). Over the longer-term, BEVs are likely to account for most of the zero-emission vehicle fleet.

However, FCEVs may offer a technical solution for some specific use cases – primarily back to base operations for taxis or vans, LGVs and intensively used fleets. The availability of models and their subsequent take-up will largely be driven through spillover effects from the success, or lack of success, of

[54] Only zero emission vehicles are considered in the roadmap, specifically battery electric vehicles and those that could be powered by hydrogen. The role for hybrid vehicles is not considered.

[55] SMMT (2021). *SMMT New Car Registrations*.

hydrogen technology developments for other modes, such as coaches, HGVs, rail and shipping. While there are few FCEVs currently available in the market and their sales are miniscule, the presence of hydrogen could provide robustness in the car and LGV decarbonisation pathway in case of unexpected risks in take-up of BEVs, for example due to constraints of key materials such as lithium or cobalt, scaling issues or other unanticipated barriers[56].

At the time of writing, the UK Government announced that it would bring forward the ending the sale of new petrol and diesel cars and vans from 2040 to 2030 (however allowing the sale of hybrid cars and vans that can drive a significant distance with zero carbon emissions from the tailpipe until 2035)[57,58]. This ambitious target means that it is essential that the infrastructure supporting charging or refuelling of low emission vehicles and the supply of vehicles provided by the market are delivered at a scale necessary to meet demand for these vehicles before 2030. Research and innovation from 2020 to 2025 (and beyond) should be focussed on supporting the increased take-up of BEVs and ensuring that they are able to serve the needs for the entire car and LGV market (at a time when take-up of BEVs will also be rising globally). It would also be useful to include FCEVs along with trials for other modes, e.g. HGVs, rail and shipping. Regulatory measures setting average emission targets will be important in ensuring manufacturers (continue to) develop and provide low, and especially zero, emission vehicle options for consumers in the market. Fiscal measures may be required in the 2020s to encourage consumer take-up of zero-emission vehicles until their total cost of ownership (TCO) is clearly more favourable than for ICEs.

3.2 2050 decarbonisation status

By 2050 there should be zero tailpipe emissions for the UK’s fleet of cars and LGVs. This is expected to be largely delivered through BEVs, in tandem with a charging infrastructure to support their use. A not insignificant portion of the fleet could consist of FCEVs, taking advantage of hydrogen refuelling stations that may develop to support the decarbonisation of other modes, namely heavy goods vehicles (HGVs), rail and shipping.

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[56] ITS International (2019). *Battery bottleneck: EV roll-out at risk*.

[57] UK Government (2020). *PM outlines his Ten Point Plan for a Green Industrial Revolution for 250,000 jobs*. Press Release, 18 November.

[58] It is noted that the Sixth Carbon Budget report published by the Climate Change Committee recommends the end of sales of hybrids by 2032, but we retain the 2035 date on the roadmap consistent with latest government policy.

3.3 Fleet turnover

In order to secure a light vehicle fleet with zero emissions by 2050, by 2030 all new vehicles entering the fleet will have to be (largely) zero-emission at point of use[59]. This assumes that all non-zero-emission vehicles purchased before that time will be moved out of the fleet by 2050, which may require incentives for scrappage towards 2050. By 2050 BEVs are likely to form a substantial part of the vehicle fleet. A key assumption is that the electricity grid will be able to cope with their mass take-up.

Along the decarbonisation pathway, regulations on the level of emissions that car manufacturers must comply with will play an important role in ensuring that there is the necessary supply of low, and especially zero, emission vehicles in the UK car market. There is an expectation that there will be an increasing number of BEV vehicle options in the market in the next few years and certainly by 2025, although the need for right-hand vehicles may cause supply concerns. This is an issue that should be monitored closely throughout the pathway. At the end of 2021, EU regulation requiring an average of 95g/km will significantly improve energy efficiency of cars in the market including changes to vehicle propulsion (as well as vehicle structures and sizes)[60]. The European Union has also recently agreed new targets to cut CO_2 emissions from new cars and vans by a further 15% from 2021 levels by 2025 and 38% by 2030 for cars and 31% for vans (again relative to 2021 levels)[61]. In December 2020 the UK adopted legislation setting GB-specific targets that are at least as ambitious as the EU ones, thus promoting a supply of low emission vehicles[62].

It will be important to monitor take-up of low emission vehicles (including in relation to the fourth, fifth and sixth carbon budgets) to assess whether additional fiscal and regulatory measures are required to ensure producer capacity and consumer demand are aligned to the phase out of CO_2 emitting cars and LGVs.

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[59] The van market could shift to electric vehicles more rapidly than car markets with decreasing costs of batteries and provision of required charging infrastructure.

[60] European Commission (2020). *CO_2 emission performance standards for cars and vans (2020 onwards)*.

[61] European Commission (2020). *CO_2 emission performance standards for cars and vans (2020 onwards)*.

[62] UK Department for Transport (2020). *Report CO2 emissions for new cars and vans: How vehicle manufacturers should report CO2 emissions for their vehicles*. December.

In the early years, from 2020, range restrictions, higher purchase costs (relative to comparable ICE vehicles) and a perceived, as well as actual, lack of charging infrastructure may hamper take-up. It is expected that increasing battery energy density will mean that range anxiety should be eliminated by 2025. Battery prices are also falling, with the expectation that BEVs will be competitive in terms of purchase cost with ICE vehicles during the 2020s[63,64,65,66]. It has been suggested that *with mass production*, FCEVs could achieve cost parity with BEVs in the period 2025 to 2030[67]. Ultimately it will be necessary for the TCO to favour zero-emission models to encourage take-up of these vehicles. This will require scaling of both the demand and supply of zero-emission light road vehicles. Fiscal and regulatory incentives may be needed from the early 2020s (and onwards) to accelerate consumer take-up.

Finally, a key assumption in the development of the roadmaps (in line with the view of the CCC) is that, in the long term, biofuels as a low carbon fuel should be prioritised for use in those areas of domestic and international transport most difficult to decarbonise.

3.4 Infrastructure development

Lack of charging infrastructure could constrain the transition to BEVs. Thus, scaling up of charging infrastructure is vitally important in the short-term. In parallel, research and innovation should be undertaken to accelerate provision of charging infrastructure, particularly targeting use cases that require rapid

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[63] The CCC report *Reducing UK emissions Progress Report to Parliament* (June 2020) cites findings from Bloomberg New Energy Finance analysis report that the cost of battery packs for electric vehicles have fallen by 87% over the period between 2010 and 2019 and that prices for BEVs are therefore likely to be close to the price needed to reach cost-parity with most light ICE vehicles within five years.

[64] CCC (2019). *Net Zero - The UK's contribution to stopping global warming*. Committee on Climate Change, May.

[65] Staffell, I., Scamman, D., Valazquez Abad, A., Balcombe, P., Dodds, P.E., Ekins, P., Shad, N. and Ward, K.R. (2019). The role of hydrogen and fuel cells in the global energy system. *Energy & Environmental Science*, 12, 463-491.

[66] Transport and Environment (2019). *Electric surge: Carmakers' electric car plans across Europe 2019-2025*.

[67] Staffell, I., Scamman, D., Valazquez Abad, A., Balcombe, P., Dodds, P.E., Ekins, P., Shad, N. and Ward, K.R. (2019). The role of hydrogen and fuel cells in the global energy system. *Energy & Environmental Science*, 12, 463-491.

charging. By the mid-2020s it would be valuable to undertake trials to explore vehicle-to-grid charging for managing peaks in electricity demand. It would also be useful to undertake research into 'smart' charging to help balance supply and demand. It will be essential to keep monitoring the roll-out of charging infrastructure, and a partnership approach between government and industry may be required to accelerate this.

There are likely to be benefits to having cars and LGVs as part of hydrogen trials for heavy vehicles so that more can be understood in operational terms regarding use cases that could be served by hydrogen (back-to-base taxi services, delivery services, intensively used fleets, etc.). Indeed, such trials are now being undertaken and cars and LGVs are part of the preparations for the planned Multi-modal Transport Hydrogen Hub in Tees Valley (TVTHH).

To meet the 2030s requirement for new vehicles entering the fleet to be zero-emission, a network of charging points allowing BEV charging for all will be required before 2030.

3.5 Research and innovation

Short-term research and innovation needs are focussed on battery improvements and provision and improvement of charging infrastructure for BEVs. Much of this is about scaling up opportunities for non-rapid charging in areas that help encourage take-up of BEVs as well as partnering with industry to provide rapid and innovative charging opportunities targeted at important use cases, such as taxis, vans and LGVs. Research on *inductive* charging should be accelerated with early deployment for targeted use cases as appropriate. Research will also be needed to ensure that the UK can deliver batteries to support the whole car and LGV market. Consistent with this aim, the Government's *Ten Point Plan for a Green Industrial Revolution* announced in November 2020 includes developing 'Gigafactories' in the UK to produce batteries needed at scale[68]. Further, research and investment focussed on reducing the *total* CO_2 costs for vehicle, fuel and battery production and vehicle recycling will also be a priority[69].

Whilst batteries are assumed to provide a pathway to decarbonisation, by 2050 FCEVs may also play a role in the cars and LGV market. As noted earlier, it is therefore important to include cars and LGVs in hydrogen trials for other modes,

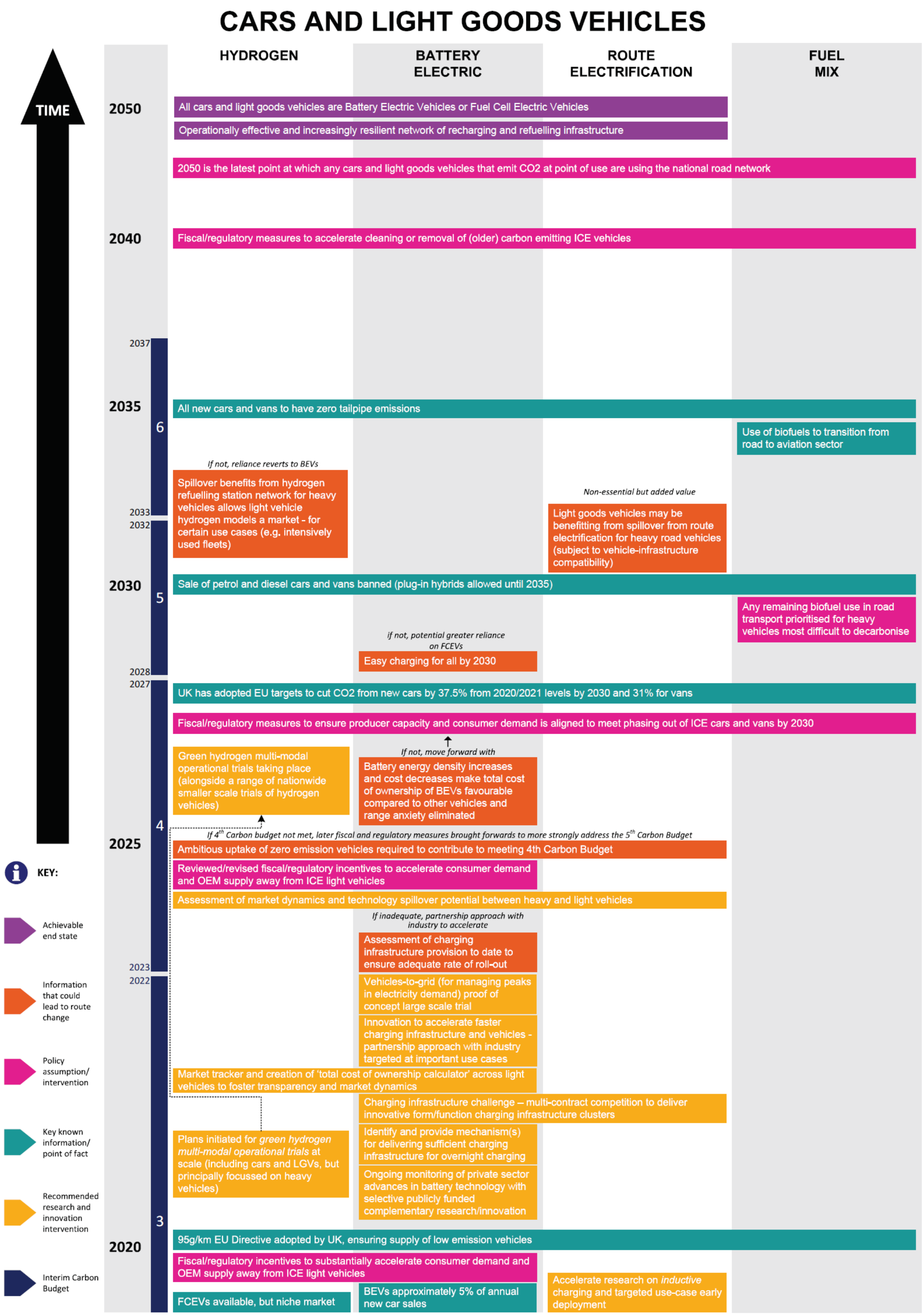
[68] GOV.UK (2020). *PM outlines his Ten Point Plan for a Green Industrial Revolution for 250,000 jobs.* November.

[69] The UK government has recently provided £318m of funding for the Government's Faraday Battery Challenge. Industry are also making substantial investments in this area.

specifically including potentially important car and LGV use cases, such as back to base taxis, LGVs and intensively used fleets to help learn about the operational advantages and disadvantages of FCEVs (indeed trials in London incorporate taxis and this is what is planned for the Multi-modal TVTHH). These trials may also facilitate FCEVs more widely, which may provide back-up for the BEV pathway, should unforeseen challenges arise around BEVs.

The cars and LGV roadmap is shown in **Figure 3.1**.

Figure 3.1: Cars and light goods vehicles roadmap



4 Roadmaps: Buses and coaches

Buses and coaches have proven and strong prospects for full decarbonisation at point-of-use by 2050 with a shared dependence with heavy goods vehicles (HGVs) upon the relative progress of alternative zero-carbon solutions involving both vehicles and infrastructure.

4.1 Overview

Buses are well positioned in terms of an innovation pathway to decarbonisation. London has one of the largest fleets of electric buses in Europe and its *Transport Strategy* aims for a zero-exhaust emissions bus fleet by 2037, with all buses being electric or hydrogen[70]. Major bus groups have made commitments to decarbonising their fleets including First Bus[71] and Go-Ahead[72], each of which aim to have zero emission bus fleets by 2035 (with commitments to purchasing no new diesel buses after 2022 and 2025 for First Bus and Go-Ahead respectively). Hydrogen powered buses have been involved in small scale operational trials such as in London, Aberdeen and Brighton, with ongoing investments also including Birmingham, Dundee and Liverpool (though subject to delay due to the pandemic). All three UK bus manufacturers (Alexander Dennis, Optare and Wrightbus) are developing hydrogen-powered vehicles.

With improvements in battery technology, BEVs could cater for rural (as well as urban) bus operations, but it is uncertainty whether they will be able to power long-distance coach services (based on current battery technology). The UK's first all-electric scheduled coach service began operating between Dundee and Edinburgh from October 2020[73]. Long distance coaches have similar operational requirements to HGVs; if an HGV-appropriate battery technology develops (see **Section 5** for HGV examples), then this will be applicable to long distance coaches as well. In March 2020, National Express set out a goal for its entire bus fleet to be zero-emission by 2030 and its coach fleet by 2035[74]. It

[70] Greater London Authority (2018). *Mayor's Transport Strategy*. March.

[71] First Bus (2020), *First Bus.*

[72] Go Ahead (n.d.). *A national strategy for bus - The Go-Ahead Group's recommendations*.

[73] Business Traveller (2020). *UK's first all-electric inter-city coach service launches between Dundee and Edinburgh*.

[74] SMMT (2020). *National Express sets out its route to zero emissions*.

should be noted meanwhile that the UK coach industry is also made up of thousands of (family run) businesses (many of which are at risk in the face of the slump in demand brought about by the pandemic)[75].

Decarbonisation of the bus industry has been buoyed by the Government announcement in February 2020[76] of a multi-billion pound five-year investment in bus services and cycle routes, including a commitment to at least 4,000 zero-emission buses over the period (set against a national bus fleet size of circa 34,000 in England (as at 2018/19)). Government also announced plans in September 2019 for Britain's first all-electric (battery) bus town or city[77]. The bus and coach industries have, however, seen unprecedented falls in passenger numbers and revenue during 2020 due to the pandemic, affecting vehicle purchasing plans.

4.2 2050 decarbonisation status

By 2050 it is assumed that all buses and coaches can feasibly, and should, be battery electric vehicles (BEVs) or hydrogen fuel cell electric vehicles (FCEVs)[78]. Route electrification may also be utilised (as a complementary solution), particularly for longer distance services (involving the Strategic Road Network - SRN). This will depend on the nature and extent of its availability by 2050 allied to prior advances in battery energy density and other potential technologies – namely development of hydrogen.

Operationally effective and increasingly resilient supporting recharging and refuelling infrastructure is assumed to be in place to ensure service requirements for vehicle operations are met.

4.3 Fleet turnover

Given time required for fleet turnover as well as market readiness and opportunity to decarbonise, it is assumed by this report that at, or around, 2035 – with regulatory support – all new coaches entering the UK fleet would be zero-emission at point of use. Given existing market developments (including

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75 Financial Times. *UK coach sector warns of looming disaster without government support*.

76 HM Government (2020). *Major boost for bus services as PM outlines new vision for local transport*. Press Release, 10 February.

77 HM Government (2020). *Britain's first all-electric bus town to pave the way for green communities of the future*. News Story, 6 February.

78 While Internal Combustion Engine use of hydrogen is a candidate technology, hydrogen power is taken to principally if not entirely be delivered through FCEVs.

substantial prior investment by Government to stimulate and accelerate change), it is assumed that for buses, this milestone *could* be up to five years earlier – at, or around, 2030.

Earlier roll out would in part be determined by Total Cost of Ownership (TCO) (which remains key for long-term value) and availability of relevant refuelling/recharging infrastructure (see **Section 4.4**). Fiscal measures to stimulate the shorter-term role of biofuels for in-service ICE vehicles during the 2020s should be considered to encourage a reduction of interim carbon emissions. Reliance on diesel or hybrid vehicles and related use of biofuels would then diminish (in line with the CCC's recommended phasing out through the 2030s).

It is assumed that to support the ongoing viability of the bus and coach industries, the TCO for zero-emission buses and coaches during or before the 2030s will be comparable to, or lower than, (former) diesel equivalents. If this is not the case then fiscal measures (further to those earlier in the timeline) may be required.

Fiscal and/or regulatory measures, informed by research and innovation, should be introduced as appropriate as early as possible to (further) catalyse new market dynamics - including vehicle design and co-ordinated fleet purchases; and infrastructure investment.

4.4 Infrastructure development

Decarbonisation of buses and coaches is dependent upon the co-development of zero-carbon vehicles and supporting recharging and refuelling infrastructure. The infrastructure is a significant determinant of, if not requirement for, investing in the vehicles. Infrastructure scaling (in accordance with the appropriate nature and extent determined earlier in the timeline) must be considered across candidate solutions for the decarbonisation of buses and coaches, namely: hydrogen refuelling stations (HRSs) (and upstream production and distribution); (rapid) charging points for BEVs; and, potentially, route electrification (influenced in particular by the needs of HGVs). The scaling that is required and deliverable for each is assumed to have been determined by earlier research and innovation (see **Section 4.5**).

While ongoing infrastructure development is expected through to 2050 and beyond, requirements for HGVs as well as long-distance coach services will potentially mean the need for a minimum viable national network of HRSs to be established by the early 2030s (prior to the regulatory requirement for coaches to be zero-emission). Meanwhile a minimum viable network of charging infrastructure for BEV buses (and coaches) will be needed by 2030 at the latest to coincide with the recommended regulatory requirement, at or around that time, for new buses entering the fleet to be zero-emission. Route electrification may address a proportion of the road network, the scale of which will need to be determined during the 2020s. It will be based upon both the nature of the technology (inductive versus conductive and static versus dynamic charging) and the use cases served (related significantly to HGVs); and will need to be in place for corridors deemed high priority by the early 2030s. Failure to progress infrastructure delivery (that will have needed to commence in the 2020s) will affect the relative market appeal of alternative options for decarbonisation, framed by the regulatory measures relating to fleet turnover.

4.5 Research and innovation

Short-term requirements in the period 2020-2025 for research and innovation are strongly oriented towards informing the direction, and catalysing the rate, of development of refuelling and recharging infrastructure. Highways England has previously demonstrated its willingness to engage in route electrification trials while highlighting the challenges this will involve. Catenary technology is being trailed on roads in Germany and Sweden. This now needs to be the subject of a UK trial (in terms of learning about infrastructure, vehicle and business case implications) in relation to this informing a decision on subsequent scaling – this is in line with the May 2019 CCC *Zero Carbon* recommendation. It is recommended that, building on such a trial, there should be an electric roads ‘Grand Challenge’ which – drawing upon related research and innovation for light road vehicles (for example in relation to inductive dynamic or static opportunity charging) and largely driven by HGV requirements – should examine innovative approaches to route electrification (including and potentially extending beyond catenary technology for dynamic conductive charging), thereby helping to concentrate state-of-the-art in the UK and with a focus upon how to achieve ‘deliverable efficiency’ in implementing route electrification.

Production of green hydrogen is a key challenge and cost. There is meanwhile an urgent need to trial a configuration of hydrogen production, distribution and refuelling that can serve a series of use cases (including those relating to coaches and buses as well as HGVs). This trial should be designed such that it serves as a building block for subsequent scaling as well as a source of important insight. The trial’s timescale is critical to explore the potential for hydrogen to support decarbonisation and the pathway to achieving this. Allied to this priority (as set out originally in the April 2020 draft version of this report) has come the Government’s announcement on 30 September 2020[79] of the development of a vision and masterplan for a Multi-modal Transport Hydrogen

[79] HM Government (2020). *UK embraces hydrogen-fuelled future as transport hub and train announced*. News Story, 30 September.

Hub in Tees Valley (TVTHH)[80]. This centres upon supporting a series of operational trials in the second half of the 2020s, powered by green hydrogen.

Analysis should be undertaken to determine the optimal locational configurations for HRSs to support heavy vehicle use cases (including primarily coaches in terms of passenger transport, but also buses), as well as other modes - for example ships, trains and LGVs. It is important to also identify optimal locational configurations for urban, regional and long-haul (rapid) BEV charging points.

As insights from research and innovation emerge, an assessment of market dynamics and technology spillover potential between heavy vehicle use cases should be undertaken. As well as technological innovation, and especially in light of the impetus provided by Government investment announcements in February 2020 for buses, there should be an examination of fiscal innovation in terms of purchasing models and downstream business opportunities from vehicles and infrastructure investment made in the bus industry particularly.

Buses and coaches are different modes with differing vehicles and operating practices. Bus services in the UK are mostly run by five major groups of bus companies. In contrast, the coach industry includes thousands of small operators, many being family businesses. Buses and coaches are at different stages of decarbonisation, with technology requirements for coaches, compared to buses, closer to those for HGVs. While there are several common roadmap features for each mode (allied also to HGVs), a separate roadmap is provided for each mode. The buses roadmap is shown in **Figure 4.1** and the coaches roadmap in **Figure 4.2.**

[80] Mott MacDonald (2021). Tees Valley Multi-Modal Transport Hydrogen Hub - Vision, Requirements and Options; and Masterplan. Reports to the Department for Transport, January.

Figure 4.1: Buses roadmap

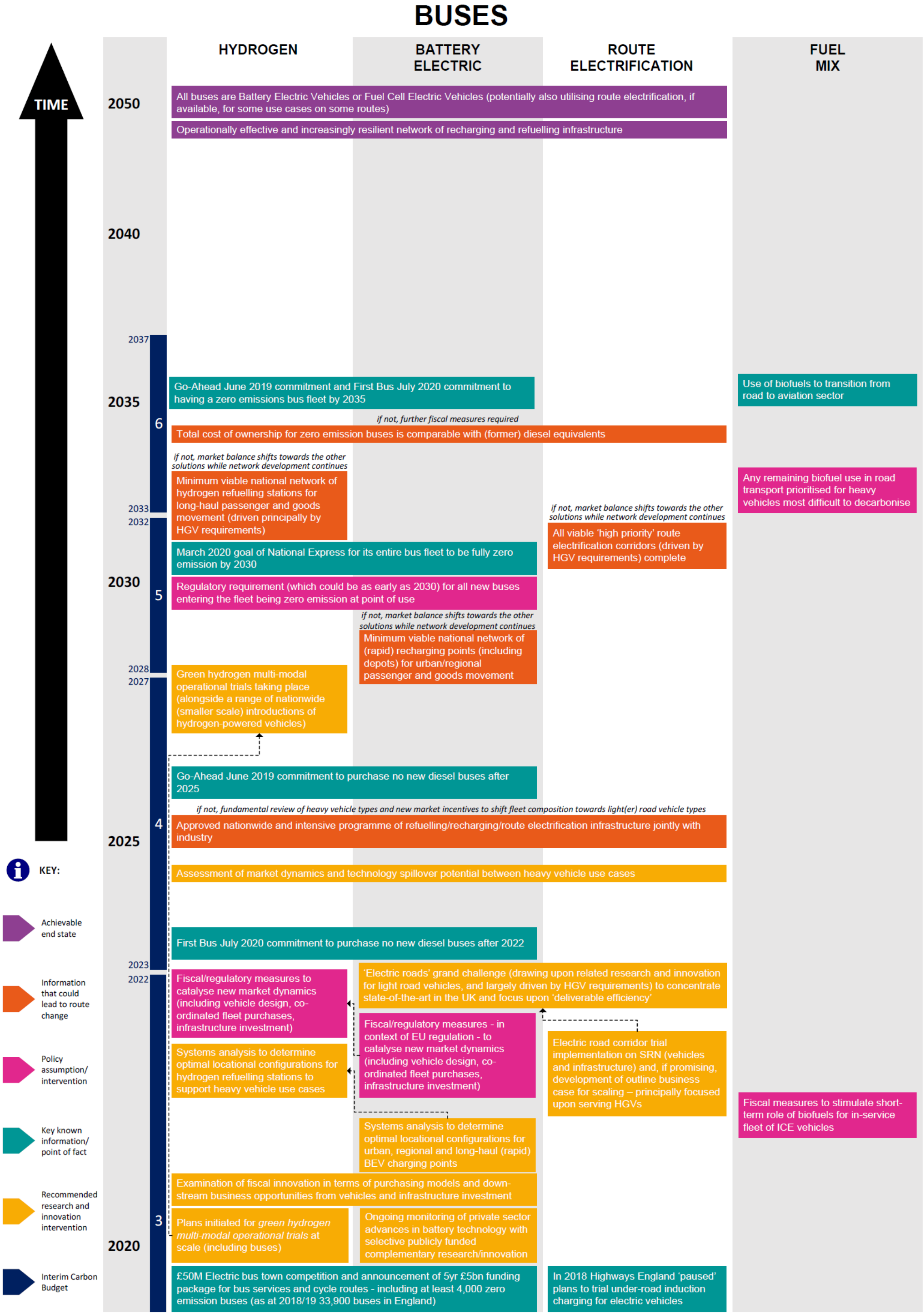
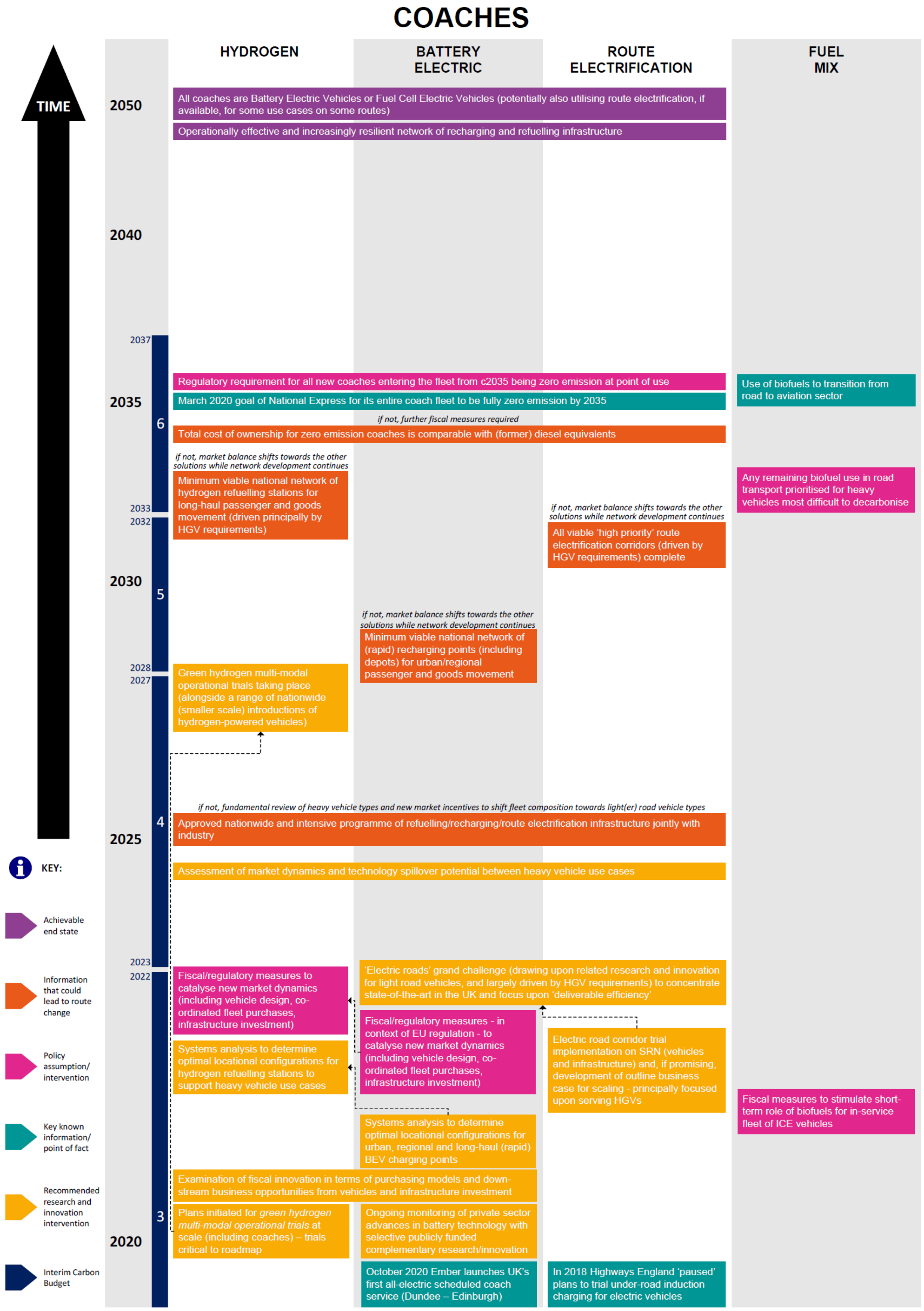


Figure 4.2: Coaches roadmap



5 Roadmap: Heavy goods vehicles

The potential for decarbonising heavy goods vehicles (HGVs) is strong for lower weight classes of vehicles, and while decarbonising long-haul vehicles in the higher weight classes is especially challenging, prospects for achieving full decarbonisation at point-of-use across classes by 2050 are encouraging. Decarbonisation will strongly depend upon the relative progress of alternative zero-carbon solutions involving both vehicles and infrastructure.

5.1 Overview

This section addresses HGVs, i.e. those vehicles with a gross weight in excess of 3.5 tonnes and up to 44 tonnes (goods vehicles up to 3.5 tonnes gross (laden) weight are classed as LGVs[81]). HGVs can be considered in two main categories: (lighter) vehicles for urban and regional deliveries; and (heavier) vehicles for longer-haul. Weight and range are significant factors in terms of the viability of alternatives to Internal Combustion Engine (ICE) vehicles.

Battery electric vehicles (BEVs) for the first, lighter, category already exist though still in small numbers.. Manufacturers are gearing up for production of vehicles to address the second, heavier, category. These include Tesla's development of a battery-electric HGV called the Tesla Semi (U.S. Class 8 heavy truck) that, following delays, is expected to go into limited production in 2021[82]. Models offering 300 and 500-mile range per charge are being developed alongside rapid (30 minute) charging point technology. In November 2020, Volvo announced European hauliers will be able to order battery electric trucks with a gross combination weight of 44 tonnes with a range, depending on battery configuration, of up to 300km. Volume production is scheduled to start in 2022[83].

FCEVs are also under development. Hyundai (part of the H2 Mobility consortium[84]) has delivered the first seven units of its hydrogen-powered HGV

[81] Department for Transport (2003). *A Simplified Guide to Lorry Types and Weights*.

[82] Car Advice (2020). *Tesla Semi electric truck delayed until 2021*.

[83] Volvo Trucks (2020). *Volvo Trucks launches a complete range of electric trucks starting in Europe in 2021*.

[84] H2 (2021). *H2 Mobility.*

to Switzerland (where taxation on diesel HGVs has created a favourable environment), with 50 (originally) scheduled to be operational by the end of the year[85]. London-headquartered Arcola Energy announced in November 2020 its development of a drop-in hydrogen fuel cell replacement for diesel-based powertrains which is expected to be introduced into a range of HGVs from 2021[86]. Compared to FCEV cars and buses, FCEV HGVs are at a lower level of technology readiness. A key challenge for the FCEV solution is unlocking the interdependency between refuelling infrastructure (and fuel supply), vehicle supply and industry demand. In February 2020 the Hydrogen Taskforce (an industry coalition) recommended an industry-government collaboration to establish a network of 100 hydrogen refuelling stations (HRSs) in the UK by 2025[87]. Viability of hydrogen in decarbonising HGVs is contingent upon clean hydrogen production[88]. In turn, notwithstanding the potential for further breakthroughs in battery technology, hydrogen remains a strong, if not fully proven, candidate technology for decarbonisation of HGVs.

Route electrification could offer the prospect of complementing BEVs (and potentially reducing battery sizes and in turn improving carry capacity by weight) and hydrogen fuel cell electric vehicles (FCEVs), particularly if focused upon the Strategic Road Network (SRN), which carries a significant proportion of freight movement. Overhead wires (catenary) used by hybrid (electric and diesel) HGVs have been under trial in Germany and Sweden involving Scania providing hybrid electric trucks[89]. In July 2020, the Centre for Sustainable Road Freight published a White Paper, *Decarbonising the UK's Long-Haul Road Freight at Minimum Economic Cost*[90] in which an Electric Road System (ERS) is suggested (focused on a catenary system) as the most efficient and cost-effective way to decarbonise long-haul HGVs in the UK (with a case for a nationwide rollout of ERS through the 2030s).

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85 Reuters (2020). *Hyundai delivers first fuel cell trucks to Switzerland*.

86 Automotive World (2020). *Arcola Energy introduces production-ready hydrogen fuel cell powertrain platform for heavy-duty vehicles*.

87 Hydrogen Task Force (2020). *The Role of Hydrogen in Delivering Net Zero*.

88 Clean hydrogen production includes green hydrogen (produced using electrolysis that draws upon electricity from renewable energy) or blue hydrogen (produced using, for example, Steam Methane Reforming that itself generates CO_2 but which is used in conjunction with Carbon Capture and Storage).

89 SCANIA (2021). *Electrification of an Industry.*

90 The Centre for Sustainable Road Freight (2020). *White Paper: Decarbonising the UK's Long-Haul Road Freight at Minimum Economic Cost*. July.

The roadmap for HGVs has several features in common with the preceding roadmaps for buses and coaches, with a shared reliance upon the development of supporting infrastructure for refuelling and recharging.

5.2 2050 decarbonisation status

By 2050 it is assumed that all HGVs across weight classes can feasibly be zero-emission. Route electrification, BEVs and FCEVs may all form part of the zero-emission future, depending on vehicle duty cycles across use cases and infrastructure roll out[91].

Operationally effective and increasingly resilient supporting recharging and refuelling infrastructure is assumed to be in place to ensure service requirements for vehicle operations are met.

5.3 Fleet turnover

In 2020 the Government announced that, with the UK having left the EU, EU regulations governing emissions of CO_2 from heavy duty vehicles would be copied into UK Law follow the end of the transition period[92]. Given time required for fleet turnover as well as the market readiness opportunity to decarbonise, it is assumed that at or around 2040 – with regulatory support – all new HGVs across all weight classes entering the fleet will be zero-emission at point of use. Moreover, with existing market developments (including substantial prior investment by Government to stimulate and accelerate change in the *bus* sector with resulting spillover effects for HGVs), it is assumed that for lower weight classes, this milestone would be some five years earlier – at or around 2035. As part of its *Ten Point Plan for a Green Industrial Revolution*, the Government announced in November 2020 that it will be consulting on the date for phasing out sales of new diesel HGVs[93]. To further advance the reduction in carbon emissions from HGVs, fiscal and/or regulatory measures should be introduced in the late 2030s to accelerate the removal (or refurbishment) of (older) carbon emitting ICE HGVs. Earlier composition of new vehicle propulsion types entering fleets would in part be determined by Total Cost of Ownership (TCO)

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[91] While Internal Combustion Engine use of hydrogen is a candidate technology, hydrogen power is taken to principally if not entirely be delivered through FCEVs.

[92] Department for Transport (2021). Government response to the consultation on proposals to regulate carbon dioxide emission performance standards for new heavy-duty vehicles in the UK. October.

[93] HM Government (2020). *The Ten Point Plan for a Green Industrial Revolution*. November.

and availability of relevant refuelling/recharging infrastructure (see **Section 5.4**). Reliance on diesel or hybrid vehicles and related use of low carbon fuels should diminish by the end of the 2030s, in line with CCC recommendations. However, fiscal measures to stimulate the shorter-term role of biofuels for in-service ICE HGVs during the 2020s and early 2030s should be considered to encourage a lowering of interim carbon emissions.

It is assumed that to support the ongoing viability of the haulage industry, TCO for zero-emission HGVs will be comparable to diesel equivalents before the late 2030s across all weight classes. If this is not the case then (further) fiscal measures may be required.

Fiscal and/or regulatory measures, informed by research and innovation, should be introduced as appropriate in the early-mid 2020s to (further) catalyse new market dynamics - including vehicle design and co-ordinated fleet purchases and infrastructure investment. The National Infrastructure Commission has recommended that the Government announce by the end of 2021 a ban on the sale of new diesel-powered HGVs by 2040[94].

5.4 Infrastructure development

Decarbonisation of HGVs is dependent upon the co-development of zero-carbon vehicles and the supporting recharging and refuelling infrastructure. The latter is a significant determinant of investing in the former. Infrastructure scaling (in accordance with the appropriate nature and extent determined earlier in the timeline) must be considered across all three candidate solutions to the decarbonisation of HGVs, namely: HRSs (and upstream production and distribution); (rapid) charging points for BEVs; and route electrification. The scaling that is required and deliverable for each is assumed to have been determined by earlier research and innovation (see **Section 5.5**).

While ongoing infrastructure development is expected through to 2050 and beyond, requirements for HGVs as well as long-distance coach services will potentially mean the need for suitable infrastructure to be in place much earlier. Decisions on which pathway(s) to take for HGVs will be informed by research and innovation (but with potential pressure to begin decision making processes and investment planning in parallel with the research and innovation) in the current decade. Potential infrastructure requirements include the following. A minimum viable national network of HRSs needs to be established by the early 2030s (prior to the regulatory requirement for coaches to be zero-emission and to offer a lead-time of confidence to the market for preparing to meet the

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[94] National Infrastructure Commission (2019). *Better Delivery: The Challenge for Freight*. April.

regulatory requirements for new HGVs to be zero-emission at point of use). Meanwhile a minimum viable network of recharging for HGVs (and buses and coaches) will be needed by 2030 at the latest to coincide with the regulatory requirement for buses to be zero-emission and to offer a lead-time to the market for preparing to meet the recommended 2035 regulatory requirement for new HGVs in lower weight classes to be zero-emission. Route electrification may address a proportion of the road network, the scale of which will need to be determined during the 2020s. If trials (see below) determine it has a role in the future HGV landscape, ERS infrastructure would need to be in place by the early 2030s. Failure to progress across this infrastructure delivery (that will have needed to commence in the 2020s) will affect the relative market appeal of alternative options for decarbonisation, framed by the regulatory measures relating to fleet turnover.

5.5 Research and innovation

Short-term requirements in the period 2020-2025 for research and innovation are strongly oriented towards informing the direction and rate of development of refuelling and recharging infrastructure. These requirements are largely shared across heavy road vehicles (HGVs, buses and coaches). Highways England has previously demonstrated its willingness to engage in route electrification trials while highlighting the challenges this will involve. Catenary technology is being trialled on roads in Germany and Sweden. This now needs to be the subject of a UK trial to inform decision making on subsequent scaling. This is in line with the May 2019 CCC recommendation[95]. It is recommended that, building upon such a trial, there should be an electric roads Grand Challenge which – drawing upon related research and innovation for light road vehicles (and largely driven by HGV requirements) – should examine innovative approaches to route electrification (including and potentially extending beyond catenary technology for dynamic conductive charging) thereby helping to concentrate state-of-the-art technology in the UK, with a focus upon how to achieve ‘deliverable efficiency’ in route electrification.

Production of green hydrogen is a key challenge and cost (as noted previously in the **Buses and coaches Section**). There is meanwhile an urgent need to trial a configuration of hydrogen production, distribution and refuelling that can serve HGVs. The trial should be designed such that it serves as a building block for subsequent scaling as well as a source of insight. This trial’s timescale is critical to explore the potential for hydrogen to support HGV decarbonisation and the pathway to achieving this. Allied to this priority (as set out originally in

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[95] Climate Change Committee (2019). *Net Zero – The UK’s contribution to stopping global warming*. May.

the April 2020 draft version of this report) has come the Government's announcement on 30 September 2020[96] of the development of a vision and masterplan for a Multi-modal Transport Hydrogen Hub in Tees Valley (TVTHH)[97]. This centres upon supporting a series of operational trials in the second half of this decade, powered by green hydrogen. As part of its *Ten Point Plan for a Green Industrial Revolution* [98] the Government also announced in November 2020 a £20 million investment in freight trials in 2021 "to pioneer hydrogen and other zero emission lorries, to support industry to develop cost-effective, zero-emission HGVs in the UK".

Analysis should be undertaken to determine the optimal locational configurations for HRSs to support HGV use cases (addressing, in particular, heavier classes of HGVs used for long-haul) as well as use cases for other modes – e.g. ships, trains, coaches and LGVs. Equally, it is important to identify optimal locational configurations for urban, regional and long-haul (rapid) BEV charging points.

As insights from research and innovation emerge, an assessment of market dynamics and technology spillover potential between heavy vehicle use cases should be undertaken. As well as technological innovation there should be an examination of fiscal innovation in terms of purchasing models and market incentives to encourage vehicle operators' behaviours in new zero-emission HGV purchases.

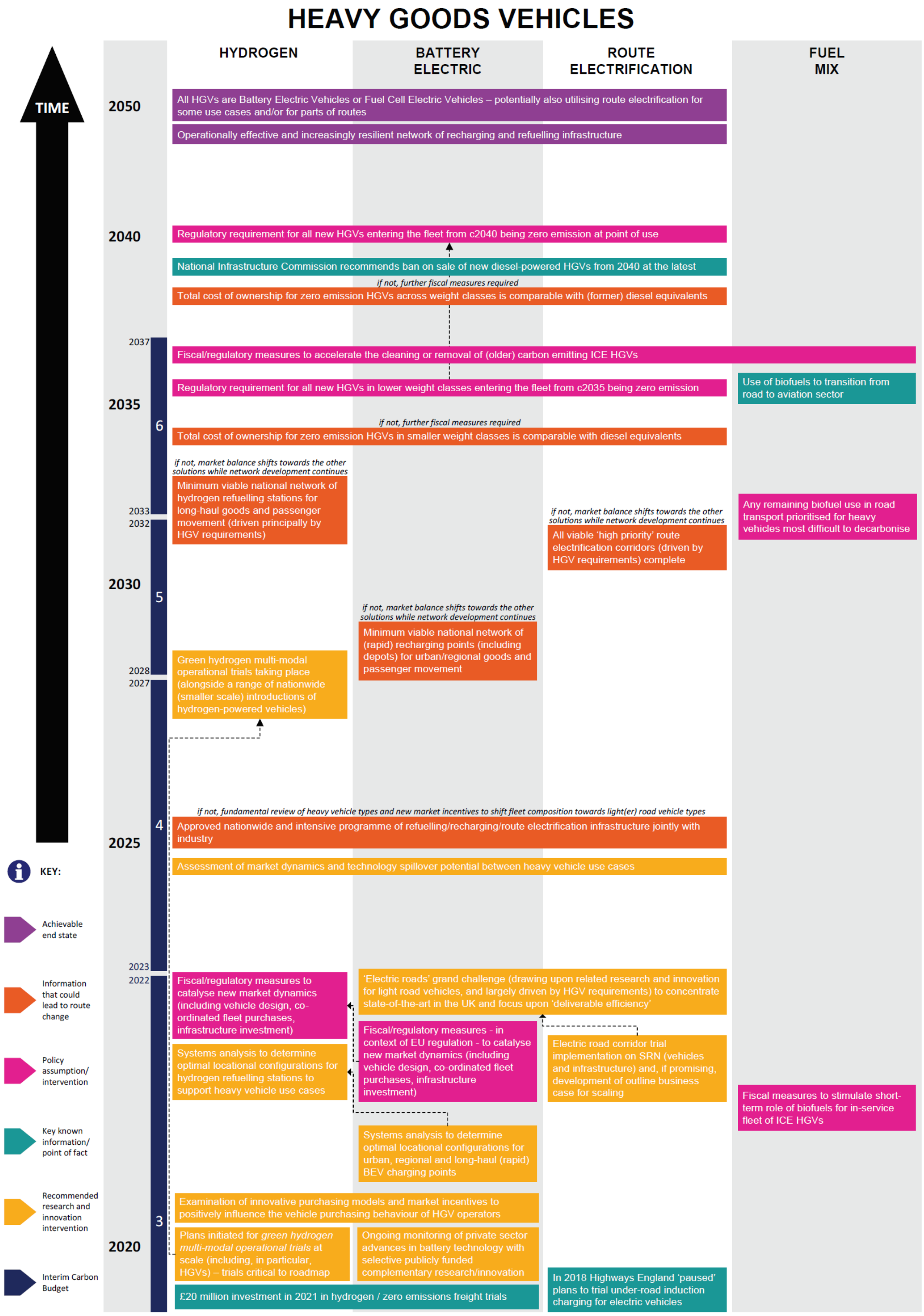
The HGV roadmap is shown in **Figure 5.1**.

[96] HM Government (2020). *UK embraces hydrogen-fuelled future as transport hub and train announced*. News Story, 30 September.

[97] Mott MacDonald (2021). Tees Valley Multi-Modal Transport Hydrogen Hub - Vision, Requirements and Options; and Masterplan. Reports to the Department for Transport, January.

[98] HM Government (2020). *The Ten Point Plan for a Green Industrial Revolution*. November.

Figure 5.1: Heavy goods vehicles roadmap



6 Roadmap: Rail

Rail has good prospects for fully or largely decarbonising its passenger network at point of use by 2050, provided that electrification of the network progresses steadily (supported by battery-electric hybrid locomotives), and hydrogen trains can be deployed to address non-electrified track. Freight is more challenging and may involve changes to operating models.

6.1 Overview

The UK rail sector is already significantly decarbonised at point of use because of its extensive electrified network, covering 38% of the network, 46% of total track kilometres[99] and more than two-thirds of passenger rail use. The industry has also collaborated effectively in developing a shared prospectus on the requirements for further decarbonisation. Network Rail published its decarbonisation report, *Traction Decarbonisation Network Strategy* (TDNS), in July[100]. This reviewed the 15,400 single track kilometres (STKs) that are currently not electrified, and recommended that just over 13,000 should be electrified to achieve (close to) zero-emission in the rail system[101].

The Rail Industry Association has completed a ‘lessons learned’ exercise on previous electrification projects, with recommendations for improvement[102]. In summary, it reviewed the electrification programme since 2007, with a particular focus on GWR’s recent problematic electrification. It recommended that a rolling programme of electrification would be more technically and commercially feasible than the UK industry’s stop-start approach to electrification.

There are multiple barriers to be overcome in getting to, or near to, zero emissions at point of use for the rail industry by 2050. These include the need:

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[99] Office of Road and Rail - *Table 6320 - Infrastructure on the mainline*

[100] System Operator Strategic Planning (2020). *Traction Decarbonisation Network Strategy: Interim Programme Business Case.* Network Rail, July.

[101] Of the balance, it is recommended that 800 STKs should use battery operation, 1,300 should use hydrogen operation, while the remainder, 260 STKs, has no clear decision yet on the best option.

[102] Railway Industry Association (2019). *RIA Electrification Cost Challenge*.

- to continue the electrification of those parts of the network where it makes operational sense, while avoiding, to the extent possible, passenger disruption and the delivery missteps of the past;
- for infill electrification in some parts of the network;
- to roll out hydrogen, battery-electric or battery-electric hybrid trainsets on non-electrified parts of the network; and
- to develop an effective decarbonisation strategy for freight, given the current 'go anywhere' operational model[103]. Credible non-carbon-emitting solutions for heavier freight beyond rail electrification are dependent on significant improvements in battery technologies[104].

A key part of reaching zero emissions for passenger services by 2050 is the need for substantial track electrification. The UK's rail network is significantly less electrified than European comparators[105]. The TDNS proposes that around seven-eighths of the network should be electrified to reach zero emissions. If this is to be done by 2050, it involves a relatively ambitious programme of electrification averaging 435 STKs per year over 30 years. Part of the rationale for the extent of this programme is that it makes possible decarbonisation of almost all of the network's freight operations. There are also operational benefits to rail freight, including train speed and weight pulled, that have positive effects for network operations as a whole[106].

Complementary to electrification is the role for hydrogen and battery powered trainsets, which under the TDNS recommendations would be deployed on the minor percentage of the network that was not electrified. Hydrogen and battery trains have similar performance characteristics, with speeds in the 75-100 mph range and re-charging times of around 15 minutes[107].

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[103] Rail freight is currently four times more carbon- and energy-efficient than road freight, as the RSSB notes. RSSB (2020). *Decarbonisation and air quality improvement: a roadmap for the rail freight industry*. T1160.

[104] RSSB (2020). Decarbonisation and air quality improvement: a roadmap for the rail freight industry. T1160, p.53.

[105] Railway Industry Association (2019). *RIA Electrification Cost Challenge*. Page 11.

[106] System Operator Strategic Planning (2020). *Traction Decarbonisation Network Strategy: Interim Programme Business Case.* Network Rail, July. p. 55.

[107] System Operator Strategic Planning (2020). *Traction Decarbonisation Network Strategy: Interim Programme Business Case.* Network Rail, July. p. 70-71.

Hydrogen trials are already advanced in other countries. The world's first hydrogen train, produced by Alstom, is operating passenger services in Germany and has recently been trialled in the Netherlands; it has a reported range of around 1,000 km[108]. Government-backed orders for hydrogen trains have followed in Germany. In the UK, the first hydrogen HydroFLEX trials took place in September 2020, in the East Midlands[109]. These were supported by a £750,000 grant from the DfT.

Electric batteries have a similar role to play. Even with a step-change in energy density, stakeholder interviewees suggested that it is unlikely that battery-powered passenger trains would have a range much greater than 100 miles. The current generation of battery trains, which have been trialled in the UK and elsewhere, have a reported range between charges of 60 miles, and an associated rapid charging system[110]. Hitachi and Hyperdrive have announced a battery development programme for the rail sector that combines Hitachi's experience of running battery-driven trains in Japan with Hyperdrive's knowledge of battery innovation in the auto-sector[111].

In the short to mid-term, as a strategy to reduce carbon emissions from diesel units, hybrid diesel-electric trains are being introduced[112]. Using battery in an on/off battery-electric hybrid overcomes some of the problems associated with the continuing electrification of the network, allowing engines to maintain power within gaps in the electrified network. Battery-electric hybrids will therefore be critical while the network is being electrified, and likely thereafter. Several companies have developed prototypes of battery-electric hybrids[113].

The Rail Industry Decarbonisation Taskforce noted that for freight, *"electrification is currently the only viable 'net zero' option"*[114]*.* The electrification

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[108] Alstom (2020). *Alstom's hydrogen train Coradia iLint completes successful tests in the Netherlands*.

[109] BBC News (2019). *All aboard Britain's first hydrogen train*.

[110] Railway Technology (2019). *Vivarail launches fast charge system for the Class 230 battery trains – the UK's only battery train with a range of 60 miles between charges.* March.

[111] Rail Advent (2020). *Improved battery powered trains to come following new Hitachi Rail and Hyperdrive partnership*.

[112] Porterbrook. *Porterbrook launch first UK hybrid rail project*.

[113] Thorne, R., Amundsen, A. and Sundvor, I. (2019). *Battery electric and fuel cell trains: Maturity of technology and market status.* TØI report 1737, Institute of Transport Economics, Norwegian Centre for Transport Research.

[114] Decarbonisation Taskforce (2019). *Final Report to the Minister for Rail*. With the support of RSSB, July.

programme proposed in the TDNS will enable most of the network used for freight operations to be decarbonised. It estimates that residual freight operations outside of this will lead to emissions at 3% of current 2020 levels, unless decarbonised freight power units are developed[115]. Diesel freight trains are currently deployed on some largely electrified lines because there are relatively small gaps in the electrified sections, and these will be addressed through the continuing electrification programme. Beyond this, however, there is currently no credible power source that is projected to have sufficient density to move fully laden freight trains on the non-electrified sections, without displacing much of the load with the necessary power source.

Options to achieve a full zero emissions outcome on the rail system would include: restricting freight services to core electrified sections; the use of low carbon drop in fuels in place of diesel; and different approaches potentially involving smaller loads on non-electrified sections. The latter would not be commercially attractive to a sector operating on small margins. If some emissions are tolerated, through offsetting, then diesel bi-modes[116] may be part of the approach to freight[117]. Removal of all freight emissions would involve electrification of 98% of the network, which the TDNS report discounts for cost-benefit reasons. Sections of track where there were limited or irregular freight operations were not recommended for electrification[118].

The Rail Safety and Standards Board (RSSB) project T1160, *Decarbonisation and air quality improvement of the freight rail industry*, which reported in 2020, notes that electrification is the most robust and effective method of rail freight decarbonisation, but there is potential to use alternative self-powered options for rail freight (e.g. natural gas, battery or hydrogen traction). These would need to be tested operationally. They would require changes in current operations management and are dependent on further research and innovation[119].

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[115] System Operator Strategic Planning (2020). *Traction Decarbonisation Network Strategy: Interim Programme Business Case.* Network Rail, July. p. 76.

[116] Which can operate on electric power where available, but also have diesel engines fitted that provide power on non-electrified sections of the network.

[117] Decarbonisation Taskforce (2019). *Final Report to the Minister for Rail*. With the support of RSSB, July.

[118] System Operator Strategic Planning (2020). *Traction Decarbonisation Network Strategy: Interim Programme Business Case.* Network Rail, July.

[119] RSSB (2020). Decarbonisation and air quality improvement: a roadmap for the rail freight industry. T1160.

6.2 2050 decarbonisation status

By 2050 it is anticipated that the rail network will be electrified wherever it makes operational sense, and that battery-electric hybrid and some infill electrification will take care of remaining gaps. Hydrogen and battery passenger trains will be deployed on regional lines with lower expectations of speed (around 75-100 miles an hour). The main freight arteries will have been sufficiently electrified to enable battery-hybrid freight trains to run end-to-end on these electric lines. Without power train or fuel source innovation, or different network rules governing freight operations, there will be small residual emissions from freight operations that will need to be offset.

6.3 Fleet turnover

In theory, locomotives have an order time of 2-3 years, a service life of around 35 years, and are refurbished around half-way through this. A train ordered today would be expected to run until around 2060. In practice, many are used for longer. Some diesel engines operating on UK railways are more than 60 years old.

Alongside electric propulsion, around 30% of passenger trains operating on UK tracks are currently diesel-based (diesel or diesel bi-mode). However, a significant number of diesel multiple units (DMUs) are due to be phased out around 2040. This has informed the Government's ambition to phase out all diesel-only trains by 2040[120].

In addition, the RSSB calculates that seven-tenths of the UK freight fleet will need to be replaced in the two decades after 2024, depending on service life assumptions[121].

The lifetime of locomotives means that new diesel engines are already likely to become 'stranded assets' for their owners, depending on policy decisions made on how to progress towards net-zero by 2050. This has so far had the perverse effect of delaying fleet turnover and prolonging the use of older, dirtier diesel

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[120] The passenger fleet has a clear transition path in this timeframe, through a combination of electrification, battery and hydrogen. Because freight trainsets are heavier, and because of the 'go anywhere' freight business model, rail freight's transition path is less assured without either a step-change in powertrains or a change in business model.

[121] RSSB (2020). Decarbonisation and air quality improvement: a roadmap for the rail freight industry. T1160, p.14

engines that are still in service[122]. Leasing structures have also encouraged the purchase of diesel rolling stock that is under-utilised. Retrofitting existing diesel engines to bi-mode or tri-mode is unwieldy.

6.4 Infrastructure development

The UK does not have a compelling record of rail electrification. Costs per mile of electrification have varied widely, even after controlling for topography and track. The programme of electrification has been stop-start due to uneven government approaches to the sector and cost and implementation issues. Research by the Rail Industry Association into more effective electrification programmes elsewhere, assessed by cost per kilometre and operational implementation, suggests that the optimal approach to electrification is to approve a steady programme that proceeds over time until electrification is completed wherever it is operationally beneficial, supported by some infill[123]. There are also significant operational lessons to be learnt from elsewhere.

Achieving electrification on all lines where it is operationally effective and cost-effective by around 2050 requires a continuing commitment to electrification. This enables several programme delivery crews to be permanently deployed, ensuring that technical and operational knowledge is captured and maintained. The RIA estimates that such a delivery crew could electrify 75-100 STKs per year[124]. This approach is also recommended by the CCC[125].

The TDNS Pathway 3 proposes electrification of around 435 STKs per year, averaged from 2021 to 2050[126]. In practice, it would take time to build the necessary skills and expertise, which implies that higher rates of electrification would be required in later years. The TDNS has not yet published a delivery

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[122] Mayers, M. and Bamford D. (2019). Decarbonising Britain's railways demands urgent action – here's how it could be done. *The Conversation*, 30th October.

[123] Railway Industry Association (2019). *RIA Electrification Cost Challenge*. Page 26.

[124] Railway Industry Association (2019). *RIA Electrification Cost Challenge*. Page 8.

[125] CCC (2019). *Net Zero – Technical Report*. Committee on Climate Change, May.

[126] Table 15 of the TDNS states that average annual electrification under Pathway 3 is 355km. However, the report proposes electrification of 13,040km of STK over 30 years.

report, but calculations for the interim report suggest that annual electrification would peak at 691 STKs[127].

The TDNS makes this assessment on the basis that the historic data in the RIA report suggests it is *"within the capabilities of the supply chain, subject to steadily building up activity from the present low level"*[128]. The industry has exceeded 450 STKs in only five of the last 50 years, and one of those years led to the widespread disruption to GWR, as reviewed in the RIA report. Qualitative assessment of capability from our interviewees would also imply that this target is at the ambitious end of realistic. In particular, developing a credible and urgent skills plan appears critical.

In general, electrification also requires new charge points to be installed by National Grid to provide power to the line. These currently have an order-to-install time of seven years.

The rail system will need access to a hydrogen supply and refuelling infrastructure. In contrast to other modes, the scheduled nature of passenger train services means that the hydrogen demand from rail is predictable. It could act as a baseload customer for a hydrogen production facility, and it should be straightforward to agree an optimal provision plan.

In the event that it proves impossible to electrify the rail network at the rates proposed in the TDNS, a heavier load will fall on battery, hybrid battery-electric, and hydrogen powered units to ensure decarbonisation in the interim period after 2050 while electrification is being completed. Such a shortfall will also increase the proportion of freight traffic that contributes to emissions, in the absence of a non-fossil fuel solution. For this reason, it is important that the rail decarbonisation plan includes regular reviews of rates of overall progress towards electrification, coupled with reasonably aggressive progress towards deployment of hydrogen and battery-powered trains on the network.

6.5 Research and innovation

Hydrogen and battery are anticipated to be a solution to delivering zero-emission passenger services on less busy regional routes, together with electric/battery bi-modes that extend the range of trains beyond the electrified network. HydroFLEX, the first trial of hydrogen trains on British railways, took

[127] System Operator Strategic Planning (2020). *Traction Decarbonisation Network Strategy: Interim Programme Business Case.* Network Rail, July. p. 136.

[128] System Operator Strategic Planning (2020). *Traction Decarbonisation Network Strategy: Interim Programme Business Case.* Network Rail, July. p. 123.

place in September 2020 in the East Midlands, as part of Abellio's franchise. Hydrogen powered trains are also expected to form part of operational trials of the Multi-Modal Transport Hydrogen Hub in Tees Valley (TVTHH), plans for which were announced on 30 September 2020 by the Secretary of State[129].

Other countries are ahead of the UK in deployment. Although different infrastructure and track configurations mean that it is not possible to import continental locomotives to the UK, there will be gains in learning about deployments elsewhere and adapting technologies used elsewhere. To ensure delivery of decarbonisation targets, the Hydroflex trial needs to be seen as only the first step in an accelerated programme of development, informed by interim targets.

Accelerating the development of battery-electric hybrids is also important, for reasons of both emissions reduction and air quality improvement. Speeding up the prototyping and development process is valuable.

Electrification can be accelerated by selective use of 'third rail' electrification[130]. This has generally been discounted in the UK for safety reasons, but this is currently being reviewed with the Regulator[131]. A feasibility study being conducted by Network Rail, RSSB and the ORR is evaluating the possibility for a 'modern day conductor rail' where overhead electrification does not make operational sense[132].

Beyond offsetting, one solution to the emissions from freight on non-electrified sections is the development of alternative low carbon fuels. It is generally assumed that deployment of biomass-derived fuels will be prioritised in other sectors where the decarbonisation challenges are more critical[133]. While it seems likely that RFNBOs will remain too expensive for use in a low-margin sector such as rail freight, the rail industry should engage with sustainable fuel trials in other sectors such as aviation.

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[129] HM Government (2020). *UK embraces hydrogen-fuelled future as transport hub and train announced*. 30 September News Story.

[130] A live rail able to provide electric power, as an alternative to catenary delivery of power.

[131] Office of Rail and Road (ORR)

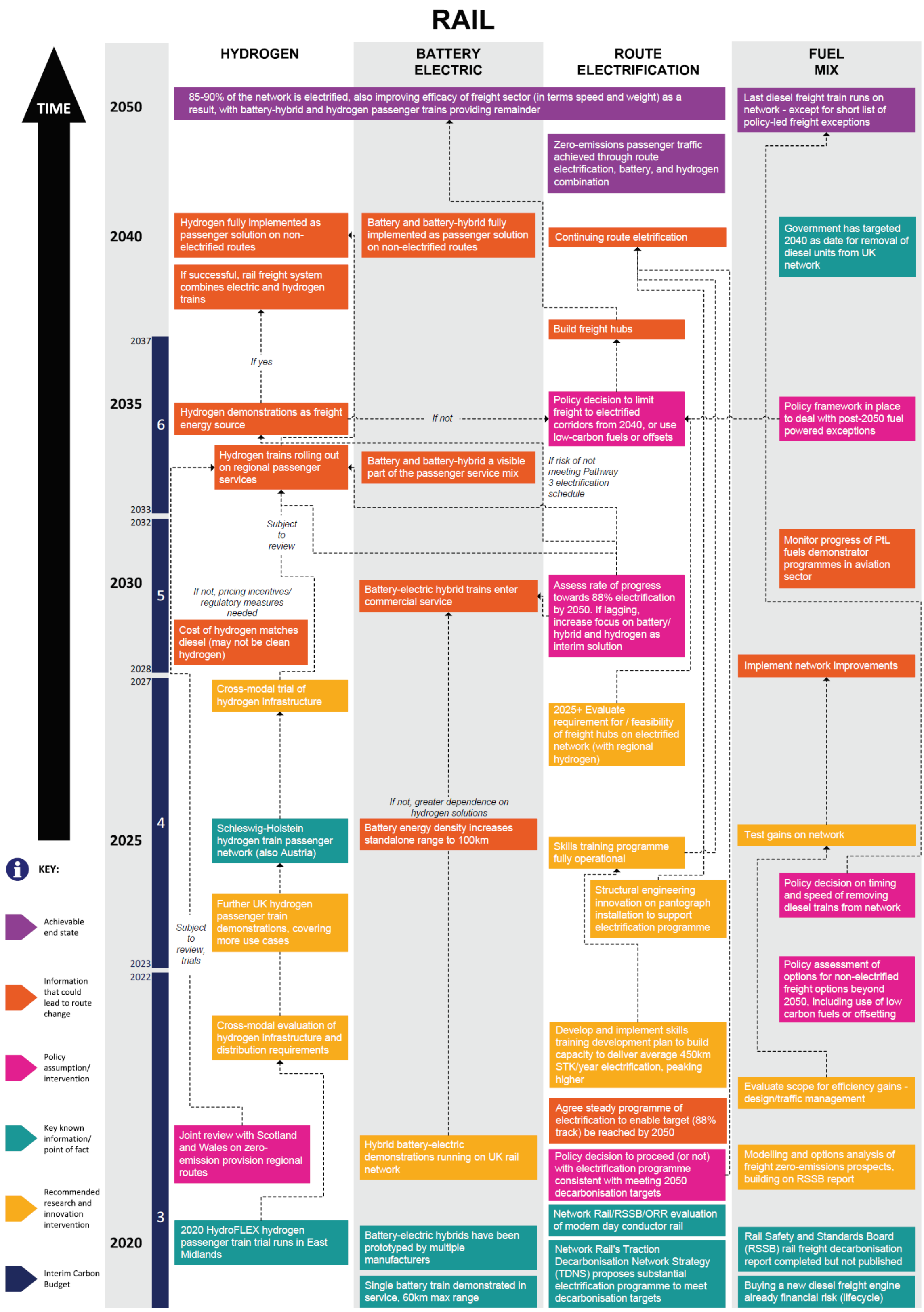
[132] System Operator Strategic Planning (2020). *Traction Decarbonisation Network Strategy: Interim Programme Business Case.* Network Rail, July. p. 85.

[133] RSSB (2020). Decarbonisation and air quality improvement: a roadmap for the rail freight industry. T1160, p.63.

Rail, like other modes, will benefit from any step changes in battery energy density and performance. However, it is likely that this innovation will come as a spillover from development of road vehicles where greater dependence for decarbonisation rests upon BEVs. The rail industry can learn from developments in the auto-sector, which will scale knowledge faster.

The rail roadmap is shown in **Figure 6.1**.

Figure 6.1: Rail roadmap



7 Roadmap: Domestic shipping

Domestic and international shipping volumes are expected to increase, meaning that reducing emissions will be challenging. Depending on the size of the vessel, significant decarbonisation is possible through: battery-powered vessels; low-carbon fuels like hydrogen, ammonia and methanol; and wind-assistive technology.

7.1 Overview

In contrast to other modes, the shipping sector is fragmented in terms of production, operations and ownership, and there is a wide range of use cases. Further, different technology options may be applicable for decarbonising domestic shipping (which is more focussed on small to mid-sized vehicles that may benefit from battery and hydrogen fuels) than for international shipping (which may be more reliant on higher energy density fuels like ammonia and methanol as well as wind and exhaust treatment technologies like Carbon Capture and Storage (CCS)). While international shipping is formally out of scope for the roadmap, we include related technologies in the discussion here because of the potential for technology development spillovers from the international to the domestic market and because international carbon emissions are incorporated into UK targets in the Committee on Climate Change's *Sixth Carbon Budget* report[134].

Progress towards decarbonisation to date is modest in the form of several trials, demonstration systems, and prototypes. More impetus is needed to drive forward zero-emission platforms in shipping and create sufficient sectoral momentum and scaling.

Emissions from shipping vessels can be tackled in three main ways:

a. substituting existing fuels with low carbon fuels, including (green) hydrogen, ammonia and methanol, as well as (where appropriate) battery electric vehicles;
b. improving fuel efficiency through technological advances (e.g. wind assistive technologies and other design improvements); and
c. treating exhaust emissions, for example through CCS.

[134] Committee on Climate Change (2020). *The Sixth Carbon Budget: The UK's path to Net Zero*. December.

Utilisation of new low carbon fuels will also require substantial infrastructure investment to produce, distribute and store these greener fuels.

In the short-term (early 2020s), research and innovation is required in all areas to help guide decisions about the most promising interventions and long-term investment strategy to support getting to zero emissions for *domestic* shipping by 2050. This will allow for scaling and infrastructure development in the 2030s and 2040s. Whilst removal of direct emissions for domestic shipping may be achievable there are higher levels of uncertainty than for some other modes (cars and LGVs, HGVs, buses and coaches, and rail), because of the reliance on the development of new technologies that are not yet in the market. However, the UK has the potential to be a sectoral leader here.

7.2 2050 decarbonisation status

To reach zero emissions by 2050 domestic shipping will have transformed the inshore fleet to battery, incorporated innovations in low carbon fuels for medium-sized and larger vessels, and incorporated innovation in (assistive) windship technology. Efficiency improvements will also have been obtained through vessel design. Onboard CCS technology may be required for larger vessels, particularly for international shipping. Shipping will have worked with other modes/sectors to achieve decarbonisation, since there are overlapping issues in the development of both sustainable fuels and hydrogen, as well as production and distribution infrastructure. Decarbonising international shipping will likely require aligned international efforts and well-developed incentives and regulation, and failure to adopt such measures in the near term will increase pressure for individual states to take steps to address international emissions.

7.3 Fleet turnover

According to the International Transport Forum, the long lifetime of ships – around 25 years – means that new technologies developed today may take decades to be adopted by the full shipping fleet. They advise that this effect can be partly mitigated through the use of retrofits and by ensuring flexibility of existing engines and fuel distribution systems for future fuels[135].

7.4 Low carbon fuels

A key pathway to decarbonisation is the development and use of low carbon fuels and specifically those of non-biological origin (RFNBOs). These include hydrogen, ammonia and methanol which could be produced in several different

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135 International Transport Forum and Nordic Energy Research (2020). *Navigating towards cleaner Maritime shipping: Lessons from the Nordic region*.

ways, including from fossil fuels (with CCS) or from electrolysis using renewable electricity[136]. A study for the DfT looking at reducing the maritime sector's contribution to climate change concludes that small changes in cost and efficiencies of these low carbon fuels could change commercial incentives to shift towards any of these options. This substantial uncertainty around both the costs and efficiencies of these fuels means that it is important "*to keep open multiple options for alternative low emission fuels until there is greater clarity over the potential pace of technology development and cost reduction and the magnitude of potential changes in the costs if using these fuels in the maritime sector"*[137]. Moreover, different fuels are likely to be more appropriate for different use cases. It is therefore important that trials are undertaken with hydrogen, ammonia and methanol (including any retrofitting needs), and that these trials be undertaken in the early 2020s to allow time for scaling of technology take-up in the 2030s and 2040s[138]. It may also be beneficial to monitor sustainable aviation fuel trials in case it is possible to scale these for shipping purposes. As well as evaluating the efficiency and costs of fuels, trials should evaluate infrastructure requirements for use of RFNBOs (including production, distribution and storage), integrated with other modal assessments, as well as skills requirements. For hydrogen, there may be benefit in including shipping vessels along with other modes in clusters of hydrogen trials, e.g. HGVs and rail.

While biofuels may be helpful to reduce carbon emissions in the short to medium term, the demand for biofuels for (international) shipping would far exceed supply of these fuels and therefore they are not expected to be a priority for shipping in the longer term. The International Transport Forum emphasises

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[136] The CCC in the Sixth Carbon Budget report focusses on ammonia as a promising low-carbon fuel on the basis that the "vast majority of existing ship types and sizes can be retrofitted to burn ammonia.

[137] Smith, T., O'Keeffe, E., Hauerhof, E., Raucci, C., Bell, M., Deyes, K., Faber, J. and 't Hoen, M. (2019). *Reducing the maritime sector's contribution to climate change and air pollution: Scenario Analysis: Take-up of emissions reduction options and their impacts on emissions and costs*. Report for the UK Department for Transport.

[138] There are trials of some small hydrogen ferries already in operation in the UK. In March of this year, the EU funded a consortium of 14 European countries, including the UK, to install the world's first ammonia-powered fuel cell on a vessel. We are not aware of any trials of methanol powered ships.

that clear sustainability criteria will be needed for advanced biofuels, including taking account of their impacts on land-use[139].

It will be necessary to roll out fuelling infrastructure in the 2030s. This will require understanding of what fuels will be appropriate for what use cases, which should be evaluated in the 2020s. Clearly, if it is feasible to bring forward roll-out of refuelling infrastructure that would be beneficial. It may be appropriate to build clean maritime clusters, accommodating multiple use cases. It will be essential to monitor and incentivise take-up of low carbon fuels in the later 2030s and 2040s. Fiscal policy incentives, such as carbon taxes on conventional fuels, may be important here[140]. It is essential that suitable infrastructure is put into place in the UK's ports and harbours to support this zero-emission maritime economy in this time period. In some places, this may be integrated strategically with other modes (e.g. HGVs and rail).

7.5 Battery electric

With increasing battery density, electrification will be feasible for short or inshore routes. Trials should be undertaken to explore use cases where battery electric power will be appropriate, or in the short-term where hybrid solutions will support decarbonisation[141]. Critical issues to explore include: (i) the role of retrofitting to increase take-up of electrification in the short-term; and (ii) required provision of power supply at ports/harbours. Similar to other modes, in the short-term there is a 'chicken and egg' problem between vessel electrification and provision of charging infrastructure: vessel owners have no incentive to move to battery electric options if harbours do not provide charging infrastructure and harbours do not have the incentive to supply charging infrastructure if there is no demand. Policy studies will therefore be required to explore how to best scale take-up of battery electric vessels and provision of necessary charging infrastructure. Monitoring take-up of battery electric options, provision of infrastructure, pushing trials where necessary and policies to encourage take-up will be important in the late 2020s and early 2030s. It will be

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139 International Transport Forum and Nordic Energy Research (2020). *Navigating towards cleaner Maritime shipping: Lessons from the Nordic region*.

140 Shipping emissions are not currently subject to a carbon price. Between July and September 2020 HM Treasury consulted on a Carbon Emissions Tax. Responses to this consultation are currently being reviewed.

141 A rapid update of (hybrid) battery-electric propulsion systems for small ferries has occurred over recent years. Three hybrid roll-on/ roll-off ferries are in operation in the Clyde and Hebrides Ferry Service. A further hybrid ferry is operated by Wightlink between Portsmouth and the Isle of Wight.

essential that all ports are grid and battery enabled by the 2040s so it is feasible to stop licencing petrol and diesel vessels.

7.6 Wind-assistive technologies

The wind propulsion sector is growing, with most technologies at late stage development. Such technologies could provide large carbon emission reductions, particularly for specific use categories (typically small vessels or larger vessels moving more slowly). It is noteworthy that the factor that caused the changeover from wind to coal in the early 20th century was scheduling: wind was cheaper but could not guarantee scheduled deliveries. Thus, changes in behaviour to support non-time critical cargo delivery may be required to support take-up of wind technology[142]. Wind-assistive technologies are also complementary to other technologies in terms of decarbonisation. As with aviation, there may be benefit from a sectoral challenge in the 2020s, building on Britain's marine engineering expertise. In addition, there are signs of market failure, where the business case for retrofitting existing vessels or converting to new ones is hampered by financing considerations, i.e. that the initial cost of the vessel is higher, but the total cost of ownership (TCO) is lower. The City of London could utilise its emerging *Green Finance* capability to help resolve this issue. In the 2020s it will be important to trial windship-assistive technologies. Incentives may also be required to encourage their take-up. Assessment of whether wind-assistive vessels will be effective in terms of decarbonisation will need to be undertaken by 2035 to allow take-up of other options, e.g. on-board CCS, batteries or new low carbon fuels.

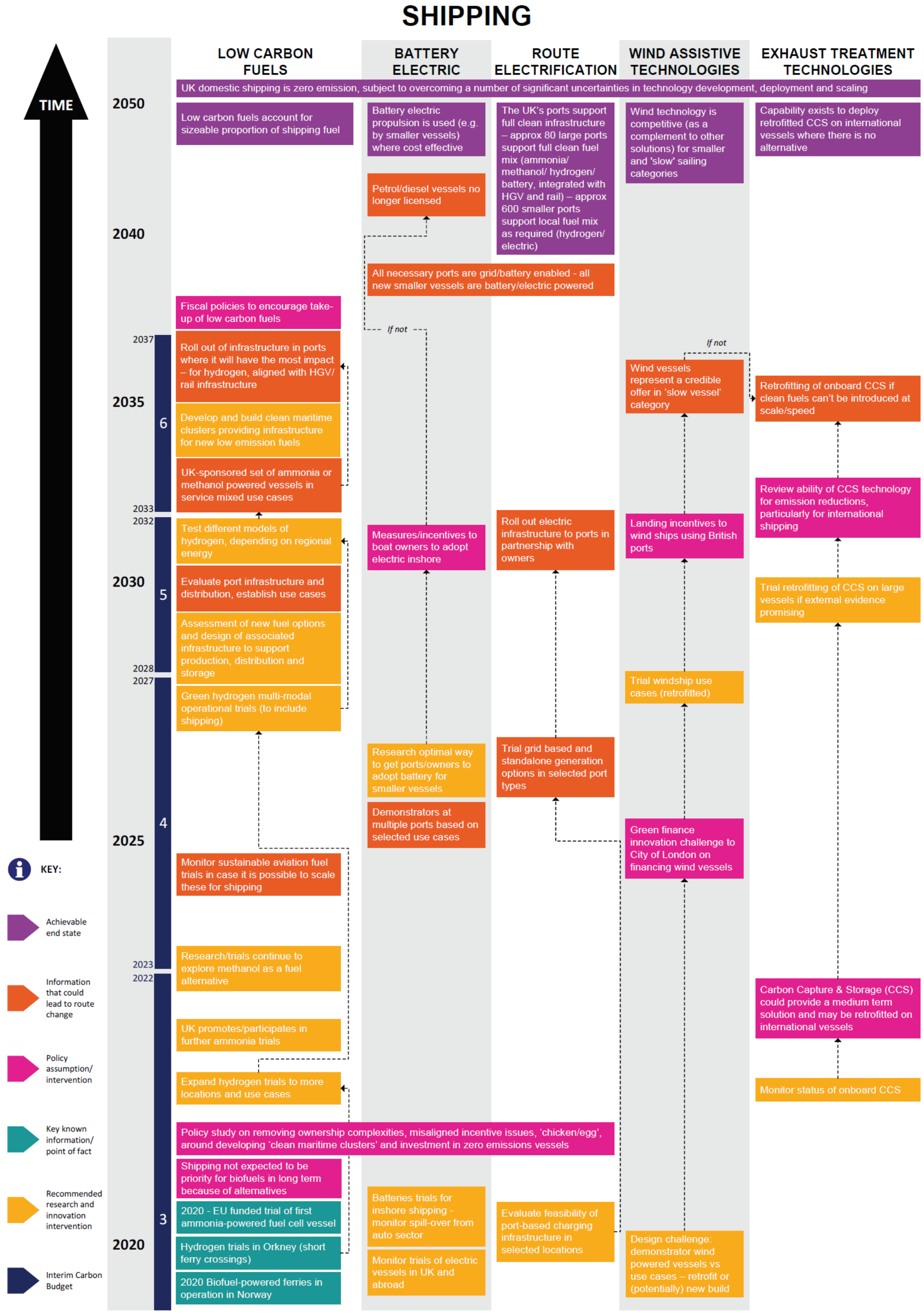
7.7 Exhaust treatment technologies

CCS can potentially reduce CO_2 emissions from the exhaust up to 85-90%. However, it is unlikely to be a long-term solution for domestic shipping, given development of low or zero-carbon fuels, but it may be important technology for international shipping vessels in the short- to medium-term. CCS may also offer an option of last resort, if other technologies do not progress at the necessary speed for development and scaling. It is therefore important to monitor the status of CCS technology in the early 2020s and trial the scope for onboard CCS in the 2030s.

The domestic shipping roadmap is shown in **Figure 7.1**.

[142] This report focusses on potential technology solutions for decarbonisation. But an important behavioural response in shipping to reduce carbon is to reduce speed of travel, which could lead to significant reductions in carbon emissions.

Figure 7.1: Domestic shipping roadmap



8 Roadmap: Domestic aviation

Domestic aviation has the prospect of achieving significant decarbonisation at point of use by 2050, depending on the progress towards commercial deployment of hydrogen planes. The aviation sector can take steps towards reducing emissions through design and flight management changes. There is some, limited, scope for fuel innovation. Alternative technologies are at an early stage, but mid-range hydrogen planes and smaller short-haul electric planes should be part of the service mix by 2050.

8.1 Overview

A longer overview is included for domestic aviation to ensure important context for the roadmap that follows is in place, particularly given the challenges of removing some degree of direct CO_2 emissions.

In broad summary, there are four ways to reduce aviation emissions at point of use. These are, in likely order of impact over time:

- improvements in fuel efficiency of existing aircraft, through performance measures and design;
- changes in operational aviation design, notably changes to flightpaths and flight management regimes;
- the introduction of sustainable aviation fuels, and more speculatively Direct Air Capture and Carbon Storage (DACCS); and
- the introduction of aircraft that are powered differently, including battery-powered craft and hydrogen-powered planes. These are still in the development stage. Battery-powered planes are expected to have a range of up to 400km by 2050. For reasons determined by aircraft life and innovation phasing, hydrogen planes - with a potential range of up to 1,000 km - should start coming into the air fleet from around 2050.

These approaches are reviewed more fully below.

It is generally accepted that taken together these measures will not reduce *global* aviation emissions at point of use to zero by 2050. The Committee on Climate Change (CCC) has noted that there "*are currently no commercially available zero-carbon planes*"[143]. Independent reviews of decarbonisation prospects tend to assume that decarbonisation of commercial aviation is

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[143] Committee on Climate Change (2019). *Net Zero technical report*.

possible for short- and medium-range craft in a 20-30 year timeframe[144]. Aerospace industry leaders have noted that "*At present we know of no other single technological pathway to decarbonise long haul flights at scale other than… sustainable fuels*"[145]. An industry-led review by the Sustainable Aviation group, assumed that if the UK industry were to achieve zero emissions by 2050 it would do this only through substantial carbon offsetting, accounting for more than a third of carbon emissions[146,147].

Technology developments in the aviation sector should therefore make it possible for the *domestic* aviation sector to get close to zero emissions in the 2050s, if current projections for evolution of battery and hydrogen planes prove correct.

In the interim, reduced emissions are likely to come from improved design and operational efficiencies. Sustainable aviation fuels (SAF) may contribute at the margins.

It is likely that between now and 2050 the UK's non-domestic emissions will be included in UK targets. The CCC recommends inclusion of international aviation in the net zero target in its *Sixth Climate Budget*[148]. We therefore review briefly the prospects for international aviation at the end of this section.

Differently powered aircraft

Battery

Small battery-powered aircraft are being trialled[149]. The general view is that commercial use of larger battery-powered aircraft is around 20 years away. This

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144 For example: IATA (undated [2019]). Aircraft Technology Roadmap to 2050; McKinsey (2020). How airlines can chart a path to zero carbon flying; Clean Sky 2 and FCH2 (2020). Hydrogen-powered aircraft.

145 Hollinger, P. (2020). Aerospace executives warn on need to press green fuel use'. *Financial Times*, 12 October. Their letter to the International Civil Aviation Organization appears not to have been published. Its signatories were the chief technology officers of Boeing, Airbus, Rolls-Royce, General Electric, Safran, Dassauly Aviation, and Raytheon.

146 SA (2020). *Decarbonisation Road-map: A Path to Net Zero – A plan to decarbonise UK aviation*. Sustainable Aviation.

147 The Guardian (2020). 'UK air industry sets zero carbon target despite 70% more flights'.

148 Committee on Climate Change (2020). *The Sixth Carbon Budget: The UK's path to Net Zero*. December. p. 95.

149 For example, a Vancouver company has retrofitted a six seater seaplane with an electric motor. Commercial use is at least two years away. See link.

is dependent on a step-change in battery performance. The International Air Transport Association's (IATA) roadmap sees battery coming into general use in the 2040s[150]. Airbus had a stated intention to introduce a 100-seater electric craft to commercial service by 2035, but more recently has said in public that battery technology is not improving quickly enough (and hence its recent pivot to hydrogen, discussed below)[151]. Nonetheless, the Aerospace Technology Institute (ATI) anticipates a gradual introduction of small battery powered aircraft, initially on short journeys, from around 2030[152]. Technical, commercial, and operational timescales for implementation are likely to vary. McKinsey suggested in 2020 that "*the use of fully electric aircraft carrying more than 100 passengers appears unlikely within the next 30 years or longer*"[153].

By 2050 it is expected that battery powered aircraft will have a range of up to 400km. For the purposes of domestic aviation, it is credible to believe that by 2050 these will be able to service flights from Belfast to the north of England and Scotland, and Britain's island communities. Shorter flights (for example servicing the Scottish islands) will be practicable sooner.

Hydrogen

As mentioned below, it is feasible that by 2050, hydrogen-powered planes are entering short-haul commercial service. Small hydrogen-powered planes are currently being trialled in New Zealand and Germany. ZeroAvia completed a test flight in the UK with a six-seater plane in September 2020, with financial support from the UK Government[154]. The company aims to deliver a 500-mile, 10-20 seat plane in the US by 2022[155]. Airbus has recently unveiled three 'concept' hydrogen planes, with the intention of introducing one into commercial service by 2035. However, the IEEE noted that most of the specifications will not be known "*for several years*"[156]. A recent EU report assessed that hydrogen

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150 IATA (undated [2019]). Aircraft Technology Roadmap to 2050.

151 FlightGlobal (2020). Airbus turns to hydrogen as energy promise of batteries fades. 21 September.

152 ATI (2019). *Accelerating Ambition: Technology Strategy 2019*.

153 McKinsey (2020). *How airlines can chart a path to zero carbon flying*.

154 Aviation Today (2020). *ZeroAvia Completes First Hydrogen-Powered Flight*.

155 Fuel Cell & Hydrogen Energy Association (2019). *Aviation*.

156 IEEE Spectrum (2020). Airbus Plans Hydrogen-Powered Carbon-Neutral Planes by 2035. Can They Work? 12 October.

propulsion "*is best suited for commuter, regional, short-range and medium range aircraft*"[157].

Hydrogen has four times the volume of kerosene for the same amount of energy, but one-third of the weight, and safety considerations require that it is stored in the body, not the wings, which has consequences for aircraft design. The Financial Times' Lex column noted "*[t]he extra weight and space involved would probably make hydrogen uneconomic for long-range aircraft*"[158]. Hydrogen does not appear on the IATA roadmap, because of concerns about the required scaling of the global hydrogen supply[159].

This concern was shared by the Clean Sky 2 EU report, which noted that long-range hydrogen-powered flight required new designs and "*may be at least 20 years away from entering into service*". The report suggested that the introduction of a short-range hydrogen-powered aircraft was "*an inspiring mid-term target*"[160]. Nonetheless, industry sources project that hydrogen planes could have a range of up to 1,000 miles by 2050, which covers all domestic flights, and is also sufficient for the majority of flight movements from UK airports.

Design and operational improvements

Fuel efficiency and performance

The current generation of planes coming into service is significantly more fuel efficient than earlier generations. In addition, aircraft design improvements will also reduce emissions. The industry (Sustainable Aviation group) decarbonisation roadmap estimated that design improvements would improve fuel efficiency by 17% by 2050, compared to its 2016 baseline, and that most of these gains would be seen by 2040[161].

Further gains can be achieved by the implementation of hybrid-electric or hybrid-low carbon fuel engine configurations, where, typically, one of four engines would be powered by an alternative power source.

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[157] Clean Sky 2 and FCH2 (2020). Hydrogen-powered aviation: A fact-based study of hydrogen technology, economics, and climate impact by 2050.

[158] Lex (2020). *Hydrogen/aviation: coming clean*. Financial Times, 25 September.

[159] IATA (undated [2019]). *Aircraft Technology Roadmap to 2050*.

[160] Clean Sky 2 and FCH2 (2020). *Hydrogen-powered aviation: A fact-based study of hydrogen technology, economics, and climate impact by 2050*.

[161] SA (2020). *Decarbonisation Road-map: A Path to Net Zero – A plan to decarbonise UK aviation*. Sustainable Aviation. Page18.

Changes in operational design

Aviation infrastructure considerations include flight paths. Current take-off patterns involve relatively steep climbs to reach cruising height; descending to land tends to require engine power rather than low-powered 'idle thrust'; congestion causes 'stacking' or 'holding' above airports[162]. The DfT and the Civil Aviation Authority are engaged in a process of airspace modernisation. Benefits include increased efficiencies, reduced airspace congestion, and reduced emissions[163].

This is a complex process and involves international negotiations (even in the context of domestic aviation). The increased emissions' impact without modernisation is estimated at 8-12% per flight[164]. This is because of increased congestion, as per the (pre-pandemic) projected increase in passenger numbers and flights.

Sustainable aviation fuels

Sustainable aviation fuels (SAF) can be produced from a wide range of pathways. Many conventional SAF pathways, where fuels are derived from waste and/or crops, are technologically well developed, but still face production cost barriers, competition for existing supplies and limits to scale[165].

"Power-to-liquid" (PtL) SAF created through synthesising hydrogen and carbon dioxide are at an early stage of development. There are a small number of facilities in Europe producing small quantities of PtL fuel. At present they involve substantial inputs of energy and are therefore expensive to produce.

Low carbon fuels are broadly compatible with existing aviation operational systems, although safety testing needs to be rigorous before they can be used commercially. Current approved SAF pathways are certified for blending at up to 50%, and as of October 2020 can use existing pipeline infrastructure. They

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[162] Spinardi, G. (2015). Up in the air: Barriers to greener air traffic control and infrastructure lock-in in a complex socio-technical system. *Energy Research and Social Science*, 6, 41-49.

[163] Our Future Skies (2020). *Modernising the UK's Infrastructure in the Sky*.

[164] SA (2020). *Decarbonisation Road-map: A Path to Net Zero – A plan to decarbonise UK aviation*. Sustainable Aviation.

[165] The CCC recommends that aviation fuel comprises no more than 10% of biofuels in 2050 - otherwise biomass is diverted from more sustainable uses. See CCC (2018). *Biomass in a low-carbon economy*. Committee on Climate Change, November.

are therefore likely to be used as a fuel mix with kerosene, rather than replacing kerosene.

The use of SAF suffers from cost barriers; they are currently three to four times as expensive as conventional jet fuels and represent less than 1% of the market[166].

The adoption of SAF in aviation also faces technological and institutional barriers[167]. Sector leaders say that common alignment on policy frameworks is a prerequisite for industry investment[168]. McKinsey projects that, depending on scale and regulatory conditions, the cost of SAF could match fossil fuel prices between 2036 and 2050[169]. In contrast, the CCC anticipates that the use of SAF will add significant operating costs to the sector[170]. Commercial scale SAF plants would require substantial investment (of the order of £250m per year) by 2040[171].

The CCC notes that demand for sustainable biomass will considerably outstrip supply; that a hierarchy of demand will be required; and that uses that sequester carbon will be more effective in reducing emissions than uses that replace fossil fuel consumption[172]. In its letter in response to the Government's Aviation 2050 consultation, the Committee noted that "*A pragmatic planning assumption would be to aim for up to 10% biofuel use in aviation in 2050*"[173]. The likely limited availability of biofuels therefore suggests that an innovation focus on PtL fuels is more valuable; this is a long-term undertaking. The

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[166] Hollinger, P. (2020). Aerospace executives warn on need to press green fuel use. Financial Times, 12 October.

[167] Scheelhase, J., Maertens, S. and Grimme, W. (2019). Synthetic fuels in aviation – Current barriers and potential political measures. *Transportation Research Procedia, 43,* 21-30.

[168] Hollinger, P. (2020). Aerospace executives warn on need to press green fuel use. Financial Times, 12 October.

[169] McKinsey (2020). *How airlines can chart a path to zero carbon flying*.

[170] Committee on Climate Change (2020). *The Sixth Carbon Budget: The UK's path to Net Zero*. December. p. 178.

[171] Committee on Climate Change (2020). *The Sixth Carbon Budget: The UK's path to Net Zero*. December. p. 162.

[172] Committee on Climate Change (2018). *Biomass in a low carbon economy*.

[173] Lord Deben (2019). *'Aviation 2050 – The future of UK aviation' Letter to the Secretary of State*. Committee on Climate Change.

Sustainable Aviation group has suggested that biofuels will have more impact in the period to 2035, and PtL SAF in the period thereafter[174].

Bioenergy with Carbon Capture and Storage (BECCS) is required to increase the effectiveness of the use of biofuels in reducing aviation emissions so that it becomes competitive with alternative non-aviation uses. However, while the component technologies of BECCS are mature, they have not been combined and tested at scale and further technological development has been slow[175]. Technologies such as BECCS and DACCS will require investment estimated in the billions of pounds per year, and sustained policy support[176]. BECCS plants operating at scale may have poor social welfare outcomes[177].

International prospects

Domestic aviation journeys remained flat during the first part of the 2010s, representing 12% of total UK passenger aviation journeys. This was split equally between leisure and business travel[178]. Although behaviour change is out of scope of this report, it is likely that the share of journeys made by short-haul flights will fall as faster long-distance rail services are introduced.

The most recent UK aviation assessment by Government, pre-pandemic, assumes that overall there will be a substantial increase in passenger numbers between now and 2050. This is in line with IATA projections of growth in global passenger numbers. The UK growth projection is from 267 million passengers[179] in 2016 to a central case in 2050 of 410 million. This assumes that existing capacity constraints are not removed. The 'unconstrained' projection is for 435m passengers[180].

It is too early to anticipate long-run effects on air passenger numbers from the current COVID-19 pandemic. IATA anticipates a return to the former growth

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[174] SA (2020). *Sustainable Aviation Fuels Road-map: Fuelling the future of UK aviation*. Sustainable Aviation.

[175] Consoli, C. (2019). *Bioenergy and Carbon Capture and Storage*. Global CCS Institute.

[176] Vivid Economics (2019). *Greenhouse Gas Removal (GGR) policy options – final report*.

[177] Donnison C. et al (2020). Bioenergy with Carbon Capture and Storage (BECCS): Finding the win–wins for energy, negative emissions and ecosystem services—size matters. *GCB Energy*.

[178] Department for Transport (2017). *UK Aviation Forecasts*.

[179] Passengers leaving UK airports.

[180] DfT (2018). *Aviation 2050: The future of UK aviation. A consultation*. December.

trajectory in passenger numbers by the middle of the 2020s and sees a strong recovery during 2021 and 2022[181]. There are also grounds for caution, however. The OECD has indicated that "*a permanent drop in demand from pre-crisis levels cannot be excluded*," through the substitution of digital services for travel or modal shift[182]. McKinsey notes that the highest levels of concern about the environmental impact of flying is among 18-44 year olds[183]. The CCC's *Balanced Net Zero Pathway* anticipates a return "*close to*" pre-pandemic passenger numbers by 2024, but thereafter "*allows for*" a 25% increase in numbers to 2050, compared to a base case of 65%[184].

It is also possible that restructuring of capacity will change supply patterns. The consultancy Roland Berger sees declining demand for new aircraft in two of their three industry projections[185]. Industry analyst Richard Aboulafia has observed that "*[w]e have way too many jetliners*" and anticipates a shift to fewer, smaller, passenger jets[186,187]. Some analysis expects ticket prices to rise, given the sector's need to rebuild reserves, together with route contraction and higher landing fees[188,189].

The larger the number of projected passengers, the harder it is for the aviation sector to reduce emission levels, given the difficulties in developing long-haul zero-emission aircraft (considered below).

8.2 2050 decarbonisation status

By 2050, decarbonisation of domestic aviation at point of use is expected to be close but incomplete, although this depends on the speed at which hydrogen planes come into commercial service[190]. Battery-powered craft will substitute on

[181] IATA. *2019 2039 Current Trends*.

[182] OECD (2020). *COVID-19 and the aviation industry: Impact and policy responses*. OECD, 15 October

[183] McKinsey (2020). *How airlines can chart a path to zero carbon flying*.

[184] Committee on Climate Change (2020). *The Sixth Carbon Budget: The UK's path to Net Zero*. December. p. 176.

[185] Roland Berger (2020). *Plunge in air traffic will deeply impact demand for new aircraft*. 8 April.

[186] Richard Aboulafia, May 2020 Newsletter.

[187] Richard Aboulafia, October 2020 newsletter.

[188] Topham, G. (2020). *Small planes and no business class*. Guardian, 16 April.

[189] Elliott, D. (2020). *Covid-19: challenging time ahead for aviation*. Frontier Economics.

[190] The decarbonisation pathways published by the industry are dependent on significant levels of offsetting.

some shorter routes. There will have been progress on the development of PtL fuels.

This suggests that the choices for aviation in a zero-emission world beyond 2050 may become starker. Taking this longer view, it is possible that achieving zero-emission aviation will require a significant reconfiguration of aviation, based on aircraft with shorter maximum ranges and lower maximum speeds. This may look more like the aviation map of the 1940s or 1950s, when long-distance travel involved refuelling stops. This also implies capacity constraints, with flying rationed generally by price or by more complex approaches, such as a frequent-flyer levy[191].

8.3 Fleet turnover

Planes have a lifecycle of 15-25 years. Current order books run for 8-10 years, or until close to the end of the 2020s. COVID-19 has accelerated existing trends away from large planes such as the 747 and A380, and towards smaller passenger jets. There is also some evidence of orders being deferred. The private jet market has prospered from the pandemic, with Gulfstream overtaking Embraer as the third largest manufacturer[192].

The industry has had an innovation cycle of about 15 years, indicating that there could be two innovation cycles between now and 2050. Innovations in the first cycle, which might include form factor changes, are already locked in. The second innovation cycle runs close to 2050. As discussed above, this second wave of innovation is likely to include hydrogen planes.

8.4 Infrastructure development

As discussed above, the scope for innovation in the sector is limited by current aircraft design, which requires upward propulsion by a high-density energy source to become airborne. The existing ground infrastructure and its spatial design is configured for, and locked into, this requirement. Innovations such as PtL fuels and battery-powered or hydrogen-powered aircraft will align with this existing spatial design.

A shift towards hydrogen and battery-powered aircraft requires dedicated refuelling and recharging infrastructure. In particular, hydrogen planes require that refuelling capacity is part of a wider hydrogen infrastructure in the UK. As multi-modal hydrogen hubs, such as the proposed Transport Hydrogen Hub in Tees Valley (TVTHH) are piloted, the aviation sector needs to be included.

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[191] A Free Ride (2021). *A free ride.*
[192] Richard Aboulafia, October 2020 newsletter.

'Infrastructure' for aviation also needs to be thought of as including virtual infrastructure, such as flight paths and airspace agreements. These are complex, and subject to international agreements, so evolving them to be more carbon-efficient is a slow process.

There is significant scope for airports to progress further towards zero emissions for their surface transport through deployment of electric or hydrogen vehicles. Such airside developments are included in the roadmap to reflect this, while noting that they are ancillary to the decarbonisation challenge for direct emissions from aviation.

Alternative aircraft designs (such as airships with hydrogen lift and solar/battery propulsion) which could substitute for short-haul flight, are technically feasible[193]. Proof of concept designs suggest these could carry 50 tonnes of cargo or up to 400 passengers at speeds of 150km/h. However, these do not align with existing ground infrastructure or flightpaths. This may be a factor that has deterred their development.

8.5 Research and innovation

To a significant extent, innovation in the aviation sector is dependent on spillovers from innovation in other modes. The most significant of these is a hydrogen economy, which is a necessary pre-condition of a viable fleet of hydrogen planes.

The evolution of battery-powered planes to a carrying capacity of around 100 people requires a step-change in battery energy density, and the aviation industry is likely to benefit from innovation in other areas, such as the auto sector, which is larger, run on a shorter innovation cycle, and also has its own pressing need for innovation.

If low carbon fuels at scale are likely to be part of the long-run solution, this will also require the effective use of CCS.

The aviation industry can be expected to proceed on its own with design improvements that increase fuel efficiency in the existing fleet, since fuel is also a significant operating cost.

The evolution of PtL fuels will potentially have a significant impact in reducing emissions from the existing fleet, and this should be an innovation priority. The inclusion of a competition to produce sustainable aviation fuels within Jet Zero,

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[193] Zedfactory (2010), *Deliverable zero carbon zero waste solutions*. Presentation delivered in Verbier. Private email from Bill Dunster, Zedfactory, 21 February 2020, confirming that technical viability remains.

with £15 million of public support, is a start to this process[194]. The roadmap anticipates that this will only be an initial stage.

The long-run future of aviation, beyond 2050, seems more likely to involve the redesign of aircraft around new forms of propulsion, rather than greening power sources that enable existing aircraft design to fly with lower (but not zero) emissions. This will include the development of hydrogen planes, as well as innovative aircraft designs, such as a new generation of airships using new materials. The 12 month-FlyZero study by the ATI, supported by Jet Zero, should be encouraged to take a broad view of the potential design forms for zero emissions flight[195].

Although the current worldwide aviation market is dominated by a small number of large manufacturers, this long-run future implies a disruptive change in the market. The UK is the world's third largest aviation manufacturer and therefore has a role to play in this transition[196]. In particular, to reach zero-emission aviation eventually requires that hydrogen-powered craft are entering commercial service before 2050. Re-imagining the aircraft should be the subject of a design Grand Challenge to ensure that the UK is ahead of this disruptive curve as it emerges in the sector.

The domestic aviation roadmap is shown in **Figure 8.1**.

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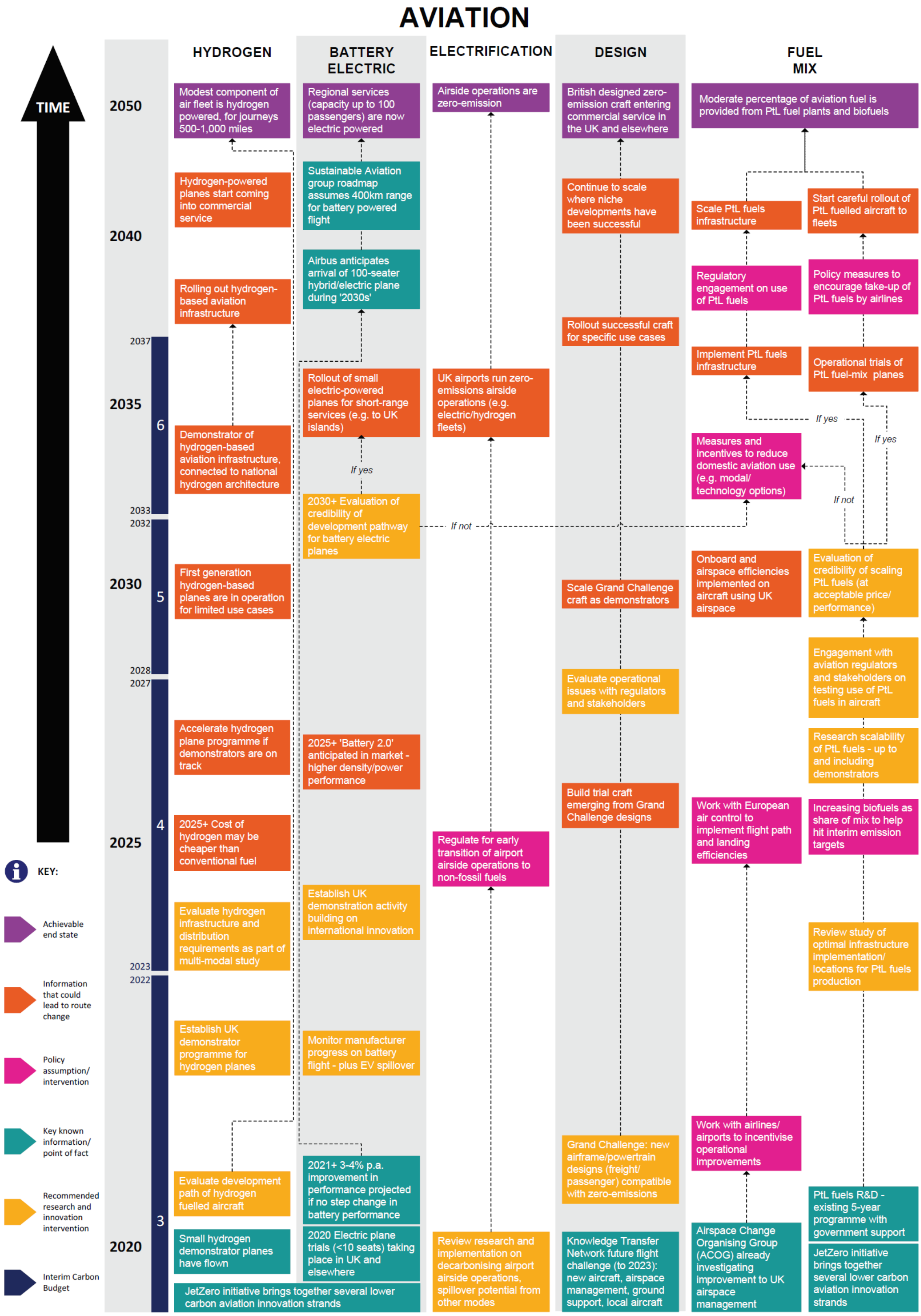
[194] Hirst, D. (2020). *Work of the Jet Zero Council*. House of Commons Library Research Briefing.

[195] HM Government (2020). *The Ten Point Plan for a Green Industrial Revolution*. November.

[196] Department for International Trade. *Aerospace*.

Figure 8.1: Domestic aviation roadmap



9 Conclusions

This study aims to provide a balance of breadth and depth of insight regarding the challenges, opportunities and priorities for decarbonising domestic transport in the UK by 2050. The resulting set of roadmaps offers a framework for informed decision making and action while underlining the formidable nature of the task that lies ahead if a regime change in forms of vehicle propulsion is to be fully realised in the next 30 years.

9.1 Changing times

This study has culminated in the production of a set of seven roadmaps that portray the considerations and priorities for progressing over the coming 30 years towards a largely decarbonised fleet of vehicles (at point of use) across the domestic transport sector. The undertakings required are formidable, representing systemic change over a relatively short time period. The roadmaps are intended to inform a way forward that is achievable. This includes a need to be resilient to significant uncertainties that could influence progress towards the outcomes required.

The study drew to a conclusion at a time when the world continued to face the shock of the COVID-19 pandemic. This has compounded any prior sense of deep uncertainty about the future. Systemic change may well emerge from this shock that could fundamentally affect the actors, processes and resources which determine the direction and speed of change towards decarbonisation that is achievable and achieved over the years and decades ahead. Yet as governments take action to support the global economy, the requirements for research and innovation, infrastructure development and vehicle fleet turnover set out in the roadmaps could generate overall long-run returns, economically, socially, and environmentally. The imperatives to address decarbonisation remain unaltered by the COVID-19 pandemic.

9.2 Roadmap dimensions

The roadmaps reflect the culmination of an iterative process that has involved examination of state-of-the-art knowledge and expert opinion regarding progress and potential to decarbonise transport. When change is being considered across a whole sector such as transport, there are multiple dimensions and, in turn, lenses through which change can be examined. The roadmaps have been designed to reflect the following important dimensions:

Mode of transport – a roadmap for each main mode of domestic transport – providing a primary focus on the priorities for decarbonising that mode (noting that 'main' modes encompass a number of different vehicle types and sizes and use cases which are acknowledged and, in some cases, given more direct attention).

Zero-carbon solutions – in each roadmap there are a series of 'lanes' reflecting candidate (partial) solutions for that mode which in turn are comprised of both lower/zero-carbon vehicles (and their propulsion technologies) and infrastructure (for charging or refuelling vehicles).

Timescale – each roadmap is in portrait orientation to depict and emphasise the 30-year time period for decarbonisation (including Interim Carbon Budgets) and in turn to map against time the developments that must be considered – especially those in the next 5-10 years.

Elements – the maps are populated (spanning the relevant lane(s)) using element types that are common across the map set – these include desired outcomes (the decarbonisation that is sought and which is achievable by 2050), interim milestones of progress, policy actions, and research and innovation interventions.

Interdependencies – roadmap content (within elements) identifies how comparable elements across two or more roadmaps can have some degree of interdependency (including spillovers and synchronisation requirements), thus signalling the importance of treating the roadmaps as a set.

Uncertainty – the nature and pace of change across the domestic transport sector in terms of decarbonisation is subject to uncertain drivers of change relating to technological advance and technology take-up - this uncertainty is accommodated by charting a course for multiple solutions within the roadmaps such that the overall path of development can be flexible over time as the relative strengths of solutions and their speed of advance become clearer.

9.3 High level insights

The following overview observations arise from examining the set of roadmaps:

A tough challenge - Notwithstanding that the elements at play in the developments ahead are identified, the makeup of actual change to the transport sector over the next 30 years is uncertain. Meanwhile, a defining feature of this study is that overall timescale for change is largely non-negotiable. The roadmaps depict what *needs* to be addressed within that fixed timescale but what is *actually* addressed is in the hands of the key players in the public and private sector. Each roadmap draws attention to the significant developments that are called for. When those developments are cross-checked with the *timeline* the extent of the challenge becomes apparent. Indeed, once this is considered across the set of roadmaps, the time criticality of action and progress cannot be overstated. The pandemic is set to have suppressed the transport sector's annual direct carbon emissions for 2020. However, in terms of transport contributing to the UK meeting its Interim Carbon Budgets ahead, such a contribution is very much dependent upon the ability to scale solutions in the marketplace at pace. For transport to positively, if not strongly, contribute to addressing Interim Carbon Budgets four and five there would need to be a significant penetration of low or zero-emission vehicles into road transport fleets – particularly for cars and LGVs. The announcement in November 2020 of the Government's commitment to bring forward the ban on sale of new petrol and diesel cars from 2040 to 2030 can be expected to have some significant if not substantial bearing on this. The December 2020 publication of the *Sixth Carbon Budget* report by the Committee on Climate Change[197] recommends that international shipping and aviation also be included. This heightens the challenge significantly.

Insurmountable direct emissions – Time-criticality is inherent to the roadmaps. Meanwhile, they have been drawn up to reflect *credible* pathways towards decarbonisation of direct (tailpipe) emissions. Achieving this across the domestic transport sector by 2050 is not certain and indeed in some respects is not likely in full. Each roadmap gives a sense of the nature and extent of decarbonisation that is achievable by 2050. Broadly speaking, a descending order of the extent of modal decarbonisation (proportion of a mode's 2020 emissions removed by 2050) can be seen as:

- cars and LGVs (full removal of direct emissions achievable);
- buses (full removal of direct emissions achievable);
- coaches (near full, if not full, removal of direct emissions achievable);
- rail (near-full removal of direct emissions achievable);
- HGVs (near full, if not full, removal of direct emissions achievable)[198];
- domestic shipping (significant removal of direct emissions achievable)[199]; and

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[197] Committee on Climate Change (2020). *The Sixth Carbon Budget: The UK's path to Net Zero*. December.

[198] Rail appears more likely to have a residual of CO_2 than HGVs but this residual could be smaller than for HGVs, if currently anticipated developments fall short in their realisation. It can be said that there are more known knows, and fewer known unknowns for rail than for HGVs.

[199] By 2050, UK domestic shipping could have zero direct CO_2 emissions. However, this is subject to overcoming a number of significant uncertainties in technology development, deployment and scaling.

- domestic aviation (partial removal of direct emissions achievable).

A combination of offsetting and changes in the use cases themselves (in terms of supply and demand) seem inescapable. Low carbon fuels may also remain part of the solution to addressing residuals of direct CO_2 emissions.

The hydrogen puzzle – Hydrogen offers a form of propulsion that has no *direct* CO_2 emissions. While it is not the dominant solution across the transport sector, it has significance for particular use cases within and across modes where alternative solutions are absent or limited. Moreover, the importance of hydrogen could increase if: (i) other solutions fail to fully deliver; and/or (ii) the wider economy's dependence on hydrogen leads to scaling up of availability and falling prices. As such, its presence is strongly felt across the roadmaps such that it becomes integral to achieving decarbonisation. Accordingly, urgent steps are needed to advance hydrogen's technology readiness and the scaling of its availability. At the same time, from a whole economy perspective, hydrogen production must be net-zero in terms of CO_2. While advances in electrolysis and CCS are not centrally addressed in the roadmaps, they are fundamental considerations as part of advancing hydrogen's technology readiness. As the European Commission has recently noted "*[h]ydrogen is enjoying a renewed and rapidly growing attention in Europe and around the world*"[200]. The UK Government's announcement at the end of September 2020 of its ambition to develop a multi-modal Hydrogen Transport Hub in Tees Valley producing green hydrogen to power operational trials later this decade is significant.

Fleet turnover – The roadmaps concern reducing and removing direct (tailpipe) emissions of CO_2 from vehicles. Decarbonising the vehicle fleet involves some shorter-term retrofit or changes to fuel mix but principally concerns replacing, over time, vehicles that produce emissions with those that do not. This relies upon technological advance and breakthroughs, it relies upon manufacturers to take advantage of such developments in their product lines, and it relies upon consumer or business demand for the vehicles. Rate of change is also dependent upon the service life of a vehicle and this can vary significantly – for example, from a few years for intensively used HGVs to decades for rail locomotives. Those responsible for producing and purchasing vehicles are looking for certainty over the return on their investment and assured fitness for purpose of the vehicle. This calls for timely signals from Government regarding

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[200] European Commission (2020). *A hydrogen strategy for a climate-neutral Europe*. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, July.

regulatory changes affecting the market over the period out to 2050 as well as for fiscal measures to promote appropriate market dynamics regarding the vehicle fleet. Significantly, the nature and pace of change in the vehicle fleet is influenced by infrastructure to support low or zero-emission vehicles.

Infrastructure – Dominant across the set of roadmaps is the need for infrastructure solutions to be further developed and better understood, followed by prioritisation of solutions and scaling up of these solutions across the country. As was the case when the regime transition from horse-drawn transport to the motor car unfolded, the process of change now before us involves concurrent developments in vehicle production, infrastructure development and consumer demand[201]. Given the significant dependence in some vehicle use cases upon recharging or refuelling infrastructure being in place, and noting the potential timescales of fleet turnover, there is an urgency for infrastructure development. In some cases, infrastructure to support decarbonisation is already well advanced, for example in relation to route electrification on the rail network. In other cases, the infrastructure is more embryonic in nature. There is a pressing short-term need to understand what is possible, what constitutes the most appropriate infrastructure solutions, and in turn to inform the identification of a suitable programme of work to deliver those solutions at scale. This involves a need to understand the makeup of demands from across modes and use cases that could be placed on that infrastructure. Infrastructure delivery, against the timescales set out, may face challenges regarding availability and capacity of workforce skills required. This will need to be addressed as a separate but related priority to matters covered by the roadmaps.

Research and innovation – Research and innovation is a precursor to market readiness and scaling. It is therefore a priority for the earlier part of the 30-year period ahead across all the roadmaps. Most notably, for road-based transport, the recommended research and innovation interventions are to start, if not have been undertaken, within the next five years. These include highly challenging trials – spanning different forms of solutions - for infrastructure development and use that in turn must inform forward developments in infrastructure roll-out. Research and innovation interventions recommended for rail, shipping and aviation extend into the rest of this decade, and in some cases beyond. Subsequent progress towards decarbonisation across the roadmaps is dependent upon these innovations being taken forward and upon their outcomes. While hydrogen features across the roadmaps, there is a

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[201] Dudley, G., (2014). *The Motorcar and the Construction of a New World*. Prepared for the New Zealand Ministry of Transport, July.

fundamental dependence upon batteries to deliver decarbonisation of domestic transport. Battery technology has relevance to all modes and there are prospects of spillovers from research and innovation from one use case to another. While significant advances have been made in battery energy density and with developments continuing concerning rapid charging capability, there is a need for such research and innovation to continue. It is assumed that the private sector will continue to have an important and indeed principal role here.

9.4 Looking ahead

This study was intended to inform the UK Government's Transport Decarbonisation Plan and the decisions therein. Roadmaps and the roadmapping process (which itself can be valuable to those who engage with it) "*can provide a means for enhancing an organization's 'radar', in terms of extending planning horizons, together with identifying and assessing possible threats and opportunities in the business environment*" [202]. This has been the purpose of this study. By drawing together a picture across the transport sector, the intention has been to help in the process of co-ordination of understanding, and subsequent prioritisation and action in terms of progression towards decarbonising domestic transport.

Throughout the study, it is apparent that consensus is often lacking across stakeholders and expert opinion. This reflects in part the lack of certainty over future developments and prospects. The roadmapping exercise has, however, seen a convergence through successive iterations in relation to identifying a composition of inter-related elements over time that are able to guard against a single point of failure for decarbonisation. It has highlighted the importance of a co-operative and collaborative approach between government and industry and the dependence on each other for mutual success. Stewardship over decarbonising transport will need to be clear, strong and sustained. This includes a need to recognise that this roadmapping exercise should not now be seen as finalised, but rather as a platform for periodic future review and revision, itself informed by an ongoing programme of monitoring to assess progress within and beyond the priorities, actions and milestones set out within the roadmaps.

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[202] Phaal, R., Farrukh, C.J.P. and Probert, D.R. (2004). Technology roadmapping—A planning framework for evolution and revolution. *Technological Forecasting & Social Change*, 71 (2004), 5–26.

Annex A - Assessing progress and potential

A wide-ranging literature review examined progress and potential, across transport modes, for a number of technology solutions to the reduction and removal of direct emissions of CO_2 as a basis for the subsequent roadmapping exercise. Table A.1 below summarises the literature review. While containing some updates, this Annex should not be taken to reflect fully the more up to date and further detailed picture that has evolved during the course of the rest of the study, accounting also for further ongoing announcements and developments.

Table A.1: Overview of decarbonisation progress and potential

Modes of domestic transport (% share of direct CO_2 emissions as at 2019)

	Cars/ LVGs (71%)	Road - HGVs (16%)	Buses/ coaches (3%)	Domestic shipping (5%)	Rail-passenger /freight (1 %)	Domestic aviation (1%)
Battery electric vehicle (BEV)	✓✓✓ ✓✓✓	✓✓ ✓✓	✓✓✓ ✓✓	✓✓ ✓✓	✓ ✓	✓ ✓✓✓
Hydrogen fuel-cell electric vehicle (FCEV)	✓✓ ✓✓	✓ ✓✓ ?	✓✓✓ ✓✓	✓✓ ✓	✓✓ ✓✓	
(Plug-in) hybrid electric vehicle (PHEV)	✓✓✓ ✓✓✓			✓✓ ✓✓		? ✓✓
Biofuels	✓✓/✓✓✓ ×			✓✓ ×	✓ ✓	See AJFs below
Ammonia/methanol				✓ ✓		
Route electrification		× × ?	× × ?		✓✓✓ ✓✓	
Route electrification + battery/fuel cell electric		× × ?	× × ?		✓✓ ✓✓✓	
Liquid Natural Gas (LNG)				✓✓✓ ?		
Drop-in alternative jet fuels (AJFs)						✓✓ ✓✓
100% AJFs						✓ ✓
Exhaust treatment technologies				✓✓ ?		
Vehicle design improvements	✓ ✓ ?			✓/✓✓ ✓✓/ ?		
Nuclear				× ×		

Progress:

- × - no strong signs of active effort to advance the technology
- ✓ - active effort to advance the technology but limited signs of success
- ✓✓ - signs (through trials) of technology being proven
- ✓✓✓ - signs of technology adoption

Potential:

- × - no strong signs of technology readiness and/or adoption in future
- ✓ - signs of ongoing technology advance and readiness in future
- ✓✓ - signs of technology readiness but limited potential for adoption at scale and pace required
- ✓✓✓ - strong signs of technology readiness and clear potential for adoption at scale and pace required
- ? - signs of technology readiness and adoption in future highly unclear

Introduction

In this Annex, summary assessments of progress and potential, based upon that provided in the interim deliverable[203] following the literature review, are set out for each mode. The interim deliverable itself goes into much more detail. It should be noted that these assessments are based upon the body of literature that was examined. They therefore precede the further understanding that evolved during the roadmapping exercise and engagement with policymakers and experts. **The main body of this report reflects current understanding**. **Table A.1** offers a summary from the review, using a set of indicators of progress and potential. We have made some revisions in this Annex to improve clarity, but **this remains a reflection of an interim stage in the study and should be viewed accordingly**.

Road-based transport (as at 2019) accounts for 91% of direct domestic GHG emissions from transport[204]. Battery electric vehicles (BEVs) and hydrogen fuel cell electric vehicles (FCEVs) together constitute the main form of progress and potential for decarbonising road transport. Plug-in hybrid electric vehicles (PHEVs) (cars/LGVs) offer a (shorter-term) transitional technology away from pure petrol/diesel vehicles.

Domestic shipping, rail and aviation account for a further 7% of direct domestic CO_2 emissions (recognising that international aviation and shipping together produce considerably higher CO_2 emissions – see **Figure 1.1**). Within and across these modes there are technology options that promise significant potential for full or partial decarbonisation of direct emissions.

Cars and LGVs

BEVs

Progress - Significant progress has been made in recent years. However, diffusion of BEVs remains hampered by several important barriers, including limited driving range, slow charging and higher purchase costs (compared to vehicles powered by internal combustion engines (ICEs)).

Potential – BEVs offer an efficient way to decarbonise cars and LGVs. Improving battery technology is seen to be key to improving the range of BEVs,

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[203] Mott MacDonald and partners (2020). *FS05 Decarbonising Transport - Phase 1 Literature Review Report*. Internal deliverable to the Department for Transport, 30 January.

[204] Department for Business, Energy & Industrial Strategy (2021). Final UK greenhouse gas emissions national statistics, 1990-2019. February.

along with provision of charging infrastructure. Carbon emissions from manufacturing and end-of-life stages, including recycling of critical materials are likely to become increasingly important.

PHEVs

Progress - PHEVs are currently available in the market and offer a means for reducing carbon emissions in the short-term. Their market share in 2018 was 6%. Take-up is hampered by higher purchase costs (compared to vehicles powered by ICEs).

Potential – Hybridisation of existing ICE vehicles has the potential to reduce emissions by 20-30%; which means they are unlikely to survive the mobility transition. However, they may reduce CO_2 in the short-term and provide a stepping-stone to BEVs.

Vehicle design improvements

Progress - Incremental improvements include improved aerodynamics, more efficient auxiliaries, lower rolling-resistant tyres and vehicle weight reduction.

Potential – Such incremental improvements have the potential to reduce emissions by 20% for cars. Such measures are complementary to new powertrains for reducing CO_2 emissions.

FCEVs

Progress – While some car manufacturers have introduced FCEVs into Europe, their take-up is significantly hampered by lack of refuelling infrastructure, limited market availability of vehicles, high purchase costs and the high cost of producing hydrogen.

Potential – While FCEVs are less efficient than BEVs, their key advantages are vehicle driving ranges and refuelling times comparable to ICE vehicles. They also allow for flexible storage of energy. Timescales for any large-scale market diffusion of FCEVs is highly uncertain. The focus for this technology within road transport is on specific use cases, particularly HGVs and coaches/buses and cases that concern vehicle fleets.

Biofuels

Progress - Low carbon fuels have been one of the most significant contributors to addressing greenhouse gas emissions of UK road transport over the last ten years.

Potential – These are expected to help reduce GHG emissions, particularly for vehicles and sectors that are harder to decarbonise. However, because the availability of sustainable biomass is limited, it is important to use this resource where it can deliver the most cost-effective carbon savings, i.e. the sectors most difficult to decarbonise by any alternative means. It is therefore important that the use of biofuels transitions away from road transport in future.

HGVs

FCEVs

Progress – Vehicles are still at the prototype stage, refuelling stations are very few in number and while hydrogen production already exists in some areas to be built upon, this tends itself to produce CO_2 as a by-product thus with a reliance on advancing CCS. The need for a large-scale demonstration is recognised to help inform policy and investment decisions.

Potential – There is a strong inter-dependence for scaling up between hydrogen production and distribution, and vehicle fleet size increase (the latter being problematic in terms of current vehicle manufacturing capacity). Hydrogen clusters centred upon viable use cases are seen as the route to scaling up. However, clean production of hydrogen, and electricity demand to do so (relative to BEVs – see below) remains an issue. Future prospects for FCEVs remain unclear until greater understanding is obtained.

BEVs

Progress – Vehicles are becoming available but in terms of long-haul HGVs, range is (currently) a limiting factor in the absence of (rapid) charging points.

Potential – There is a greater degree of consensus on future prospects of BEVs than FCEVs at present and for urban and regional use cases they are considered highly applicable. As with FCEVs, the lack of current availability of BEV models for the UK HGV market is a constraining factor. Refitting/upgrading vehicle depots for recharging also needs to be addressed. Battery technology is improving over time. Dynamic charging via Electric Roads System (ERS) has potential (for long-haul highly utilised routes) but with high infrastructure costs.

Route electrification

Combined with battery/fuel cell electric, route electrification is recognised as a technological possibility (both for HGVs and buses and coaches) however infrastructure costs are high with major roll-out needed before vehicle deployment and a risk of declining need for this solution over time. It is suggested that the main intervention needed is a decision on whether to commit to this solution.

Buses and coaches

FCEVs

Progress – Several relatively small-scale trials are already underway in the UK (including ultra-low emission bus scheme winners announced in February 2019 and the Office for Low Emission Vehicles' (OLEV) hydrogen for transport programme) and in Europe. Some FCEVs are in operation.

Potential – FCEVs offer potential for longer distance routes and possibly some coach services with commercial availability emerging.

BEVs

Progress – Several relatively small-scale trials are already underway in parts of the UK and Europe and BEVs are in operation, notably in London.

Potential – BEVs offer most potential for denser networks of shorter-haul routes. Strengthening the local electricity grid is required. The current competition model for provision of bus services inhibits adoption. Funding is needed to assist with significant expansion beyond small-scale trials. The configuration of chargers within the network is a key consideration for BEV charging and larger-scale trials are required.

Route electrification

Combined with battery/fuel cell electric, route electrification is recognised as a technological possibility (both for buses and coaches, and HGVs) however infrastructure costs are high with major roll-out needed before vehicle deployment and a risk of declining need for this solution over time. It is suggested that the main intervention needed is a decision on whether, or not, to commit to this solution.

Domestic shipping

Domestic shipping accounts for a relatively small share of carbon emissions in transport (5% of emissions in 2018). However, it is expected that demand for domestic shipping (and international shipping as well) will increase, meaning that reducing emissions is going to be challenging. Emissions from shipping vessels can be tackled in three main ways: (i) capture/treatment of exhaust emissions, including GHG and air pollutant emissions, (ii) improving fuel efficiency (through technological or energy efficiency), and (iii) substituting existing fuels with greener alternatives.

Exhaust capture/treatment technologies

Progress – Technologies to reduce CO_2 emissions are at an early stage of development.

Potential - In the long to medium term, CCS systems have the potential to reduce CO_2 emissions significantly (85-90%). There was little detailed information on barriers, enablers, risks and assumptions for these technologies in the papers reviewed for this study.

Vehicle design improvements

Progress – Many design improvement technologies are in the early stage of market development.

Potential –The potential of these in terms of decarbonisation varies for each technology, with wind technologies predicted to provide larger carbon emission reductions, although reduction estimates are highly uncertain. Many of these technologies are complementary to technologies to treat exhaust emissions and/or improve the carbon efficiency of fuel.

Greener fuels

Progress - There are many greener fuel options for decarbonising maritime transport. Liquid natural gas (LNG) has the potential to lead to large reductions in all air pollution emissions, but with limited GHG savings. Additionally, biofuels are not expected to play a significant role in decarbonisation of the domestic shipping sector, given the limited availability of sustainable biomass and demands from other modes that are more difficult to decarbonise.

Potential - The development of ammonia and/or methanol marine fuels are still in the research and development phase, but they could offer a decarbonisation pathway in the medium to long-term. Hydrogen is also a developing fuel option, with some small hydrogen ferries in the UK. It may be a realistic option in the medium term. Nuclear could be a long-term solution, but there are significant uncertainties associated with its development and diffusion.

Rail

FCEVs

Progress – To date there has been limited progress in the use of hydrogen fuel cells to power trains. However, Alstom recently began hydrogen fuel cell powered passenger rail services in Germany, and in the Schleswig-Holstein region, also in Germany there are plans to roll out hydrogen trains across its entire 680-mile network by 2025.

Potential – Hydrogen-powered services have the greatest potential to replace diesel engines for shorter distance, slower services. For faster and/or longer journeys, the major barrier is the limited space on board existing rolling stock to carry enough hydrogen tanks; this means the technology is less suitable for inter-city services. Its greatest potential is therefore if used in combination with electrification in bi-mode engines which allow trains to switch to hydrogen mode on unelectrified sections of the network, particularly in the short-term.

Route electrification

Progress – Within the UK 42% of the total track mileage is now electrified. However, three major electrification schemes were cancelled in 2017 due to budget constraints so progress in the near future will be limited. Progress towards electrification has been higher for passenger services with over 70% of the passenger fleet now electrified. This has been aided by several train operating companies launching bi-mode passenger trains (which can operate on electric power where available, but also have diesel engines fitted that provide power on non-electrified sections of the network) to address gaps in the electrified network. However, only 10% of the UK's freight fleet is electrified and only 3% is bi-mode. In part this is due to an operational expectation that rail freight locomotives should be capable of travelling anywhere on the network, particularly on more remote sections of the network such as to/from ports which are typically non-electrified. A further barrier is the high cost of replacing old diesel locomotives used for rail freight or retrofitting them with bi-mode engines.

Potential – Electric traction, where the line is sufficiently well used and a low carbon energy generation mix is used, provides the lowest whole life carbon impact and greater use of bi-mode vehicles could bridge gaps in the electrified rail network, expanding the rail freight network and encouraging transfer from road to rail for further decarbonisation. Physical infrastructure constraints such as bridges and tunnels remain a significant barrier to electrification of some parts of the network.

Biofuels

Progress – Discussion of biofuels in rail mostly refers to biodiesel. Biodiesel remains the most widely used form of renewable energy in transport and its contribution has been significantly increasing recently, with most of it consumed in rail transport. The first biodiesel train in the UK was launched in 2007, running on 80% petrodiesel and 20% biodiesel.

Potential – However, while the industry has a sufficiently large fleet of diesel freight locomotives that could potentially be converted to run on biodiesel, it is not seen as a complete solution, it has not been tested, and there is no established supply chain for it in the UK. Biofuels are therefore viewed as having greater potential in freight, and as a complementary measure to other more effective steps to decarbonisation, rather than in passenger services due to the existing refuelling infrastructure. It is also noted that biofuels are not strictly zero-carbon.

Domestic aviation

Drop-in Alternative Jet Fuels (AJFs)

Progress - Significant progress has been made in the development and testing of ‘drop in’ AJFs. These fuels represent the simplest substitution for hydrocarbon fuel but are currently limited to a small percentage of fuel composition. There is some scope for the use of biofuels, noting that there would be competition from other sectors for this and that it is not strictly a zero-emission fuel.

Potential - The close relationship between domestic and international aircraft technology suggests that the development of AJFs will continue rapidly. The key issue is the lack of long-term compatibility of biofuels and existing aircraft and infrastructure. Research suggests that there is a commitment both among governments and aircraft manufacturers/operators to move towards AJFs. Currently there is no alternative for longer flights (which is ensuring continued funding for AJF research). The proportion of AJF mixed with conventional jet fuel is likely to see a gradual increase in the near term.

BEVs

Progress - Progress has been made in the areas of unmanned aircraft and in the general aviation market (smaller private aircraft). The development of the appropriate aircraft equipment, principally motors and batteries is continuing. In terms of passenger aircraft these have been largely conversions of existing aircraft, effectively replacing turbo-prop engines with electric fans.

Potential - There is significant optimism around the area of electric propulsion. Recent research and development have proved the feasibility of low weight high power motors suitable for use in aircraft. In parallel, battery development is progressing at a rapid rate. Current assessment suggests that a battery capable of propelling a regional aircraft large enough to operate commercially could be available in 5-10 years.

The adoption of electrically powered aircraft for domestic aviation is potentially in parallel with adoption of 100% AJFs.

Hybrid Electric Vehicles (HEVs)

Progress - Progress has been limited to development of conceptual aircraft design, recognising that hybrid propulsion systems will require a different airframe configuration. Similarly, the propulsion systems advanced to date are currently only in the research phase.

Potential - The hybrid concepts developed so far require significant development in technology from the current state. They rely on superconducting generators and motors which are only in the very earliest stages of development. However, the hybrid propulsion aircraft is, in the long-term, considered the most likely option for long haul/international flights, and therefore will continue to attract investment and interest.

Overall potential for aviation - It is difficult to truly separate the domestic and international aviation sectors. It is recognised that long haul flights will not be served by electric propulsion aircraft in the near or medium term if at all. Therefore, the near-term potential for long haul will be to the use of increasing proportions of AJFs with conventional jet fuel. There is a strong opportunity for the short haul fleet to benefit from this development. The alternative technology of electric propulsion is being driven by the ambition of a zero tailpipe emission aircraft, which has the added benefit of relatively small infrastructure disruption.

Roadmapping insights

In addition to the many factors relating to progress and potential for decarbonisation across different modes using different technology solutions, the production of a roadmap (or roadmaps) itself also involves several important considerations. Together they are likely to influence how the balance is struck between timely completion of the roadmapping exercise, the purpose to which it is intended to be put, and the degree of confidence and direction that the resulting roadmap(s) can provide to the relevant audience(s) in the face of multiple dynamics and uncertainties at play. The following five considerations stood out from examination of the literature, *prior to* embarking upon the roadmapping exercise in phase 2 of this study:

Framing the development of a roadmap - Clarity over the outcomes being pursued by the roadmap, its scope in terms of system(s) addressed by the transition, and an understanding regarding the stewardship over its application and revision once developed all set an important context for roadmap development. Its development is also informed by an ability to judge and prioritise the different prospects for realising decarbonisation across modes.

Socio-technical change of relevance to technology roadmaps - The roadmap(s) envisaged are to address transition to low-carbon technologies rather than changes to the nature and extent of mobility in terms of the demand placed upon the transport system. However, the behaviour of actors is still an important determinant of any roadmapping in terms of fostering private sector willingness to innovate and invest and consumer support to enable the timely diffusion of innovation.

Matters of opinion in roadmapping - Actors, as stakeholder and/or experts, constitute an important part of the roadmapping process in terms of (i) ownership and agency in helping define pathways forward to decarbonisation; and (ii) ensuring diversity of perspective and risks of unconscious bias are addressed where uncertainty and judgement prevail in the course of decision-making on the roadmap(s).

Handling uncertainty in roadmapping - In some if not all areas of the roadmapping task, deep uncertainty about the future prevails in the form of change factors that lie beyond the control of the (principal) actors. Accommodating such uncertainty holds the prospect of adding resilience to the roadmapping and better assuring the subsequent effectiveness of the roadmap(s) produced. Acknowledging uncertainty is not the same as addressing it. To do the latter demands more time and resource for the roadmapping process. Methodologies for combining scenario planning with roadmapping are available if not widely used.

The mixed blessings of a mixed economy of solution pathways - A Government position of specifying the ends and leaving the market to innovate in addressing the means is reasonable. This can encourage competition, protect consumer interests and help avoid single solution risks. Meanwhile, lack of clarity from Government on solution preferences (and associated public sector investment) can create uncertainty that may stifle private sector investment in, and slow the pace of, innovation.

Building upon the roadmapping insights above and drawing further upon the overall insights elicited from the literature review, the following matters were put forward as a basis for subsequent discussion with the DfT in December 2019[205]:

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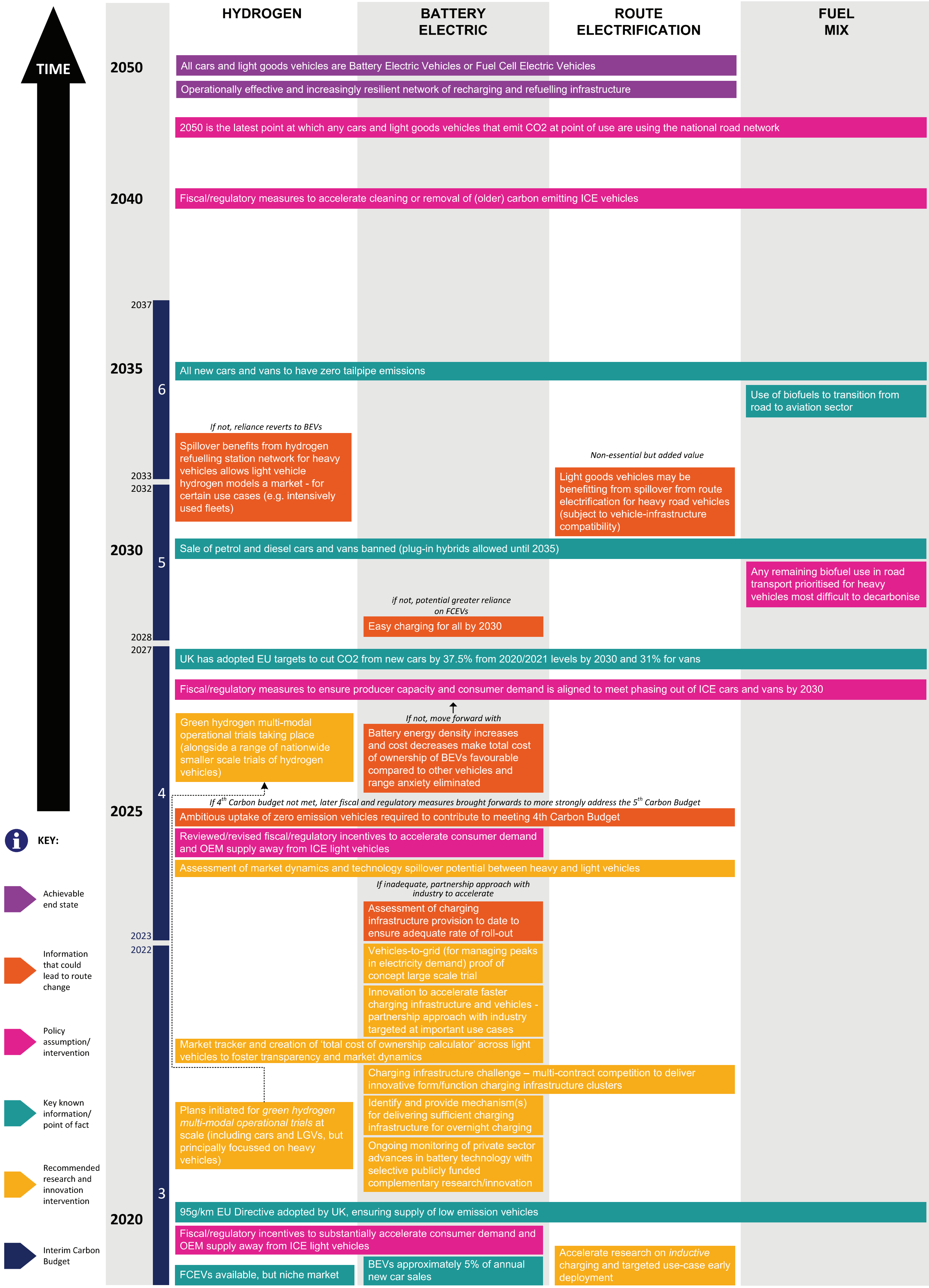
[205] This review report informed discussion that took place in an internal stakeholder workshop within the DfT on 18 December 2019. A note of this workshop captures the more focused considerations and requirements that emerged and which would help define the subsequent phase of the roadmapping work. As such, it should not be taken that all the matters as set out have been seen as a priority within the scope of subsequent work. It should be emphasised that this piece of work forms *part of* a wider undertaking by the DfT to develop its decarbonisation plan.

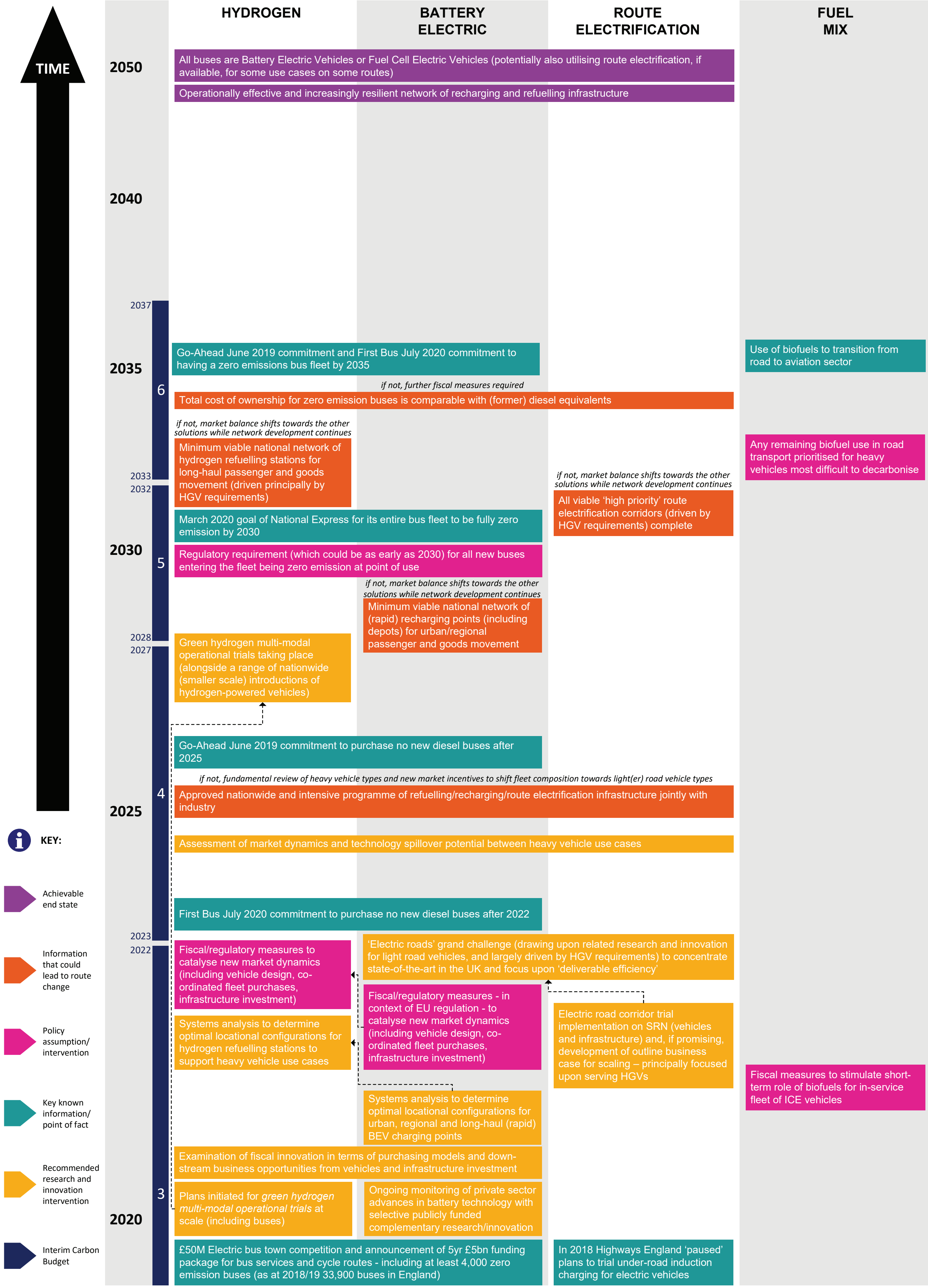
1. How should the *velocity* of change (a combination of direction and speed of transition) be addressed in the roadmapping?
2. What are the bounds of investment and expectations of return on investment dictating what is plausible for roadmapping to assume?
3. What are the implications of whether and how deep uncertainty is addressed as part of roadmapping?
4. How should flexibility and adaptability be incorporated into the roadmaps and how they are used?
5. How high level should the roadmaps be, and with what accompanying guidance, in relation to their intended purpose(s) and use?
6. How is the roadmapping framed by the degree of (signalled) Government preference between different technology-mode combinations?
7. To what extent should the roadmaps be representative of socio-technical rather than only technical transition in terms of decarbonisation?
8. How participatory should the roadmapping exercise be and with the involvement of which groups of actors?
9. What form of stewardship over the developed roadmaps and their application is envisaged and with what implications for the roadmapping exercise?

Annex B - Roadmaps Set

CARS AND LIGHT GOODS VEHICLES

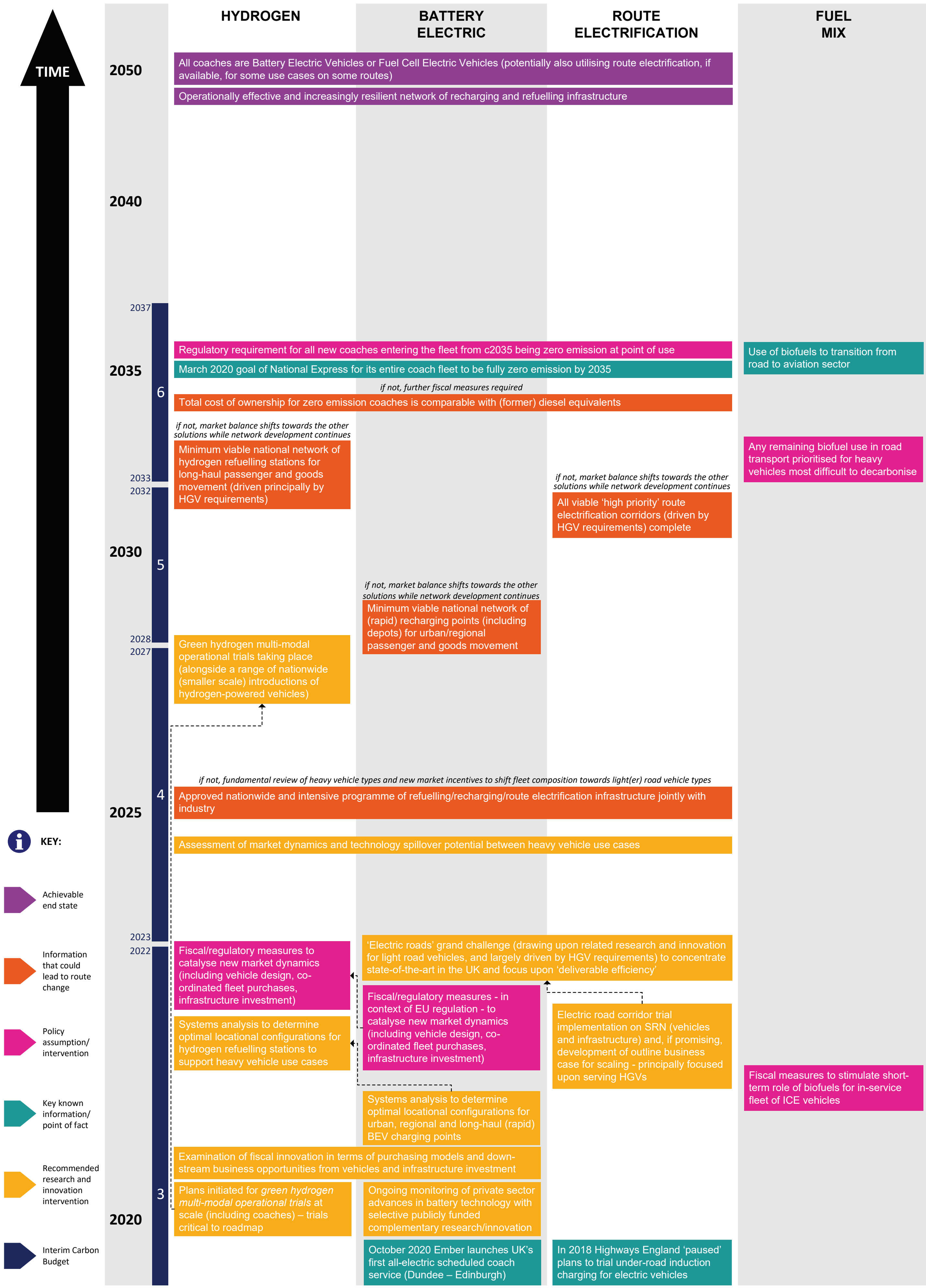


BUSES

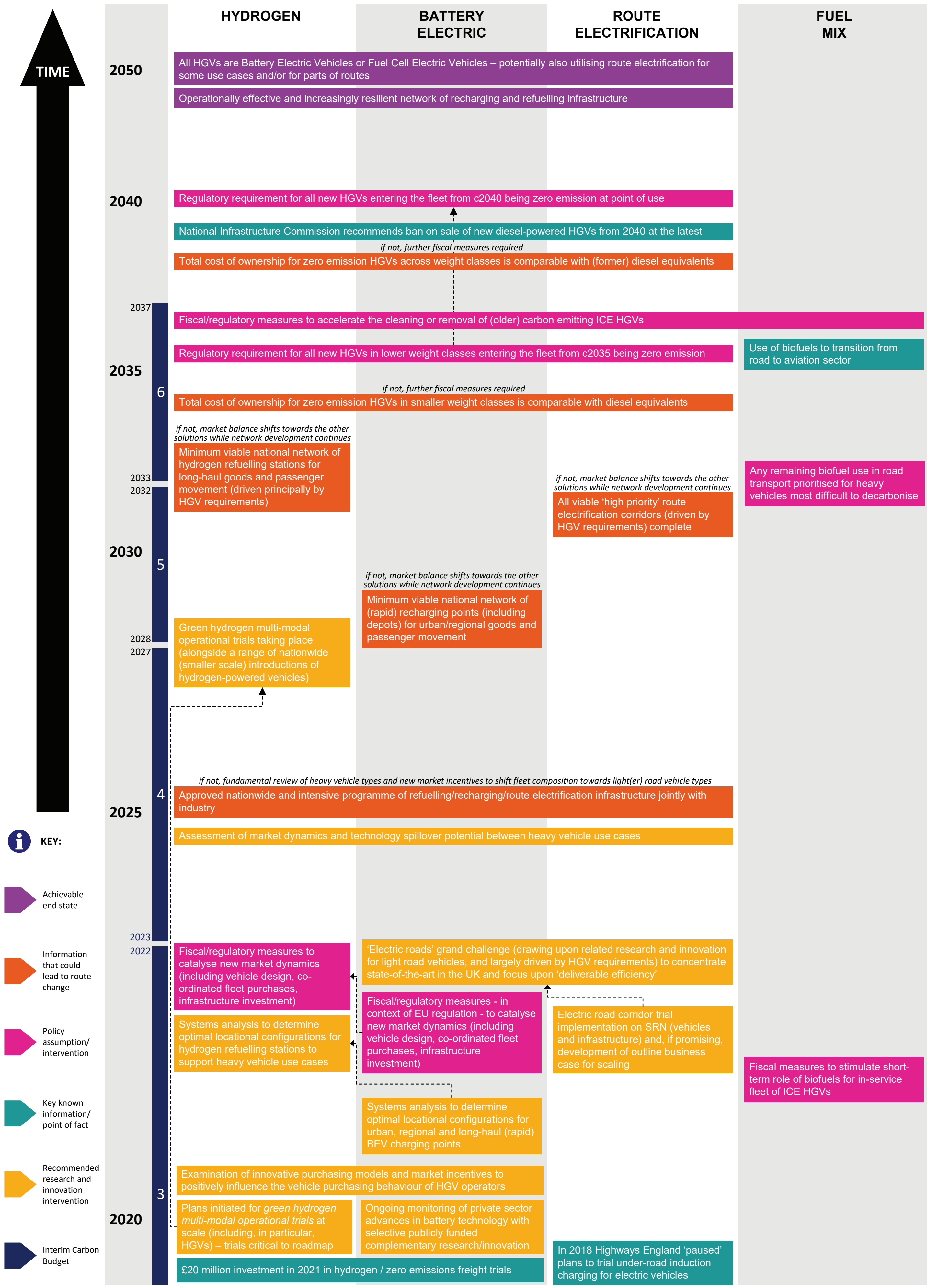


TIME
HYDROGEN
BATTERY ELECTRIC
ROUTE ELECTRIFICATION
FUEL MIX
2050
All buses are Battery Electric Vehicles or Fuel Cell Electric Vehicles (potentially also utilising route electrification, if available, for some use cases on some routes)
Operationally effective and increasingly resilient network of recharging and refuelling infrastructure
2040
2037
2035
6
Go-Ahead June 2019 commitment and First Bus July 2020 commitment to having a zero emissions bus fleet by 2035
Use of biofuels to transition from road to aviation sector
if not, further fiscal measures required
Total cost of ownership for zero emission buses is comparable with (former) diesel equivalents
if not, market balance shifts towards the other solutions while network development continues
Minimum viable national network of hydrogen refuelling stations for long-haul passenger and goods movement (driven principally by HGV requirements)
Any remaining biofuel use in road transport prioritised for heavy vehicles most difficult to decarbonise
2033
2032
if not, market balance shifts towards the other solutions while network development continues
All viable 'high priority' route electrification corridors (driven by HGV requirements) complete
March 2020 goal of National Express for its entire bus fleet to be fully zero emission by 2030
2030
5
Regulatory requirement (which could be as early as 2030) for all new buses entering the fleet being zero emission at point of use
if not, market balance shifts towards the other solutions while network development continues
Minimum viable national network of (rapid) recharging points (including depots) for urban/regional passenger and goods movement
2028
2027
Green hydrogen multi-modal operational trials taking place (alongside a range of nationwide (smaller scale) introductions of hydrogen-powered vehicles)
Go-Ahead June 2019 commitment to purchase no new diesel buses after 2025
if not, fundamental review of heavy vehicle types and new market incentives to shift fleet composition towards light(er) road vehicle types
4
Approved nationwide and intensive programme of refuelling/recharging/route electrification infrastructure jointly with industry
2025
Assessment of market dynamics and technology spillover potential between heavy vehicle use cases
First Bus July 2020 commitment to purchase no new diesel buses after 2022
2023
2022
Fiscal/regulatory measures to catalyse new market dynamics (including vehicle design, co-ordinated fleet purchases, infrastructure investment)
'Electric roads' grand challenge (drawing upon related research and innovation for light road vehicles, and largely driven by HGV requirements) to concentrate state-of-the-art in the UK and focus upon 'deliverable efficiency'
Fiscal/regulatory measures - in context of EU regulation - to catalyse new market dynamics (including vehicle design, co-ordinated fleet purchases, infrastructure investment)
Electric road corridor trial implementation on SRN (vehicles and infrastructure) and, if promising, development of outline business case for scaling – principally focused upon serving HGVs
Systems analysis to determine optimal locational configurations for hydrogen refuelling stations to support heavy vehicle use cases
Fiscal measures to stimulate short-term role of biofuels for in-service fleet of ICE vehicles
Systems analysis to determine optimal locational configurations for urban, regional and long-haul (rapid) BEV charging points
Examination of fiscal innovation in terms of purchasing models and down-stream business opportunities from vehicles and infrastructure investment
3
Plans initiated for green hydrogen multi-modal operational trials at scale (including buses)
Ongoing monitoring of private sector advances in battery technology with selective publicly funded complementary research/innovation
2020
£50M Electric bus town competition and announcement of 5yr £5bn funding package for bus services and cycle routes - including at least 4,000 zero emission buses (as at 2018/19 33,900 buses in England)
In 2018 Highways England 'paused' plans to trial under-road induction charging for electric vehicles
KEY:
Achievable end state
Information that could lead to route change
Policy assumption/ intervention
Key known information/ point of fact
Recommended research and innovation intervention
Interim Carbon Budget

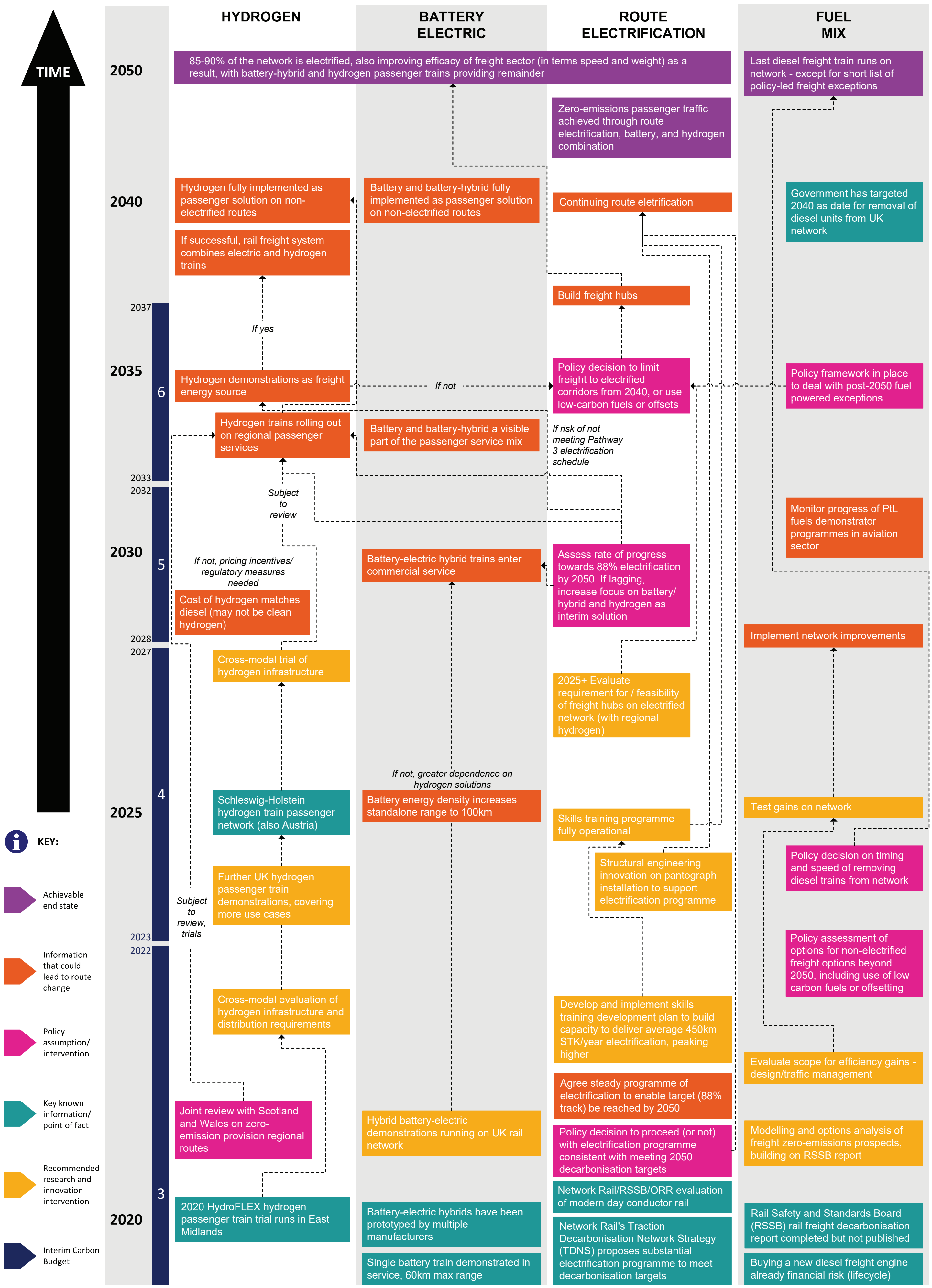
COACHES


TIME
HYDROGEN
BATTERY ELECTRIC
ROUTE ELECTRIFICATION
FUEL MIX
2050
All coaches are Battery Electric Vehicles or Fuel Cell Electric Vehicles (potentially also utilising route electrification, if available, for some use cases on some routes)
Operationally effective and increasingly resilient network of recharging and refuelling infrastructure
2040
2037
6
2033
Regulatory requirement for all new coaches entering the fleet from c2035 being zero emission at point of use
Use of biofuels to transition from road to aviation sector
2035
March 2020 goal of National Express for its entire coach fleet to be fully zero emission by 2035
if not, further fiscal measures required
Total cost of ownership for zero emission coaches is comparable with (former) diesel equivalents
if not, market balance shifts towards the other solutions while network development continues
Minimum viable national network of hydrogen refuelling stations for long-haul passenger and goods movement (driven principally by HGV requirements)
Any remaining biofuel use in road transport prioritised for heavy vehicles most difficult to decarbonise
if not, market balance shifts towards the other solutions while network development continues
All viable 'high priority' route electrification corridors (driven by HGV requirements) complete
2032
5
2030
if not, market balance shifts towards the other solutions while network development continues
Minimum viable national network of (rapid) recharging points (including depots) for urban/regional passenger and goods movement
2028
2027
Green hydrogen multi-modal operational trials taking place (alongside a range of nationwide (smaller scale) introductions of hydrogen-powered vehicles)
4
if not, fundamental review of heavy vehicle types and new market incentives to shift fleet composition towards light(er) road vehicle types
Approved nationwide and intensive programme of refuelling/recharging/route electrification infrastructure jointly with industry
2025
Assessment of market dynamics and technology spillover potential between heavy vehicle use cases
2023
2022
Fiscal/regulatory measures to catalyse new market dynamics (including vehicle design, co-ordinated fleet purchases, infrastructure investment)
'Electric roads' grand challenge (drawing upon related research and innovation for light road vehicles, and largely driven by HGV requirements) to concentrate state-of-the-art in the UK and focus upon 'deliverable efficiency'
Fiscal/regulatory measures - in context of EU regulation - to catalyse new market dynamics (including vehicle design, co-ordinated fleet purchases, infrastructure investment)
Electric road corridor trial implementation on SRN (vehicles and infrastructure) and, if promising, development of outline business case for scaling - principally focused upon serving HGVs
Systems analysis to determine optimal locational configurations for hydrogen refuelling stations to support heavy vehicle use cases
Fiscal measures to stimulate short-term role of biofuels for in-service fleet of ICE vehicles
Systems analysis to determine optimal locational configurations for urban, regional and long-haul (rapid) BEV charging points
Examination of fiscal innovation in terms of purchasing models and down-stream business opportunities from vehicles and infrastructure investment
3
Plans initiated for green hydrogen multi-modal operational trials at scale (including coaches) – trials critical to roadmap
Ongoing monitoring of private sector advances in battery technology with selective publicly funded complementary research/innovation
2020
October 2020 Ember launches UK's first all-electric scheduled coach service (Dundee – Edinburgh)
In 2018 Highways England 'paused' plans to trial under-road induction charging for electric vehicles
KEY:
Achievable end state
Information that could lead to route change
Policy assumption/ intervention
Key known information/ point of fact
Recommended research and innovation intervention
Interim Carbon Budget

HEAVY GOODS VEHICLES



RAIL



TIME
HYDROGEN
BATTERY ELECTRIC
ROUTE ELECTRIFICATION
FUEL MIX
2050
2040
2035
2030
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2020
2037
2033
2032
2028
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2023
2022
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3
85-90% of the network is electrified, also improving efficacy of freight sector (in terms speed and weight) as a result, with battery-hybrid and hydrogen passenger trains providing remainder
Last diesel freight train runs on network - except for short list of policy-led freight exceptions
Zero-emissions passenger traffic achieved through route electrification, battery, and hydrogen combination
Hydrogen fully implemented as passenger solution on non-electrified routes
Battery and battery-hybrid fully implemented as passenger solution on non-electrified routes
Continuing route eletrification
Government has targeted 2040 as date for removal of diesel units from UK network
If successful, rail freight system combines electric and hydrogen trains
Build freight hubs
If yes
Hydrogen demonstrations as freight energy source
If not
Policy decision to limit freight to electrified corridors from 2040, or use low-carbon fuels or offsets
Policy framework in place to deal with post-2050 fuel powered exceptions
Hydrogen trains rolling out on regional passenger services
Battery and battery-hybrid a visible part of the passenger service mix
If risk of not meeting Pathway 3 electrification schedule
Subject to review
Monitor progress of PtL fuels demonstrator programmes in aviation sector
If not, pricing incentives/ regulatory measures needed
Battery-electric hybrid trains enter commercial service
Assess rate of progress towards 88% electrification by 2050. If lagging, increase focus on battery/ hybrid and hydrogen as interim solution
Cost of hydrogen matches diesel (may not be clean hydrogen)
Implement network improvements
Cross-modal trial of hydrogen infrastructure
2025+ Evaluate requirement for / feasibility of freight hubs on electrified network (with regional hydrogen)
If not, greater dependence on hydrogen solutions
Schleswig-Holstein hydrogen train passenger network (also Austria)
Battery energy density increases standalone range to 100km
Skills training programme fully operational
Test gains on network
Structural engineering innovation on pantograph installation to support electrification programme
Policy decision on timing and speed of removing diesel trains from network
Further UK hydrogen passenger train demonstrations, covering more use cases
Subject to review, trials
Policy assessment of options for non-electrified freight options beyond 2050, including use of low carbon fuels or offsetting
Cross-modal evaluation of hydrogen infrastructure and distribution requirements
Develop and implement skills training development plan to build capacity to deliver average 450km STK/year electrification, peaking higher
Evaluate scope for efficiency gains - design/traffic management
Agree steady programme of electrification to enable target (88% track) be reached by 2050
Joint review with Scotland and Wales on zero-emission provision regional routes
Hybrid battery-electric demonstrations running on UK rail network
Policy decision to proceed (or not) with electrification programme consistent with meeting 2050 decarbonisation targets
Modelling and options analysis of freight zero-emissions prospects, building on RSSB report
Network Rail/RSSB/ORR evaluation of modern day conductor rail
2020 HydroFLEX hydrogen passenger train trial runs in East Midlands
Battery-electric hybrids have been prototyped by multiple manufacturers
Network Rail's Traction Decarbonisation Network Strategy (TDNS) proposes substantial electrification programme to meet decarbonisation targets
Rail Safety and Standards Board (RSSB) rail freight decarbonisation report completed but not published
Single battery train demonstrated in service, 60km max range
Buying a new diesel freight engine already financial risk (lifecycle)
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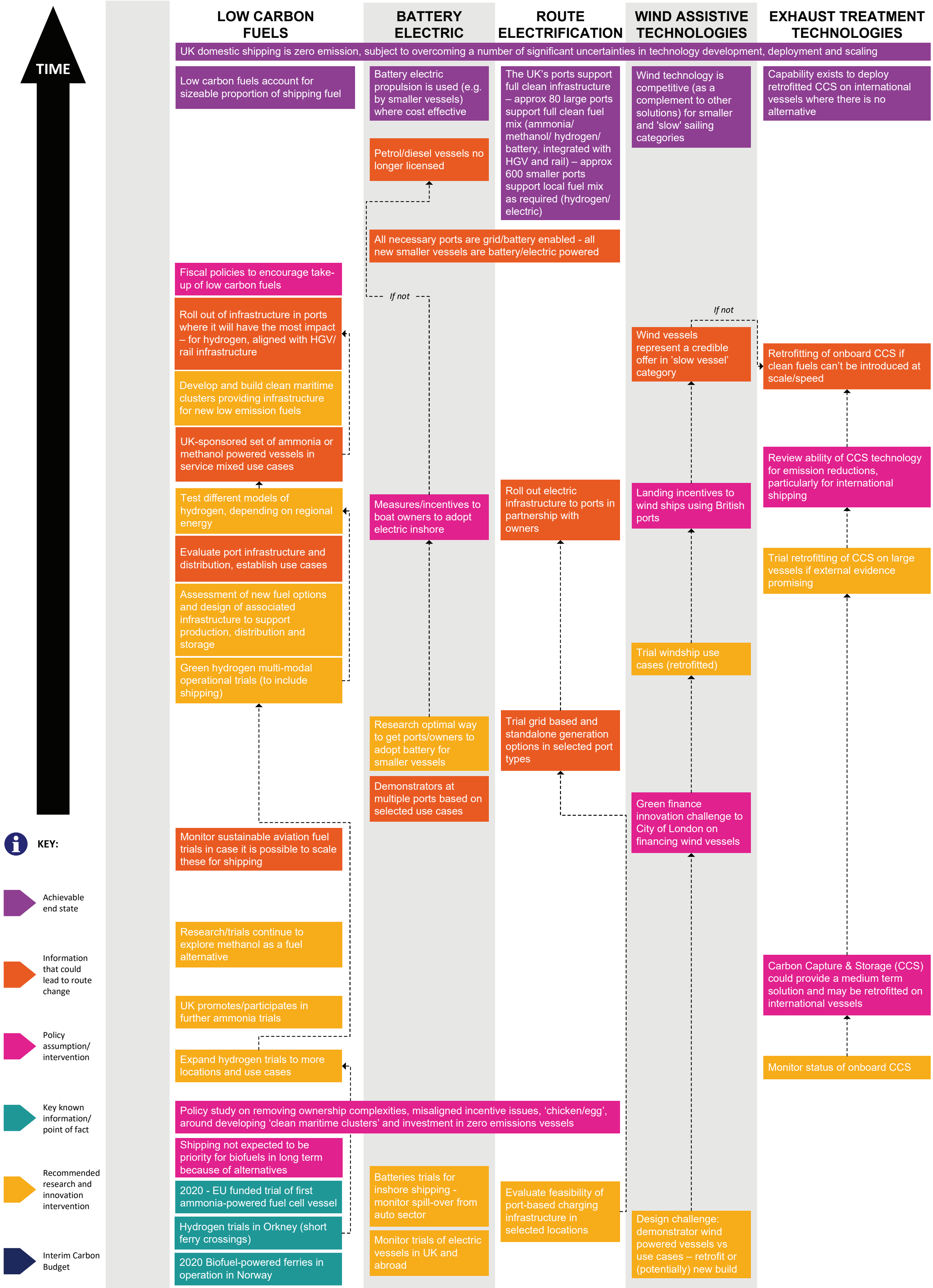
SHIPPING


TIME
LOW CARBON FUELS
BATTERY ELECTRIC
ROUTE ELECTRIFICATION
WIND ASSISTIVE TECHNOLOGIES
EXHAUST TREATMENT TECHNOLOGIES
UK domestic shipping is zero emission, subject to overcoming a number of significant uncertainties in technology development, deployment and scaling
Low carbon fuels account for sizeable proportion of shipping fuel
Fiscal policies to encourage take-up of low carbon fuels
Roll out of infrastructure in ports where it will have the most impact – for hydrogen, aligned with HGV/ rail infrastructure
Develop and build clean maritime clusters providing infrastructure for new low emission fuels
UK-sponsored set of ammonia or methanol powered vessels in service mixed use cases
Test different models of hydrogen, depending on regional energy
Evaluate port infrastructure and distribution, establish use cases
Assessment of new fuel options and design of associated infrastructure to support production, distribution and storage
Green hydrogen multi-modal operational trials (to include shipping)
Monitor sustainable aviation fuel trials in case it is possible to scale these for shipping
Research/trials continue to explore methanol as a fuel alternative
UK promotes/participates in further ammonia trials
Expand hydrogen trials to more locations and use cases
Policy study on removing ownership complexities, misaligned incentive issues, 'chicken/egg', around developing 'clean maritime clusters' and investment in zero emissions vessels
Shipping not expected to be priority for biofuels in long term because of alternatives
2020 - EU funded trial of first ammonia-powered fuel cell vessel
Hydrogen trials in Orkney (short ferry crossings)
2020 Biofuel-powered ferries in operation in Norway
Battery electric propulsion is used (e.g. by smaller vessels) where cost effective
Petrol/diesel vessels no longer licensed
All necessary ports are grid/battery enabled - all new smaller vessels are battery/electric powered
If not
Measures/incentives to boat owners to adopt electric inshore
Research optimal way to get ports/owners to adopt battery for smaller vessels
Demonstrators at multiple ports based on selected use cases
Batteries trials for inshore shipping - monitor spill-over from auto sector
Monitor trials of electric vessels in UK and abroad
The UK's ports support full clean infrastructure – approx 80 large ports support full clean fuel mix (ammonia/ methanol/ hydrogen/ battery, integrated with HGV and rail) – approx 600 smaller ports support local fuel mix as required (hydrogen/ electric)
Roll out electric infrastructure to ports in partnership with owners
Trial grid based and standalone generation options in selected port types
Evaluate feasibility of port-based charging infrastructure in selected locations
Wind technology is competitive (as a complement to other solutions) for smaller and 'slow' sailing categories
If not
Wind vessels represent a credible offer in 'slow vessel' category
Landing incentives to wind ships using British ports
Trial windship use cases (retrofitted)
Green finance innovation challenge to City of London on financing wind vessels
Design challenge: demonstrator wind powered vessels vs use cases – retrofit or (potentially) new build
Capability exists to deploy retrofitted CCS on international vessels where there is no alternative
Retrofitting of onboard CCS if clean fuels can't be introduced at scale/speed
Review ability of CCS technology for emission reductions, particularly for international shipping
Trial retrofitting of CCS on large vessels if external evidence promising
Carbon Capture & Storage (CCS) could provide a medium term solution and may be retrofitted on international vessels
Monitor status of onboard CCS
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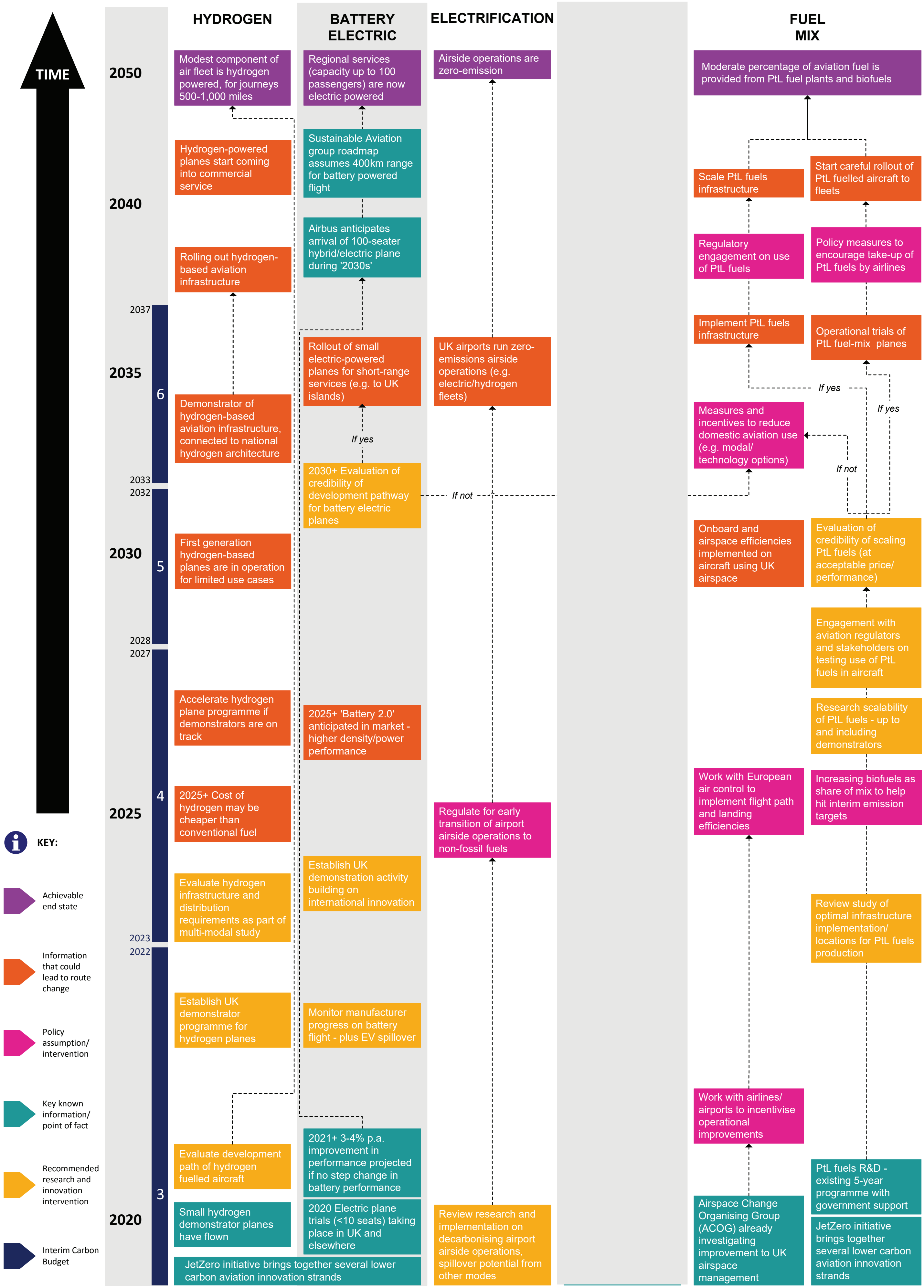
AVIATION



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Modest component of air fleet is hydrogen powered, for journeys 500-1,000 miles
Regional services (capacity up to 100 passengers) are now electric powered
Airside operations are zero-emission
Moderate percentage of aviation fuel is provided from PtL fuel plants and biofuels
Hydrogen-powered planes start coming into commercial service
Sustainable Aviation group roadmap assumes 400km range for battery powered flight
Scale PtL fuels infrastructure
Start careful rollout of PtL fuelled aircraft to fleets
Airbus anticipates arrival of 100-seater hybrid/electric plane during '2030s'
Rolling out hydrogen-based aviation infrastructure
Regulatory engagement on use of PtL fuels
Policy measures to encourage take-up of PtL fuels by airlines
Implement PtL fuels infrastructure
Operational trials of PtL fuel-mix planes
Rollout of small electric-powered planes for short-range services (e.g. to UK islands)
UK airports run zero-emissions airside operations (e.g. electric/hydrogen fleets)
If yes
If yes
Demonstrator of hydrogen-based aviation infrastructure, connected to national hydrogen architecture
Measures and incentives to reduce domestic aviation use (e.g. modal/ technology options)
If yes
If not
2030+ Evaluation of credibility of development pathway for battery electric planes
If not
First generation hydrogen-based planes are in operation for limited use cases
Onboard and airspace efficiencies implemented on aircraft using UK airspace
Evaluation of credibility of scaling PtL fuels (at acceptable price/ performance)
Engagement with aviation regulators and stakeholders on testing use of PtL fuels in aircraft
Accelerate hydrogen plane programme if demonstrators are on track
2025+ 'Battery 2.0' anticipated in market - higher density/power performance
Research scalability of PtL fuels - up to and including demonstrators
2025+ Cost of hydrogen may be cheaper than conventional fuel
Regulate for early transition of airport airside operations to non-fossil fuels
Work with European air control to implement flight path and landing efficiencies
Increasing biofuels as share of mix to help hit interim emission targets
Establish UK demonstration activity building on international innovation
Evaluate hydrogen infrastructure and distribution requirements as part of multi-modal study
Review study of optimal infrastructure implementation/ locations for PtL fuels production
Establish UK demonstrator programme for hydrogen planes
Monitor manufacturer progress on battery flight - plus EV spillover
Work with airlines/ airports to incentivise operational improvements
Evaluate development path of hydrogen fuelled aircraft
2021+ 3-4% p.a. improvement in performance projected if no step change in battery performance
PtL fuels R&D - existing 5-year programme with government support
Small hydrogen demonstrator planes have flown
2020 Electric plane trials (<10 seats) taking place in UK and elsewhere
Review research and implementation on decarbonising airport airside operations, spillover potential from other modes
Airspace Change Organising Group (ACOG) already investigating improvement to UK airspace management
JetZero initiative brings together several lower carbon aviation innovation strands
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