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Battery strategy goes flat: Net-zero target at risk

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SUMMARY

The UK's current trajectory of battery manufacture is insufficient to support the automotive industry's transition to electric vehicles or to meet our net-zero commitment. Despite recent announcements of UK gigafactories, the pace and scale of building these facilities will not meet demand for batteries, and automotive manufacturing will most likely move overseas.

In the face of this risk, we were astonished by the stark disconnect between the optimism of Ministers and officials that the UK could retain its position in the automotive sector, and the concerns of our other witnesses that the UK is far behind its competitors and faces significant challenges with innovation, supply chains and skills.

The most immediate deadline facing the automotive sector is 2027, when the Rules of Origin agreement with the EU will require that the battery and 55% of a vehicle's components be manufactured in the EU or the UK. Without the necessary UK supply chains, manufacture will move to the EU. The next pressing deadline is 2030, when the sale of new petrol and diesel cars and vans in the UK will come to an end. Without major expansion in production capacity, the 2030 target will be undeliverable or will have to be achieved using imported batteries and vehicles.

To support the automotive sector's transition from mechanical to electrical technology, the Government must support training and upskilling, and must ease the limits on recruiting overseas staff for manufacturing and research.

To support the growth in UK supply chains, the Government must urgently develop a strategy for critical raw materials. The UK should utilise its natural resources, develop industrial-scale recycling, and use its expertise in mineral processing to leverage collaboration with countries with larger natural resources. This strategy must address ethical and environmental issues associated with resource extraction, processing and recycling.

In the current international race to manufacture lithium-ion batteries, competitor nations have already invested more heavily than the UK. The UK cannot catch up with the leading manufacturers; it can only try to attract enough investment to supply its automotive industry. However, the UK has a real opportunity to leapfrog to next-generation batteries, and achieve a competitive advantage in future. This would be dependent on the UK retaining its manufacturing capacity and automotive industry, and providing substantial long-term support for research and scale-up.

Heavy transport has received insufficient Government focus, such that a lack of regulations and incentives has severely hindered the use of batteries and fuel cells. The heavy road freight sector needs urgent clarity about which technological options are best suited to its needs, and firm commitments that infrastructure will be deployed at scale. The recent consultation on a ban on the sale of new diesel HGVs by 2040 is welcome, and needs to be supported by concerted research and deployment of alternative technologies. Decarbonisation of the railways is being held back by major delays in the electrification programme. Shipping and aviation will be included in the UK's carbon budgets from 2033, but technological solutions for these sectors are far from readiness.

The Government must publish its hydrogen strategy as soon as possible, coordinated with strategies for transport and buildings. It should provide support for innovation and scale-up for hydrogen technologies, similar to that afforded to batteries, and should promote the UK's expertise to achieve a leading global role. Fuel cells would play an integral part in the proposed hydrogen economy, and yet are a 'Cinderella' in UK energy policy; that is, they receive less attention than they deserve. Fuel cells offer solutions for heavy transport, heating and power generation, but they receive comparatively little public funding for research, innovation and deployment. The UK has several world-class companies in this sector, and yet the Government is not helping adequately to realise their full potential.

Facilitating these applications of batteries and fuel cells requires significant deployment of new infrastructure. The electricity system will experience at least a doubling of demand by 2050 due to electric transport and heating, requiring increased capacity of generation and networks. These costs can be minimised by the use of smart controls and battery storage, but this will require alignment of regulations and incentives to bring about the necessary investment.

To support battery electric vehicles, there must be 'charging for all', at homes, workplaces and public locations. Work on the public charging network is progressing too slowly: the network has to be expanded greatly, with Government providing support for local authorities to deploy and maintain charging points, and ensuring standardisation of technologies and payments methods.

To support the deployment of fuel cell road vehicles, there must be hydrogen fuelling infrastructure at depots and on the strategic road network. Operators of heavy goods vehicles in particular need to be given greater confidence that the facilities will be in place to support their investments in new fleets.

Public confidence in performance and safety underpins the deployment of batteries and hydrogen technologies. The concerns of drivers, local residents and the emergency services must be taken seriously. Action must be taken to mitigate risks, develop effective emergency protocols and provide training to first responders. Regulations and incentives should be used to drive development of safer battery technologies.

The Government needs to align its actions with its rhetoric in order to achieve net zero emissions and to take advantage of the great opportunity presented by batteries and fuel cells for UK research and manufacturing. The UK risks losing not only its existing automotive industry, but also potential global leadership in fuel cells and next-generation batteries. The Government's ambition is not matched by its actions. It must develop a coherent successor to the industrial strategy and promote its objectives clearly, both domestically and internationally, supported by investments commensurate with those of the UK's international competitors.

Battery strategy goes flat: Net-zero target at risk

CHAPTER 1: INTRODUCTION

Overview

1. Batteries and fuel cells are expected to play an important role in decarbonisation in many countries, including contributing to the UK's goal of reaching net-zero greenhouse gas emissions by 2050. These two technologies would contribute to this objective by facilitating the use of low-carbon energy sources and improving the efficiency of energy systems. Batteries are used to store electrical energy for use at later times or on the move. They will allow low-carbon electricity to be used in more applications and with less waste. Fuel cells are devices that use a chemical fuel to generate electricity (and heat), more efficiently than many alternatives. They will allow wider use of fuels that can be manufactured by low-carbon processes; for example, hydrogen can be produced by electrolysis using renewable electricity (essentially the opposite process to a fuel cell), or in future by advanced nuclear reactors.[1] Fuel cells coupled with electrolysers are already available as a scalable method of storing energy as hydrogen for the generation of electricity at a later time.

2. The focus in the UK and comparator countries has been on batteries for light road transport: for cars, and for vans to a lesser extent. A wider array of applications is envisaged for batteries and fuel cells in other modes of transport (heavy-duty road, rail, shipping and aviation, as well as off-road and industrial robots). The technologies can also be used in non-transport sectors (so-called 'stationary applications'), for example to store and supply energy on networks and in buildings.

3. Changing from our current dependence on fossil fuels will be a significant undertaking. It has been made more urgent by the introduction of the targets to reduce emission by 78% by 2035 (compared to 1990 levels) and to reach net-zero emissions by 2050.[2] The electricity generation mix must be decarbonised by 2035, and the supply of electricity must at least double by 2050. Following analysis by the Committee on Climate Change,[3] the Government has decided that all new cars and vans sold from 2030 onwards

1 Hydrogen can be produced in several different ways. Currently the most common method is steam methane reforming (SMR) which uses heat to break up methane gas into hydrogen and carbon dioxide. The most widely available low-carbon method is electrolysis, whereby electricity is used to split water into hydrogen and oxygen. If the electricity is generated by low-carbon sources, then the hydrogen would be considered to be low-carbon. Hydrogen can also be produced via processes such as the 'sulfur-iodine cycle', the heat for which could be provided by some designs of advanced nuclear reactor. Some fuel cells use other chemicals such as ammonia or methane, which are produced by processes that could be decarbonised to some extent.

2 HM Government, 'UK enshrines new target in law to slash emissions by 78% by 2035' (20 April 2021): https://www.gov.uk/government/news/uk-enshrines-new-target-in-law-to-slash-emissions-by-78-by-2035 [accessed 14 July 2021]

3 The Committee on Climate Change (CCC) is an independent, statutory body established under the Climate Change Act 2008. Its purpose is to advise the UK and devolved governments on emissions targets, and to report to Parliament on progress made in reducing greenhouse gas emissions and preparing for and adapting to the impacts of climate change.

will be powered by electricity or hydrogen, rising from 5% of sales today.[4] For heavy transport and stationary applications, batteries and fuel cells are starting to be used, but further development is needed for solutions that can make sufficient impact. Shipping and aviation are yet further behind due to onerous technical requirements. Once solutions are identified for these sectors, they will have to be deployed at great pace to contribute to the UK's 2050 net-zero target.

4. Transitioning to the use of batteries and fuel cells offers opportunities for countries that are developing these technologies. Research and innovation can be translated into commercial products, and industrial-scale manufacture can be expanded to meet domestic demand and potentially to allow export to other markets. Countries such as the UK are seeking to expand their industries in order to achieve these economic gains and avoid becoming reliant on imported technologies.

Structure of report

5. Chapter 2 of this report introduces batteries, fuel cells and their applications, and outlines the expectations of the people who use them. Chapter 3 delves into the detail of the technologies, examining likely future developments and their ability to meet users' expectations. Chapter 4 examines the UK's battery and fuel cell sectors to understand their requirements at all stages from research to manufacturing, and sets out global strategic issues that will affect these sectors' ability to grow and to contribute to the UK's decarbonisation ambitions.

6. We are grateful to all those who gave evidence to our inquiry. We also thank our specialist adviser, Professor Clare Grey FRS of the University of Cambridge.

Technical terms and useful data

7. This report discuses a number of technical matters. Terms are explained when first used, and a glossary is included at the end of the report. Some common terms and helpful data are presented in table 1.

Table 1: Technical terms and useful data

Term or data	Description
Battery	A device that uses chemicals to store energy that can be released as electrical energy
Fuel cell	A device that reacts a chemical fuel (such as hydrogen) with another chemical (such as oxygen) without causing combustion, to produce electricity and heat
Electrolyser	A device that uses electricity to break down chemicals, for example water into oxygen and hydrogen (the opposite of a fuel cell)

4 The Committee on Climate Change has forecast that the number of battery-electric vehicles in the UK will need to increase from around 5% of current sales to almost 100% by 2030. See Committee on Climate Change, *The Sixth Carbon Budget: The UK's path to Net Zero* (9 December 2020) p 98: https://www.theccc.org.uk/wp-content/uploads/2020/12/The-Sixth-Carbon-Budget-The-UKs-path-to-Net-Zero.pdf [accessed 2 July 2021]

Term or data	Description
Orders of magnitude	Refers to quantities being 10, 100, 1,000, etc times larger or smaller. Prefixes are put in front of units: kilo (k) = thousand; mega (M) = million, giga (G) = billion, tera (T) = trillion i.e. 1 with 12 zeros, etc.
Energy	The total amount of work that can be done, such as lighting a light or turning a motor. The greater the energy available, the more work that can be done. The basic unit of energy in electrical engineering is the watt-hour (Wh). Larger amounts of energy are measured in units such as kilowatt-hours (kWh) i.e. one thousand watt-hours, megawatt-hours (MWh) i.e. one million watt-hours, etc.
Power	How quickly work can be done: that is, power is the 'energy per unit time'. The greater the power, the more rapidly work is being done. The basic unit of power is the watt (W). Larger amounts of power are measured in units such as kilowatt (kW) i.e. one thousand watts, megawatts (MW) i.e. one million watts, etc.
UK energy demand	In 2019, the UK used around 2,100 terawatt-hours (TWh) of energy. This includes all of the different sources and uses of energy. The biggest contributions to energy supply were from oil (44%, used mostly for transport) and natural gas (29%, used for heating and electricity generation).[5]
UK electricity demand	In 2019, total UK electricity demand was around 300 terawatt-hours (TWh). This electricity was supplied mainly by natural gas (40%), renewables (37%) and nuclear (17%). The use of electricity was split roughly into thirds between industry, homes and 'other uses'.[6]
Household energy consumption	Based on data for 2018 and 2019, average annual household consumption was 3.1MWh for electricity and 12MWh for gas, for a household with 'medium' consumption and a single tariff electricity meter.[7] For homes that do not have electrical heating, electricity demand equates to about 8–10 kWh per day, with some seasonal variation. Gas demand varies more significantly by season.

5 Department for Business, Energy and Industrial Strategy, *UK Energy Statistics, 2019 & Q4 2019* (26 March 2020): https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/877047/Press_Notice_March_2020.pdf [accessed 7 July 2021]

6 Department for Business, Energy and Industrial Strategy, *UK Energy Statistics, 2019 & Q4 2019* (26 March 2020): https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/877047/Press_Notice_March_2020.pdf [accessed 7 July 2021]

7 Ofgem, *Decision on revised Typical Domestic Consumption Values for gas and electricity and Economy 7 consumption split* (6 January 2020): https://www.ofgem.gov.uk/sites/default/files/docs/2020/01/tdcvs_2020_decision_letter_0.pdf [accessed 8 July 2021]

CHAPTER 2: APPLICATIONS OF BATTERIES AND FUEL CELLS

Overview

8. Batteries and fuel cells have long histories and play important roles in energy systems. Batteries were invented in their familiar form in 1800 by Italian physicist Alessandro Volta, and use chemicals to store energy that can be released as electrical energy.[8] Fuel cells were invented in 1839 by Welsh physicist and judge William Grove, and use chemical reactions without combustion to produce electricity and heat.[9] The technologies have advanced considerably and their use has increased in recent decades. Batteries have become ubiquitous in the era of portable electrical and electronic devices.[10] Fuel cells were advanced in the 1950s–60s for powering NASA spacecraft and have since found a range of applications such as power generation in remote locations and combined heat and power (CHP) units in buildings.[11]

9. Batteries and fuel cells are now seen as key components for decarbonising the economy. This new imperative is directing their continued development. Batteries are increasingly being used in light road transport (cars and vans). Fuel cells and batteries may have applications in other transport modes including heavy road transport (trucks, buses and coaches), rail, shipping and aviation. In stationary, non-transport applications, batteries are being deployed at scales ranging from individual households to substantial grid installations, to provide energy storage and short-term balancing services.[12] Fuel cells can serve a range of functions, partly because they can be designed to use different fuels. If power grids were linked with future hydrogen systems, then fuel cells would play an integral role by using stored hydrogen to help balance electricity supply and demand. Where high energy densities are required (for example in shipping or off-road transport), fuel cells could use ammonia, but there are challenges due to ammonia's toxicity and the production of air pollution during combustion.[13]

UK energy supply and demand

10. In the evidence about batteries and fuel cells, there was frequent discussion of energy and power; these are introduced in box 1, along with the concept of 'energy vectors'.

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8 Encyclopaedia Britannica, 'Development of batteries': https://www.britannica.com/technology/battery-electronics/Development-of-batteries [accessed 2 July 2021]

9 Encyclopaedia Britannica, 'Development of fuel cells': https://www.britannica.com/technology/fuel-cell/Development-of-fuel-cells [accessed 2 July 2021]

10 Q 20 (Professor Paul Shearing)

11 Written evidence from Ceres Power (BAT0016)

12 Balancing services are those measures used by the electricity System Operator (National Grid in the case of the UK) to maintain key grid parameters within acceptable ranges, for example the voltage and frequency. These balancing actions have to be taken very rapidly, such that the power can be more important than the energy that is available. Over longer timescales, the total amount of available energy become important, in order to meet demand.

13 Ammonia is itself toxic, and some of its combustion products are harmful. Ammonia consists of nitrogen and hydrogen, and during combustion the nitrogen combines with oxygen to produce nitrogen oxide (NO_x) gases, much the same as when nitrogen in the air reacts with oxygen in internal combustion engines. Of these gases, nitric oxide (NO) and nitrogen dioxide (NO_2) contribute to urban air pollution and affect ozone in the troposphere; and nitrous oxide (N_2O) is a potent greenhouse gas.

Box 1: Energy and power

Energy and power are closely related, but need to be distinguished. Energy is the total amount of work that can be done; power is how quickly that work can be done; that is, power is the 'energy per unit time'. Energy is measured in units such as kilowatt-hours (kWh); power is measured in units such as kilowatts (kW).

For example, a battery might be able to store 50kWh of energy and its maximum power might be 25kW. This means that it could run at full power for two hours or at 10kW for five hours, and so on. For a battery (particularly in a vehicle) the stored energy is often the more important factor because it determines the range; but the power can matter for more applications such as providing immediate back-up for a power grid.

Fuel cells tend to be described in terms of power, because the energy is determined not by the fuel cell but by the fuel supply (which could be finite tank or an essentially unlimited supply from a gas grid). A fuel cell might have a power rating of 500kW but the amount of energy that it can generate depends on how long it operates. For example, if operating for 75% of time, it would produce 3.3 gigawatt-hours per year (GWh/yr).

Finally, energy can be spoken of as sources and 'vectors'. Energy sources are self-explanatory, and include natural gas, nuclear and renewables. Energy vectors are the 'media' that transport energy, and include sources such as gas but also 'intermediaries' such as electricity and hydrogen.

11. In 2019, the UK used around 2,100 terawatt-hours (TWh) of energy[14] (where 'tera' means 'one billion billion', or 'one followed by 12 zeros'). This includes all of the different sources and uses of energy. The biggest contributions to energy supply were from oil (44%, used mostly for transport) and natural gas (29%, used for heating and electricity generation). Total electricity demand was around 300 terawatt-hours. This electricity was sourced mainly from natural gas (40%), renewables (37%) and nuclear (17%), and the use of electricity was split roughly into thirds between industry, homes and 'other uses'.

12. Traditionally, each energy source and energy vector has been largely confined to particular sectors of the economy, albeit with some overlaps. Liquid fuels have been used for transport and some heating. Electricity has been used for appliances, some heating and in industry. Gas has been used for heating and industry, and in some power generation (a 'one-way link' to the electricity system).

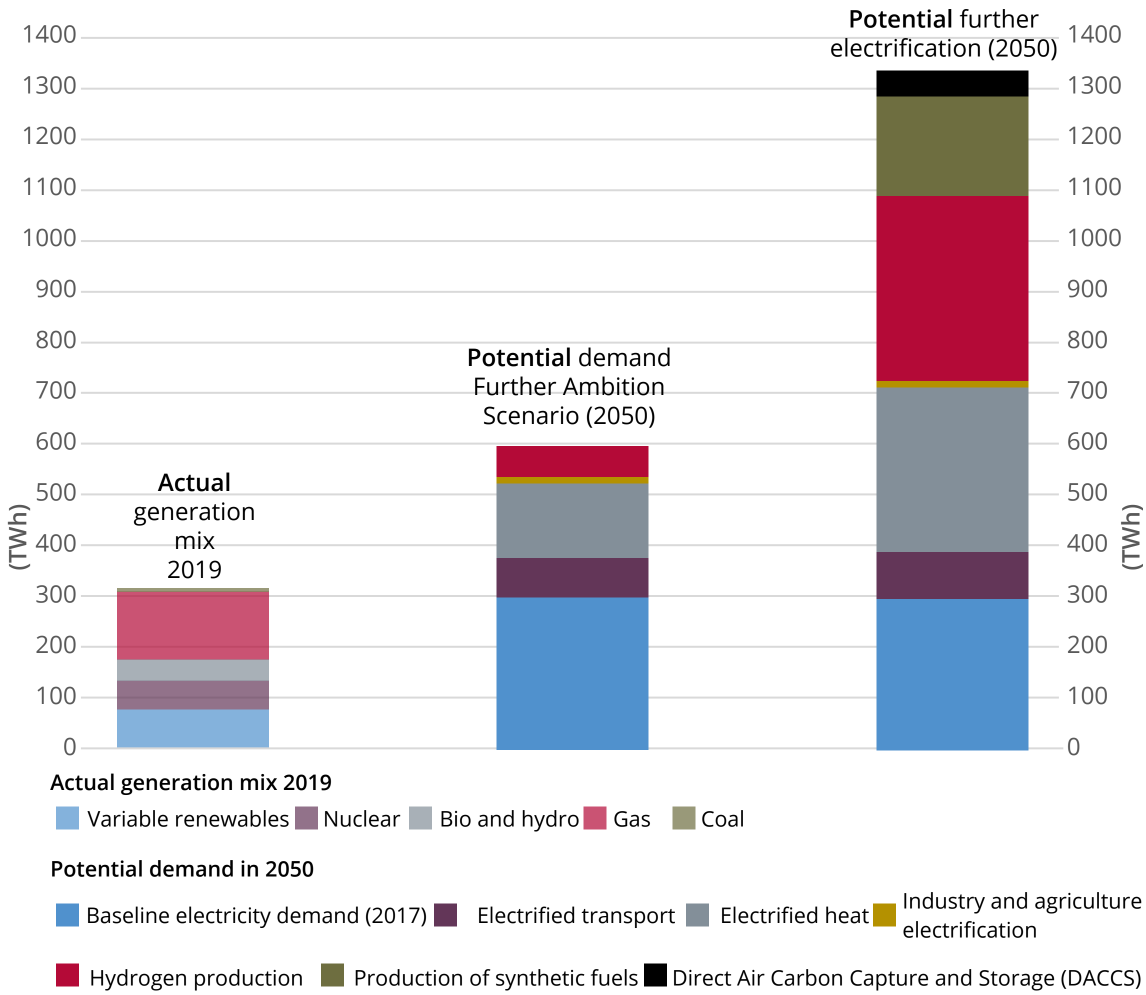
13. These delineations are becoming increasingly blurred, creating added complications but new opportunities. Transport and heating increasingly use the electricity system, adding to demand but offering storage opportunities (for example, in vehicle batteries). Hydrogen could replace natural gas and other fuels, including in power generation (allowing a two-way link with the electricity system if the hydrogen has been produced by electrolysis).

14. Electricity demand in the UK is forecast to grow considerably. In figure 1, the actual generation mix in 2017 (which is roughly the same as demand)

14 Department for Business, Energy and Industrial Strategy, *UK Energy Statistics, 2019 & Q4 2019* (26 March 2020): https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/877047/Press_Notice_March_2020.pdf [accessed 7 July 2021]

is compared to two illustrative scenarios for potential electricity demand in 2050. These scenarios by the Committee on Climate Change envisage at least a doubling of electricity demand due to transport, heating and hydrogen production, and a possible quadrupling of demand in the event of further electrification. These scenarios are considered further in the discussion about energy storage for electricity systems, along with the related deadline of 2035 for decarbonising the electricity generation mix.

Figure 1: Scenarios of future electricity demand and generation mix



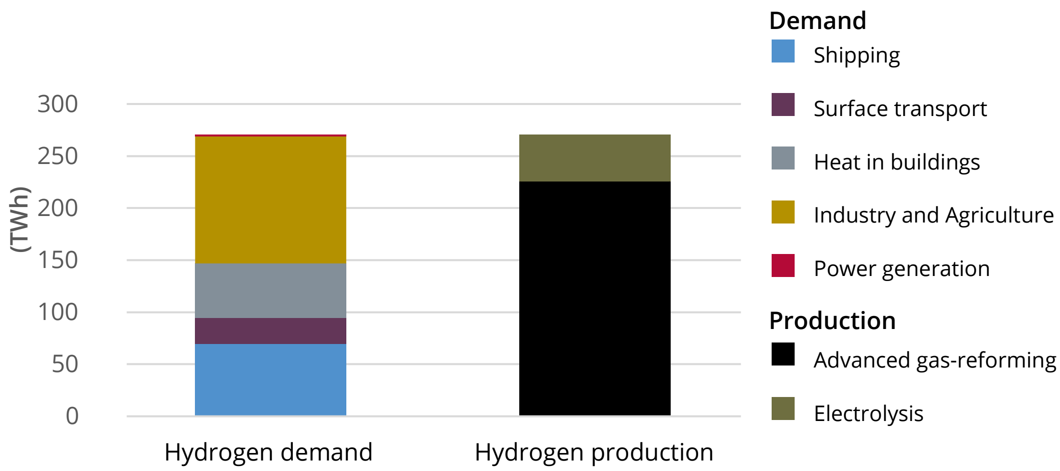
Source: Department for Business, Energy and Industrial Strategy, UK Energy Statistics, 2019 & Q4 2019 (26 March 2020): https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/877047/Press_Notice_March_2020.pdf *[accessed 7 July 2021]. And: Committee on Climate Change, Net Zero—Technical Report (2 May 2019):* https://www.theccc.org.uk/wp-content/uploads/2019/05/Net-Zero-Technical-report-CCC.pdf *[accessed 7 July 2021]*

15. Similarly, figure 2 presents a potential scenario of hydrogen demand in 2050, and how that might be supplied, again based on work by the Committee on Climate Change. This scenario envisages hydrogen demand of around 270 TWh per year by 2050, which is the same amount of energy as natural gas currently provides for electricity generation.[15] The Government has an initial

15 Department for Business, Energy and Industrial Strategy, *UK Energy Statistics, 2019 & Q4 2019* (26 March 2020): https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/877047/Press_Notice_March_2020.pdf [accessed 7 July 2021]. It should be noted that gas-powered electricity generation is up to around 60% efficient, so the amount of electrical energy generated is less than the chemical energy in the gas.

target of 5GW of hydrogen production by 2030; if this operated constantly, it would produce 44 TWh of hydrogen per year (around 16% of the scenario's demand in 2050).

Figure 2: Potential hydrogen demand and production in 2050



Source: Committee on Climate Change, Net Zero—Technical Report (2 May 2019): https://www.theccc.org.uk/wp-content/uploads/2019/05/Net-Zero-Technical-report-CCC.pdf *[accessed 7 July 2021]*

Transport applications

16. Transport accounted for around one third of the UK's 522 $MtCO_2e$ of greenhouse gas emissions in 2019. Surface transport (that is, road and rail) accounted for around two-thirds of transport emissions (22% of the UK's emissions).[16] The UK's share of emissions from international shipping and aviation contribute 3% and 7% of the UK total, respectively.[17] There are currently no international agreements for including these emissions in national accounting, but in 2021 the UK Government committed to include the UK's share in the sixth carbon budget (for 2033–37).[18]

17. Two decarbonisation options are considered relevant for transport: internal combustion engines (ICEs) using low-carbon fuels, such as synthetic fuels, biofuels, hydrogen or ammonia; and electric propulsion powered by a battery or by a fuel cell that operates on a fuel such as hydrogen, ammonia or an alcohol. Hybrid vehicles have both an internal combustion engine and an electric drivetrain. Batteries are used not only in battery electric vehicles (BEVs) and hybrids, but also on a smaller scale in fuel cell electric vehicles (FCEVs).

Road transport

18. The decarbonisation options for different types of road transport will depend on factors such as the purpose (passenger or freight) and the duty cycle

16 Committee on Climate Change, *The Sixth Carbon Budget: The UK's path to Net Zero* (9 December 2020) pp 24 and 29: https://www.theccc.org.uk/wp-content/uploads/2020/12/The-Sixth-Carbon-Budget-The-UKs-path-to-Net-Zero.pdf [accessed 2 July 2021]
17 Committee on Climate Change, *The Sixth Carbon Budget: The UK's path to Net Zero* (9 December 2020) p 30: https://www.theccc.org.uk/wp-content/uploads/2020/12/The-Sixth-Carbon-Budget-The-UKs-path-to-Net-Zero.pdf [accessed 2 July 2021]
18 HM Government, 'UK enshrines new target in law to slash emissions by 78% by 2035' (20 April 2021): https://www.gov.uk/government/news/uk-enshrines-new-target-in-law-to-slash-emissions-by-78-by-2035 [accessed 2 July 2021]

(light or heavy). The duty cycle is the proportion of time spent operating, and correlates with vehicle weight, average distance travelled per trip and propulsion type. Roughly speaking, light vehicles include those up to a weight of 3.5 tonnes (minibuses and equivalent-sized vans), and heavy vehicles are everything above that weight.[19]

Light road vehicles

19. Light road transport (cars and vans) has seen the most progress of any transport sector to-date. BEVs accounted for 6.1% of sales of new cars in the UK in 2021, and 10.7% of sales from January to June 2021 (in addition to plug-in hybrids and non-plug-in hybrids).[20] The Department for Transport's *Public Attitudes Tracker* survey in relation to EVs found that 87% of car owners plan to replace their current vehicle (via purchase or a lease); of these, 30% plan to seek a hybrid and 9% an EV.[21]

20. This progress is largely due to the sector having a clear technology pathway. This has given the automotive industry the confidence to invest. Globally the industry has decided to focus on battery electric vehicles more so than on fuel cell electric vehicles. Ian Constance, the CEO of the Advanced Propulsion Centre, made the analogy of light-duty transport being "a two-horse race with battery electric winning but fuel cell still in the mix".[22] Witnesses believed that BEVs would dominate the market for low-carbon light road vehicles, in part due to reductions in the cost of lithium ion batteries. However, Ian Constance foresaw "fuel cell penetration into that sector [of] perhaps 5% or 10%" for "certain applications and users that need to travel long distances or haul relatively heavy loads".[23] Several hydrogen fuel cell cars and vans have been developed globally. Some models are available in the UK[24] and over 250 light FCEVs are running on UK roads.[25]

21. The clearer technology pathway for light road transport has given governments the confidence to set targets and apply regulatory pressure. In the UK, the Government has banned the sale of new petrol and diesel cars and vans from 2030,[26] following a recommendation of the Committee on Climate Change.[27]

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19 Q 99 (Ian Constance)

20 SMMT (Society of Motor Manufacturers and Traders), 'SMMT Vehicle Data: Car Registrations': https://www.smmt.co.uk/vehicle-data/car-registrations/ [accessed 12 July 2021]

21 The results cited in the text are from the sixth edition of this survey, dated November 2020: Kantar and Department for Transport, *Transport and Technology: Public Attitudes Tracker—Wave 6: Summary report* (November 2020): https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/955253/DfT-Kantar-Transport-and-Transport-Technology-Public-Attitudes-Tracker-Wave-6-Summary-Report.odt [accessed 2 July 2021]. This survey has been conducted six times since 2018, and the full set of results is available here: Department for Transport, 'Transport and transport technology: public attitudes tracker' (28 January 2021): https://www.gov.uk/government/publications/transport-and-transport-technology-public-attitudes-tracker [accessed 2 July 2021]

22 Q 99 (Ian Constance)

23 Q 99 (Ian Constance)

24 FCEVs available in the UK include the Toyota Mirai and the Hyundai Nexo. See Toyota (GB) plc, 'Hydrogen-powered Mirai' (March 2017): https://www.toyota.co.uk/new-cars/new-mirai/ [accessed 12 July 2021]. See also Hyundai Motor UK Ltd, 'All-new Nexo' (2018): https://www.hyundai.co.uk/new-cars/nexo [accessed 12 July 2021]

25 Written evidence from UK H2Mobility (BAT0022)

26 HM Government, *Government takes historic step towards net-zero with end of sale of new petrol and diesel cars by 2030* (18 November 2020): https://www.gov.uk/government/news/government-takes-historic-step-towards-net-zero-with-end-of-sale-of-new-petrol-and-diesel-cars-by-2030 [accessed 21 June 2021]

27 Committee on Climate Change, *Reducing UK emissions: Progress Report to Parliament* (25 June 2020) p 19: https://www.theccc.org.uk/wp-content/uploads/2020/06/Reducing-UK-emissions-Progress-Report-to-Parliament-Committee-on-Cli.._-002-1.pdf [accessed 21 June 2021]

This will be followed by a ban on the sale of hybrid cars and vans from 2035, covering both plug-in hybrids and non-plug-in hybrids. However, because of the large variation in emissions of different hybrids models, sales of some hybrids could cease in 2030 based on the outcome of an upcoming Government consultation on distances travelled with zero tailpipe emissions (called 'significant zero emission capability' or the 'significant distance' measure).[28]

Buses and coaches

22. In the heavy-duty road passenger sector, the bus industry has growing confidence that batteries and fuel cells are good options for local buses, with recharging or refuelling provided at depots.[29] Cities such as London might need buses with longer ranges, because limited space for parking means they cannot stop for long to charge. Similarly, the technological challenges are greater for long-distance coaches, due to their greater range and weight. The UK Government's Ten Point Plan of 2020 committed to "invest £120 million next year to begin the introduction of at least 4,000 more British built zero emission buses".[30] The commitment to introduce at least 4,000 zero-emission buses was reiterated in 2021 in the first national bus strategy.[31] The Government has consulted on the date for banning the sale of new diesel buses and a decision is pending.[32]

23. Currently the UK's bus fleet consists of 2% zero-emission buses, 14% hybrids and 84% diesel vehicles.[33] Electric buses are being deployed in large numbers in the UK, for example: there are over 400 in London;[34] Coventry and Oxford are transitioning to fully electric fleets;[35] and First Bus is installing 162 charging points at a Glasgow depot.[36] There are almost 100 hydrogen

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28 In the Government's response to its consultation on the phase-out of petrol and diesel cars and vans it said that "significant zero emission capability will be defined through consultation later this year." See the Department for Transport and the Office for Zero Emission Vehicles, 'Outcome and response to the ending the sale of new petrol, diesel and hybrid cars and vans' (10 March 2021): https://www.gov.uk/government/consultations/consulting-on-ending-the-sale-of-new-petrol-diesel-and-hybrid-cars-and-vans/outcome/ending-the-sale-of-new-petrol-diesel-and-hybrid-cars-and-vans-government-response [accessed 12 July 2021]

29 See, for example, Written evidence from Wrightbus and Ryse Hydrogen (BAT0039)

30 HM Government, *The Ten Point Plan for a Green Industrial Revolution* (November 2020) p 16: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/936567/10_POINT_PLAN_BOOKLET.pdf [accessed 21 June 2021]

31 The national bus strategy reiterated the commitment to introduce 4,000 zero-emission buses, and set out plans to support British bus manufacturing, but did not explicitly reiterate the commitment that the 4,000 buses would be British-built. Department for Transport, *Bus Back Better: National Bus Strategy for England* (2021) pp 13 and 73: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/980227/DfT-Bus-Back-Better-national-bus-strategy-for-England.pdf [accessed 21 June 2021]

32 Department for Transport and the Office for Zero Emission Vehicles, 'Ending the sale of new diesel buses' (15 March 2021): https://www.gov.uk/government/consultations/ending-the-sale-of-new-diesel-buses [accessed 21 June 2021]

33 Department for Transport, *Annual bus statistics: England 2019/20* (28 October 2020) p 11: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/929992/annual-bus-statistics-year-ending-march-2020.pdf [accessed 21 June 2021]

34 Transport for London, *London's buses now meet ULEZ emissions standards across the entire city* (14 January 2021): https://tfl.gov.uk/info-for/media/press-releases/2021/january/london-s-buses-now-meet-ulez-emissions-standards-across-the-entire-city [accessed 21 June 2021]

35 Department for Transport, 'Coventry and Oxford set to be UK's first all-electric bus cities' (6 January 2021): https://www.gov.uk/government/news/coventry-and-oxford-set-to-be-uks-first-all-electric-bus-cities [accessed 21 June 2021]

36 First Bus, 'First Bus begin works on UK's biggest electric vehicle charging station at flagship Glasgow depot' (7 June 2021): https://www.firstbus.co.uk/greater-glasgow/news-and-service-updates/news/first-bus-begin-works-uks-biggest-electric-vehicle [accessed 21 June 2021]

buses in operation in Europe, including 10 in London and six in Aberdeen.[37] Wrightbus and Ryse Hydrogen told us about the development of hydrogen buses, including the world's first hydrogen electric double-decker bus. They discussed the fuelling infrastructure for bus depots, explaining that "10 MW of electrolysis provides a capacity of more than 4 tonnes hydrogen per day … sufficient to fuel … 200–250 buses".[38]

Heavy road freight

24. The heavy-duty road freight sector has made only limited progress on decarbonisation, largely because it is not yet clear which technological solutions are most appropriate for meeting its more demanding requirements. In contrast with light duty vehicles, Ian Constance referred to heavy-duty road transport being in "a three-horse race with hydrogen fuel cells, battery electric with the potential perhaps for on-road charging, and then zero-carbon fuels".[39] Professor Nigel Brandon, Dean of the Faculty of Engineering at Imperial College London, said that for "larger vehicles, off-road vehicles … or long-distance trucks … hydrogen fuel cell electric is competing with synthetic fuel combustion … [and] with ammonia".[40] As noted earlier, ammonia's toxicity would pose challenges, for example in the event of a fuel spillage.

25. The Government told us that trials that are under way to try to identify the best options for HGVs. In the Energy White Paper, the Government announced £20 million of investment in road freight trials in 2021 to "pioneer hydrogen and other zero emission truck technologies to support industry to develop cost-effective, zero emission HGVs in the UK."[41] The £23 million *Hydrogen for Transport Programme* "is funding the deployment of around 300 hydrogen vehicles, eight new refuelling stations and upgrades to five existing stations." The £2 million *FCEV Fleet Support Scheme* is "supporting public and private sector fleets to become early adopters" of hydrogen technology.[42]

26. Companies are developing low-carbon propulsion systems for HGVs. In November 2020, the Volvo Group and Daimler Truck AG signed an agreement for a "joint venture to develop, produce and commercialize fuel-cell systems for use in heavy-duty trucks as the primary focus, as well as other applications."[43] Volta Trucks told us about its *Volta Zero*, "the world's first purpose-built full-electric 16-tonne commercial vehicle designed specifically for inner-city logistics and freight distribution." It explained that the vehicle can be "equipped with either a 150kWh or 225kWh battery … [for] an operating range of 90–125 miles".[44]

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37 Fuel Cell Electric Buses, 'Knowledge Base—map of deployments in Europe' (2021): https://fuelcellbuses.eu/ [accessed 21 June 2021]

38 Written evidence from Wrightbus and Ryse Hydrogen (BAT0039)

39 Q 99 (Ian Constance). On-road charging includes two potential options: pantographs to draw energy from overhead wires (as electric trains do), and wireless electromagnetic induction to draw energy from cables buried in the road.

40 Q 13 and Q 3 (Professor Nigel Brandon OBE)

41 Department for Business, Energy and Industrial Strategy, *Energy White Paper: Powering our Net Zero Future*, CP 337, December 2020, p 94: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/945899/201216_BEIS_EWP_Command_Paper_Accessible.pdf [accessed 5 July 2021]

42 Written evidence from HM Government (BAT0041)

43 Daimler AG, 'Fuel-cell joint venture: Volvo Group and Daimler Truck AG sign binding agreement' (2 November 2020): https://www.daimler.com/company/news/fuel-cell-joint-venture-volvo.html [accessed 21 June 2021]

44 Written evidence from Volta Trucks (BAT0003)

27. The Committee on Climate Change has recommended a ban on the sale of new diesel HGVs by 2040.[45] At the end of our inquiry, the Government published its *Decarbonising Transport* plan[46] and opened a consultation on ending the sale of new diesel HGVs weighing up to 26 tonnes by 2035, and HGVs weighing over 26 tonnes by 2040.[47]

28. **In order to make the transition to low-carbon technologies, the heavy road freight sector needs urgent clarity about which technological options are best-suited to its needs, and firm commitments that infrastructure will be deployed at scale. Clear deadlines from the Government, such as a finalised timetable for ending the sale of HGVs, would focus efforts as is happening in the light road sector.**

29. ***We recommend that the Government promptly confirms the end of sales of new diesel HGVs from 2040 or earlier. This will provide a clear timeline for research and development of technologies (including batteries and fuel cells), manufacture of vehicles and deployment of infrastructure.***

Rail

30. The rail sector accounts for 1.4% of transport emissions (0.5% of all UK emissions).[48] Emissions per passenger-kilometre and tonne-kilometre for freight are already lower for rail than for other modes of transport. Rail will retain this advantage as decarbonisation continues, and the strategy for decarbonising transport relies on a degree of modal shift of freight and passengers onto rail.[49]

31. Freight and passenger trains can be powered by diesel or electric systems. It should be noted that *electric* trains (powered by overhead cables or live rails) are distinct from *battery* trains. The UK Government proposed in 2018 that diesel trains should be removed from the network by 2040.[50] A report in 2019 by the Rail Industry Decarbonisation Taskforce detailed how this could be achieved.[51]

32. The Railway Industry Association told us that electrification of additional high-use routes is "the gold-standard of zero-carbon transport solutions".

45 Q 77 (Rachel Maclean MP). See also Committee on Climate Change, *The Sixth Carbon Budget: The UK's path to Net Zero* (9 December 2020) p 29: https://www.theccc.org.uk/wp-content/uploads/2020/12/The-Sixth-Carbon-Budget-The-UKs-path-to-Net-Zero.pdf [accessed 2 July 2021]

46 Department for Transport, *Decarbonising Transport: A Better, Greener Britain* (July 2021): https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1002285/decarbonising-transport-a-better-greener-britain.pdf [accessed 14 July 2021]

47 Department for Transport, *Consultation on when to phase out the sale of new, non-zero emission heavy goods vehicles* (July 2021): https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1002124/consultation-on-when-to-phase-out-the-sale-of-new-non-zero-emission-heavy-good-vehicles.pdf [accessed 14 July 2021]

48 Written evidence from the Railway Industry Association (BAT0043)

49 Office of Rail and Road, *Rail Emissions 2019–20* (5 November 2020) p 5: https://dataportal.orr.gov.uk/media/1843/rail-emissions-2019–20.pdf [accessed 21 June 2021] This report notes that: "Railways made up 1.4% of the UK's transport CO_2 emissions in 2018, but in comparison 10% of all passenger kilometres were made using rail. Rail emissions account for 0.5% of the UK's total CO2 emissions."

50 HM Government, 'Let's raise our ambitions for a cleaner, greener railway' (22 February 2018): https://www.gov.uk/government/speeches/lets-raise-our-ambitions-for-a-cleaner-greener-railway [accessed 21 June 2021]

51 Rail Industry Decarbonisation Taskforce, *Final Report to the Minister For Rail* (July 2019) p 4: https://www.rssb.co.uk/-/media/Project/RSSB/RssbWebsite/Documents/Public/Public-content/Research-and-Technology/rail-industry-decarbonisation-taskforce-final-report-for-the-minister-for-rail-july-2019-final.pdf [accessed 21 June 2021]

Electric trains have proven performance, and their main advantage is their lighter weight because they do not carry fuel or batteries. Where electrification is uneconomical, trains would be powered by batteries or hydrogen fuel cells. This would include routes with limited usage and routes that are otherwise electrified but have sections where that is too expensive. Electrification will need to be extensive enough such that the remaining sections are manageable for batteries or fuel cells.[52]

33. The Railway Industry Association explained that batteries and fuel cells were unsuited to freight or higher-speed passenger trains, due to the size and weight of systems that would be needed to provide the necessary range.[53] Helen Simpson, Projects Director at Porterbrook, said that batteries offer a range of 50–60 miles and hydrogen fuel cells several hundred miles but with the disadvantage of large hydrogen tanks.[54] For particular applications, trains are being developed that use fuel cells,[55] and trains that use both batteries and fuel cells.[56]

34. Battery trains are being used for some short routes[57] and various applications are foreseen for small batteries: on routes where other options are uneconomical; on electric trains for 'discontinuous electrification' over short distances that are too costly to electrify; and in conjunction with rapid, wireless charging to allow trains to operate with smaller batteries.[58] In addition, Helen Simpson observed that "there is a large and increasing market in the parcels and light logistics sector that could be adapted for other technologies such as hydrogen and batteries".[59]

35. The UK's rail electrification programme is falling behind schedule.[60] We heard concerns that the UK's strategy was not as clear some other countries' and lacked long-term funding. One result is "a boom-and-bust cycle" for the supply chain, which is detrimental to the development of new technologies.[61] More generally, we were told that the UK faces a practical impediment to modifying its railways and trains: namely, confined space compared with many other countries. The UK's trains have a smaller loading gauge (width and height), such that it can be harder to fit the new technologies on board. The UK's bridges and tunnels are commensurately lower, such that there is

52 Written evidence from the Railway Industry Association (BAT0043)
53 Written evidence from the Railway Industry Association (BAT0043)
54 Q 101 (Helen Simpson)
55 For example, the French rail manufacturer Alstom has used fuel cell technology developed by Cummins for its 'Coradia iLint' fuel cell powered train, which entered service in Lower Saxony in September 2018. See Alstom, 'World premiere: Alstom's hydrogen trains enter passenger service in Lower Saxony' (16 September 2018): https://www.alstom.com/press-releases-news/2018/9/world-premiere-alstoms-hydrogen-trains-enter-passenger-service-lower [accessed 23 June 2021]
56 For example, we were told about the HydroFLEX project that has retrofitted an existing Class 319 train with a hydrogen fuel cell and batteries. See written evidence from Porterbrook (BAT0042)
57 Battery trains are being trialled on a route in Denmark in 2021. See 'Denmark to get battery-powered trains from next year', *The Local* (29 November 2019): https://www.thelocal.dk/20191129/denmark-to-get-battery-powered-trains-from-next-year/ [accessed 23 June 2021]
58 Written evidence from the Railway Industry Association (BAT0043)
59 Q 103 (Helen Simpson)
60 Network Rail electrified 251km of lines in 2019–20, compared with the average of 450km per year needed to achieve the 13,000km that is estimates will be needed by 2050. See Railway Industry Association, 'Railway industry urges Government to begin programme of rail electrification now, in order to meet Net Zero legal commitments' (22 April 2021): https://riagb.org.uk/RIA/Newsroom/Press_Releases/Railway_Industry_urges_programme_of_Electrification_to_meet_Net_Zero_Targets.aspx [accessed 23 June 2021]
61 Q 99 (Helen Simpson)

less space for overhead electrical cables. Developing these bespoke solutions for the UK adds to the cost.[62]

36. **Electrification of the railway network (using cables and live rails) will have to be strategic and extensive, to allow greater use of electric trains and so that those sections left without electrification are within the capabilities of trains powered by batteries and fuel cells. Otherwise, sections may be left for which decarbonisation is more expensive or more challenging. This poses the risk that the necessary increases in freight and passenger rail may not occur, and indeed that some usage could shift to roads.**

37. ***The Government must ensure that the railway electrification programme is accelerated in order that it reaches as far as is economically and technically feasible by 2040, when diesel trains will be phased out. The development of battery and fuel cell trains should be supported to serve those parts of the network that remain non-electrified.***

Shipping

38. The main requirement for shipping fuels is that they must have sufficient energy density. Weight and space are less constrained than in other modes of transport, but are still important considerations. As with any mode of transport, higher speeds incur disproportionately higher fuel consumption, and there can be particular pressure on shipping operators to increase speed in order to reduce the time taken on routes of days or weeks. Batteries can be used for small boats over shorter distances, for example harbour tugs, pleasure craft and oilrig supply vessels.[63] For larger ships, the energy source must be dense enough to propel their large weight over long voyages without refuelling.[64] The two main maritime fuels at present are diesel and fuel oil: diesel is used near to ports and other population centres because it is less polluting than fuel oil, which is generally used only out at sea.

39. However, fuel oil pollution is a problem in any location. Professor John Irvine of the University of St Andrews told us that this is a driver for adopting alternative fuels such as methanol or ammonia. He recommended using ammonia in a high-temperature fuel cell connected to an electric drivetrain, which would provide the required range (whereas hydrogen could not) and improve energy efficiency by 50% compared to an internal combustion engine. The downside, he noted, was the high cost of fuel cells, but this would be expected to fall as their market share grew.[65] The impacts of nitrous oxide pollution produced by the combustion of ammonia would need to be assessed.

40. Early development programmes are under way. Dr Mark Selby told us that ammonia fuel cells for shipping are being developed by companies in South Korea and Europe.[66] In March 2021 UK Research and Innovation and the Department for Transport, launched a "£20m funding opportunity

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62 Q 99 (Helen Simpson)
63 Ship Technology, 'Electric ships: the world's top five projects by battery capacity', (25 August 2020): https://www.ship-technology.com/features/electric-ships-the-world-top-five-projects-by-battery-capacity/ [accessed 23 June 2021]
64 Written evidence from Frazer-Nash Consultancy (BAT0030)
65 Q 35 (Professor John Irvine)
66 Q 93 (Dr Mark Selby)

… around maritime decarbonisation, for which both battery and fuel cell projects are sought."[67]

Aviation

41. Aviation has the most stringent technical requirements of all modes of transport. Fuels must have high energy densities in order to minimise their weight and volume (and to enable long distances in some cases), and must be handled with extreme caution to mitigate the risk of serious incidents in the air. UK Research and Innovation told us that research initiatives are under way through the Aerospace Technology Institute Programme, the Future of Flight Challenge and the new Jet Zero Council (a partnership between industry and government).[68]

42. Paul Stein, Chief Technology Officer at Rolls Royce, predicted that propulsion technologies in the aviation sector would diverge in future according to energy requirements. He said that long-distance flights by large aircraft (that is, flights of over 1,500km, which account for 75% of global aviation's CO_2 emissions) have such high energy demands that they will continue to need energy-dense liquid fuels.[69] He suggested that medium-to-large planes on short-distance routes could use liquid hydrogen in fuel cells, having sufficient space and low enough energy requirements to cope with its lower energy density. We heard that Airbus has announced plans for a hydrogen fuel cell plane.[70]

43. We heard about a future generation of small, fixed-wing, vertical take-off aircraft powered by fuel cells or batteries. Paul Stein said that these would undertake short flights (including most internal UK flights) and operate as emergency vehicles.[71] He said: "We can fly about 10 people about 200 kilometres with today's technology. That will extend up to about 350 kilometres by the end of the decade as battery technology develops, and we are targeting 500 kilometres by 2040."[72] The Aerospace Technology Institute said that electric aircraft offered significant cost benefits: "a nine-seater aircraft flying a 160km flight required around $6 worth of electricity compared to a conventional combustion engine which would have used around $300–400 worth of fuel".[73]

44. **The aviation sector is very challenging to decarbonise, particularly its long-distance routes. However, battery and fuel cell technologies could offer solutions for shorter routes, and their application to electric vertical take-off and landing aircraft could allow aviation to play a more flexible role in national transport and emergency services.**

Stationary applications

45. Batteries and fuel cells can play roles on power grids and other stationary energy systems. Batteries can provide short-term balancing services on electricity grids, and can store excess electricity generation for use at a later

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67 Written evidence from UK Research and Innovation (BAT0045)
68 Written evidence from UK Research and Innovation (BAT0045)
69 Q 98 (Paul Stein). See also Q 46 (Professor John Irvine)
70 Q 44 (Professor Anthony Kucernak)
71 Q 98 (Paul Stein). See also Q 46 (Professor John Irvine)
72 Q 100 (Paul Stein)
73 Written evidence from the Aerospace Technology Institute (BAT0021)

time. This is particularly relevant for intermittent renewable electricity sources, allowing energy produced at times when is not needed to be released when demand is higher or when the renewable output is too low. Fuel cells do not store energy but can be used to generate electricity using a stored chemical fuel such as hydrogen, which ideally will have been produced by electrolysis powered by low-carbon generation. Fuel cells can also produce heat for buildings and hot water. Each of these applications can be at different scales, from individual buildings to communities to supporting the wider energy system.

46. The electricity sector has had the most success in reducing greenhouse gas emissions thus far, out of the various sectors in the UK. However, further improvements could become incrementally harder. The commitment to reduce emissions by 78% by 2035[74] will require the electricity generation mix to be decarbonised by that time, ahead of sectors that are harder to decarbonise. The anticipated doubling (or more) of electricity demand by 2050 (see figure 1) will require a range of measures,[75] as discussed below.

Energy storage for electricity systems

47. Storing energy decouples production and consumption; that is, it allows energy to be used at a different time to when it was produced. This is becoming increasingly important with the changes in the methods of supply and patterns of demand required by decarbonisation. The different scales and durations over which balancing must occur mean that there are opportunities for various storage technologies, including: pumped hydroelectric, hot water tanks, thermochemical systems, batteries, and low-carbon chemical fuels coupled with fuel cells or turbines.[76] The energy that can be stored in a device at any one time depends upon its capacity, whereas the energy stored over the course of a year depends on how often the device is charged or discharged. Therefore, making thorough comparisons between batteries and other storage systems requires detailed assumptions about the operating regimes, and are not attempted in this report.

48. Scenarios of possible future demand for electricity are modelled by various organisations.[77] Nick Winser, Chair of the Energy Systems Catapult, told us that UK electricity demand is currently 300 terawatt-hours per year (TWh/yr). He said that demand is expected to be at least twice that level by 2050 (partly driven by BEVs) but that it could be up to four times the current level depending on the extent to which heat pumps[78] are deployed and smart systems are used to manage demand. He cautioned that these scenarios would raise "some very serious issues for the electricity system" and recommended getting "the absolute maximum out of the existing infrastructure, because

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74 HM Government, 'UK enshrines new target in law to slash emissions by 78% by 2035' (20 April 2021): https://www.gov.uk/government/news/uk-enshrines-new-target-in-law-to-slash-emissions-by-78-by-2035 [accessed 14 July 2021]

75 Q 105 (Dr Jane Dennett-Thorpe) and Q 105 (Professor Tim Green)

76 See, for example, Q 106 (Dr Keith MacLean) and Q 106 (Nick Winser CBE)

77 See, for example, National Grid ESO, 'Welcome to the ESO Future Energy Scenarios' (2021): https://www.nationalgrideso.com/future-energy/future-energy-scenarios [accessed 23 June 2021]

78 Heat pumps are a technology for heating buildings, and most versions are powered by electricity. They are essentially the opposite of a fridge. Heat pumps are highly efficient, exploiting thermodynamical principles to provide more energy as heat than they consume as electricity. However, even with this efficiency, heat pumps would shift significant energy demand from the gas networks to the electricity networks.

building a system that is three or four times as big is enormously expensive and very time-consuming.”[79]

49. Increased electricity demand will require action on three fronts: more capacity to generate electricity; upgraded networks to distribute electricity; and smarter systems to balance supply and demand.[80] We were told that the system will need low-carbon baseload generation capacity, such as nuclear, biomass, and fossil fuels with carbon capture and storage (CCS),[81] and that interconnectors to other countries allow access to a wider range of power generation.[82] However, witnesses agreed that most electricity generation will come from wind and solar power.[83] These sources cannot be controlled and some of their output is lost when demand is low by comparison, and making use of the ‘excess energy’ is one of the rationales for storage.

50. Flexible operation of the electricity system offers alternative ways of balancing supply and demand with less need for new generation capacity and upgrades to networks. Flexibility includes shifting demand (for example through ‘smart tariffs’) and storing energy for use at later times. Witnesses explained that storage is needed over a range of timescales: intraday (seconds to hours), short-term (days and weeks) and seasonal (months). They warned that the scales can be very large and that providing this in future could be challenging. For example, Dr Keith MacLean, Managing Director of Providence Policy, noted that the gas grid currently provides 3–4TWh per day of storage in its pipes and tanks, which is almost as much gas as the UK uses for a cold winter’s day.[84] This gives the system inherent flexibility to cover peaks in demand such as hot water in the morning and the varying need for electricity during the day. He said that energy storage requirements will remain at the scale of “terawatt hours per day, tens of terawatt hours per season, and over 100 terawatt hours across the year.”[85]

51. Professor Tim Green, Co-Director of the Energy Futures Laboratory at Imperial College London, explained that longer-term storage would have to be able to cover several successive days in winter with high demand and low wind speeds, and that these large scales necessitated a chemical fuel such as hydrogen (which has a high energy density when compressed). He calculated that a “a one-in-10-year winter” with particularly long incident of low wind speeds would equate to around 20–40 terawatt-hours of electricity, and that conversion inefficiencies translated that into around 60 terawatt-hours of hydrogen.[86]

52. Batteries are being used on the UK power grids to provide balancing services. That is, they are one of the technologies that provide short-term changes in flows to help maintain parameters such as voltage and frequency within the correct operational ranges. As such, batteries are sometimes spoken of in terms of their power as opposed to their energy. That said, as batteries are increasingly used for providing energy over longer periods of time, their

79 Q 105 (Nick Winser CBE)
80 See, for example, Q 110 (Dr Jane Dennett-Thorpe)
81 Q 105 (Nick Winser CBE) and Q 105 (Professor Tim Green)
82 Q 107 (Professor Tim Green)
83 Q 105 (Nick Winser CBE) and Q 105 (Professor Tim Green).
84 Watson *et al.*, ‘Decarbonising domestic heating: What is the peak GB demand?’, *Energy Policy*, vol. 126 (2019) pp 533–544: https://linkinghub.elsevier.com/retrieve/pii/S0301421518307249 [accessed 23 June 2021]
85 Q 106 (Dr Keith MacLean OBE)
86 Q 106 (Professor Tim Green)

energy capacity will also be important to grid operators. As an example, the Thurcroft battery site in South Yorkshire has a maximum power of 50 MW and a storage capacity of 75 MWh.[87] This energy could supply around 7,500 homes for one day, or it could be released at maximum power for up to 1.5 hours.[88] The UK's largest planned battery installation will be at London Gateway, which will have a power of 320MW and a storage capacity of 640MWh.[89] This energy could supply 64,000 homes for one day, or it could be released at maximum power for up to 2 hours.

53. Nick Winser estimated that the UK would need storage across all energy vectors with a total power rating of 200–500GW, of which batteries might need to provide 20–35% (that is, a lower limit of 40GW). In terms of scale, he noted that 50GW is the size of the current electricity system (that is, the typical power flow). In terms of deployment, he said that "we are a long way short of the amount of battery [storage] that would be on an optimised grid system.[90] However, even those large numbers of batteries offer limited storage compared to chemical fuels. The energy stored at any one time would depend on the battery technology and the specific design. Using current types of batteries to provide 50GW of power would equate to stored energy in the range of 100–200GWh.[91] Larger amounts energy storage could be achieved using alternative technologies such as flow batteries (which are discussed in chapter 3). As noted above, the energy stored over the course of a year would depend on how often the batteries were charged and discharged.

54. Battery storage would be needed at different scales, as Professor Green said: "There is a role for megawatt-scale batteries… but the kilowatt-scale domestic batteries provide an additional service, which is to take some of the stress off a local distribution network."[92] He said that two-hour batteries would be particularly useful for "balancing of short-term variations in load and wind speeds".[93] Professor Brandon said flow batteries might be considered for durations of 10–12 hours.[94]

55. We heard that other battery technologies might be needed: technologies such as sodium-ion batteries and flow batteries may offer advantages over lithium-ion, including lower cost, better safety and less reliance on materials that are rare and/or toxic (as discussed in chapter 3).[95]

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87 Flexitricity, 'UK's largest battery set to help keep the nation's lights on' (November 2020): https://www.flexitricity.com/resources/press-release/uks-largest-battery-set-help-keep-nations-lights/ [accessed 14 July 2021]

88 Average daily household electricity consumption is around 8–10kWh (where heating is not provided by electricity). The upper level of 10kWh is used in these examples for simplicity.

89 Intergen, 'InterGen gains consent to build one of the world's largest battery projects in Essex' (30 November 2020): https://www.intergen.com/news-insights/categories/news/intergen-gains-consent-to-build-one-of-the-world-s-largest-battery-projects-in-essex/ [accessed 14 July 2021]

90 Q 106 (Nick Winser CBE)

91 This assumption is based on data for typical battery installations such as those cited above with an 'energy-to-power ratio' of around 2 MWh-to-MW, and others such as a 250MW/1,000MWh project by AGL in Australia with a ratio of 4 MWh-to-MW. National Grid's Future Energy Scenarios assume a ratio of around 2 MWh-to-MW. See Energy Storage News, 'UK's largest battery storage project at 640MWh gets go ahead from government' (30 November 2020): https://www.energy-storage.news/news/uks-largest-battery-storage-project-at-320mw-gets-go-ahead-from-government [accessed 14 July 2021]. See also National Grid ESO, *Future Energy Scenarios* (July 2020) p 112, Figure SV.45: https://www.nationalgrideso.com/document/173821/download [accessed 14 July 2021]

92 Q 115 (Professor Tim Green)

93 Q 106 (Professor Tim Green)

94 Q 14 (Professor Nigel Brandon OBE) Flow batteries are discussed in chapter 3. In summary, they can store more energy than conventional battery designs by using tanks containing additional electrolyte.

95 Q 22 (Dr jerry Barker) and Q 31 (Professor Paul Shearing)

56. In the context of batteries, there are interesting links between stationary storage and low-carbon transport. On the one hand, the impacts of charging EVs can be partially mitigated by adding batteries to homes or local power grids.[96] These stationary batteries can be charged at times of lower demand and then EVs can be charged without the need for (any or as much) grid reinforcement.[97] On the other hand, the batteries in EVs can be controlled such that they charge at optimal times and even feed energy into the grid if needed: so-called 'vehicle-to-grid' flows. National Grid's *Future Energy Scenarios 2020* estimated that in 2050 vehicle-to-grid technologies could offer up to 38GW of power to the grid.[98] These two-way interactions offer greater flexibility for grid management but require the development of control algorithms to deal with large quantities of data and tariffs to incentivise consumer engagement.[99]

57. **In order to decarbonise the electricity system by 2035 and to meet at least a doubling of demand by 2050, there need to be large upgrades to network capacity, smart controls need to be implemented, and a wide array of storage technologies must be deployed. Without batteries of different scales and potentially fuel cells drawing on stored hydrogen, increasing amounts of renewable energy will be wasted. Without smart operation and storage, the costs of grid expansion will be significantly higher. For larger grid-connected batteries, there is merit in developing alternatives such as sodium-ion and flow batteries. For smaller batteries in homes and businesses, there will need to be more sophisticated tariffs and control systems to optimise the benefits. To provide inter-seasonal storage, there may be a need for grid-scale fuel cells to be deployed as part of the UK's wider hydrogen strategy.**

58. ***The Government and Ofgem must ensure that electricity network regulations and incentives are aligned to bring about the necessary investment in networks, storage and smart systems. They must ensure that energy market rules facilitate more sophisticated services, including tariffs to enable demand shifting, extensive use of battery storage, and smooth interactions with hydrogen systems.***

Fuel cells for power and heat

59. We heard about a number of applications for fuel cells, in homes and businesses, in local communities and at larger scales on energy networks. Fuel cells produce electricity but also heat, which can be harnessed to provide space heating and/or hot water. That is, they can operate as a combined heat and power (CHP) unit, with an overall efficiency of well over 90%.[100] Heat

96 Written evidence from Solar Energy UK (BAT0017)

97 For example, the Evalu8 project trialled the use of batteries to address grid constraints at service stations. The batteries were charged overnight when demand was low, and then used to charge EVs. See the European Commission, 'Exploiting the business potential of electric vehicles' (10 December 2014): https://ec.europa.eu/regional_policy/en/projects/united-kingdom/exploiting-the-business-potential-of-electric-vehicles [accessed 23 June 2021]

98 National Grid ESO, *Future Energy Scenarios* (July 2020) p 6: https://www.nationalgrideso.com/document/173821/download [accessed 23 June 2021]

99 Q 107 (Professor Tim Green) and Written evidence from Johnson Matthey (BAT0011)

100 Written evidence from Ceres Power (BAT0016)

accounts for over a third of UK carbon emissions. Decarbonising this sector will be crucial for reaching the Government's net zero target.[101]

60. Micro-CHP units (which have power ratings of a few tens of kilowatts) can be used as a substitute for boilers in individual homes.[102] Of the various CHP technologies that are available, fuel cell CHP units have higher efficiency and lower emissions.[103] Fuel cell CHP units are not used widely in the UK. Japan has high uptake compared to most countries, with 45,000 purchased in 2019 and 350,000 installed overall to-date.[104] Professor Kucernak from Imperial College London noted that "Some of them also operate in a grid independent mode, so they can operate for 72 hours without any electricity … in the event of a grid failure."[105] Because fuel cells could use a gaseous fuel delivered by existing gas infrastructure, Professor Brandon pointed out that a fuel cell could charge an electric vehicle without having to invest as much in the electricity network.[106]

61. Fuel cells could also be used for heating in non-domestic settings; for example, a construction site for National Grid's Viking Link project was heated using fuel cells.[107] Similarly, fuel cells can provide power for business premises. Professor Irvine told us that "applications are already quite well spread throughout the US", for example providing uninterruptible electricity supplies for internet companies and data centres.[108]

62. Several witnesses advocated the use of larger fuel cells (for example, with power ratings of a few megawatts) at a local and community level. Professor Andrea Russell of the University of Southampton recommended using larger fuel cells for "making localised use of hydrogen that is produced."[109] Professor Irvine agreed, saying that fuel cells "can generate electricity at high efficiency in decentralised systems".[110] Professor Kucernak supported fuel cells as a way to "delocalise electricity production in the UK, give greater resilience and offset the requirements for reinforcement of the grid", and to "distribute … hot water around the local houses in a local heating network." He told us that a one-megawatt fuel cell system is "about the size of a 20-foot standard shipping container would power about 160 homes" and that the systems "are very quiet and do not produce any pollutants."[111] There are examples of local projects using renewable electricity to power electrolysis

101 Department for Business, Energy and Industrial Strategy, *Clean Growth—Transforming Heating* (December 2018): https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/766109/decarbonising-heating.pdf [accessed 24 June 2021]
102 See for example, PACE, 'Fuel Cell micro-Cogeneration': https://pace-energy.eu/micro-cogeneration/ [accessed 24 June 2021]
103 Staffell *et al.*, 'The role of hydrogen and fuel cells in the global energy system', *Energy & Environmental Science*, Issue 2 (2019) pp 463–491: https://doi.org/10.1039/C8EE01157E [accessed 24 June 2021]
104 Q 14 (Professor Nigel Brandon OBE) and Q 34 (Professor Anthony Kucernak)
105 Q 34 (Professor Anthony Kucernak)
106 Q 14 (Professor Nigel Brandon)
107 National Grid, 'World's first hydrogen heated construction site' (7 September 2020): https://www.nationalgrid.com/stories/journey-to-net-zero-stories/worlds-first-hydrogen-heated-construction-site [accessed 24 June 2021]
108 Q 42 (Professor John Irvine) and Q 43 (Professor John Irvine)
109 Q 35 (Professor Andrea Russell)
110 Q 35 (Professor John Irvine)
111 Q 42 (Professor Anthony Kucernak)

to produce hydrogen that can then fuel FCEVs or be stored and used to generate power and heat at a later time.[112]

63. **The UK could make better use of fuel cells in conjunction with electrolysers in a range of stationary applications. Trials of local and community-scale systems could quickly be replicated, to increase the use of excess renewable electricity to produce hydrogen for transport, heating and power. The use of fuel cells in buildings connected to the gas grid would have merit if those buildings were supplied with 'low-carbon' hydrogen.**

64. Fuel cells would be needed at larger scales if there was to be more widespread use of hydrogen. In addition to using hydrolysis to utilise excess electricity from renewables, hydrogen might in future be produced using high-temperature chemical cycles such as the 'sulfur-iodine cycle'.[113] The necessary temperature (around 1,000°C) could be achieved by concentrated solar-thermal collectors or advanced next-generation nuclear reactors (also called 'Generation IV' technology).[114] Advanced reactors are being trialled in small-scale demonstration projects,[115] and could be designed at different scales including as small modular reactors (with powers or around 300 megawatts) that could be deployed at the level of small cities.

65. **A clear strategy is needed for large-scale hydrogen storage in order to make better use of excess renewable electricity (by producing hydrogen via electrolysis), and in the future to be coupled with hydrogen produced using advanced nuclear reactors.**

Expectations and acceptance

66. If a technology is to make a contribution to decarbonisation, it must work in a technical sense and provide the required service in a way that meets user expectations and gains public acceptance. This is true of batteries and fuel cells, which are being used to replace familiar technologies and perform core tasks for daily life and work.

67. Comparisons may be made in factors such as: performance and reliability; convenience and ease-of-use; cost and payment models; safety; and environmental impacts. Those making these judgements depend on the context. For example, many individuals decide on which technologies to use in their homes (for heating and energy storage) and for their cars. The Department for Transport provided a list of research projects that seek to understand people's views about electric vehicles.[116] The *Transport and Tech Tracker* survey of attitudes and behaviours relevant to transport found that

112 There are several hydrogen projects in Orkney, including BIG HIT, Surf'n'Turf, HyDIME, HyFlyer. Each has its own website, but for a general overview, see Orkney.com, 'Hydrogen' (2021): https://www.orkney.com/life/energy/hydrogen [accessed 24 June 2021]

113 The International Union of Pure and Applied Chemistry (IUPAC) has decided that only the spelling 'sulfur' should be used, replacing the spelling 'sulphur' in the UK.

114 International Atomic Energy Agency, *Hydrogen Production Using Nuclear Energy* (2013): https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1577_web.pdf [accessed 12 July 2021]

115 HM Government, *The Ten Point Plan for a Green Industrial Revolution* (November 2020) p 12: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/936567/10_POINT_PLAN_BOOKLET.pdf [accessed 21 June 2021]

116 Supplementary written evidence from the Department for Transport (BAT0049)

88% of people think that BEVs offer advantages over internal combustion engines but the same proportion mentioned at least one disadvantage.[117]

68. However, some decisions about technologies are made not by individual users but by landlords for rented homes and workplaces, by utility companies for energy networks, and by transport operators for freight and passenger services. In all cases, there are elements of public acceptance by those who are not directly using the technology or services.

Infrastructure

Charging infrastructure

69. We heard concerns over charging of electric vehicles, including the need for more rapid chargers in towns and on the strategic road network. According to the *Transport and Tech Tracker* survey, *t*he most common group of concerns about EVs relate to charging (45%), including lack of charging points (22%), where or how to charge (10%) and the time taken to recharge (10%).[118] The Committee on Climate Change wrote in a 2020 report that the UK currently has around 400,000 plug-in electric cars and vans and around 18,000 public charging points, and that a forecast fleet of 23.2 million EVs in 2032 would need 325,000 public charging points.[119]

70. Ian Constance spoke of the need for "the ubiquitous supply of energy and charging points". He said that the "home charging regime is well under way", but that more public chargers were needed in order to "give people the confidence that they can go out and use their cars".[120] The Government's announcement in the Ten-Point Plan of £1.3 billion to accelerate the rollout of the charging infrastructure[121] was "a good start", but there "will be the need for a huge amount of chargers in rural locations, in city locations and on the strategic road network and in towns and cities."[122]

71. One solution could be rapid wireless charging. Dr Jeffrey Chamberlain, CEO of Volta Energy Technologies, said that with "a ubiquitous fast charge network, you can make cars with smaller batteries so the cost can go down" and that this could soon be delivered by wireless charging.[123]

72. We heard about challenges to the deployment of chargers. Ian Constance observed: "One of the big issues is the fact that land costs in the UK are very high, and providing the land to put these chargers in will be very expensive."[124]

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117 Kantar and Department for Transport, *Transport and Technology: Public Attitudes Tracker—Wave 6: Summary report* (November 2020): https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/955253/DfT-Kantar-Transport-and-Transport-Technology-Public-Attitudes-Tracker-Wave-6-Summary-Report.odt [accessed 2 July 2021]

118 Kantar and Department for Transport, *Transport and Technology: Public Attitudes Tracker—Wave 6: Summary report* (November 2020): https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/955253/DfT-Kantar-Transport-and-Transport-Technology-Public-Attitudes-Tracker-Wave-6-Summary-Report.odt [accessed 2 July 2021]

119 Committee on Climate Change, *Briefing document: The UK's transition to electric vehicles* (2020) p 2: https://www.theccc.org.uk/wp-content/uploads/2020/12/The-UKs-transition-to-electric-vehicles.pdf [accessed 12 July 2021]

120 QQ 99–100 (Ian Constance)

121 HM Government, *The Ten Point Plan for a Green Industrial Revolution* (November 2020) p 17: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/936567/10_POINT_PLAN_BOOKLET.pdf [accessed 21 June 2021]. See also Q 165 (Rachel Maclean MP)

122 Q 100 (Ian Constance)

123 Q 150 (Dr Jeffrey Chamberlain)

124 Q 100 (Ian Constance)

Deployment of public chargers varies between local authorities[125] (and between the nations of the UK). There are concerns that some areas lack the resources to develop a strategy and make use of available funds.[126]

73. Where extra power flows necessitate grid reinforcements, these are generally undertaken by the local Distribution Network Operator. Their work is funded via price controls set by Ofgem, which recently announced £300 million of funding to support 1,800 rapid chargers at motorway service areas and key trunk road locations (tripling the current network), and a further 1,750 charge points in towns and cities.[127]

74. There can be problems with operation of chargers. We heard that too many public chargers are out of commission, which is partly due to the expiration of maintenance contracts.[128] There are concerns that companies' different payment methods create complexity that can deter customers. Rachel Maclean MP, Parliamentary Under Secretary of State at the Department for Transport, told us that the Government has consulted on "consumer experience" and will "lay regulations [to] require all charge-point operators to have a simple, standard contactless payment mechanism." She added: "it has to be just as easy for people to fill up their electric car as it is at the moment to fill up a diesel or petrol car."[129]

75. **In order to give individuals and companies the confidence to invest in electric vehicles, there needs to be faster deployment of infrastructure for charging, including rapid chargers in towns and on the strategic road network. Charging has to be accessible to all, with suitable options provided for those without dedicated parking spaces or driveways. In the longer-term, wireless charging could be important, and should be developed and evaluated for transport applications. The user experience has to be simplified, with standardisation of technology and payment methods.**

76. ***The Government should ensure electric vehicle charging for all users, including by accelerating the expansion of the public charging network, to deliver around 325,000 charging points by around 2032, as recommended by the Committee on Climate Change. This will require supporting local authorities to develop and implement strategies for deployment and maintenance of public charging-points. Regulations to standardise charging and payments methods should be introduced at the earliest possible time. We ask the Government to confirm the legislative timings in its response to this report.***

Hydrogen infrastructure

77. An advantage of fuel cell electric vehicles (FCEVs) is that, like conventional vehicles, they can be completely refuelled in a few minutes. In addition, users

125 Q 165 (Rachel Maclean MP)

126 See, for example, Energy Saving Trust, *Procuring electric vehicle charging infrastructure as a local authority* (September 2019) p 14: https://energysavingtrust.org.uk/wp-content/uploads/2020/10/Local-Authority-Guidance-Procuring-electric-vehicle-charging-infrastructure.pdf [accessed 25 June 2021]

127 Ofgem, 'Ofgem delivers £300 million down payment to rewire Britain' (24 May 2021): https://www.ofgem.gov.uk/publications/ofgem-delivers-ps300-million-down-payment-rewire-britain [accessed 25 June 2021]

128 Q 163 (Dr Bob Moran)

129 Q 165 (Rachel Maclean MP)

might appreciate the similarity and familiarity of refuelling infrastructure compared with conventional fuelling stations. However, the UK currently lacks sufficient hydrogen supply infrastructure. In 2019 there were only 15 hydrogen stations in the UK (compared to 8,500 petrol stations).[130] The Committee on Climate Change estimates that the UK will need around 100 hydrogen stations by 2035 and 250 by 2040.[131]

78. Ian Constance said that "there is a need for a clear hydrogen strategy" without which "this kind of activity will stall". He pointed out: "Some countries already have it, particularly in Asia. Japan has a very clear hydrogen strategy and understands where it is going. That enables a much clearer route to investing and putting in place the products that are required to go forward."[132]

79. **In order for companies to have greater confidence in hydrogen vehicles, there needs to be an expansion of the hydrogen fuelling network, particularly on the strategic road network to support road freight.**

Performance

80. *Users can be unsure whether a new technology will perform as well as (or in the same way as) the technology with which they have been familiar. For transport applications, performance includes range, acceleration, time to refuel and so on. In the Transport and Tech Tracker the second most common concern about EVs* was the range provided by the batteries (36%).[133] These concerns are higher amongst rural dwellers. These issues are primarily a matter of battery performance, which is discussed in chapter 3.[134]

Cost

81. New technologies generally start off more expensive than the incumbents, in terms of upfront costs and/or running costs such as fuel. For EVs, the *Transport and Tech Tracker* survey[135] found that the third-most-cited benefit was cheaper running costs (24%), but the third most-cited concerns were various costs (22%), including the cost of purchasing a BEV (10%). Ian Constance said that innovation can "bring those costs down to something that will be broadly acceptable and accessible for everybody".[136] Professor Brandon noted that FCEV cars are more expensive than alternatives.[137] He said that economies of scale will reduce costs, noting that hydrogen buses

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130 Staffell *et al.*, 'The role of hydrogen and fuel cells in the global energy system', *Energy & Environmental Science*, Issue 2 (2019) pp 463–491: https://doi.org/10.1039/C8EE01157E [accessed 2 July 2021]

131 Committee on Climate Change, *The Sixth Carbon Budget: The UK's path to Net Zero* (9 December 2020) p 99: https://www.theccc.org.uk/wp-content/uploads/2020/12/The-Sixth-Carbon-Budget-The-UKs-path-to-Net-Zero.pdf [accessed 2 July 2021]

132 Q 103 (Ian Constance)

133 Kantar and Department for Transport, *Transport and Technology: Public Attitudes Tracker—Wave 6: Summary report* (November 2020): https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/955253/DfT-Kantar-Transport-and-Transport-Technology-Public-Attitudes-Tracker-Wave-6-Summary-Report.odt [accessed 2 July 2021]

134 Range is also affected by driving style (acceleration, speed and braking), so there is scope for improvements from behaviour change.

135 Kantar and Department for Transport, *Transport and Technology: Public Attitudes Tracker—Wave 6: Summary report* (November 2020): https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/955253/DfT-Kantar-Transport-and-Transport-Technology-Public-Attitudes-Tracker-Wave-6-Summary-Report.odt [accessed 2 July 2021]

136 Q 99 (Ian Constance)

137 Q 10 (Professor Nigel Brandon OBE)

are "sort of boutique, and made in low volume, and are therefore expensive products."[138]

82. In terms of energy costs, electricity for cars and vans is currently cheaper than petrol or diesel, whereas hydrogen is more expensive.[139] The carbon intensity of electricity will continue to fall as the generation mix changes, whereas for hydrogen there is a trade off at present between cost and carbon-intensity. The Aerospace Technology Institute told us that 'green hydrogen' (produced by electrolysis) costs $3.00–7.50 per kg, compared with $0.90–3.20 per kg for 'brown hydrogen' (produced by steam methane reformation).[140] Professor Irvine said that the aim is for hydrogen to cost $2 per kilogram,[141] which is around £1.50 per kilogram and would be cheaper than petrol, diesel and electricity for cars on a per kilometre basis.[142]

83. Amer Gaffar, Director of the Manchester Fuel Cell Innovation Centre, told us that businesses focus on the total cost of ownership when making investment decisions. Relevant factors include "future electricity prices, clean air zones or the likelihood of taxation on electric vehicles or hydrogen fuel in the future." He explained that these businesses "think that they can make an impact, especially with fuel cells in heavy goods vehicles", but the "lack of hydrogen refuelling infrastructure is informing many decisions [by] multiple fleet operators".[143]

84. At present, most batteries for stationary applications are lithium-ion. They benefit from the cost reductions seen in recent years due to economies of scale in the automotive sector. Additional savings are made by using 'second life' batteries, which have been removed from vehicles when they can charge to only around 80% capacity.[144] Other battery chemistries could become cheaper once they achieve economies of scale. As well as the battery costs, we heard about taxation. Solar Energy UK said, "Since October 2019, residential solar and storage installations have been subject to complex VAT rules, in many cases increasing VAT from 5% to 20%." They recommended that VAT should be zero for "solar and storage installations, including maintenance".[145]

Safety

85. Users and the general public may have concerns about the safety of new technologies, including the risks posed by electrical and hydrogen systems. INFACTNI is an organisation representing people in Northern Ireland living close to very large Battery Energy Storage Systems facilities. They

138 Q 10 (Professor Nigel Brandon OBE)

139 Typical fuel consumption for a new conventional car is 5.7 litres per 100 km (petrol) and 5.1 litres per 100 km (diesel); at fuel costs of around £1.30 per litre, these equate to about £7.40 and £6.60 per 100km, respectively. Typical hydrogen consumption is approximately 1 kg per 100 km, with each kilo of hydrogen currently costing £10–15, and is hence about twice the price of petrol or diesel. A BEV would typically require approximately £3 of charge to cover the same distance, which is about half the price of petrol or diesel. See RAC Foundation, 'Environment' (2021): https://www.racfoundation.org/motoring-faqs/environment [accessed 12 July 2021]. See also House of Commons Library, 'Electric vehicles and infrastructure', Library Note, CBP-7480, 23 June 2021, p 14

140 Written evidence from the Aerospace Technology Institute (BAT0021)

141 Q 36 (Professor John Irvine)

142 Using the same data as in the previous example, but reducing the cost of hydrogen from £10–15 per kg to £1.50 per kg, gives a cost of about £1.40 per 100km, which is lower than the current values for petrol, diesel and electricity.

143 Q 12 (Amer Gaffar)

144 Written evidence from Johnson Matthey (BAT0011)

145 Written evidence from Solar Energy UK (BAT0017)

told us about risks posed by lithium-ion batteries: "Lithium-ion fires are notoriously difficult to extinguish … Often they are just left to burn out, as [dousing] them for several days with water causes toxic fire-water runoff which contaminates land and water ways. However, leaving them to burn out means that huge clouds of toxic gas are released into the air damaging human health and soil." They cited fire departments in the UK and abroad whose concerns included lack of information about the contents of large battery installations and lack of clarity about how to treat battery fires at installations or in vehicles.[146]

86. Ian Constance said that EV battery fires that took several hours to extinguish were "down to early development issues" and "In general the automotive industry has a very strong safety track record". He said that "a new approach will be required from the fire service and the first responders"; they "will need new equipment as well". Similarly, he was concerned about vehicle maintenance workers who are not trained to work with high-voltage systems.[147] The Faraday Institution is providing £1.52 million over 4 years for the SAFEBATT project that is seeking to understand the degradation and damage that can lead to fires and to "develop a consensus around the optimal method of fighting large [lithium-ion battery] fires".[148]

87. Regarding hydrogen for FCEVs, Professor Marcus Newborough, Development Director at ITM Power, pointed out that the fire risk is small, in that "If you make [hydrogen] electrochemically and then use it electrochemically, there are no ignition sources in that chain."[149] Jo Godden, Managing Director for Fuel Cells at Johnson Matthey, told us that "The hydrogen tanks within the vehicle will vent safely if there was an accident, and that removes the stored energy on the vehicle, which is difficult to do with other fuels." She added, "For public perception, the more used the public are to seeing hydrogen-fuelled buses on our roads, and using them regularly, as well as the battery electric vehicles and fuel cell powered commercial vehicles, trains and cars, the more it brings that confidence in the technology … [that it] is a safe design".[150]

88. Helen Simpson told us about safety issues in the rail sector. For batteries, there was "monitoring and detection of battery temperatures at individual cell level", and "packaging of batteries is different in rail from other sectors because we have these higher levels of safety integrity for rail." On hydrogen, the first step was having tanks that are "tested … to a very high level of pressure", and "release and venting is done in a controlled manner and only in an emergency". She explained that "Once hydrogen is in the air, it dissipates very quickly indeed", but there is a risk when it is contained in a small space such as a railway tunnel. Looking ahead to the first fleets of hydrogen passenger trains, she said there was the need to consider "the infrastructure and skills needed for refuelling trains with hydrogen. That is very different from what we do now."[151]

146 Written evidence from INFACTNI (BAT0001)
147 Q 104 (Ian Constance)
148 The Faraday Institution, 'SAFEBATT—The Science of Battery Safety' (2021): https://www.faraday.ac.uk/research/lithium-ion/BATTERY-SAFETY/ [accessed 23 June 2021]
149 Q 95 (Professor Marcus Newborough)
150 Q 95 (Jo Godden)
151 Q 104 (Helen Simpson)

89. Aviation has the most stringent safety requirements of all transport sectors. Electric planes pose challenges with their high currents and voltages, because air at high altitude has lower density and hence lower electrical resistance. Paul Stein said the industry is "having to come up with whole new regimes to manage safety". The less dense air is a poorer thermal conductor; he highlighted the need for "thermal runaway containment" for batteries, which had to "go to another level over and above what can be tolerated on land and sea." For hydrogen, he noted its "incredibly low flash point", such that it is essential to avoid leaks and to ensure the "accident integrity" of storage tanks. His view was that most of the challenges were surmountable but "Liquid hydrogen is the one where the jury is still out." Finally, he discussed non-physical safety, saying that electrical vertical take-off and landing aircraft would require advances in "digital flight control systems … collision avoidance algorithms … and air traffic management systems probably using artificial intelligence."[152]

90. ***The Government should take steps to build public confidence in the safety of batteries and hydrogen technologies. The concerns of residents and drivers about the fire safety of batteries must be taken seriously. Action must be taken to mitigate the risks of existing battery installations, including more stringent safety standards. Regulations and incentives should be used to drive development of safer battery technologies in transport and stationary applications. Effective fire-fighting protocols need to be developed, with provision of training and equipment for fire fighters, other first responders and vehicle maintenance workers.***

Environmental impacts

91. Batteries and fuel cells are being deployed to bring about environmental benefits, including reducing emissions of greenhouse gases and other air pollution. Batteries emit nothing during operation and hydrogen fuel cells emit only water[153] (although other fuels such as ammonia do produce air pollutants). In the most recent *Transport and Tech Tracker* survey, the top benefits cited were environmental, such as reduced pollution (77%), and third on the list was being quieter than traditional vehicles (9%).[154] However, negative environmental impacts could affect levels of public acceptance. For example, as noted above, there are concerns about battery fires putting toxic chemicals into the air and water courses.[155] Chapter 4 considers unwanted impacts that can occur at different stages of the technologies' life cycles, such as resource extraction and end-of-life.

152 Q 104 (Paul Stein)
153 Q 33 (Professor John Irvine):
154 Kantar and Department for Transport, *Transport and Technology: Public Attitudes Tracker—Wave 6: Summary report* (November 2020): https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/955253/DfT-Kantar-Transport-and-Transport-Technology-Public-Attitudes-Tracker-Wave-6-Summary-Report.odt [accessed 2 July 2021]
155 Written evidence from INFACTNI (BAT0001)

CHAPTER 3: TECHNOLOGICAL DEVELOPMENTS

92. Batteries and fuel cells are the subject of research and development across all 'technology readiness levels' (TRLs).[156] Battery development is occurring across a wider range of technology readiness levels, with technologies such as lithium-ion being mature but several others at earlier stages of research. Fuel cells are generally considered to be a more mature technology and efforts are focused on higher technology readiness levels, seeking innovations to improve performance and reduce costs. This chapter outlines avenues of research and innovation that may enable the technologies to meet the needs of users more effectively in the applications discussed in chapter 2. (More detail is provided in appendix 1.)

Batteries

93. In the UK, battery research and development since 2017 has primarily been supported by the Faraday Battery Challenge, which is administered by UK Research and Innovation.[157] The Challenge has invested £318 million since 2017, primarily to set up two new organisations and to fund operations until 2022. The Faraday Institution funds public sector research projects, and acts as a central coordinating body for much of the UK's activity.[158] The UK Battery Industrialisation Centre provides facilities for product developers to trial the manufacture of new batteries.[159] However, we heard that funding is short-term, for example the Faraday Institution was initially funded for four years up to March 2022, and is currently bidding for renewal of funding primarily for electrochemical research.[160]

Basic operation

94. All batteries operate in the same basic manner, storing chemical energy that can be converted into electrical energy. Once discharged, rechargeable batteries can have their store of energy replenished by the application of electricity; non-rechargeable (or 'primary') batteries are not relevant to this report. The simplest form of battery technology is called a 'cell', and a battery or 'battery pack' is a collection of cells (there around 10,000 cells in an EV battery)[161] although in common parlance this distinction is often not made. The structure and operation of a cell is illustrated in figure 3 and explained in box 2.

156 Technology Readiness Levels (TRLs) were originally developed by NASA as a method of measuring the maturity of space exploration technology, and are now used widely in technology sectors. They range from TRL1 (basic principles), TRL2 (invention and research), and so on though piloting and up to TRL9 (operations).

157 UK Research and Innovation, 'Faraday Battery Challenge' (May 2021): https://www.ukri.org/our-work/our-main-funds/industrial-strategy-challenge-fund/future-of-mobility/faraday-battery-challenge/ [accessed 25 June 2021]

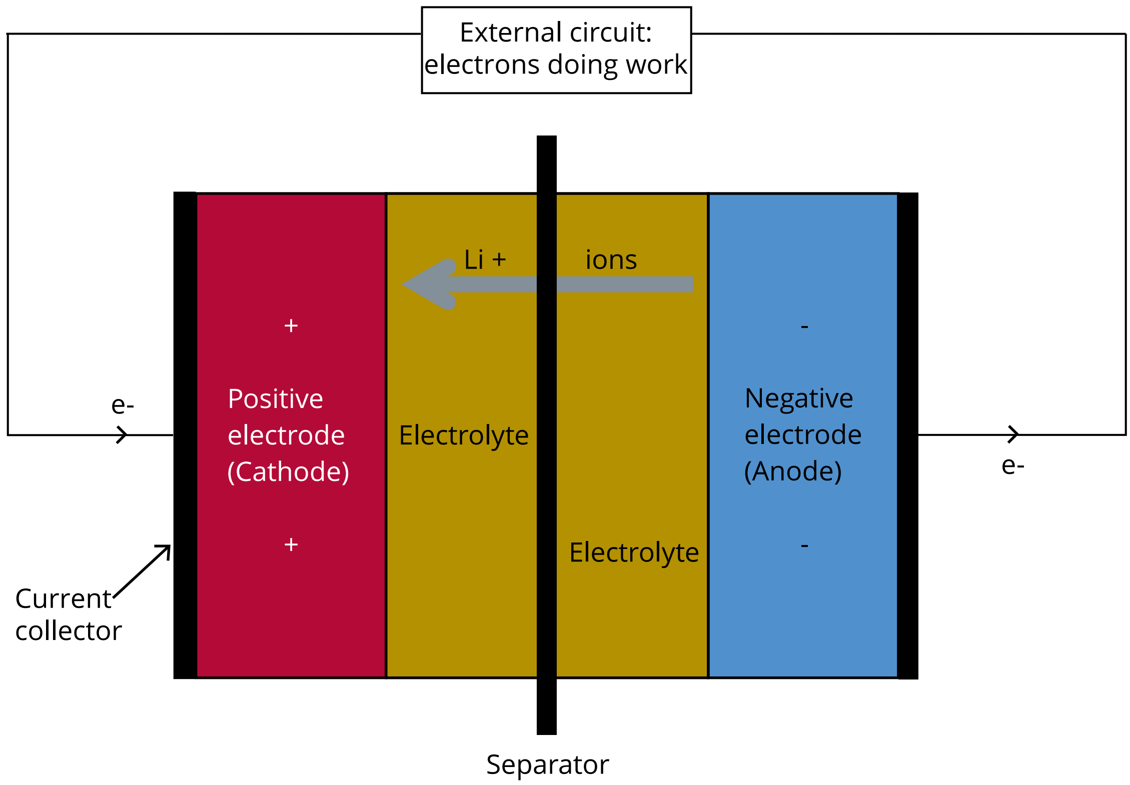
158 The Faraday Institution, 'About the Faraday Institution' (2017): https://www.faraday.ac.uk/about-2/ [accessed 25 June 2021]

159 UK Battery Industrialisation Centre, 'Who we are' (2020): https://www.ukbic.co.uk/about/background/ [accessed 25 June 2021]

160 Supplementary written evidence from The Faraday Institution (BAT0046)

161 Q 18 (Professor Mauro Pasta)

Figure 3: Structure and operation of a battery



Box 2: Structure and operation of a cell

A cell consists of two electrodes (an anode and a cathode), an electrolyte surrounding the electrodes, and a semi-permeable membrane separating the electrodes. A casing encloses the components of the cell, and multiple identical cells can be combined to form a battery.

The electrolyte is a material containing chemicals that perform the electrochemical reactions (called 'redox' reactions), and that conducts charged particles between the electrodes. When the electrodes of a charged battery are connected to an external electrical circuit, negatively-charged electrons flow from the anode, through the circuit (where their energy performs work, such as driving an electrical motor), and into the cathode. Positively-charged ions (formed when an electron is removed from an atom) travel through the electrolyte to the cathode and recombine with electrons. Some cells can be recharged by reversing the voltage that is applied via the external circuit, such that electrons and ions return to the anode, via the external circuit and the electrolyte, respectively.

95. Battery performance is measured by several metrics. Dr Jerry Barker, Founder and Chief Technology Officer at Faradion Ltd, explained that developers focus on performance, but also on cost and safety.[162] The most significant measures are set out in table 2 along with examples of data for typical electric vehicle batteries.[163]

162 Q 20 (Dr Jerry Barker)
163 See for example, Electric Vehicle Database, 'Energy consumption of electric vehicles' (2021): https://ev-database.uk/cheatsheet/energy-consumption-electric-car [accessed 23 June 2021]

Table 2: Battery parameters

Parameter	Description and examples
Energy density[164]	The amount of energy a battery contains in proportion to its mass, typically measured in watt-hours per gram (Wh/g). A typical lithium-ion battery has an energy density of 250Wh/kg (and 250Wh happens to be enough energy to drive an EV for one mile).
Total energy stored	This is the product of the battery's energy density and mass. A typical EV battery can store 50kWh of energy (where k stands for kilo, which means 1,000). With an energy density of 250Wh/kg, the battery would weigh around 200kg. With an energy consumption of around 250Wh per mile, its range would be around 200miles.
Charging time	How long it takes to recharge the battery after its charge has been depleted. This depends on the battery's total capacity and the current that it can tolerate without overheating.
Cycle life	The number of times the battery can be charged and discharged before its performance falls below an acceptable level. Cycle life is not to be confused with 'life cycle', which refers to the sequence of manufacture, use and disposal or recycling of a product.
Cost	Cost is measured in dollars per kilowatt-hour (kWh). For example, the cheapest lithium-ion cell produced in 2021 cost \$100 per kWh. If the industry could achieve that cost for a battery pack, then a 50kWh EV battery would cost around \$5,000.

96. A similar technology is the 'supercapacitor'.[165] It too stores energy for release in electrical form, but it stores less energy and releases it more rapidly compared to a battery. Supercapacitors were used by some vehicle manufacturers to provide extra power, but present two problems: supercapacitors can suffer from rapid self-discharging; and must be coupled with a higher energy density battery in a BEV adding complexity and cost. Now the favoured approach for vehicles is to develop more powerful batteries or combined 'battery supercapacitor'. Supercapacitors may still play a role in some applications requiring short bursts of energy, such as power grids, trams, construction vehicles, and so on.

Lithium-ion batteries

97. Lithium-ion batteries are the most common type of rechargeable battery. The technology is named after the lithium ions that serve as the charged particles that move within the electrolyte. Lithium is attractive for two main reasons: it can lose an electron to become an ion more easily than other metals, and

164 Technically, this is 'specific energy' or 'gravimetric energy density', but the terms are used somewhat loosely. A related metric is 'volumetric energy', defined as the battery's energy content in relation to its volume, usually measured in Watt-hours per litre (Wh/l).

165 All capacitors perform the function of storing electrical energy for rapid release. Standard capacitors are made of ceramics. Supercapacitors have larger capacity, and tend to include more advanced materials.

it has a low mass[166] such that its ions move more rapidly in response to an applied voltage.[167] A non-rechargeable lithium battery chemistry was first developed in the early 1970s.[168] After various iterations, the current design was commercialised in 1991.[169] The Nobel Prize for Chemistry was awarded in 2019 to three of the researchers involved in developing these batteries, reflecting the impact of this technology.[170]

98. We heard that lithium-ion batteries have been optimised over several decades to reach the performance level that has enabled them to dominate most battery markets. [171] Improvements have involved new materials and more exacting manufacturing processes, but the resultant extra costs have been offset by the efficiencies of mass-production.[172] The average cost globally of lithium-ion cells fell by 89% in 10 years, from $1,200 per kWh in 2010 to $137 per kWh in 2020, and has reached $100 per kWh in 2021.[173] The costs of battery packs per kWh are higher.

99. A mature technology such as the lithium-ion battery naturally has less scope for further improvements. However, an analogy can be drawn with the semiconductor industry, where the performance of microprocessors was long predicted to be reaching a limit, but advanced engineering pushed the boundaries such that the sector has only recently had to change tack.[174] Strategies include: optimising electrode materials to improve batteries' lifetimes, energy densities and costs; optimising electrolyte additives (for improved energy density, lifetime and cost); and reducing the volume of inactive components (to improve energy density and cost).[175]

100. A key performance objective is higher energy density for transport applications, in order to reduce the battery's weight and/or increase the vehicle's range. Professor Paul Shearing from University College London told us about the likely trajectory of energy density of lithium-ion batteries in coming years. He said that currently a good quality, off-the-shelf lithium-ion battery provides energy density of around 250 watt-hours per kilogram; that "more specialist manufacturing" might get to 300 watt-hours per kilogram;

166 The atomic mass of an element is a measure of the mass of an atom of that element, with the unit atomic mass unit (amu). The atomic mass corresponds approximately to the number of protons and neutrons in the atom's nucleus. The number for any element is not an exact integer due to the existence of isotopes of elements (atoms with the same number of protons and hence the same chemistry, but different numbers of neutrons).

167 As per Newton's first law of motion, acceleration is inversely proportional to mass, so a lighter ion will accelerate faster in response the force caused by a given electrical potential, reducing its travel time.

168 *United States Patent Office, Electrochemical Cell* (25 November 1975): https://patentimages.storage.googleapis.com/1b/79/6c/28b79e24477d6c/US3922174.pdf [accessed 14 July 2021]

169 Sony Energy Devices Corporation, 'Keywords to understanding Sony Energy Devices' (2016): https://web.archive.org/web/20160304224245/http://www.sonyenergy-devices.co.jp/en/keyword/ [accessed 14 July 2021]

170 The Royal Swedish Academy of Sciences, 'Press release: The Nobel Prize in Chemistry 2019' (2019): https://www.nobelprize.org/prizes/chemistry/2019/press-release/ [accessed 14 July 2021]

171 Q 5 (Professor Mauro Pasta)

172 Q 5 (Professor Mauro Pasta)

173 BloomberNEF, 'Battery Pack Prices Cited Below $100/kWh for the First Time in 2020, While Market Average Sits at $137/kWh' (16 December 2020): https://about.bnef.com/blog/battery-pack-prices-cited-below-100-kwh-for-the-first-time-in-2020-while-market-average-sits-at-137-kwh/ [accessed 2 July 2021]

174 Encyclopaedia Britannica, 'Moore's Law': https://www.britannica.com/technology/Moores-law [accessed 14 July 2021]

175 Clare Grey and David Hall, 'Prospects for lithium-ion batteries and beyond—a 2030 vision', *Nature Communications*, vol. 11, article 6279 (8 December 2020): https://doi.org/10.1038/s41467–020-19991-4 [accessed 2 July 2021]

and that "tweaks to the materials and the design of the materials" could reach 350 or 400 watt-hours per kilogram.[176] The Aerospace Technology Institute estimated that "With the introduction of new materials, and new types of electrochemical cell, the market should expect an increase in energy density in the region of 30%, a peak power increase in the range of 300%, and costs decreasing by 60–80% over the next 10 years."[177]

101. The Faraday Institution is funding a number of projects aiming to improve current lithium-ion battery technology, including improved electrode manufacture to increase performance, and reduced degradation to increase the lifetime.[178] Professor Pam Thomas, CEO of the Faraday Institution, told us that "The incremental changes are worthwhile, and that is what we will have in the short term", but for the "step changes that we require for net zero at 2050, just pushing the incremental envelope will not be sufficient."[179]

102. **There is merit in the automotive sector continuing to adopt incremental improvements in lithium-ion technology, to make the best use of existing investments in manufacturing. However, it is important that manufacturing processes are adaptable so that non-lithium-ion chemistries can be adopted in future without incurring the full costs of establishing new manufacturing facilities.**

Next-generation batteries

103. Several avenues are being explored to take battery technology beyond the limits of lithium-ion chemistry. Witnesses told us about the approaches set out below; these are discussed in more detail in the *Nature Communications* article from 2020.[180] Each approach would take the technology in a different direction, offering different advantages. They all can be developed in parallel but some could be implemented in combination to give a range of benefits. The Faraday Institution *Beyond Lithium Ion* portfolio is funding three next-generation batteries "that are looking beyond the fundamental limits of lithium ion technology to the development and commercialisation of new battery chemistries"[181].

Sodium-ion

104. Lithium could be replaced with sodium and other metals that have similar chemistries, including, magnesium, calcium and aluminium. Sodium is abundant and easily accessible, and hence has the potential for cheap batteries.[182] Dr Barker told us that sodium-ion technology is more sustainable than lithium-ion owing to its lack of "lithium, … copper or cobalt", and it is safer than lithium-ion[183] (in terms of ease of shipping). He added that the sodium battery being designed by Faradion "could be built on existing lithium-ion lines, so you do not have to go off and develop a new manufacturing

176 Q 21 (Professor Paul Shearing)
177 Written evidence from the Aerospace Technology Institute (BAT0021)
178 The Faraday Institution, 'Lithium-ion': https://www.faraday.ac.uk/research/lithium-ion/ [accessed 2 July 2021]
179 Q 4 (Professor Pam Thomas)
180 Clare Grey and David Hall, 'Prospects for lithium-ion batteries and beyond—a 2030 vision', *Nature Communications*, vol. 11, article 6279 (8 December 2020): https://doi.org/10.1038/s41467–020-19991-4 [accessed 2 July 2021]
181 The Faraday Institution, 'Beyond lithium-ion': https://www.faraday.ac.uk/research/beyond-lithium-ion/ [accessed 2 July 2021]
182 Q 5 (Professor Mauro Pasta)
183 Q 20 (Dr Jerry Barker)

process."[184] The Faraday Institution is providing £11.5 million over 4 years for the *Nexgenna* sodium-ion research project.,[185] This project aims to develop the technology (from research through to manufacturing) for applications in stationary storage and low-cost vehicles.

105. However, the energy density of sodium-ion technology is lower that of lithium-ion (essentially because sodium ions are larger and hence fewer fit into the same volume). Dr Barker told us that the sodium-ion battery being developed by Faradion has an energy density of around 160 watt hours per kilogram, and that this is expected to rise to "well over 200 watt hours per kilogram". He said that sodium-ion will not displace the "top-end of the lithium-ion market", and explained a strategy of "looking to replace lead-acid technology in mobility applications, forklifts, telecoms, and lots of other different application." He added that "When you have no constraint on weight or volume, you can have large-format applications for renewable storage and grid storage".[186]

Solid-state batteries

106. Some of the challenges in battery performance can be addressed by moving away from liquid electrolytes, to a solid-state battery with metal electrodes (including lithium, as discussed below) and a 'solid-state electrolyte'.[187] There are four potential advantages of solid-state batteries compared with liquid electrode batteries:[188] improved fire safety; higher energy density; faster charging times; and longer life. Due to these advantages, Professor Pasta from the University of Oxford said "every automotive company is looking quite heavily into solid state" but timescales for development are uncertain, ranging from the 2030s to the 2040s, whilst some believe it will be "difficult to get solid state produced at cost."[189] The Faraday Institution is providing £15.3 million over 5 years for the SOBALT project that is researching solid-state batteries.[190] This project aims to remove barriers to manufacturing, for example through new materials or processes, in order to enable commercialisation of solid-state batteries.

Lithium-sulfur and lithium-air batteries

107. One strategy for next-generation batteries is to replace the standard anode with one made of pure lithium, to reduce the mass of the anode (by removing the need for graphite) and to be the source of lithium ions in the cell.[191] Two options are being considered: lithium-sulfur batteries and lithium-air batteries. Johnson Matthey anticipates that these technologies can increase energy density by up to ten times with respect to current lithium-ion batteries.[192] They would be cheaper and more sustainable than lithium-ion because they do not use some of the more expensive materials and sulfur is abundant,

184 Q 20 (Dr Jerry Barker)
185 The Faraday Institution, 'Nexgenna—Sodium-ion batteries': https://www.faraday.ac.uk/research/beyond-lithium-ion/sodium-ion-batteries/ [accessed 2 July 2021]
186 Q 22 (Dr Jerry Barker)
187 Q 21 (Professor Serena Corr)
188 The Faraday Institution, *Solid-State Batteries: The Technology of the 2030s but the Research Challenge of the 2020s* (February 2020): https://faraday.ac.uk/wp-content/uploads/2020/04/Faraday-Insights-5_Updated.pdf [accessed 2 July 2021]
189 Q 5 (Professor Mauro Pasta)
190 The Faraday Institution, 'Solbat—Solid-state metal anode batteries': https://www.faraday.ac.uk/research/beyond-lithium-ion/solid-state-batteries/ [accessed 2 July 2021]
191 Q 23 (Dr Melanie Loveridge)
192 Written evidence from Johnson Matthey (BAT0011)

and lithium air would avoid even the cost of sulfur. Another advantage of lithium-air batteries is better recyclability. The Faraday Institution is providing £7.5 million over 4 years for the *LISTAR* lithium-sulfur research project.[193] This project aims to advance the technology through fundamental materials research, but also to develop the systems engineering needed to create a commercial product.

Redox flow batteries

108. A redox flow battery (or simply a 'flow battery') uses the same basic electrochemical processes as other rechargeable batteries with liquid electrolytes. The difference is that its electrolytes are pumped through the cell from external tanks, allowing larger volumes of electrolyte to interact with the electrodes. The technology decouples the power (determined by the size of the battery) and energy (determined by the size of the tanks), so that it can be deployed at larger scales simply by increasing the amount of electrolyte available in tanks. Flow batteries can offer a number of other advantages: less material-intensive manufacture; less degradation over time; and better fire safety.[194]

109. The large size of flow batteries (including the tanks and pumps for the electrolytes) make them less suited to transport applications, and they are seen as an option for large-scale stationary energy storage.[195] The Faraday Institution has two projects under its *Batteries for Emerging Economies* portfolio.[196] However, the current lower cost of lithium-ion batteries (including putting used batteries from cars onto power grids) has meant that flow batteries have not yet become established in the UK.[197]

UK research and development

110. We heard that the UK's current investment in batteries research and development is lower and of shorter duration compared to initiatives in competitor countries. The Faraday Battery Challenge has received £318 million over four years, primarily for the Faraday Institution and the UK Battery Industrialisation Centre. The Faraday Institution's current funding is £30 million per year out to March 2022, and it is applying for continuation of this core funding.[198] It is also bidding for an additional £20 million per year to expand its work to include engineering aspects. By comparison, in 2019 the European Commission approved €3.2 billion of investments by seven Members States out to 2031, to support "research and innovation projects in all segments of the battery value chain". This equates to an average of

193 The Faraday Institution, 'LiSTAR—The Lithium-sulfur technology accelerator': https://www.faraday.ac.uk/research/beyond-lithium-ion/lithium-sulfur/ [accessed 2 July 2021]
194 See, for example, discussion here: DNV, 'Can Flow Batteries compete with Li-ion?': https://www.dnv.com/article/can-flow-batteries-compete-with-li-ion--179748 [accessed 2 July 2021]
195 Weber *et al.*, 'Redox flow batteries: a review', *Journal of Applied Electrochemistry*, vol. 41, article 1137 (21 September 2011): https://link.springer.com/article/10.1007/s10800–011-0348-2 [accessed 2 July 2021]
196 The Faraday Institution, 'Batteries for emerging economies': https://www.faraday.ac.uk/research/batteries-emerging-economies/ [accessed 7 July 2021]
197 See, for example, discussion in: GTM, 'Flow Batteries Struggle in 2019 as Lithium-Ion Marches On' (4 November 2019): https://www.greentechmedia.com/articles/read/flow-batteries-struggle-in-2019-as-lithium-ion-marches-on [accessed 2 July 2021]
198 Supplementary written evidence from The Faraday Institution (BAT0046)

around £270 million per year over ten years. It includes €960 million of investments by France and €1.25 billion by Germany.[199]

111. We heard that the UK lacks sufficient funding across the technology readiness levels. Dr Barker said of battery research and development in the UK that there are funds for lower technology readiness levels, but less for demonstration projects.[200] This echoed concerns from other witnesses about challenges with scaling up, such as lack of availability of materials. For automotive applications, the UK Battery Industrialisation Centre can help to move work through the scale-up stage, but its focus is not on stationary batteries.

112. The number of patents filed is one measure of research and innovation. A joint study by the European Patent Office and the International Energy Agency found that Japanese companies including Panasonic and Toyota Motors hold more than a third of the world's patents for vehicle batteries. From 2000 to 2018, Asian companies account for nine of the top ten global applicants, and for two-thirds of the top 25.[201]

113. We heard about the need for long-term strategy in research funding. Dr Chamberlain explained that the US battery industry was currently benefitting from research funded in the 1990s. He said that "The United Kingdom has just lagged a bit in overall funding into research", but that "it is not too late to ramp up your research dollars, so that five to 10 years from now those research projects are turning into companies."[202] Professor Pam Thomas said: "From a UK perspective, we will not overtake existing manufacturers of the current lithium battery technology. It would serve us better to leapfrog the current technology and look at where we might be able to have a world lead in establishing next-generation technologies."[203]

114. **The UK's current investments in battery research and development are welcome, but need to be increased and put on a longer-term footing if the UK is to compete internationally. Proposals for additional funding for research and development in the UK should be seen in the context of the Government's ambition for the UK to be a 'science superpower'. The Government has made clear spending commitments for research and development: public funding is to reach £22 billion per year by 2024–25 (up from around £15 billion in 2021–22); and total annual UK spending on research and development is to reach 2.4% of GDP by 2027.**

115. ***UK Research and Innovation should prioritise initiatives for batteries and fuel cells in its bid for the 2021 Spending Review. It should seek***

199 European Commission, 'State aid: Commission approves €3.2 billion public support by seven Member States for a pan-European research and innovation project in all segments of the battery value chain' (9 December 2019): https://ec.europa.eu/commission/presscorner/detail/en/ip_19_6705 [accessed 2 July 2021]

200 Q 27 (Dr Jerry Barker)

201 European Patent Office (EPO) and the International Energy Agency (IEA), Innovation in batteries and electricity storage—a global analysis based on patent data (September 2020): http://documents.epo.org/projects/babylon/eponet.nsf/0/969395F58EB07213C12585E7002C7046/$FILE/battery_study_en.pdf [accessed 2 July 2021] The data used is 'International patent families' (IPFs), defined as "a high-value invention for which patent applications have been filed at two or more patent offices worldwide".

202 Q 143 (Dr Jeffrey Chamberlain)

203 Q 4 (Professor Pam Thomas)

to support technologies all the way through the technology readiness levels to manufacture.

116. ***The Government should provide additional funds for the development of batteries and fuel cells, which are essential for achieving the net-zero target and for achieving the UK's industrial ambitions. This funding can be provided within the budget increases for research and development out to 2024–25. Funding should be comparable to international competitors, and should have long-term certainty in order to build the UK's research base, develop momentum and ensure that advances are fully exploited.***

117. ***UK Research and Innovation should expand the remit of the Faraday Institution and the UK Battery Industrialisation Centre to include stationary batteries, with commensurate additional funding from Government.***

118. ***UK Research and Innovation should expand its portfolio for developing next generation batteries, with commensurate additional funding from Government. This will help to establish a long-term advantage for the UK, for example in solid-state batteries for vehicles and sodium-ion batteries for stationary storage.***

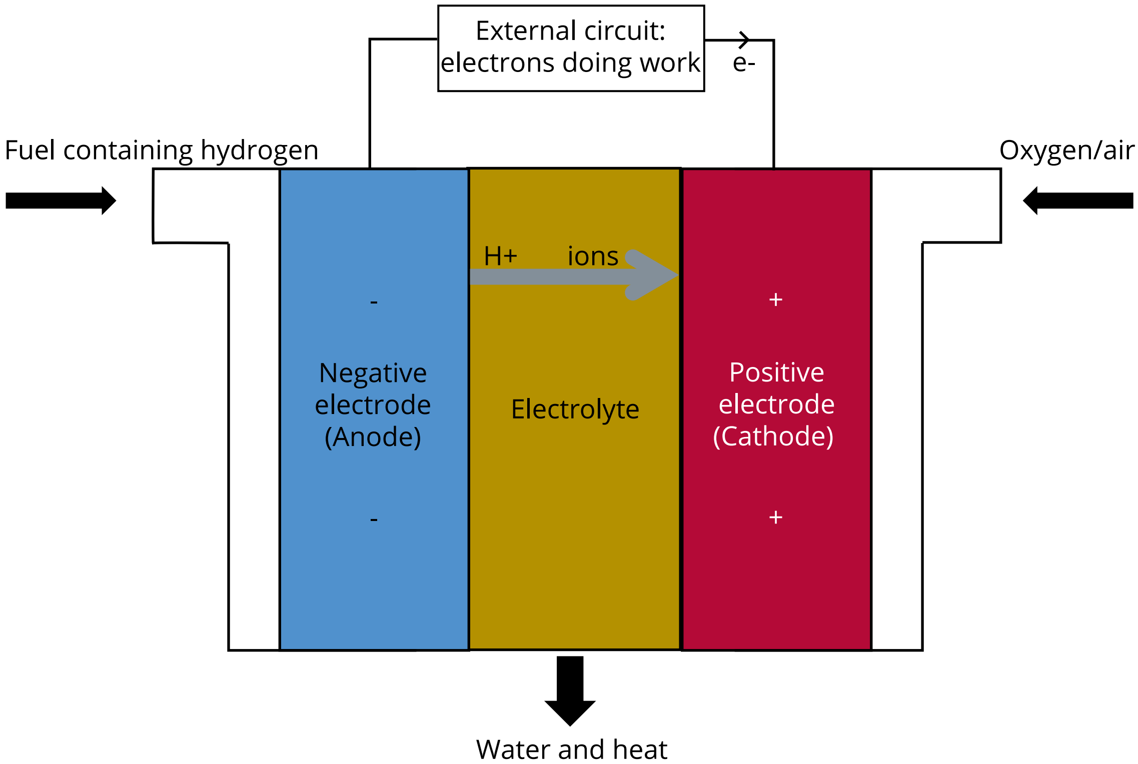
Fuel cells

Basic operation

119. Fuel cells are an energy conversion technology, transforming chemical energy from hydrogen-rich fuel (by combining it with oxygen) into electricity and heat (and producing water, along with other by-products when using fuels other than hydrogen). Fuel cells can be complementary to electrolysers, a technology that essentially operates in reverse to fuel cells, in that an electrolyser uses electricity to break down a chemical, for example to break down water to produce hydrogen and oxygen.

120. There are several different types of fuel cell, but they all share a common structure and means of operation, which is illustrated in figure 4 and described in box 3. Fuel cells can be designed to operate with different fuels that contain hydrogen. For the purposes of decarbonisation, most of the interest is in hydrogen. Ammonia is also being considered for applications such as shipping, but poses challenges such as the production of nitrous oxide pollution.

Figure 4: Structure and operation of a fuel cell



Box 3: Structure and operation of a fuel cell

Fuel cells contain an anode and a cathode, with an electrolyte in between, and. a structure called a 'flow field' that sits on the outside of each electrode. The flow field allows fuel and air to flow continuously to the anode and cathode, respectively. Common fuels are pure hydrogen (H_2), methanol (CH_3OH), ammonia (NH_3), and methane or biomethane (CH_4). The anode is coated with a catalyst (such as platinum), which is a material that assists a chemical reaction but is not itself changed by the reaction, and hence remains in place to assist the reaction again. The catalyst at the anode helps to separate each atom of hydrogen into its constituent protons (H^+) and electrons (e^-). The electrons flow into an external circuit as an electrical current that can perform work (for example, turn an electric motor) and into the cathode. The protons move through the electrolyte into the cathode. When the protons and electrons meet in the cathode, they combine with the oxygen (O_2) atoms from the air that is being pumped across the cathode, generating water (H_2O) and heat (again assisted by a catalyst, usually a platinum alloy). Carbon-based materials called 'ionomers' are used to bind the catalyst particles in position and to form membranes.

Current technologies

121. There are several different types of fuel cell, broadly distinguished by the type of electrolyte they use and/or by their operating temperature.[204] They

204 Encyclopaedia Britannica, 'Types of fuel cells': https://www.britannica.com/technology/fuel-cell/Types-of-fuel-cells [accessed 22 June 2021]. See also Sergio Yesid Gómez and Dachamir Hotza, 'Current developments in reversible oxide fuel cells', *Renewable and Sustainable Energy Reviews*, Volume 61 (August 2016) pp 155–174: https://www.sciencedirect.com/science/article/abs/pii/S1364032116002409 [accessed 22 June 2021]

can be grouped into three broad types based on their operating temperature, as summarised in table 3. Within each group there are many variations.

Table 3: Types of fuel cell technology

Operating temperature	Description of technology
Low temperature (60–100°C)	Also known as 'polymer electrolyte membrane' or 'proton-exchange membrane' (PEM) fuel cells. They are well-suited to low-carbon transport applications: they can be designed to run on hydrogen, can start in sub-zero temperatures, and they can be tailored to either light- or heavy-duty vehicles.[205] They use platinum group metals as catalysts, which are expensive.
Intermediate temperature (200–300°C)	These are a newer version of fuel cell. The temperature of the heat produced can be useful for other processes (e.g. in industry). They do not use platinum group metals as catalysts.[206]
High temperature (up to 1,000°C)	Also called solid oxide fuel cells (SOFC).[207] These can be used for power generation, heating and industrial processes. Their high temperature necessitates thermal shielding, and makes them less suited to portable and transport applications.

122. The main type of electrolyser technology is polymer electrolyte membrane. This technology is very similar to low-temperature proton-exchange membrane fuel cells.[208] Currently, most hydrogen is manufactured from methane using a process called 'steam methane reforming' (SMR), which emits CO_2 and is associated with upstream methane leakage. As noted earlier, another option being explored is the use of advanced nuclear reactors (also called 'Generation IV' technology), for which small-scale demonstration projects are underway.[209]

Developments and innovation

123. Recent advances and ongoing research are mainly aimed at improving fuel cells' lifespans and reducing their costs. These advances have primarily been achieved through modifying the materials that are used in fuel cells to be more efficient, longer lasting, and cheaper to acquire and produce.[210] Areas of ongoing research include: alternative catalysts; reduction of degradation; efficiency of manufacturing processes; and provision of ancillary equipment.

Cost reduction

124. Cost reduction is a key objective that runs through several of the topics discussed below. Intelligent Energy told us that fuel cell costs have fallen by

205 Q 90 (Jo Godden)
206 Q 40 (Professor Anthony Kucernak)
207 Q 32 (Professor Andrea Russell) and Q 32 (Professor Anthony Kucernak)
208 Written evidence from ITM Power plc (BAT0013)
209 Nuclear Engineering International, 'UK's ten point plan supports small and advanced reactors' (20 November 2020): https://www.neimagazine.com/news/newsuks-ten-point-plan-supports-small-and-advanced-reactors-8371307/ [accessed 7 July 2021]
210 G.J.K. Acres, 'Recent advances in fuel cell technology and its applications', *Journal of Power Sources*, vol. 100 (30 November 2001) pp 60–66: https://doi.org/10.1016/S0378–7753(01)00883-7 [accessed 25 June 2021]

50% over the past five years, due to improvements in materials, components, manufacturing and supply chains.[211] For transport applications, the Automotive Council's 2020 Fuel Cell Roadmap notes that "Light duty vehicles prioritise cost reductions, which will largely be achieved through economies of scale of key components" whereas "Heavy duty vehicles … prioritise durability and can be slightly more tolerant to higher costs if the total cost of ownership for fleet operators is kept low."[212]

125. UK H2Mobility provided forecasts of performance and cost to 2030. The expectation is that the cost of fuel cells for light-duty vehicles will fall by 42% per kW of power output and the cost of fuel cells for heavy-duty vehicles by a third. In addition, the data suggest that the hydrogen consumption of both types of fuel cell will fall by over 10%.[213] Johnson Matthey told us that the total cost of ownership for fuel cell HGVs is expected to "drop below that of diesel trucks in the second half of the 2020s".[214]

Catalyst materials

126. Platinum alloys are the most common catalysts in low-temperature polymer electrolyte membrane fuel cells.[215] Platinum is expensive, and researchers are exploring various avenues to reduce costs whilst maintaining efficiency. The efficiency of platinum-based catalysts can be improved, allowing the amount of platinum to be reduced. The industry aims to cut the content by two-thirds by 2030.[216] An added benefit of reducing the amount of platinum in the catalyst is reduced susceptibility to contaminants in the fuel.[217]

Reduced degradation

127. Fuel cells can suffer from issues such as 'side reactions' at the electrodes and contamination of the catalysts, which degrade their performance over time and hence their reduce lifespan. Degradation is more of an issue for high temperature (solid oxide) fuel cells, in which reactions (including damaging processes) proceed more rapidly. Improvements have been made,[218] with Johnson Matthey noting that "performance and durability have increased significantly over the past 10 years".[219] However, some of the processes are poorly understood,[220] and further research is required.

Increased efficiency

128. We heard that fuel cells convert chemical energy into electricity with an efficiency of around 60%, with the rest emitted as heat. If that heat is utilised (as in a CHP unit) then the overall efficiency is well over 90%.[221] However,

211 Written evidence from Intelligent Energy (BAT0038)
212 Written evidence from the Advanced Propulsion Centre UK Ltd—Fuel Cells (BAT0019)
213 Written evidence from UK H2Mobility (BAT0022)
214 Written evidence from Johnson Matthey (BAT0011)
215 Q 38 (Professor Andrea Russell)
216 Q 4 (Professor Nigel Brandon OBE) and Written evidence from ITM Power plc (BAT0013)
217 H2FC Supergen, 'Polymer Electrolyte Fuel cells' (2021): http://www.h2fcsupergen.com/research-type/polymer-electrolyte-fuel-cells/ [accessed 25 June 2021]
218 See, for example, Graves *et al.*, 'Eliminating degradation in solid oxide electrochemical cells by reversible operation', *Nature Materials*, vol. 14 (December 2014) pp 239–244: https://www.nature.com/articles/nmat4165 [accessed 25 June 2021]
219 Written evidence from Johnson Matthey (BAT0011)
220 The European Materials Research Society, the Materials Science and Engineering Expert Committee and the European Science Foundation, *Materials for Key Enabling Technologies* (21 June 2011): http://archives.esf.org/fileadmin/Public_documents/Publications/ket_report.pdf [accessed 25 June 2021]
221 Q 36 (Professor Anthony Kucernak)

for applications such as transport in which there is no use for the heat, the aim is to improve the efficiency of electrical generation. Professor Kucernak told us that the long-term goal is efficiency "of over 70%, which seems reasonably achievable". He said that low-temperature fuel cells are currently optimised for transport, with the aim being to "achieve the largest power density possible" and so the fuel cells are "not necessarily optimised for efficiency". He advised that for "fuel cells for energy production, for instance in power plants, we can quite easily improve the efficiency by decreasing the power density".[222]

Tailoring to applications

129. Fuel cells can be manufactured at different scales. Further reductions in size would open up more opportunities in transport and portable systems.[223] For the development of smaller, portable high-temperature fuel cells, one challenge is ensuring the safety of the thermal shielding.[224] There are also drivers for developing larger fuel cells, which are more efficient.[225] Professor Russell said that "the better utilisation of fuel cells is with the larger ones, in integrating that into the whole system [and] making localised use of hydrogen that is produced."[226]

Ancillary technology

130. Fuel cells are supported by other equipment, in which improvements are being made, such as compressors, sensors and storage tanks. Professor Brandon told us that "The most expensive part of a hydrogen fuel cell car today is the hydrogen tank, so there is room for innovation in how you carry the fuel.[227] Professor Kucernak said that research into hydrogen storage is needed "to reduce the cost of the storage and improve the efficiency and density", noting that the current carbon fibre tanks are "quite an expensive technology at the moment" but "mass scale-up will reduce the cost of those materials significantly."[228] Ammonia can be stored more easily than hydrogen, such that it is being considered for fuel cells applications such as shipping that require higher energy density.[229] However, as noted earlier combustion of ammonia presents a hazard in the event of a spillage, and its combustion produces air pollution, both of which would have to be addressed were ammonia to be used as a fuel.

131. Several witnesses supported deploying fuel cells as part of a wider hydrogen strategy, in which hydrogen would be produced by electrolysers. There is scope to improve performance of electrolysers in terms of energy efficiency, and the separation of the gases that are produced. There is merit in ensuring that the fuel cells and electrolysers can be deployed together and integrated efficiently. Professor Kucernak said it was important to "increase the round-

222 QQ 36–37 (Professor Anthony Kucernak)
223 The European Materials Research Society, the Materials Science and Engineering Expert Committee and the European Science Foundation, *Materials for Key Enabling Technologies* (21 June 2011): http://archives.esf.org/fileadmin/Public_documents/Publications/ket_report.pdf [accessed 25 June 2021]
224 The European Materials Research Society, the Materials Science and Engineering Expert Committee and the European Science Foundation, *Materials for Key Enabling Technologies* (21 June 2011): http://archives.esf.org/fileadmin/Public_documents/Publications/ket_report.pdf [accessed 25 June 2021]
225 Q 34 (Professor Anthony Kucernak)
226 Q 35 (Professor Andrea Russell)
227 Q 4 (Professor Nigel Brandon OBE)
228 Q 37 and Q 39 (Professor Anthony Kucernak)
229 Q 41 (Professor John Irvine)

trip efficiency of the conversion of renewable electricity to hydrogen and then convert that hydrogen back into electricity".[230]

132. **Fuel cells will benefit from ongoing innovation to improve performance and durability and to reduce costs. They are well-suited to a range of applications, but the sector may require support to tailor the technology to each application.**

UK research and development

133. We heard that public sector funding of fuel cell research and development in the UK is very low compared to its international competitors. UK funding for fuel cell research has fallen in recent years, and it received only £8 million in 2021–22, which equates to 0.14% of the portfolio of the Engineering and Physical Sciences Research Council (EPSRC).[231] The EPSRC website states: "Fuel Cell Technology is not currently a high priority for government or industry and has a comparatively lower impact than other technologies on the UK's ability to reach its ambitious 2050 greenhouse gas reduction targets."[232] In 2012, UK Research and Innovation established the H2FC Supergen Hub, which seeks to coordinate activities by convening researchers from universities and industry, and has directed some public sector grant funding.[233] However, some fuel cell development may be able to draw on battery research, for example in electrochemistry and in developing electrodes. By comparison we were told that, Japan provided around £220 million in 2019 for research and development in hydrogen and fuel cells.[234]

134. We heard that some types of fuel cells are a mature technology. ITM Power said that "Low TRL research is not a prerequisite to commercial deployment, but ongoing R&D is important to help improve the economics of [fuel cells] and electrolysers across the 2020s."[235] Professor Irvine told us that funding for hydrogen in the UK focuses on demonstration projects rather than lower technology readiness levels.[236] One approach that was discussed was to establish organisations similar to those in the battery sector to support research and scale-up.[237]

135. **The current funding for fuel cell research and development is inadequate, and the sector needs to be supported through the establishment of initiatives and organisations akin to the Faraday Institution and the UK Battery Industrialisation Centre. These proposals should be seen in the context of the Government's commitments to significantly increase public funding for research and development.**

230 Q 37 (Professor Anthony Kucernak)
231 Engineering Physical Sciences Research Council (EPSRC), 'Fuel cell technology' (2021): https://epsrc.ukri.org/research/ourportfolio/researchareas/fuelcells/ [accessed 28 June 2021]
232 Engineering Physical Sciences Research Council (EPSRC), 'Fuel cell technology' (2021): https://epsrc.ukri.org/research/ourportfolio/researchareas/fuelcells/ [accessed 28 June 2021]
233 H2FC Supergen, 'About H2FC Supergen' (2021): http://www.h2fcsupergen.com/about/ [accessed 25 June 2021]. See also H2FC Supergen, *H2FC Supergen: Five Years of Impact* (April 2017): http://www.h2fcsupergen.com/wp-content/uploads/2017/05/H2FC_Five_years_of_research_report-22052017-WEB-low-res.pdf [accessed 25 June 2021]
234 Written evidence from Ceres Power (BAT0016). See also Q 60 (Professor Paul Dodds)
235 Written evidence from ITM Power (BAT0013)
236 Q 45 (Professor John Irvine)
237 Q 64 (Professor Philip Taylor) and Q 65 (Professor David Greenwood)

136. ***The Government should establish organisations to support research and scale-up for the fuel cell and hydrogen sector, equivalent to the Faraday Institution and the UK Battery Industrialisation Centre, guided by a clear analysis of where research and demonstrations are needed.***

CHAPTER 4: STRATEGIC ISSUES FACING THE UK

137. The development and deployment of batteries and fuel cells have to be viewed in an international context. Their applications (as set out in chapter 2) are being pursued by many countries, some with long-term strategies and significant funding. Similarly, the potential improvements in performance and cost (as described in chapter 3) are being investigated by researchers around the world, some with considerable resources. This chapter compares the UK's battery and fuel cell sectors with those of its main international competitors, and identifies strategic issues that the UK will have to address if it is to succeed in these sectors.

Battery sector

138. The rise of batteries has been a global trend. Starting in the early-2000s, vehicle manufacturers have been exploring various routes towards decarbonisation, including biofuels, fuel efficiency, hybridisation, batteries and fuel cells.[238] Their plans tended to focus on incremental changes to internal combustion engine technology and did not propose a switch to batteries or fuel cells for many years to come. Dr Chamberlain suggested that major manufacturers "were not taking electric vehicles seriously" at that stage.[239] Then, in the late-2010s, various developments increased the pace of the transition, with a focus on batteries. The 'diesel-gate' emissions scandal over air pollution tests cast doubt on whether ICE technology could deliver the forecast reductions in greenhouse gas emissions.[240] Batteries were shown to offer sufficient performance, and Tesla's entry into the market showed that BEVs could be popular in the mainstream. Fuel cell vehicles are available on the market,[241] but have not been prioritised by most manufacturers.

Automotive sector

139. The automotive sector around the world is now investing heavily to build battery manufacturing facilities (dubbed 'gigafactories') to supply their manufacture of BEVs; more information can be found in box 4. The International Energy Agency published a report in May 2021 forecasting that "Annual battery production for EVs leaps from 160GWh today to 6,600GWh in 2030, the equivalent of adding almost 20 gigafactories each year for the next ten years", assuming output of 35GWh per year, per factory.[242] Dr Colin Herron, Managing Director at Zero Carbon Futures, told us about global plans for gigafactories, saying that "China has 149 planned by 2030,

238 In the UK, the Automotive Council and UK Advanced Propulsion Centre publish Technology Roadmaps covering a range of automotive technology, including internal combustion, battery electric and fuel cells. The most recent versions, published in 2020, are available via this webpage: Automotive Council and Advanced Propulsion Centre UK, 'Technology Roadmaps' (2020): https://www.apcuk.co.uk/technology-roadmaps/ [accessed 28 June 2021]

239 Q 143 (Dr Jeffrey Chamberlain)

240 Energy Research Partnership, *Energy Options for Transport: Deployment and Implications* (April 2016) pp 20–22: https://erpuk.org/wp-content/uploads/2016/04/54541_ERP_Transport_Report_Main-18-Apr-16.pdf [accessed 28 June 2021]

241 Examples of hydrogen fuel cell cars available in the UK are the Toyota Mirai and the Hyundai Nexo. Toyota (GB) plc, 'Hydrogen-powered Mirai' (March 2017): https://www.toyota.co.uk/new-cars/new-mirai/ [accessed 12 July 2021]. Hyundai Motor UK Ltd, 'All-new Nexo' (2018): https://www.hyundai.co.uk/new-cars/nexo [accessed 12 July 2021]

242 International Energy Agency, *Net Zero by 2050: A Roadmap for the Global Energy Sector* (May 2021) p 21: https://iea.blob.core.windows.net/assets/ad0d4830-bd7e-47b6-838c-40d115733c13/NetZeroby2050-ARoadmapfortheGlobalEnergySector.pdf [accessed 28 June 2021]

[the EU] 19, the USA 11, and UK two".[243] Analysis by T&E in June 2021 identified 17 confirmed projects across Europe, with a combined production capacity of 474GWh per year.[244]

Box 4: Gigafactories

A 'gigafactory' is a large factory that manufactures battery cells or fuel cells. A battery gigafactory may also assemble cells into battery packs, or this may be done by another company in the supply chain.

A battery gigafactory's annual output is measured in gigawatt-hours per year (GWh/yr). For example, if a factory produces cells or batteries that can each store 25kWh of energy, and it has an annual production output of 2GWh/yr, then it is manufacturing around 80,000 batteries per year. However, once installed in their applications, those batteries could be charged and discharged many times per year; doing so on average once a week would mean that the total amount of energy stored would be around 100GWh/yr.

Fuel cells tend to be referred to in terms of their power, because they do not store energy. If a factory manufactures fuel cells that each have a power rating of 500kW, and it produces 4,000 units per year, then its manufacturing output is 2 gigawatts per year (GW/yr). However, the energy produced by those fuel cells each year would depend on how often they operated; if used for half the time on average, then they would produce 8,760GWh/yr.

140. The UK currently has two major battery manufacturing facilities. The Envision AESC gigafactory at Sunderland was originally built to manufacture cells and battery packs for the neighbouring Nissan car plant. It has an annual production capacity of 2GWh and was the largest plant in Europe when it opened in 2010. Hyperdrive Innovation's HYVE facility purchases cells and assembles them into battery packs for a range of customers.[245]

141. The Faraday Institution predicts that UK battery demand will necessitate at least one new gigafactory from 2022, and another from 2025. Assuming an average production capacity of 15 GWh pa, it estimates that the UK will mostly likely need eight gigafactories by 2040.[246] The Society of Motor Manufacturers and Traders (SMMT) estimates that, by 2030, the UK will need battery manufacturing capacity of at least 60 GWh per year (enough for 1 million electric vehicles).[247] Some vehicle manufacturers are making commitments that will contribute to that demand for cells. For example, in July 2021, Vauxhall announced that it would invest £100 million in its Ellesmere plant (supported by the Government) to produce electric vans and

243 Q 81 (Dr Colin Herron CBE)

244 Transport and Environment, 'UK auto industry left behind as carmakers focus EV production in EU countries' (11 June 2021): https://www.transportenvironment.org/press/uk-auto-industry-left-behind-carmakers-focus-ev-production-eu-countries [accessed 28 June 2021]

245 Q 81 (Chris Pennison)

246 The Faraday Institution, *UK electric vehicle and battery production potential to 2040* (March 2020): https://faraday.ac.uk/wp-content/uploads/2020/03/2040_Gigafactory_Report_FINAL.pdf [accessed 29 June 2021]

247 Q 132 (David Wong). See also Society of Motor Manufacturers and Traders (SMMT), 'Full Throttle: Driving UK Automotive Competitiveness' (29 June 2021) https://smmt.publicfirst.co.uk/ [accessed 20 July 2021]

passenger equivalents. It will assemble the battery packs but not manufacture the cells.[248]

142. Nissan made a series of announcements in May and July 2021 about its operations in Sunderland, including that it would build a new gigafactory with Envision AESC (with an undisclosed level of financial support from the Government) that will have a production capacity of 9GWh per year (200,000 batteries per year), potentially rising to 25GWh per year.[249] Britishvolt is constructing a gigafactory at Blyth, which is expected to begin manufacturing in 2023 and reach a production capacity of 24GWh per year.[250] AMTE Power is currently considering building a new cell manufacturing facility, with plans to announce their final decision in 2022.[251] These announcements are welcome, but do not amount to the level of manufacturing capacity required by 2030, as estimated by the automotive industry.

143. We heard that building gigafactories is just one part of the challenge. The UK then has to ensure that the automotive industry places sufficient orders to justify the gigafactories. The Advanced Propulsion Centre explained that a country seeking to build a gigafactory needs "Aggregate local demand that is high enough to justify a gigafactory investment". It said: "For a 15GWh factory to land in the UK, Nissan or JLR would need to fully commit their entire UK production facilities to full BEVs immediately. Alternatively, numerous vehicle manufacturers could pool their short-term demand to justify the initial investment. Both strategies require ambitious planning and co-ordination on behalf of UK vehicle manufacturers."[252] David Wong from the Society of Motor Manufacturers and Traders suggested that "the Government could step in to facilitate some offtake agreements" to "get around the chicken-and-egg problem of whether batteries and fuel cells or vehicle manufacturing come first."[253]

144. We heard that vehicle manufacturers prefer to have their supply chains, which now include battery manufacture, close to their factories. Jeff Pratt, Managing Director of UK Battery Industrialisation Centre, told us that the capital cost of a 30GWh gigafactory is around £2.5 billion, but that this accounts for only 20% of the cost of battery. He said: "The other 80% of the value is in the materials supply chain. You need the automotive industry initially to be the draw for the gigafactory, but once you have the gigafactory you need to follow on and get the supply chain into the UK to maximise the value. Currently, there is no established supply chain in the UK."[254] Rob Millar said that the "principal vulnerability that we see … is with the supply of cells", but "It appears that many of the other supporting industries are already here in some format, whether directly involved in

248 Vauxhall Corporate News, 'Ellesmere Port will support sustainable mobility through the production of an all-electric vehicle, starting in 2022' (6 July 2021): https://gb-media.vauxhall.co.uk/en-gb/07-06-ellesmere-port-electric-lcvs [accessed 8 July 2021]

249 Nissan Motor Corporation, 'Nissan unveils EV36Zero—a £1bn Electric Vehicle (EV) Hub to accelerate the journey to carbon neutrality' (1 July 2021): https://uk.nissannews.com/en-GB/releases/release-10e81128ff45380ddab0a113f8007bb5-nissan-unveils-ev36zero-a-1bn-electric-vehicle-ev-hub-to-accelerate-the-journey-to-carbon-neutrality [accessed 7 July 2021]

250 Q 81 (Isobel Sheldon). See also BritishVolt, 'Britishvolt selects Blyth, Northumberland, as the site of its first battery gigaplant' (11 December 2020): https://britishvolt.com/news/britishvolt-selected-blyth-northumberland-as-the-site-of-its-first-battery-gigaplant/ [accessed 7 July 2021]

251 AMTE Power, 'Announcement of intention to float on AIM' (8 February 2021): https://amtepower.com/wp-content/uploads/2021/02/AMTE-Power-ITF-Final.pdf [accessed 7 July 2021]

252 Written evidence from the Advanced Propulsion Centre UK Ltd—Batteries (BAT0018)

253 Q 130 and Q 136 (David Wong)

254 Q 77 (Jeff Pratt)

battery manufacturing or in something that can easily be adapted."[255] David Wong said that "government needs to create the right conditions and have a proper, fully costed and well-supported comprehensive transformation plan for the entire industry and the supply chain."[256]

145. Dr Jeffrey Chamberlain suggested that the coordination of supply chains might become simpler in the automotive sector because of greater involvement by vehicle manufacturers. He said that manufacturers were controlling "who makes their cells for them and … the innovations underneath the cell manufacturing". He recommended that governments should support these moves in order to secure gigafactories, "because … cars are made where they are used. If you support the [original equipment manufacturers] in the moves they are making now, ultimately the batteries will be made there as well."[257]

146. The UK automotive sector faces an urgent need for significant change. In just over eight years, the ban on the sale of new petrol and diesel cars and vans will come into force. The sector must arrange sufficient manufacturing capacity and supply chains to maintain its market share in the face of competition from overseas. Before that, the 'Rules of Origin' will come into force in 2027 as part of the UK-EU Trade and Co-operation Agreement. David Wong told us that these rules will mean "55% of the value added has to be local content—originating content—from either the UK or the EU" and "the battery has to originate from either the UK or the EU."[258] Non-compliant vehicles will be subject to import duty of 10%.

147. Battery gigafactories will take time to reach the stage of manufacturing. David Wong told us that "it takes something like 30 to 42 months to get everything off the ground, including development, construction, test runs and, finally, the commissioning of a gigafactory."[259] Similarly, it takes time to adapt car manufacturing plants. Ian Constance told us that car manufacturers update their "platform designs, the basis on which they build their vehicles" every 10–12 years, and that the transition to electric vehicles would add to this, such that the cycle could take up to 14 years.[260]

148. We heard that manufacturers need close relationships with research partners. Professor Patrick Grant of the University of Oxford told us that researchers contribute to the development of battery chemistries and to the optimisation of manufacturing processes.[261] Professor Emma Kendrick of the University of Birmingham explained the process of scaling up from proof of concept to industrial manufacturing. She said that scale-up was difficult in the UK due to a lack of companies that could produce intermediate quantities of new materials, which instead had to be sourced from overseas.[262]

149. **The UK is competing with other countries to attract automotive battery manufacturing. Failure to do so would likely lead to vehicle manufacturing moving elsewhere. Recent announcements of future increases in the manufacture of cells and electric vehicles are**

255 Q 136 (Rob Millar)
256 Q 136 (David Wong)
257 Q 143 (Dr Jeffrey Chamberlain)
258 Q 132 (David Wong)
259 Q 133 (David Wong)
260 Q 99 (Ian Constance)
261 Q 73 (Professor Patrick Grant)
262 Q 72 (Professor Emma Kendrick)

welcome, but are still insufficient to meet anticipated demand. The Government will need to commit further funds for gigafactories, supply chains and training ahead of the 2027 and 2030 deadlines, to ensure that the UK's automotive sector can maintain manufacturing at its current scale. These resources will have to reach from research through to manufacturing, and will have to be commensurate to those of international competitors.

150. **Despite the urgency of the 2027 and 2030 deadlines, the UK also needs to plan on longer timescales. Manufacturing and supply chains require ongoing innovation in order to remain competitive, and need to be future-proofed to allow improvements in battery technology to be implemented with minimal cost and disruption.**

Stationary storage

151. We heard of the importance of not neglecting other applications of batteries. At a research level, the Faraday initiatives focus on the automotive sector. There would be merit in expanding its remit to include batteries on power grids and in buildings. At a policy level, there are few drivers for the deployment of batteries in these applications. The upcoming decarbonisation strategies for buildings and for transport offer opportunities to encourage greater use of batteries.

152. James Sprinz, Vice President of Strategy and Business Development in Europe at Energy Impact Partners singled out the UK as "one of the largest markets for stationary storage systems" due to "market opportunities that were developed by National Grid, such as the enhanced frequency response products".[263] It is not clear whether that success could be replicated on the much larger scale of storage deployment required for decarbonisation. Beverley Gower-Jones, Managing Partner of the Clean Growth Fund, said that such investments are hindered by two factors: "the Government [does] not have a formal target for storage"; and "Storage is currently considered a subset of generation under Ofgem's regulation … which can create difficulties in planning, licensing and … network usage charges".[264]

Fuel cell sector

International context

153. The uptake of fuel cells is lower than for batteries, in the UK and most other countries; but we heard that demand has grown by "40% to 50% per year over the last five years".[265] Several countries are making strong commitments to hydrogen. For example, Germany is spending €9 billion on hydrogen technologies; South Korea aims to install 15GW of fuel cell power by 2040 and to produce 6.2 million FCEVs by 2040; Japan aims to have fuel cells in 5.3 million homes by 2030; and China aims to deploy 1 million FCEVs by 2030.[266] In contrast, the UK Hydrogen and Fuel Cell Association said that "In the context of hydrogen and fuel cell innovation specifically, (and from a cash perspective) the UK is 'orders of magnitude' behind".[267]

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263 Q 140 (James Sprinz)
264 Q 145 (Beverley Gower-Jones)
265 Q 37 (Professor Anthony Kucernak)
266 Written evidence from Ceres Power (BAT0016)
267 Written evidence from UK Hydrogen and Fuel Cell Association (BAT0008)

154. Manufacturing is led by companies in Asia, but several UK companies have strong reputations in the manufacture of fuel cells (such as Ceres Power and Intelligent Energy) and electrolysers (such as ITM Power). Jo Godden explained that fuel cells and electrolysers involve two types of manufacturing and that the UK should seek to do well at both aspects. She said that "manufacturing at scale for the components … is more of a modular approach … . We are pretty much at that scale now." She added that the next step was "improving the automation, improving the process and getting to a lower cost of production so that we can scale as the market scales." By contrast, she said that the assembly of components into 'the stack' (the core of a fuel cell or electrolyser) is well-served by mass production in a gigafactory.[268] For example, in January 2021 ITM Power opened a new electrolyser gigafactory in Sheffield with a production output of 1GW per year.[269] Also in January 2021, Intelligent Energy announced plans for a new collaboration with GKN Aerospace to develop a hydrogen fuel cell propulsion for aircraft, including creating a gigafactory in the East Midlands.[270]

155. The UK's small market for hydrogen technologies poses two challenges for the sector. First, most of the UK's manufacturing output and expertise is used abroad, with a risk that manufacturing could move overseas. The UK Hydrogen and Fuel Cell Association said that major markets are "courting UK companies to establish subsidiaries there".[271] Ceres Power told us that manufacture on the scale required overseas was "much more commercially attractive", but UK fuel cell manufacturing "has not been offshored yet".[272] Second, some UK companies cannot expand as rapidly as their overseas markets are growing. Fuel cells are not currently manufactured at scale in the UK.[273] We heard that developing the processes to manufacture at scale is a key challenge, although innovations are being developed.[274] As such, Ceres Power said that "The UK is experiencing real-time technology loss as global appetite for fuel cells soars".[275] Without sufficient government support to UK companies internationally, those companies could be overtaken by competitors. In that case, if in future the UK wanted to increase its use of fuel cells and electrolysers, that demand would be met by overseas suppliers instead of UK manufacturing.[276]

156. Several witnesses portrayed a more positive future for the UK fuel cell and electrolyser sector. The UK Hydrogen and Fuel Cell Association said that "the UK could become amongst the leaders in the global market. Unlike

268 Q 93 (Jo Godden)

269 ITM Power, 'Manufacturing Commences at the ITM Power Gigafactory' (4 January 2021): https://www.itm-power.com/news/manufacturing-commences-at-the-itm-power-gigafactory [accessed 29 June 2021]. The factory is rated as '1GW per year', which is the combined power rating of the fuel cells it can manufacture in one year. The amount of hydrogen energy produced by those electrolysers each year would depend on their operating duration.

270 Intelligent Energy, 'Intelligent Energy collaboration partner of GKN Aerospace in development of ground-breaking hydrogen propulsion system for aircraft' (January 2021): https://www.intelligent-energy.com/news-and-events/company-news/2021/01/27/intelligent-energy-collaboration-partner-of-gkn-aerospace-in-development-of-ground-breaking-hydrogen-propulsion-system-for-aircraft/ [accessed 29 June 2021]

271 Written evidence from UK Hydrogen and Fuel Cell Association (BAT0008)

272 Written evidence from Ceres Power (BAT0016)

273 H2FC Supergen, *Opportunities for hydrogen and fuel cell technologies to contribute to clean growth in the UK* (May 2020): http://www.h2fcsupergen.com/wp-content/uploads/2020/04/2020_04_H2FC_Supergen_Hydrogen_Fuel_Cells_P_Dodds_DIGITAL_W_COVER_v05.pdf [accessed 29 June 2021]

274 Q 12 (Professor Nigel Brandon OBE) and Q 37 (Professor Anthony Kucernak)

275 Written evidence from Ceres Power (BAT0016)

276 Written evidence from UK Hydrogen and Fuel Cell Association (BAT0008)

batteries, there is still 'plenty to play for' in this space … there is a 'window of opportunity' remaining for the UK to scale up and build on its current activities to take a leadership role."[277] Some felt that overseas companies could be attracted to the UK by the manufacturing expertise there; for example, ITM Power said "The UK could easily manufacture [polymer electrolyte membrane] fuel cells in volume for vehicles, especially if the Asian manufacturers wanted to establish production here as the size of the UK/European FCEV market grows."[278] Others noted the potential for UK companies to succeed elsewhere in the sector, for example in the supply chain for components and in the production of software for integrating fuel cells into wider systems.[279]

UK market expansion

157. As per the evidence discussed in chapter 2, there are several applications to which fuel cells are well-suited. It seems likely that the UK will need to use fuel cells in heavy road transport and rail. Fuel calls may have applications in shipping (possibly using ammonia if the issue of nitrous oxide pollution can be addressed) and in aviation (if safety issues with hydrogen can be addressed).They may also be used in buildings and for grid balancing. We heard that products for each application could be manufactured in the UK.[280] However, the growth of the UK market is being held back. The Government's policy of 'technology agnosticism' has arguably persisted too long, such that the heavy transport sector has no clear policy direction. Relatedly, the lack of strong regulatory pressure has meant that the heavy transport sector has had little incentive to make the decision itself. The Committee on Climate Change recommended a ban on the sale of new diesel HGVs from 2040,[281] and at the end of our inquiry the Government launched a consultation on proposals to phase out diesel HGVs between 2035 and 2040.[282] A similar ban for car and vans was credited by witnesses as an important driver for change, but the Government has yet to decide on this for HGVs.

158. We were told about an added problem: "the delay in publishing the hydrogen strategy is actively delaying investment into UK-based projects and in a number of cases is forcing investment abroad".[283] We note that decarbonisation strategies for buildings and for transport are pending, as well as the Treasury's Net Zero Review. Each of these reviews will have implications for low-carbon energy resources such as hydrogen, and coordination will be needed if these resources are to be used in the optimal manner in sectors that need them the most. Hydrogen applications could have regional aspects, such as storage in offshore gas fields near to coastal counties, which links to the Government's levelling-up agenda.

277 Written evidence from UK Hydrogen and Fuel Cell Association (BAT0008)
278 Written evidence from ITM Power (BAT0013)
279 Q 48 (Professor Anthony Kucernak)
280 See, for example, Q 35 (Professor John Irvine) and Q 100 (Paul Stein)
281 Q 77 (Rachel Maclean MP). See also Committee on Climate Change, *The Sixth Carbon Budget: The UK's path to Net Zero* (9 December 2020) p 29: https://www.theccc.org.uk/wp-content/uploads/2020/12/The-Sixth-Carbon-Budget-The-UKs-path-to-Net-Zero.pdf [accessed 2 July 2021]
282 Department for Transport, *Consultation on when to phase out the sale of new, non-zero emission heavy goods vehicles* (July 2021): https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1002124/consultation-on-when-to-phase-out-the-sale-of-new-non-zero-emission-heavy-good-vehicles.pdf [accessed 14 July 2021]
283 Written evidence from UK H2Mobility, Element Energy (BAT0022)

159. **The UK's fuel cell and electrolyser manufacturers have done well to establish themselves internationally despite being largely neglected by UK policy and public funding. These companies need support to expand manufacturing in the UK, compete internationally and contribute to the UK's hydrogen ambitions.**

160. **The development and uptake of fuel cell technologies by the transport sector will be aided by clear regulatory signals, in particular the ending of the sale of new diesel HGVs, on which the Government is currently consulting.**

161. ***The Government should publish its hydrogen strategy this summer. This strategy must be coordinated with the Government's other decarbonisation strategies to enable use of hydrogen in those sectors for which it is the most viable option. The hydrogen strategy should make effective use of the UK's expertise in fuel cells and electrolysers, both to support UK decarbonisation efforts and to seek a leading role internationally.***

Cross-cutting issues

Skills and training

162. The battery and fuel cell sectors require similar types of skills at the different levels of development through to manufacture. These skills are in short supply in the UK. This is not a new issue; the Government's Build Back Better strategy refers to the UK's "persistent technical skills shortage".[284] We note that training and upskilling in areas of higher unemployment will support the Government's levelling-up agenda. At the end of our inquiry, the Green Jobs Taskforce published its report. It noted that "there are gaps in the automotive sector workforce that will need to be overcome at a relatively fast pace, with a focus on retraining and upskilling of the current workers, and a push in new recruitment".[285]

163. Regarding research, Professor Russell told us that electrochemical researchers can apply their expertise to batteries or fuel cells, and have tended to switch between the two based on availability of funding.[286] She thought that, whilst the UK was "world-leading" in training electrochemists, it was more limited in teaching electrochemical engineering, which was needed for integrating batteries and fuel cells into systems.[287] Professor Thomas agreed, saying that the Faraday Institution needed to improve engagement by electrochemical scientists with engineers in academia and industry.[288]

164. Regarding the automotive sector, the skills required for battery and fuel cells are different to those traditionally used in the transport sector. Supply chains, manufacturing, maintenance and recycling roles will shift from largely mechanical engineering to more electrical engineering, electronics and digital engineering. There will be a need for widespread training and upskilling.

284 HM Treasury, *Build Back Better: Our Plan for Growth* (March 2021) p 45: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/968403/PfG_Final_Web_Accessible_Version.pdf [accessed 29 June 2021]

285 Green Jobs Taskforce, *Report to Government, Industry and the Skills sector* (July 2021) p 22: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1002112/green-jobs-taskforce-report__1_.pdf [accessed 14 July 2021]

286 Q 45 (Professor Andrea Russell)

287 Q 39 (Professor Andrea Russell)

288 Q 19 (Professor Pam Thomas)

David Wong outlined the scale of the challenge. For manufacturing, "The Automotive Council estimates that about 10,000 workers currently need reskilling. This number is likely to grow to about 50,000 by 2025 and 100,000 by 2035." For engineering skills, he said that the skills gaps "is around 5,000 workers".[289] Training programmes were established as part of the automotive industry's 'Sector Deal' under the (former) Industrial Strategy.

165. The scientific community and advanced manufacturing sectors have tended to rely to some extent on international movement of skilled workers. Recent changes to immigration rules may affect the availability of these workers. Engineering professions are included on the Government's list of 'shortage occupations'. This scheme makes it easier for employers to offer jobs to overseas workers, by automatically contributing 20 points towards the 70 required for eligibility, and by reducing the salary threshold by 20%.[290] The Global Talent Visa[291] has been broadly welcomed as a route to employing overseas researchers. However, its costs can pose a barrier, particularly to researchers on lower salaries or with dependents who live with them in the UK, and for short-term contracts. Each applicant and any dependents moving with them must pay one-off fees of £608,[292] plus the healthcare surcharge of £624 per year (or £470 per year for those under 18 years of age).[293]

166. ***The Government should take action to ensure that there are sufficient skilled workers in the automotive sector and conducting research into batteries and fuel cells. 1) There needs to be more support for training to enable the automotive sector's transition to electric vehicles. 2) There need to be pipelines for training more researchers and engineers and supporting their longer-term careers. 3) There needs to be greater flexibility for recruiting international staff for research and manufacturing, including by reducing the costs associated with visas, particularly for short-term contracts.***

Critical raw materials and recycling

167. One of the main limiting factors for manufacturing batteries (and to a lesser extent fuel cells) is the availability of materials. In particular, critical raw materials are those that are essential for national objectives. The Department for Environment, Food and Rural Affairs commissioned a report into critical raw materials across the economy, which was published in 2020.[294] The report's recommendations were echoed by several witnesses in the points discussed below. It appears that many of these recommendations are yet to be implemented.

289 Q 137 (David Wong)

290 UK Visas and Immigration, 'Skilled Worker visa: shortage occupations' (6 April 2021): https://www.gov.uk/government/publications/skilled-worker-visa-shortage-occupations/skilled-worker-visa-shortage-occupations [accessed 8 July 2021]. See also discussion at Free Movement, 'How to apply for the UK's Global Talent visa': https://www.freemovement.org.uk/uk-global-talent-visa/ [accessed 15 July 2021]

291 The Global Talent Visa is a UK immigration category for talented and promising individuals in specific sectors wishing to work in the UK. It replaced the Tier 1 (Exceptional Talent) visa in February 2020.

292 HM Government, 'Apply for the Global Talent visa': https://www.gov.uk/global-talent [accessed 8 July 2021]

293 HM Government, 'Pay for UK healthcare as part of your immigration application': https://www.gov.uk/healthcare-immigration-application [accessed 8 July 2021]

294 Department for the Environment, Food and Rural Affairs, *Review of the Future Resource Risk Faced by the UK Economy* (17 July 2020): http://sciencesearch.defra.gov.uk/Document.aspx?Document=14982_EunomiaFutureResourceRisk-FinalReportv3.pdf [accessed 8 July 2021]

168. Lithium-ion batteries have the disadvantage of containing several critical raw materials. Professor Richard Herrington of the Natural History Museum told us that "Every single [BEV] will need 75 kilograms more copper than an internal combustion car, and it will need rare-earth metals, 8 kilograms of lithium, 7 kilograms of cobalt and about 25 kilograms of graphite."[295] Dr Evi Petavratzi of the British Geological Survey said fuel cells require "platinum, and potentially cobalt", and electrolysers require nickel and zirconium. She explained that none of the elements used in batteries or fuel cells are inherently rare; the term 'rare earth elements' applied to some of the minerals can be a misnomer.[296]

169. Availability of these critical raw materials is affected by geopolitics more than by geological or technical issues. Resources are concentrated in a relatively small number of countries. For example, around half of global reserves of lithium are in the South American 'lithium triangle'.[297] China has a long-running strategy of securing access to critical materials. Newcastle University told us that "China dominates the raw material supply chain … and there is a risk that it may exercise some controls."[298] ZeroAvia wrote that "Significant shortages of [lithium] and other materials might be expected globally and might adversely impact global and UK supply chains."[299] Shortages of supplies have already elicited responses on the international stage. For example, the Advanced Propulsion Centre UK said: "In the wake of semiconductor shortages and rare earth price scares, Joe Biden has issued an Executive Order into the United States' position on critical supply chains like batteries, semiconductors, and the rare earth supply chain."[300]

170. Extraction of critical resources can be detrimental to the environment, and to the health of workers and wider communities. Onshore mining can pollute air and waterways with toxic metals such as mercury and cadmium, open-pit mining removes ecosystems. Extraction of lithium from brines (as in the South American 'lithium triangle') uses significant volumes of water (approximately 500,000 gallons per metric ton of lithium), and can lead to contamination of water, soil and air.[301] Cobalt is toxic in larger quantities, and studies show harmful effects upon miners who are exposed to dust.[302] It is particularly damaging in terms of the greenhouse gas emissions due to the energy used for extraction and processing, and in terms of eutrophication (the enriching of water by nutrients so as to change the ecosystem).[303] The emerging field of seabed mining can cause long-term damage to ecosystems.[304]

171. There are situations in which human rights are violated; for example, cobalt mining the in the Democratic Republic of Congo has attracted significant

295 Q 121 (Professor Richard Herrington)
296 Q 121 (Dr Evi Petavratzi)
297 Q 7 (Professor Mauro Pasta). The 'lithium triangle' is a region of the Andes around the borders of Argentina, Bolivia and Chile that is rich in lithium reserves in the form of salt deposits.
298 Written evidence from Newcastle University (BAT0035)
299 Written evidence from ZeroAvia (BAT0032)
300 Written evidence from Advanced Propulsion Centre UK Ltd—Batteries (BAT0018)
301 Institute for Energy Research, 'The Environmental Impact of Lithium Batteries' (12 November 2020): https://www.instituteforenergyresearch.org/renewable/the-environmental-impact-of-lithium-batteries/ [accessed 18 May 2021]
302 Farjana *et al.*, 'Life cycle assessment of cobalt extraction process', *Journal of Sustainable Mining*, vol. 18, Issue 3 (August 2019) pp 150–161: https://doi.org/10.1016/j.jsm.2019.03.002 [accessed 18 May 2021]
303 Farjana *et al.*, 'Life cycle assessment of cobalt extraction process', *Journal of Sustainable Mining*, vol. 18, Issue 3 (August 2019) pp 150–161: https://doi.org/10.1016/j.jsm.2019.03.002 [accessed 18 May 2021]
304 Nature News Feature, 'Seabed mining is coming—bringing mineral riches and fears of epic extinctions' (24 July 2019): https://www.nature.com/articles/d41586–019-02242-y [accessed 18 May 2021]

criticisms. The Warwick Manufacturing Group told us: "Cobalt is primarily sourced in the Democratic Republic of the Congo, a region historically characterized by political instability, social impacts in the mining sector, and lack of supply chain transparency."[305] These issues mean that safeguards are lacking against the environmental and health impacts of cobalt extraction. Protection Approaches highlighted the risk that expansion in the use of cobalt in the UK will likely exacerbate the problem.[306]

172. Witnesses said that the UK could struggle to secure access to other countries' mineral resources, but it could offer its processing expertise, which is where most value exists in the mineral supply chain, for the benefit of both parties.[307] Witnesses proposed two alternative approaches to sourcing critical raw materials: UK indigenous resources and recycling. Professor Herrington told us about Cornish lithium, saying that estimated resources were over 30,000 tonnes per year, compared with the UK's forecast demand of 75,000 tonnes per year.[308]

173. Dr Paul Anderson highlighted findings from a recent report by the Birmingham Centre for Strategic Elements and Critical Materials,[309] including the opportunity to use recycling of batteries as a source of materials. However, he explained that difficulties in extracting some materials led to widely differing recycling rates, saying "it is estimated that the figure for cobalt and nickel is quite high, maybe 70% to 80%", whereas "for lithium [it] is much lower, perhaps only around 10% or less". He said that "by around 2040, we might be able to source somewhere between 25% and 35% of our lithium and cobalt from secondary sources".[310] The main challenge facing the UK is that it does not recycle any lithium-ion batteries; they have to be sent to a facility in Belgium. Unless the UK develops its own facilities, recycled materials would be another import. Another cross-border issue is that recycling may have to be undertaken in line with standards such as the EU battery recycling directive.[311]

174. Fuel cells require less in the way of critical raw materials. The main issue is to reduce the amount of platinum in the catalyst. Nonetheless, there is interest in recycling materials. The Advanced Propulsion Centre UK told us that the sector is "focusing on closed-loop solutions due to the high value of raw materials", primarily platinum, carbon fibre, ionomers and stainless steel.[312]

175. ***The Government should produce a critical raw materials strategy. This strategy should make use of the UK's natural resources such as Cornish lithium, and should utilise the UK's expertise in mineral processing to incentivise collaboration from countries with larger natural resources.***

305 Written evidence from WMG (Warwick Manufacturing Group) (BAT0014)
306 Written evidence from Protection Approaches (BAT0044)
307 Q 122 (Professor Richard Herrington) and Q 122 (Professor Magda Titirici)
308 Q 122 (Professor Richard Herrington)
309 Birmingham Centre for Strategic Elements and Critical Materials, *Securing Technology-Critical Metals for Britain* (April 2021): https://www.birmingham.ac.uk/documents/college-eps/energy/policy/policy-comission-securing-technology-critical-metals-for-britain.pdf [accessed 15 May 2021]
310 Q 127 (Dr Paul Anderson). See also footnote 6 in that transcript.
311 Proposal for a Regulation of the European Parliament and of the Council concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) No 2019/1020, COM(2020) 798/3
312 Written evidence from the Advanced Propulsion Centre UK Ltd—Fuel Cells (BAT0019)

176. ***The Government should set out clear plans for developing industrial-scale recycling in the UK. As part of this, it should require manufacturers to incorporate 'sustainability by design' and to conduct full life-cycle analyses of the environmental and social impacts of batteries and fuel cells. The Government should introduce incentives and regulations to speed the transition to more sustainable technologies.***

Investment

177. New technologies in any sector require funding at the various stages of development, from research to large-scale manufacture. Each stage can attract different types of funding. Research at low technology readiness levels is usually funded by the public sector. Once a technology has been proven in the lab and is at the latter stages of technological development, venture capital funds may provide funding in exchange for a stake in the business. These early investors tend to sell their stake once the company has grown to a certain size, at which point larger funds will invest. Ultimately, a successful technology company needs to find project finance for large-scale manufacturing. In the case of capital-intensive products such as batteries or fuel cells, this would likely involve large corporate funds, such as pension funds, automotive manufacturers or multinational oil companies.

178. Witnesses discussed the key factors that affect investment decisions. James Sprinz said investors look for companies with global potential and are more interested in "the company's technology, the business model and the team that manages that company", whereas the "policy environment and the country within which they are operating are very much secondary".[313] We heard concerns that the UK's reputation had been damaged by earlier policy changes (on carbon capture and storage, feed-in tariffs and buildings' energy efficiency) that had caused investors to lose money,[314] but Beverly Gower-Jones said the UK was attracting investment at each stage of development for batteries and fuel cells.[315]

179. There was general agreement that governments had an important role in de-risking investments, via the various means discussed in this report. John Bromley, Head of Clean Energy Strategy at Legal and General Capital, spoke about how investors might approach a gigafactory proposal, saying they "would be very keen to understand how the supply chain, the research, the development and the engineering and then ultimately the product will fit together" to give "confidence that there will be an offtake for that product."[316]

180. Dr Jeffrey Chamberlain talked about the merits of long-term government strategies. "In the US, the Government started deploying capital … into research back in the 1990s … As a result, those technologies that were seeded back then are now maturing." He added: "The United Kingdom has just lagged a bit in overall funding into research, but … it is not too late. … This boom will last for decades, not years. Therefore, it is not too late to ramp up your research dollars, so that five to 10 years from now those research

313 Q 142 (James Sprinz)
314 Q 118 (Dr Keith MacLean OBE)
315 Q 140 (Beverley Gower-Jones)
316 Q 141 (John Bromley)

projects are turning into companies. It is already happening in the United Kingdom."[317]

181. Finally, we heard that it is important for the Government to communicate its plans in a manner that is understood on the international stage. All the UK's major competitors have had industrial strategies for many years. The UK's Industrial Strategy was launched in 2017 but ended in 2021 with the introduction of the 'Build Back Better' strategy. Dr Jeffrey Chamberlain said: "the removal of the industrial strategy signals a decrease in seriousness by the UK Government … relative to others." He added: "It may not be an accurate perception, but it is a perception."[318]

182. ***The Government should explain to industry what will replace the industrial strategy, and should promote its industrial objectives clearly, both domestically and internationally. Its objectives should be supported by investments in the battery and fuel cell sectors, commensurate with those of the UK's international competitors, including de-risking expansion of manufacturing and supply chains in order to attract the significant private sector investment that is required.***

Progress of the transition

183. Ministers and officials who gave evidence were optimistic about the prospects of the UK overcoming challenges in order to decarbonise and transform its industries—in contrast with other witnesses. Anne-Marie Trevelyan MP, Minister for Business, Energy and Clean Growth at the Department of Business, Energy and Industrial Strategy, gave us her perspective on how industry views the challenges: "It is not easy; some of the challenges are technically very real. But everyone in every industry tells me that they are more enthused than they ever thought they would be if you had asked them even two or three years ago. I find that very encouraging."[319] Regarding research to meet the 2035 target for 78% cuts in emissions, the Minister said:

> "We have brought everything forward by 15 years. That is cohering an incredible energy requirement, and a real energy, from across R&D and innovation with businesses. Businesses are leaning in. … There is great energy there. Carbon budget six has created much greater enthusiasm as well as necessity for us to push that forward. It is very exciting to see."[320]

184. Ministers told us about funding in the UK for research and innovation, and investments in manufacturing and supply chains, and seemed unconcerned about comparisons suggesting that the UK Government is investing less than its competitors. Rachel Maclean MP said: "quite often stakeholders will come up with figures of various investments which they claim other countries are ahead of us on. All I will say is that it is always a fair challenge, but often they are counting completely different things." She explained that the Government is primarily relying on the use of regulatory levers (such as phasing out the sale of particular technologies) to stimulate industry investment: "The Government have a huge role to play, but those dates, those policy frameworks and those signals to the market are critical to this."[321]

317 Q 143 (Dr Jeffrey Chamberlain)
318 Q 146 (Dr Jeffrey Chamberlain)
319 Q 177 (Anne-Marie Trevelyan MP)
320 Q 170 (Anne-Marie Trevelyan MP)
321 Q 177 (Rachel Maclean MP)

185. The Government's *Decarbonising Transport plan was published at the end of our inquiry*. It provides further detail about issues that were discussed with Ministers in our inquiry, but does not fully address concerns raised by many of our witnesses. Regarding automotive supply chains, the strategy reiterates previous spending commitments but does not announce additional support. Furthermore, the plan does not address the issue of supplies of critical raw materials, nor does it set out further resources or incentives to introduce industrial-scale recycling of batteries.[322]

186. The evidence we heard showed that the UK faces a series of very tight deadlines in its efforts to achieve its 2050 net-zero target. These are listed below and noted on the timeline in figure 5.

- The UK automotive industry is in a global race to attract battery manufacturers to build around eight gigafactories in the UK by 2040, who in turn are in a global race to source critical raw materials.
- The UK automotive industry has to comply with EU Rules of Origin regulations from 2027, the UK's ban on the sale of new petrol and diesel cars and vans from 2030, and the phase-out of the sale of new hybrids in the period 2030–35 (details of which have yet to be confirmed).
- The rail sector is seeking to remove diesel trains from the network by 2040, but the electrification programme is proceeding at only half the necessary pace.
- Shipping and aviation are being added to the UK's carbon budget from 2033, but technological solutions have yet to be developed.
- The electricity sector has to decarbonise its generation mix by 2035, and will have to meet at least double the present demand by 2050.
- The UK's battery sector has an opportunity to leapfrog international competitors in the develop of next-generation technologies that may come into play in the 2030s.
- The UK's fuel cells sector has a chance to take a leading global role, if it is supported now.

187. All these activities need to be underpinned by Government, with long-term strategies, clear regulations and effective policies. Several strategies are overdue and key decisions have yet to be made. These are listed below, and their urgency is noted on the timeline in figure 5.

- Following the publication of its *Transport Decarbonisation* strategy, the Government needs to publish its inter-related decarbonisation strategies on hydrogen, and heating and buildings, its overarching decarbonisation strategy, and the Treasury's *Net Zero Review*.

322 Department for Transport, *Decarbonising Transport: A Better, Greener Britain* (July 2021): https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1002285/decarbonising-transport-a-better-greener-britain.pdf [accessed 14 July 2021]. The strategy reiterated spending commitments of £1.5 billion for 2015–21 to support uptake of EVs, and £2.8 billion during the current Parliament (£1 billion for automotive manufacturing and supply chains, £1.3 billion for charging infrastructure, and £582 million for plug-in vehicle grants). These had been discussed previously by the Government, for example in the Ten Point Plan published in 2020.

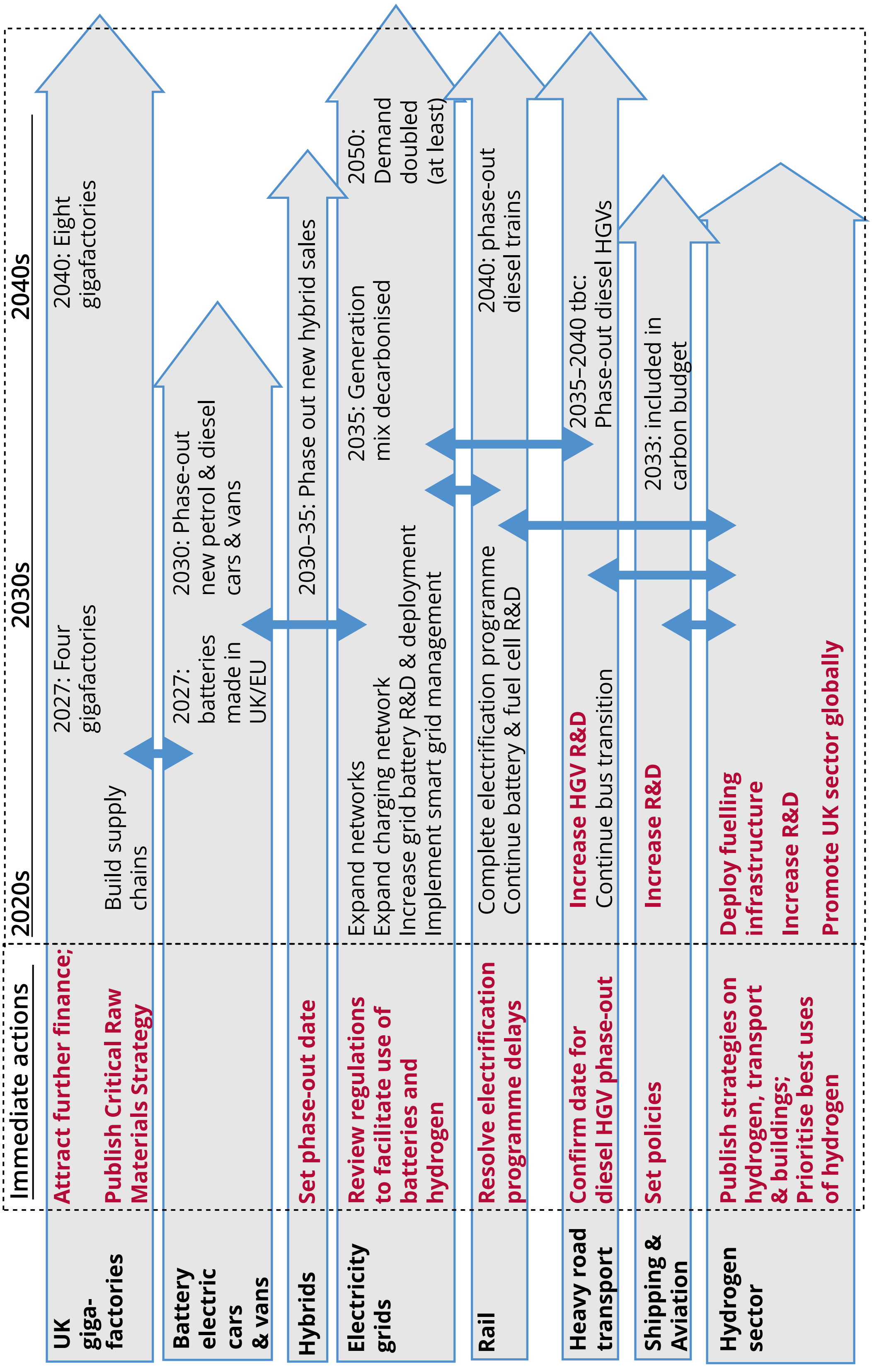
- The Government needs to give clarity about the 'significant distance' measure for the phase-out of hybrid cars and vans from 2030–35, confirm the timings for phasing out diesel HGVs, and develop policies and regulations to decarbonise shipping and aviation.
- The Government needs to oversee the strategic deployment of infrastructure, including rapid chargers, grid-scale battery storage, hydrogen supply and fuelling stations, and rail electrification. This includes reviewing electricity regulations to ensure that they facilitate widespread use of batteries and hydrogen technologies.

188. **The UK's current trajectory of battery manufacture risks missing the Government's target for the transition to electric light road transport, such that the UK may not be able to retain its automotive industry at its current scale. The situation is similarly serious for heavy transport and stationary energy systems, where lack of regulations and incentives have hindered decarbonisation using batteries and fuel cells.**

189. **The Government's plans for decarbonisation and industrial growth lack detail about how it will overcome significant challenges to achieve ambitious targets with short deadlines. There was a stark disconnect between the optimism of Ministers and officials that UK industries can transition in very tight timescales, and the concerns of our other witnesses that the UK is far behind its competitors and faces significant challenges with innovation, supply chains and skills.**

190. ***The Government should publish its decarbonisation strategies as a matter of urgency, and make a series of key decisions by the end of 2021, as set out above. We ask that the Government explains in its response to this report how it will meet each of the deadlines that we have discussed, with details of how it will ensure that the UK has the necessary research, skills, supply chains and finance.***

Figure 5: Timeline of key deadlines and decisions



Blue arrows indicate interactions between major topics.

Summary of conclusions and recommendations

Applications of batteries and fuel cells

1. In order to make the transition to low-carbon technologies, the heavy road freight sector needs urgent clarity about which technological options are best-suited to its needs, and firm commitments that infrastructure will be deployed at scale. Clear deadlines from the Government, such as a finalised timetable for ending the sale of HGVs, would focus efforts as is happening in the light road sector. (Paragraph 28)

2. *We recommend that the Government promptly confirms the end of sales of new diesel HGVs from 2040 or earlier. This will provide a clear timeline for research and development of technologies (including batteries and fuel cells), manufacture of vehicles and deployment of infrastructure.* (Paragraph 29)

3. Electrification of the railway network (using cables and live rails) will have to be strategic and extensive, to allow greater use of electric trains and so that those sections left without electrification are within the capabilities of trains powered by batteries and fuel cells. Otherwise, sections may be left for which decarbonisation is more expensive or more challenging. This poses the risk that the necessary increases in freight and passenger rail may not occur, and indeed that some usage could shift to roads. (Paragraph 36)

4. *The Government must ensure that the railway electrification programme is accelerated in order that it reaches as far as is economically and technically feasible by 2040, when diesel trains will be phased out. The development of battery and fuel cell trains should be supported to serve those parts of the network that remain non-electrified.* (Paragraph 37)

5. The aviation sector is very challenging to decarbonise, particularly its long-distance routes. However, battery and fuel cell technologies could offer solutions for shorter routes, and their application to electric vertical take-off and landing aircraft could allow aviation to play a more flexible role in national transport and emergency services. (Paragraph 44)

6. In order to decarbonise the electricity system by 2035 and to meet at least a doubling of demand by 2050, there need to be large upgrades to network capacity, smart controls need to be implemented, and a wide array of storage technologies must be deployed. Without batteries of different scales and potentially fuel cells drawing on stored hydrogen, increasing amounts of renewable energy will be wasted. Without smart operation and storage, the costs of grid expansion will be significantly higher. For larger grid-connected batteries, there is merit in developing alternatives such as sodium-ion and flow batteries. For smaller batteries in homes and businesses, there will need to be more sophisticated tariffs and control systems to optimise the benefits. To provide inter-seasonal storage, there may be a need for grid-scale fuel cells to be deployed as part of the UK's wider hydrogen strategy. (Paragraph 57)

7. *The Government and Ofgem must ensure that electricity network regulations and incentives are aligned to bring about the necessary investment in networks, storage and smart systems. They must ensure that energy market rules facilitate more sophisticated services, including tariffs to enable demand shifting, extensive use of battery storage, and smooth interactions with hydrogen systems.* (Paragraph 58)

8. The UK could make better use of fuel cells in conjunction with electrolysers in a range of stationary applications. Trials of local and community-scale systems could quickly be replicated, to increase the use of excess renewable electricity to produce hydrogen for transport, heating and power. The use of fuel cells in buildings connected to the gas grid would have merit if those buildings were supplied with 'low-carbon' hydrogen. (Paragraph 63)

9. A clear strategy is needed for large-scale hydrogen storage in order to make better use of excess renewable electricity (by producing hydrogen via electrolysis), and in the future to be coupled with hydrogen produced using advanced nuclear reactors. (Paragraph 65)

10. In order to give individuals and companies the confidence to invest in electric vehicles, there needs to be faster deployment of infrastructure for charging, including rapid chargers in towns and on the strategic road network. Charging has to be accessible to all, with suitable options provided for those without dedicated parking spaces or driveways. In the longer-term, wireless charging could be important, and should be developed and evaluated for transport applications. The user experience has to be simplified, with standardisation of technology and payment methods. (Paragraph 75)

11. *The Government should ensure electric vehicle charging for all users, including by accelerating the expansion of the public charging network, to deliver around 325,000 charging points by around 2032, as recommended by the Committee on Climate Change. This will require supporting local authorities to develop and implement strategies for deployment and maintenance of public charging-points. Regulations to standardise charging and payments methods should be introduced at the earliest possible time. We ask the Government to confirm the legislative timings in its response to this report.* (Paragraph 76)

12. In order for companies to have greater confidence in hydrogen vehicles, there needs to be an expansion of the hydrogen fuelling network, particularly on the strategic road network to support road freight. (Paragraph 79)

13. *The Government should take steps to build public confidence in the safety of batteries and hydrogen technologies. The concerns of residents and drivers about the fire safety of batteries must be taken seriously. Action must be taken to mitigate the risks of existing battery installations, including more stringent safety standards. Regulations and incentives should be used to drive development of safer battery technologies in transport and stationary applications. Effective fire-fighting protocols need to be developed, with provision of training and equipment for fire fighters, other first responders and vehicle maintenance workers.* (Paragraph 90)

Technological developments

14. There is merit in the automotive sector continuing to adopt incremental improvements in lithium-ion technology, to make the best use of existing investments in manufacturing. However, it is important that manufacturing processes are adaptable so that non-lithium-ion chemistries can be adopted in future without incurring the full costs of establishing new manufacturing facilities. (Paragraph 102)

15. The UK's current investments in battery research and development are welcome, but need to be increased and put on a longer-term footing if the UK is to compete internationally. Proposals for additional funding for research and development in the UK should be seen in the context of

the Government's ambition for the UK to be a 'science superpower'. The Government has made clear spending commitments for research and development: public funding is to reach £22 billion per year by 2024–25 (up from around £15 billion in 2021–22); and total annual UK spending on research and development is to reach 2.4% of GDP by 2027. (Paragraph 114)

16. *UK Research and Innovation should prioritise initiatives for batteries and fuel cells in its bid for the 2021 Spending Review. It should seek to support technologies all the way through the technology readiness levels to manufacture.* (Paragraph 115)

17. *The Government should provide additional funds for the development of batteries and fuel cells, which are essential for achieving the net-zero target and for achieving the UK's industrial ambitions. This funding can be provided within the budget increases for research and development out to 2024–25. Funding should be comparable to international competitors, and should have long-term certainty in order to build the UK's research base, develop momentum and ensure that advances are fully exploited.* (Paragraph 116)

18. *UK Research and Innovation should expand the remit of the Faraday Institution and the UK Battery Industrialisation Centre to include stationary batteries, with commensurate additional funding from Government.* (Paragraph 117)

19. *UK Research and Innovation should expand its portfolio for developing next generation batteries, with commensurate additional funding from Government. This will help to establish a long-term advantage for the UK, for example in solid-state batteries for vehicles and sodium-ion batteries for stationary storage.* (Paragraph 118)

20. Fuel cells will benefit from ongoing innovation to improve performance and durability and to reduce costs. They are well-suited to a range of applications, but the sector may require support to tailor the technology to each application. (Paragraph 132)

21. The current funding for fuel cell research and development is inadequate, and the sector needs to be supported through the establishment of initiatives and organisations akin to the Faraday Institution and the UK Battery Industrialisation Centre. These proposals should be seen in the context of the Government's commitments to significantly increase public funding for research and development. (Paragraph 135)

22. *The Government should establish organisations to support research and scale-up for the fuel cell and hydrogen sector, equivalent to the Faraday Institution and the UK Battery Industrialisation Centre, guided by a clear analysis of where research and demonstrations are needed.* (Paragraph 136)

Strategic issues facing the UK

23. The UK is competing with other countries to attract automotive battery manufacturing. Failure to do so would likely lead to vehicle manufacturing moving elsewhere. Recent announcements of future increases in the manufacture of cells and electric vehicles are welcome, but are still insufficient to meet anticipated demand. The Government will need to commit further funds for gigafactories, supply chains and training ahead of the 2027 and 2030 deadlines, to ensure that the UK's automotive sector can maintain manufacturing at its current scale. These resources will have to reach from research through to manufacturing, and will have to be commensurate to those of international competitors. (Paragraph 149)

24. Despite the urgency of the 2027 and 2030 deadlines, the UK also needs to plan on longer timescales. Manufacturing and supply chains require ongoing innovation in order to remain competitive, and need to be future-proofed to allow improvements in battery technology to be implemented with minimal cost and disruption. (Paragraph 150)

25. The UK's fuel cell and electrolyser manufacturers have done well to establish themselves internationally despite being largely neglected by UK policy and public funding. These companies need support to expand manufacturing in the UK, compete internationally and contribute to the UK's hydrogen ambitions. (Paragraph 159)

26. The development and uptake of fuel cell technologies by the transport sector will be aided by clear regulatory signals, in particular the ending of the sale of new diesel HGVs, on which the Government is currently consulting. (Paragraph 160)

27. *The Government should publish its hydrogen strategy this summer. This strategy must be coordinated with the Government's other decarbonisation strategies to enable use of hydrogen in those sectors for which it is the most viable option. The hydrogen strategy should make effective use of the UK's expertise in fuel cells and electrolysers, both to support UK decarbonisation efforts and to seek a leading role internationally.* (Paragraph 161)

28. *The Government should take action to ensure that there are sufficient skilled workers in the automotive sector and conducting research into batteries and fuel cells. 1) There needs to be more support for training to enable the automotive sector's transition to electric vehicles. 2) There need to be pipelines for training more researchers and engineers and supporting their longer-term careers. 3) There needs to be greater flexibility for recruiting international staff for research and manufacturing, including by reducing the costs associated with visas, particularly for short-term contracts.* (Paragraph 166)

29. *The Government should produce a critical raw materials strategy. This strategy should make use of the UK's natural resources such as Cornish lithium, and should utilise the UK's expertise in mineral processing to incentivise collaboration from countries with larger natural resources.* (Paragraph 175)

30. *The Government should set out clear plans for developing industrial-scale recycling in the UK. As part of this, it should require manufacturers to incorporate 'sustainability by design' and to conduct full life-cycle analyses of the environmental and social impacts of batteries and fuel cells. The Government should introduce incentives and regulations to speed the transition to more sustainable technologies.* (Paragraph 176)

31. *The Government should explain to industry what will replace the industrial strategy, and should promote its industrial objectives clearly, both domestically and internationally. Its objectives should be supported by investments in the battery and fuel cell sectors, commensurate with those of the UK's international competitors, including de-risking expansion of manufacturing and supply chains in order to attract the significant private sector investment that is required.* (Paragraph 182)

32. The UK's current trajectory of battery manufacture risks missing the Government's target for the transition to electric light road transport, such that the UK may not be able to retain its automotive industry at its current scale. The situation is similarly serious for heavy transport and stationary

energy systems, where lack of regulations and incentives have hindered decarbonisation using batteries and fuel cells. (Paragraph 188)

33. The Government's plans for decarbonisation and industrial growth lack detail about how it will overcome significant challenges to achieve ambitious targets with short deadlines. There was a stark disconnect between the optimism of Ministers and officials that UK industries can transition in very tight timescales, and the concerns of our other witnesses that the UK is far behind its competitors and faces significant challenges with innovation, supply chains and skills. (Paragraph 189)

34. *The Government should publish its decarbonisation strategies as a matter of urgency, and make a series of key decisions by the end of 2021, as set out above. We ask that the Government explains in its response to this report how it will meet each of the deadlines that we have discussed, with details of how it will ensure that the UK has the necessary research, skills, supply chains and finance.* (Paragraph 190)

APPENDIX 1: LIST OF MEMBERS AND DECLARATIONS OF INTEREST

Members

Baroness Blackwood of North Oxford
Baroness Brown of Cambridge (co-opted)
Viscount Hanworth
Lord Holmes of Richmond
Lord Kakkar
Lord Krebs
Baroness Manningham-Buller
Lord Mitchell
Lord Patel (Chair)
Baroness Rock
Lord Sarfraz
Baroness Sheehan
Baroness Walmsley
Baroness Warwick of Undercliffe
Lord Winston

Declaration of Interest

Baroness Blackwood of North Oxford
Board Member, Alan Turing Institute
Baroness Brown of Cambridge (co-opted)
Chair, The Carbon Trust
Non-Executive Director, Ørsted
Shareholding in Rolls-Royce plc
Member, BEIS Hydrogen Advisory Council
Chair, Sir Henry Royce Institute for Advanced Materials
Board Member, Ceres Power (from 17 June 2021)
Viscount Hanworth
No relevant interests declared
Lord Holmes of Richmond
No relevant interests declared
Lord Kakkar
Professor of Surgery, University College London
Member, Advisory Board, Royal Society
Lord Krebs
Fellow, Royal Society
Advisor to Drax plc
Baroness Manningham-Buller LG
No relevant interests declared
Lord Mitchell
Previous shareholder in International Energy
Lord Patel
Member, Advisory Board, Warwick Manufacturing Group (non-remunerated)
Baroness Rock
Board member, Centre for Data Ethics & Innovation
Lord Sarfraz
Venture Partner, Draper Associates (Venture Capital)

Founding Partner, Mineable Ltd (from 8 July 2021)

Baroness Sheehan

No relevant interests declared

Baroness Walmsley

No relevant interests declared

Baroness Warwick of Undercliffe

Chair, Board of the National Housing Federation

Chair, Board of The Property Ombudsman

Vice Chair, Board of Nottingham Trent University

Lord Winston

Professor of Science and Society, Imperial College London

Hon Fellow, Royal Academy of Engineering

Fellow, Academy of Medical Sciences

Member, Council of Data Ethics and Innovation

A full list of Members' interests can be found in the Register of Lords Interests: http://www.parliament.uk/mps-lords-and-offices/standards-and-interests/register-of-lords-interests/

Specialist Adviser

Professor Clare Grey FRS, Geoffrey Moorhouse Gibson Professor of Chemistry, Department of Chemistry, University of Cambridge

Recipient of funding for research into batteries and fuel cells from: the Engineering and Physical Sciences Research Council (EPSRC), the Faraday Institution, the EU, and the Royal Society

Co-founder and major shareholder of CB2Tech (now renamed Nyobolt), a manufacturer of fast charging batteries based in a priority niobium-based anode

APPENDIX 2: LIST OF WITNESSES

Evidence is published online at https://committees.parliament.uk/work/1083/role-of-batteries-and-fuel-cells-in-achieving-net-zero/publications/ and available for inspection at the Parliamentary Archives (020 7219 3074).

Evidence received by the Committee is listed below in chronological order of oral evidence session and in alphabetical order. Those witnesses marked with ** gave both oral evidence and written evidence. Those marked with * gave oral evidence and did not submit any written evidence. All other witnesses submitted written evidence only.

Oral evidence in chronological order

*	Professor Nigel Brandon OBE, Dean of the Faculty of Engineering, Imperial College London	QQ 1–19
**	Professor Pam Thomas, CEO, The Faraday Institution	
*	Amer Gaffar, Director of Manchester Fuel Cell Innovation Centre, Manchester Metropolitan University	
*	Professor Mauro Pasta, Associate Professor in the Department of Materials, University of Oxford	
*	Professor Serena Corr, Chair in Functional Nanomaterials, and Director of Research, Department of Chemical and Biological Engineering, University of Sheffield	QQ 20–31
*	Professor Paul Shearing, Professor in Chemical Engineering, University College London (UCL)	
*	Dr Jerry Barker, Founder and Chief Technology Officer, Faradion Ltd	
**	Dr Melanie Loveridge, Associate Professor, Warwick Manufacturing Group (WMG), University of Warwick	
*	Professor Andrea Russell, Professor of Physical Electrochemistry, University of Southampton	QQ 32–48
*	Professor Anthony Kucernak, Professor of Physical Chemistry, Faculty of Natural Sciences, Department of Chemistry, Imperial College London	
*	Professor John Irvine, Professor, School of Chemistry, University of St Andrews	
*	Tony Harper, Industrial Strategy Challenge Director, Faraday Battery Challenge at UKRI, Innovate UK	QQ 49–59
*	Dr Lucy Martin, Deputy Director of Cross-Council Programmes and lead for Net Zero, Engineering and Physical Sciences Research Council (EPSRC)	
**	Dr Bob Moran, Deputy Director, Head of Environment Strategy, Department for Transport	

**	Professor Paul Monks, Chief Scientific Adviser, Department for Business, Energy and Industrial Strategy (BEIS)	
*	Professor Philip Taylor, Director, EPSRC Supergen Energy Networks Hub; and Pro-Vice Chancellor for Research and Enterprise, University of Bristol	QQ 60–69
**	Professor David Greenwood, CEO, High Value Manufacturing Catapult at Warwick Manufacturing Group (WMG); and Director for Industrial Engagement, WMG; and Professor of Advanced Propulsion Systems, University of Warwick	
*	Professor Paul Dodds, Professor of Energy Systems, University College London (UCL)	
*	Professor Patrick Grant, Vesuvius Chair of Materials and Pro-Vice-Chancellor (Research), University of Oxford	QQ 70–80
*	Professor Emma Kendrick, Chair of Energy Materials and Professor of Energy Materials, University of Birmingham	
**	Jeff Pratt, Managing Director, UK Battery Industrialisation Centre	
*	Isobel Sheldon OBE, Chief Strategy Officer, Britishvolt	QQ 81–89
*	Chris Pennison, CEO, Hyperdrive Innovation	
*	Dr Colin Herron CBE, Managing Director, Zero Carbon Futures	
**	Jo Godden, Managing Director, Fuel Cells, Johnson Matthey	QQ 90–97
**	Dr Mark Selby, Chief Technology Officer, Ceres Power	
**	Professor Marcus Newborough, Development Director, ITM Power	
**	Ian Constance, CEO, Advanced Propulsion Centre	QQ 98–104
**	Helen Simpson, Innovation and Projects Director, Porterbrook	
*	Paul Stein, Chief Technology Officer, Rolls Royce plc	
*	Dr Keith MacLean OBE, Managing Director, Providence Policy; and Chair, UK Energy Research Centre	QQ 105–120
*	Nick Winser CBE, Chair, Energy Systems Catapult	
*	Professor Tim Green, Co-Director, Energy Futures Laboratory (EFL); and Deputy Head, Department of Electrical and Electronic Engineering, Imperial College London	

*	Dr Jane Dennett-Thorpe, Deputy Director for Net Zero Transition, Ofgem	
*	Professor Magda Titirici, Chair in Sustainable Energy Materials, Imperial College London	QQ 121–128
*	Professor Richard Herrington, Head of Earth Sciences Department, Natural History Museum (NHM)	
*	Dr Paul Anderson, Reader in Inorganic and Materials Chemistry, University of Birmingham; and Principal Investigator of RELIB project, Faraday Institution	
*	Dr Evi Petavratzi, Senior Mineral Commodity Geologist, British Geological Survey	
*	Rob Millar, Head of Electrical and Battery Systems, Williams Advanced Engineering; and Expert Panel Member, Faraday Institution	QQ 129–138
**	David Wong, Senior Innovation and Technology Manager, Society of Motor Manufacturers and Traders (SMMT)	
*	Buta Atwal, Chief Executive Officer, Wrightbus	
*	James Sprinz, Vice President of Strategy and Business Development—Europe, Energy Impact Partners	QQ 139–150
*	Dr Jeffrey Chamberlain, Chief Executive Officer, Volta Energy Technologies, LLC; Board Member at the Faraday Institution; and formerly of Argonne Labs and US Department of Energy	
*	Beverley Gower-Jones, Managing Partner, Clean Growth Fund	
*	John Bromley, Head of Clean Energy Strategy, Legal and General Capital	
**	Dr Bob Moran, Deputy Director, Head of Environment Strategy, Department for Transport	QQ 151–164
**	Damitha Adikaari, Director of Science and Innovation for Climate and Energy, Department of Business, Energy and Industrial Strategy (BEIS)	
**	Hannah Boardman, Director of Advanced Manufacturing, Department of Business, Energy and Industrial Strategy (BEIS)	
**	Rt Hon Anne-Marie Trevelyan MP, Minister of State (Minister for Business, Energy and Clean Growth), Department of Business, Energy and Industrial Strategy (BEIS)	QQ 165–177
**	Rachel Maclean MP, Parliamentary Under Secretary of State, Department for Transport	
**	Hannah Boardman, Director of Advanced Manufacturing, Department of Business, Energy and Industrial Strategy (BEIS)	

**	Dr Bob Moran, Deputy Director, Head of Environment Strategy, Department for Transport	

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**	Advanced Propulsion Centre UK Limited—Batteries (QQ 98–104)	BAT0018
**	Advanced Propulsion Centre UK Limited—Fuel Cells (QQ 98–104)	BAT0019
	Aerospace Technology Institute	BAT0021
*	Dr Paul Anderson, Reader in Inorganic and Materials Chemistry, University of Birmingham (QQ 121–128)	
	Anglo American	BAT0026
*	Professor Nigel Brandon OBE, Dean of the Faculty of Engineering, Imperial College London (QQ 1–19)	
*	British Geological Survey (QQ 121–128)	
*	Britishvolt (QQ 81–89)	
	Cadent Gas	BAT0033
**	Ceres Power (QQ 90–97)	BAT0016 BAT0048
*	Clean Growth Fund (QQ 139–150)	
*	Professor Serena Corr, Chair in Functional Nanomaterials, and Director of Research, Department of Chemical and Biological Engineering, University of Sheffield (QQ 20–31)	
	Cumulus Energy Storage Ltd	BAT0024
	Dr Mohamed Darwish, Dr Chun Sing Lai, Professor Gareth Taylor, Brunel University London and Professor Giorgio Locatelli, University of Leeds	BAT0009
**	Department of Business, Energy and Industrial Strategy (BEIS) (QQ 49–59) (QQ 151–164) (QQ 165–177)	BAT0041 BAT0050
**	Department for Transport (QQ 49–59) (QQ 151–164) (QQ 165–177)	BAT0041 BAT0049
*	Professor Paul Dodds, Professor of Energy Systems, University College London (UCL) (QQ 60–69)	
*	Energy Futures Laboratory (EFL) (QQ 105–120)	
*	Energy Impact Partners Europe (QQ 139–150)	
	Energy Networks Association	BAT0007
*	Energy Systems Catapult (QQ 105–120)	
*	Engineering and Physical Sciences Research Council (EPSRC) (QQ 49–59)	

*	EPSRC (Engineering and Physical Sciences Research Council) Supergen Energy Networks Hub (QQ 60–69)	
**	The Faraday Institution (QQ 1–19)	BAT0012
		BAT0046
*	Faradion Ltd (QQ 20–31)	
	Frazer-Nash Consultancy	BAT0030
*	Amer Gaffar, Director of Manchester Fuel Cell Innovation Centre, Manchester Metropolitan University (QQ 1–19)	
	The Geological Society	BAT0034
*	Professor Patrick Grant, Vesuvius Chair of Materials and Pro-Vice-Chancellor (Research), University of Oxford (QQ 70–80)	
**	HM Government (QQ 49–59) (QQ 151–164) (QQ 165–177)	BAT0041
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*	Hyperdrive Innovation (QQ 81–89)	
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*	Innovate UK (QQ 49–59)	
	Institute of Materials, Minerals and Mining (IOM3)	BAT0031
	Institution of Mechanical Engineers	BAT0029
	Intelligent Energy	BAT0038
*	Professor John Irvine, Professor, School of Chemistry, University of St Andrews (QQ 32–48)	
**	ITM Power (QQ 90–97)	BAT0013
**	Johnson Matthey (QQ 90–97)	BAT0011
*	Professor Emma Kendrick, Chair of Energy Materials and Professor of Energy Materials, University of Birmingham (QQ 70–80)	
*	Professor Anthony Kucernak, Professor of Physical Chemistry, Faculty of Natural Sciences, Department of Chemistry, Imperial College London (QQ 32–48)	
	Dr Chun Sing Lai, Professor Gareth Taylor, Dr Mohamed Darwish, Brunel University London and Professor Giorgio Locatelli, University of Leeds	BAT0009
*	Legal and General Capital (QQ 139–150)	
	Professor Giorgio Locatelli, University of Leeds and Dr Mohamed Darwish, Dr Chun Sing Lai, Professor Gareth Taylor, Brunel University London	BAT0009

	National Oceanography Centre	BAT0006
★	Natural History Museum (NHM) (QQ 121–128)	
	Newcastle University	BAT0035
★	Ofgem (QQ 105–120)	
★	Professor Mauro Pasta, Associate Professor in the Department of Materials, University of Oxford (QQ 1–19)	
★★	Porterbrook (QQ 98–104)	BAT0042
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	Railway Industry Association (RIA)	BAT0043
	Regen (and the Electricity Storage Network)	BAT0027
	Riversimple Movement Ltd	BAT0036
★	Rolls Royce plc (QQ 98–104)	
	Royal Society of Chemistry	BAT0025
★	Professor Andrea Russell, Professor of Physical Electrochemistry, University of Southampton (QQ 32–48)	
★	Professor Paul Shearing, Professor in Chemical Engineering, University College London (UCL) (QQ 20–31)	
	Society of Chemical Industry (SCI)	BAT0037
★★	Society of Motor Manufacturers and Traders (SMMT) (QQ 129–138)	BAT0040
	Solar Energy UK	BAT0017
	Professor Gareth Taylor, Dr Mohamed Darwish, Dr Chun Sing Lai, Brunel University London and Professor Giorgio Locatelli, University of Leeds	BAT0009
	Teeside University	BAT0015
★	Professor Magda Titirici, Chair in Sustainable Energy Materials, Imperial College London (QQ 121–128)	
★★	UK Battery Industrialisation Centre (UKBIC) (QQ 70–80)	BAT0020
★	UK Energy Research Centre (UKERC) (QQ 105–120)	
	UK H2Mobility, Element Energy	BAT0022
	UK Hydrogen and Fuel Cell Association	BAT0008
	UK Research and Innovation (UKRI)	BAT0045
★	Volta Energy Technologies, LLC (QQ 139–150)	
	Volta Trucks	BAT0003
★	Williams Advanced Engineering (QQ 129–138)	

**	WMG (Warwick Manufacturing Group), University of Warwick (QQ 20–31) (QQ 60–69)	BAT0014
*	Wrightbus (QQ 129–138)	
	Wrightbus and Ryse Hydrogen	BAT0039
	Zemo Partnership	BAT0023
		BAT0028
	ZeroAvia	BAT0032
*	Zero Carbon Futures (QQ 81–89)	

Private seminars

The Committee held a number of private seminars on various aspects of decarbonisation in order to inform its choice of inquiry topics.

Seminar held remotely at the House of Lords on 2 February 2021

Members of the Committee present were Lord Patel (Chair), Baroness Blackwood of North Oxford, Viscount Hanworth, Lord Krebs, Baroness Manningham-Buller, Lord Mitchell, Viscount Ridley, Baroness Rock, Lord Sarfraz, Baroness Sheehan, Baroness Walmsley, Baroness Warwick of Undercliffe and Lord Winston.

Presentations were heard from:

- Professor Julian Allwood, Professor of Engineering and the Environment, University of Cambridge;
- Professor Sir Chris Llewellyn Smith, Emeritus Professor, University of Oxford and former Director of Energy Research, University of Oxford;
- Dr David Joffe, Head of Carbon Budgets, Committee on Climate Change; and
- Philip Sellwood CBE, former Chief Executive, Energy Saving Trust.

Seminar held remotely at the House of Lords on 9 February 2021

Members of the Committee present were Lord Patel (Chair), Baroness Blackwood of North Oxford, Viscount Hanworth, Lord Kakkar, Lord Krebs, Baroness Manningham-Buller, Lord Mitchell, Viscount Ridley, Baroness Rock, Lord Sarfraz, Baroness Sheehan, Baroness Walmsley, Baroness Warwick of Undercliffe and Lord Winston.

Presentations were heard from:

At 9.00am:

- Professor Pete Smith, Chair in Plant and Soil Science, University of Aberdeen;
- Professor Richard Davies, Pro-Vice Chancellor: Global, University of Newcastle;
- Professor Stuart Haszeldine OBE, Professor of Carbon Capture and Storage, University of Edinburgh; and
- Professor Geoffrey Maitland CBE, Professor of Energy Engineering, Imperial College London.

At 10.00am:

- Professor Clare Grey, Geoffrey Moorhouse Gibson Professor of Chemistry, University of Cambridge;
- Professor Robin Grimes, Professor of Materials Physics and BCH Steele Chair in Energy Materials, Imperial College London;
- Professor Jenny Nelson, Professor of Physics, Imperial College London; and
- Nick Winser CBE, Chairman, Energy Systems Catapult.

At 11.00am:

- Professor Bill David, Professor of Chemistry, University of Oxford;
- Professor Graham Hutchings CBE, Regius Professor of Chemistry, Cardiff University;
- Professor Nigel Brandon OBE, Dean of the Faculty of Engineering, Imperial College London; and
- Professor Yulong Ding, Founding Chamberlain Chair of Chemical Engineering and Director of the Birmingham Centre for Energy Storage, University of Birmingham.

APPENDIX 3: CALL FOR EVIDENCE

The House of Lords Science and Technology Committee, Chaired by Lord Patel, is conducting an inquiry into the role of battery and fuel cell technologies in achieving the UK's ambition to reach net-zero greenhouse gas emissions by 2050. The deadline for receiving written submissions is Monday 29 March 2021.

Background

Electrification will be crucial to achieving Net Zero, and battery and fuel cell technologies will be needed to support electrification, particularly in the land transport sector. Under the Climate Change Committee's Balanced Net Zero Pathway, the number of battery-electric vehicles in the UK will need to increase from around 5% of current sales to 100% by 2032 at the latest. This will require considerable scaling up of the manufacture of batteries and deployment of charging infrastructure, as well as advances in the energy density, capacity and charging times of battery systems, in parallel with further cost reductions. For heavy transport such as HGVs and trains, batteries and hydrogen fuel cells could also have an important role to play if some of these technical challenges can be overcome.

The Committee also seeks to understand the potential role for battery and fuel cell technologies in other sectors (for example aviation, agricultural machinery, heat production), and will consider how these technologies will interact with the wider energy system (for example, the use of batteries as energy storage on the electricity grid).

The Committee is seeking evidence on the following questions (there is no requirement to answer all questions in your submission):

Questions

1. To what extent are battery and fuel cell technologies currently contributing to decarbonisation efforts in the UK?

   - What are the primary applications of battery and fuel cell technologies for decarbonisation, and at what scale have they been deployed?

2. What advances have been made in battery and fuel cell technologies in recent years and what changes can we expect in the next ten years (for example, in terms of energy density, capacity, charging times, lifetimes and cost reduction)?

   - What advances are expected beyond this timeframe, but in time to have an impact upon the 2050 net-zero target? Are there any fundamental limits to these technologies that would affect their contribution to the target?
   - Are there any implications of next generation battery technologies that could make the charging infrastructure we will be installing between now and 2030 obsolete?
   - What are the implications on battery life of multiple charge/discharge cycles, for example when used to support storage and frequency management on the grid?

3. What are the opportunities and challenges associated with scaling up the manufacture of batteries and fuel cells, and for manufacturing batteries and

fuel cells for a greater number and variety of applications? Is the UK well placed to become a leader in battery and fuel cell manufacture?

- What supply chain considerations need to be taken into account when scaling up battery and fuel cell manufacture in the UK?

4. Is the right strategy, funding and support in place to enable the research, innovation and commercialisation of battery and fuel cell technologies in the UK?

- Is the UK doing enough to accelerate new developments from low technology readiness levels right through to commercial application in the UK?
- Does the UK have the workforce and skillsets required for battery and fuel cell research and manufacture? If not, what are the challenges associated with developing this expertise?

5. Which countries are currently the leaders in battery and/or fuel cell science and technology and where, if anywhere, does the UK have a lead or other advantages?

6. In what sectors could battery and fuel cell technologies play a significant role?

- What are the engineering and commercial challenges associated with using these technologies, or deploying them to a greater extent, in these sectors?
- What will be the likely balance between battery and hydrogen fuel cell technologies (and other options) in a fully decarbonised land transport sector (e.g. heavy and light vehicle transport)?

7. How should battery and fuel cell technologies be integrated into the wider UK energy system, and what are the challenges associated with integration (e.g. infrastructure, deployment, system operation, regulatory frameworks)?

- To what extent can batteries (including vehicle batteries) be used for energy storage and frequency management on the grid, and what needs to happen to enable this?
- Into which other parts of the UK's energy system could batteries or fuel cells be integrated, and what would be the challenges and opportunities associated with these uses?

8. What are the life cycle environmental impacts associated with batteries and fuel cells (e.g. in resource extraction, product manufacture, operation, reuse and recycling), and how can these be managed as production and usage increase?

- Please give examples of successful battery reuse or recycling, including the intentional design of second life applications.
- Given a potential global vehicle fleet approaching 2 billion vehicles by 2050, will all of the materials needed for battery and fuel cell production be available for manufacturing based in the UK?

9. What are the costs and benefits of using battery and fuel cell technologies in their various applications, including when integrated into the wider energy system?

- To what extent are costs and benefits of the technologies affected by the levels of deployment or their regulatory treatment?
- Are there alternatives that should be considered for particular sectors?

3 March 2021

APPENDIX 4: ABBREVIATIONS, ACRONYMS AND TECHNICAL TERMS

Anode	The positive electrode. Electrons flow into the anode from the external circuit, and recombine with positive ions
Balancing services	A set of interventions that are used to keep the electricity grid operating within normal parameters. For example, the output of electricity sources (and the demand from some large customers) can be increased or decreased to help balance supply and demand, and to maintain the correct voltage and frequency. In the UK, there interventions are secured via contracts between the National Grid as the System Operator and the owners of electricity sources and customers with high demand
Battery	A device that stores chemical energy and supplies an electrical current. A battery is also called a battery pack, and is composed of multiple cell
BEIS	Department for Business, Energy and Industrial Strategy
BEV	Battery electric vehicle. A vehicle that is propelled by an electric motor powered by a battery that is charged from an external power source
Cell	A device that stores chemical energy and supplies an electrical current. A cell consists of two electrodes, an electrolyte, a membrane and a casing. Multiple cells are combined to form a battery (also called a battery pack)
Catalyst	A material that assists a chemical reaction but is not itself changed by the reaction, and hence remains in place to assist the reaction again
Cathode	The negative electrode. Electrons separate from atoms (which become positively charged ions) at the cathode, and then flow out into the external circuit
Charging time	How long it takes to recharge the battery after its charge has been depleted
CHP	Combined heat and power. A CHP unit uses an energy source (e.g. natural gas or hydrogen) to produce electricity and to use the 'waste' heat (e.g. for heating buildings or water)
Critical raw materials	Materials that are essential for national objectives, including minerals used in the manufacture of batteries and fuel cells
Cycle life	The number of times the battery can be charged and discharged before its performance falls below an acceptable level
DfT	Department for Transport
EFL	Energy Futures Laboratory

Electric trains	Locomotives propelled by electric motors that are powered by an external source of electricity that is provided via overhead cables or live rails. This is distinct from a battery train that uses an electric motor that is powered by an onboard battery
Electrode	A component within a battery or fuel cell where electrons and ions separate or recombine
Electrolyte	A material in a battery that contains particles that react at the anode and cathode to form electrical charge carriers. The electrolyte can conduct ions between the electrodes
Electrolyser	A device that uses electricity to break down water into oxygen and hydrogen; it is essentially the opposite of a fuel cell. The process is called electrolysis
Electron	A negatively charged particle that composes the electrical current in most circuits.
Energy	The total amount of work that can be done, such as lighting a light or turning a motor. The greater the energy available, the longer the work can be maintained. The basic unit of energy in electrical engineering is the watt-hour (Wh)
Energy density	The amount of energy a battery contains in proportion to its mass, typically measured in watt-hours per gram (Wh/g)
Energy stored	The product of a battery's energy density and mass, giving the total amount of energy that it can contain, measured in Wh
Energy vector	The media that transport energy. Energy vectors include primary energy sources such as gas that can be transported easily, and 'intermediaries' such as electricity and hydrogen
EPSRC	Engineering and Physical Sciences Research Council
EV	Electric vehicle, a generic term, referring to any of the other types noted in this glossary, such as BEVs, PHEVs and FCEVs
FCEV	Fuel cell electric vehicle. A vehicle that uses a fuel cell to power an electric motor
Fuel cell	A device in which a fuel (containing hydrogen) reacts with another chemical (such as oxygen) without combustion, to produce an electrical current, heat and water (as well as other chemicals in the case of fuels other than pure hydrogen)
Heat pump	A device that uses a power source (e.g. electricity) to pump a fluid around a system of pipes in order to move heat from a cooler region to a warmer region. It operates in essentially the opposite manner to a refrigerator, and is an option for heating buildings
High temperature fuel cell	A fuel cell that operates at up to 1,000°C. Also called solid oxide fuel cells (SOFC)

Ion	A charged particle, formed when an atom gains or loses one or more electron
Intermediate temperature fuel cell	A fuel cell that operates at 200–300°C
On-road charging	Charging an electric vehicle either using via a pantograph to make contact with overhead cables or using electromagnetic induction to access energy from cables buried within the road
Life cycle	The sequence of manufacture, use and disposal or recycling of a product
Lithium-air	A next-generation battery technology that is being developed
Lithium-ion	The standard battery for most applications at present, in which lithium-ions are the ions that conduct the electrical charge through the electrolyte
Lithium-sulfur	A next-generation battery technology that is being developed
Low temperature fuel cell	A fuel cell that operates at 60–100°C. Also known as 'polymer electrolyte membrane' or 'proton-exchange membrane' (PEM) fuel cells
Membrane	A thin sheet that separates two regions. In a battery, the membrane sits between the anode and the cathode to prevent them from touching each other, but the membrane is 'semi-permeable' to allow ions to flow through it. The membrane in a battery is also called a separator
NHM	Natural History Museum
PHEV	Plug-in hybrid electric vehicle. A vehicle that can use either internal combustion engine fuelled by a liquid fuel or an electric motor powered by battery that is charged from an external power source
Power	How quickly work can be done—that is, power is the 'energy per unit time'. The greater the power, the more rapidly work is done. The basic unit of power is the watt (W)
Redox flow battery	A battery in which liquid electrolytes are pumped through the cell from external tanks, allowing larger volumes of electrolyte to interact with the electrodes. Also called simply a 'flow battery'
SMMT	Society of Motor Manufacturers and Traders
Sodium-ion	A next-generation battery technology that operates in much the same way as lithium-ion technology, but with different materials, including sodium in place of lithium
Solid-state battery	A next-generation battery technology in which all components are solid, including the electrolyte (which is liquid is current batteries)

Stationary	A term used to describe applications other than transport, for example batteries or fuel cells used in electricity grids or in buildings are said to be 'stationary applications'
Supercapacitor	A device that stores energy for release in electrical form. Compared to a battery, it stores less energy and releases it more rapidly
UKERC	UK Energy Research Centre
WMG	Warwick Manufacturing Group