Faraday Report – April 2023

The Role of Hydrogen and Batteries in Delivering Net Zero in the UK by 2050

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Customer:	The Faraday Institution Quad One, Becquerel Avenue, Harwell Campus, Didcot, OX11 0RA	
Customer contact:	Stephen Gifford	
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Prepared by:	Verified by:	Approved by:
Till Beckford	Till Beckford	Graham Bennett
Gwen Jackson-Johns	Graham Bennett	
Ali Daoud	Grant Finn	
Grant Finn		
Timothy Dowden		

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Table of abbreviations

Abbreviation	Explanation
AEL	Alkaline Water Electrolysers
AVGAS	Aviation Gasoline (Aviation -grade fuel) petrol
BE	Battery Electric
BEIS	Department for Business, Energy & Industrial Strategy
BESS	Battery Energy Storage Systems
BEV	Battery Electric Vehicle
CCGT	Combined-cycle Gas Turbine
CCUS	Carbon Capture Utilisation and Storage
CCS	Carbon Capture and Storage
COMAH	Control of Major Accident Hazards
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide equivalent
DNV	Det Norske Veritas. The consultancy company conducting this study
EFR	Enhanced Frequency Response
ESG	Environmental, Social and Governance
ETO	DNV's Energy Transition Outlook
EV	Electric Vehicle
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse Gases
Gp km	Giga passenger kilometres
Gt km	Giga tons kilometres
H_2	Hydrogen
HFO	Heavy Fuel Oil
HICE	Hydrogen fuelled Internal Combustion Engine
ICE	Internal Combustion Engine
IEA	International Energy Agency
LCO	Lithium Cobalt Oxide
LFP	Lithium Iron Phosphate
LOHC	Liquid Organic Hydrogen Carrier
LPG	Liquefied Petroleum Gas
Li-ion	Lithium-ion battery
Li-S	Lithium-sulphur Cells
MGO	Marine Gas Oil
MtCO2e	Million Tonnes Carbon Dioxide Equivalent
NCA	Lithium Nick Cobalt Aluminium Oxide
NMC	Lithium Nickel Manganese Cobalt Oxide
OCGT	Open Cycle Gas Turbine
PEM	Polymer Electrolyte Membrane Electrolysers
PHEV	Plug-In Hybrid Electric Vehicle
Pkm	Rail Passenger-kilometre (one rail passenger travelling by rail over a distance of one kilometre)
PM	Particulate Matter
RPM	Revolutions per minute
RTE	Round Trip Efficiency
SAF	Synthetic Aviation Fuel
SIB	Sodium-Ion Batteries
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolysers
SOH	State of Health
SSBs	Solid State Batteries
SUV	Sports Utility Vehicle
Tkm	Tonne-kilometre (freight transport of one tonne of goods over a distance of one kilometre)
TRL	Technology Readiness Level
VTOL (eVTOL)	Vertical Take-Off and Landing (electric Vertical Take-Off and Landing)
VRES	Variable Renewable Energy Sources

CONTENTS

1 EXECUTIVE SUMMARY

1.1 Background

The UK is facing pressure to transition to a low-carbon future due to the dual critical concerns of climate change and energy security. This energy transition will involve changes across different sectors of the economy and will take place over the next three decades, delivering the UK's obligation to reach net zero by 2050. Technological innovation will be crucial in this process and numerous studies have been undertaken showing scenarios and forecasts for the future energy system make-up.

A consistent feature in these predictions is the significant increase in electricity required and potential use of hydrogen as an energy carrier. With the increased electrification of society, dominated by the electrification of transport and building heating, and the increased share of that electricity being provided by variable renewable energy sources such as wind energy and solar power, the requirement for additional resilience and significant energy storage is apparent. To meet this need, battery and hydrogen are two technologies expected to play an ever-increasing role.

This report presents an analysis of how hydrogen and battery technologies are likely to be utilised in different sectors within the UK, including transportation, manufacturing, the built environment, and power. In particular, the report compares the use of hydrogen and battery technology across these sectors. In addition, it evaluates where these technologies will be in competition, where one technology will dominate, and where a combination of the two may be used.

This sector analysis draws on DNV's knowledge and experience within both the battery and hydrogen industries, along with a review of studies available in the public domain. The analysis has been incorporated into DNV's Energy Transition Outlook model, an integrated system-dynamics simulation model covering the energy system which provides an independent view of the energy outlook from now until 2050. The modelling which includes data on costs, demand, supply, policy, population, and economic indicators enables the non-linear interdependencies between different parameters to be considered so that decisions made in one sector influence the decision made in another.

1.2 The Battery and Hydrogen Market to 2050

According to DNV's analysis and modelling, the demand and importance for both batteries and hydrogen technology in the UK's decarbonisation efforts is expected to grow rapidly from today to 2050. Batteries and hydrogen are key to enabling the use of abundant renewable energy and to provide society with reliable, affordable, and sustainable energy. Batteries and hydrogen have very different characteristics however, making them well-suited for different applications, and therefore should be considered as complementary technologies, rather than competitors.

Demand

Total energy carried by battery and hydrogen technology (including hydrogen derived fuels) in the future UK energy system increases rapidly over the next three decades to reach approximately 130 TWh and 105 TWh respectively per year by 2050 (Figure 1-1). The very rapid rise in both technologies presents a significant supply chain challenge in terms of maturity and implementation for the UK and other countries undertaking similar transitions. The use of batteries is dominated by the road transport sector whereas there is greater diversity in the sectors using hydrogen. It is important to note that values derived from the DNV ETO model are based upon current government policy positions and analysis of how the market will develop, and DNV do not speculate on how unstated policy changes in the future may change this mix.

In the case of battery technology, the road transport sector accounts for 88% of the energy used in 2050 with aviation and the power sector making up the remaining energy use. The growth in the use of battery electric vehicles (BEVs) from today is expected to be rapid and continue from what has been seen in recent years, remaining strong through to the late 2030s before reducing, as the share of the market reaches saturation. Only limited use of batteries is expected in the rail and maritime sectors, and no significant use in manufacturing or the built environment, with vehicle-to-grid and behind-the-meter solar PV applications captured within the power sector.

For hydrogen, under current policies, growth is delayed with no significant use as an energy carrier until the late 2020s, with an increased growth rate in the 2040s as its use in road transport takes hold. The use of hydrogen energy is more evenly distributed with aviation, maritime, and manufacturing providing the largest demand, along with contributions from road transport and the power sector.

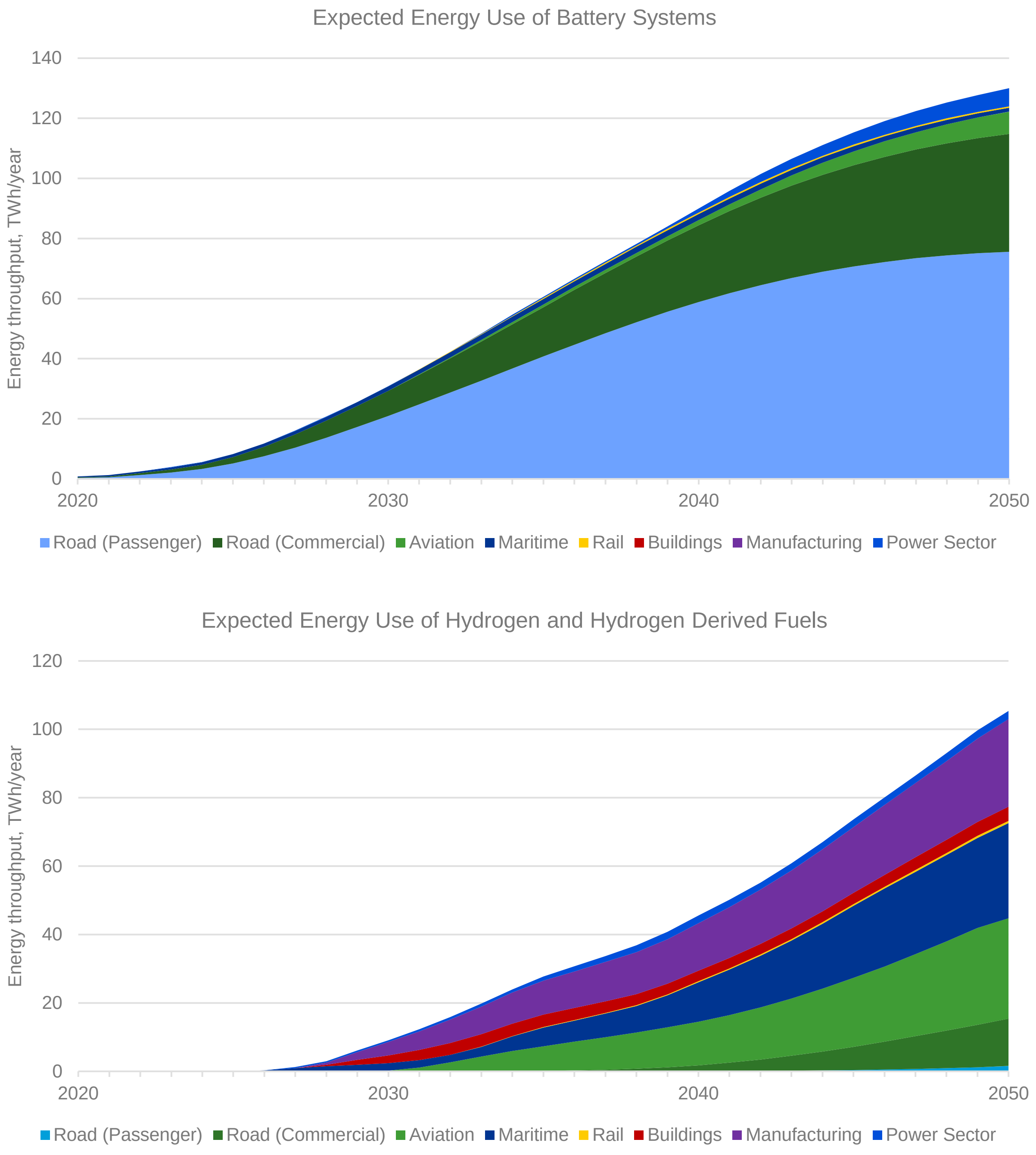

Figure 1-1 Expected energy use of battery and hydrogen systems between 2010 and 2050. Hydrogen use includes the use of hydrogen derived fuels such as ammonia and e-methanol

Competition and Complementarity

Analysing the potential for batteries and hydrogen within the transport, manufacturing, built environment and power sectors, DNV has considered where a single technology is expected to dominate, where multiple technologies are expected to complement each other and even offer hybrid solutions, and where both are in direct competition.

In general, the review of the different sectors shows that the instances of direct competition between batteries and hydrogen are limited, and instead one of the two technologies is typically more suited to a particular application. For instance, battery technology is expected to dominate passenger vehicles, leaving little room for hydrogen, whereas in both the built environment and manufacturing sectors, the demand for batteries is expected to be low, as any electrification will be achieved directly through the electricity grid. Therefore, for these sectors, the demand for hydrogen is in competition with grid connected electricity, rather than batteries.

Hydrogen in many applications is expected to be more expensive and overall less efficient compared to direct electrification and should therefore be thought of as the low-carbon energy carrier of last resort. Electrification on the other hand is typically the most efficient energy carrier, with battery technology used where storage is required. Therefore, renewables should ideally first be used to reduce the use of fossil fuels in the electricity mix, with hydrogen production via electrolysis being deployed later in the transition.

Battery technologies are generally high efficiency and lower cost when compared with other technologies. This higher efficiency and lower cost means that battery technology is generally considered the preferred solution for transport applications, particularly road transport. The capabilities of battery technologies have advanced in recent years due to the rapid uptake of EVs, expanding the areas in which batteries can operate.

The main area of competition for battery and hydrogen technology is in the parts of the transport sector where individual vehicles have a high demand for power and energy. This includes aviation and maritime sectors, rail where it is not possible to directly electrify the tracks, and heavy-duty applications in road transport. Heavy goods vehicles, buses and coaches can be served by batteries in many instances with today’s technology, whereas previously these applications were considered to be too onerous.

Short range applications in aviation and shipping are areas where batteries have the potential to meet demand where previously only liquid fuels were thought to be suitable. In particular, battery technology is considered to be in competition with hydrogen for short-distance aviation and to compliment hydrogen in medium haul scenarios, however there is additional competition from other hydrogen derived fuels and biofuels. With further improvements in battery technology, more areas of transport may be able to be served by battery technology.

Both hydrogen and battery technologies are expected to operate in the power sector, but in different areas. Batteries are expected to dominate in providing short term energy storage solutions, improving grid stability and balancing supply and demand within the daily cycles of renewable electricity generation and changing demand. Hydrogen on the other hand is expected to play a role as a form of dispatchable generation, which allows for the seasonal storage or production of energy – producing hydrogen in seasons with excess electricity generation from renewables, to then convert it back to electricity during periods with reduced wind and solar availability. In this sense the two technologies complement each other in helping to ensure a secure supply of electricity and to enable the decarbonisation of the electricity grid.

Figure 1-2 compares the energy throughput[1] of batteries and hydrogen by sector by 2050, including snapshots in 2030 and 2040. It shows the single largest use is that of battery technology within the road transport sector, with 115 TWh per year, giving batteries a dominant position over hydrogen. Outside of road transport, battery technology is expected to have a lower but significant market share in the aviation and maritime sectors with particular prominence in niche sub-markets such as short-haul aviation and domestic shipping, along with providing significant energy storage capacity within the power sector. The use of hydrogen is spread across the different sectors, particularly in the form of hydrogen

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[1] Energy throughput is the total amount of energy that is exported from an application over a period of time.

derived fuels such as synthetic aviation fuel, ammonia and e-methanol in the aviation and maritime sectors where it has significantly higher use than batteries. The largest use of pure hydrogen is expected to be in the manufacturing sector.

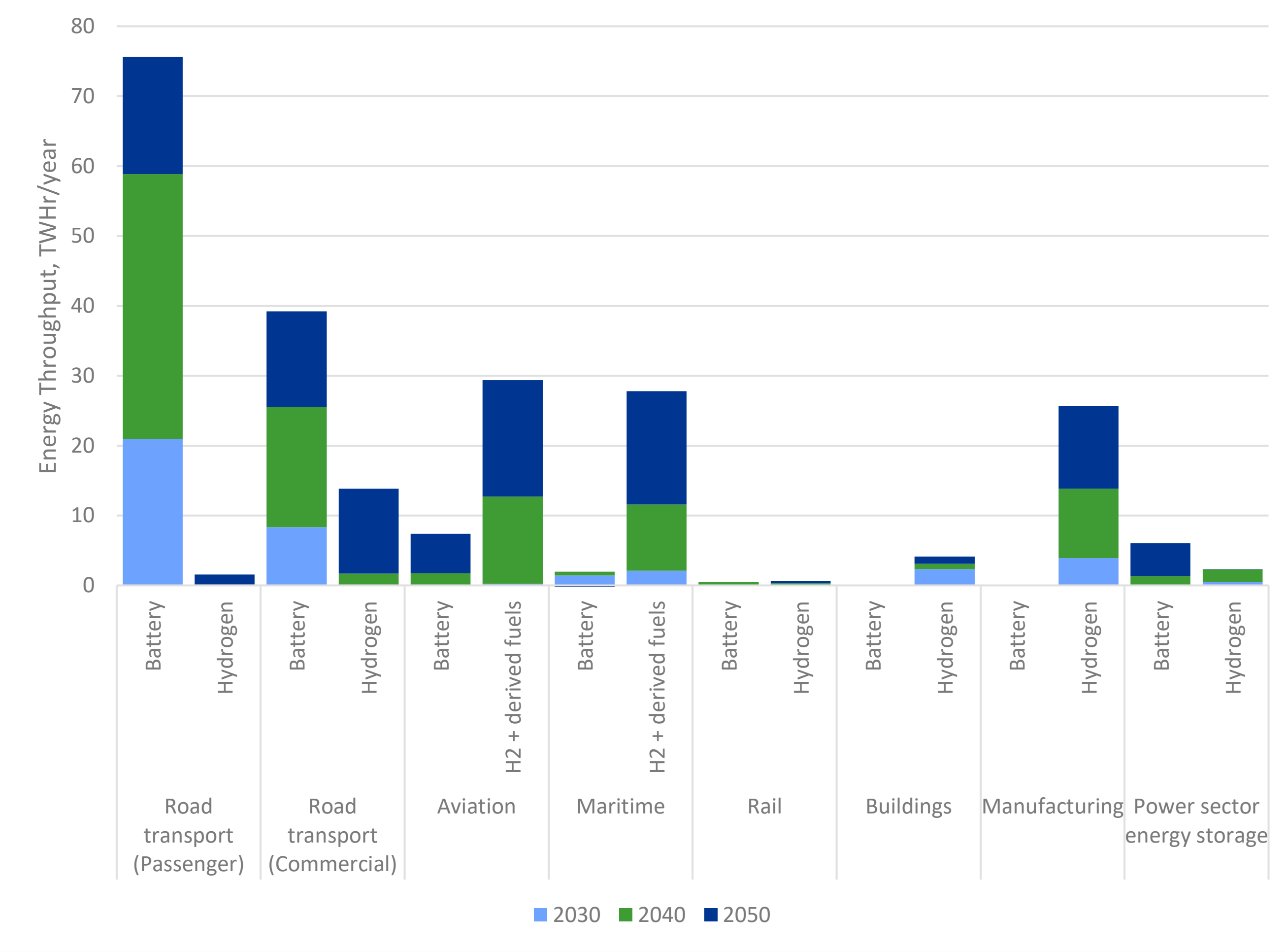

Figure 1-2 Comparison between the energy use of battery and hydrogen systems in different sectors within the UK to 2050. Hydrogen use includes the use of hydrogen derived fuels such as ammonia and e-methanol

The different market sectors reviewed in this report are outlined in more detail in the sections below along with an assessment of the potential UK market by battery and hydrogen technology.

1.3 Road Transport

The road transport sector plays a major role in the energy demand and CO_2 emissions from the UK, accounting for 2/3rds of all transport emissions and approximately 1/5th of the total UK CO_2 emissions today. Passenger cars account for the largest share of vehicle numbers and emissions, followed by heavy good vehicles (HGVs), light-duty vehicles (LDVs), buses and coaches. The number of vehicles in the UK is expected to rise in the coming years, reaching almost 44 million by 2050. Historically, petrol and diesel internal combustion engines have dominated the market, and in 2022, they are expected to have contributed over 2 million of the expected 2.5 million new vehicle sales.

Both battery and hydrogen technology are potential solutions for lower greenhouse gas emissions in road transport and are therefore in competition with one another to address the growing market for vehicles that are in accordance with future legislation that limits combustion engine usage. The UK will experience a decline in road sector energy demand thanks to the significant improvements in overall energy efficiency of electric mobility.

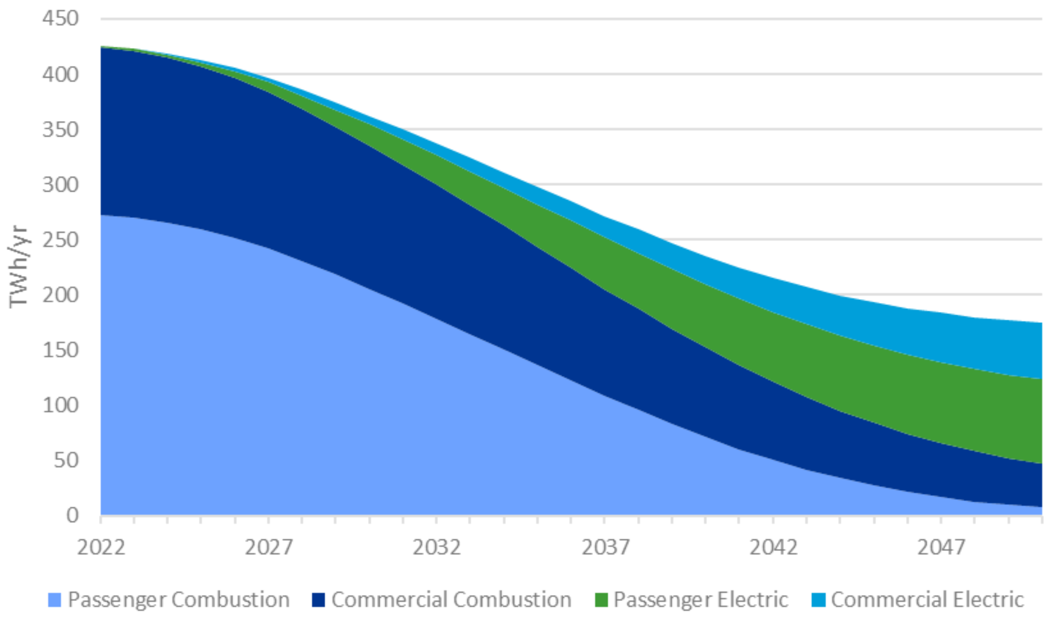

Figure 1-3 UK vehicle annual energy demand by vehicle and engine type, up to 2050[106]

Battery Potential

The potential for battery technology in road transport is high, and BEVs are expected to dominate the passenger car and light duty vehicles (LDV) markets. They already have a significant share of new vehicle sales today (10% in 2021). For passenger vehicles (including vans and SUVs), both the number of sales and total number of vehicles shifts dramatically from ICEV dominated to BEV dominated between today and 2050. By 2030, BEVs account for over 92% of new passenger vehicle sales, with PHEVs accounting for the remaining 8%. By 2050, BEVs are expected to account for 99% of passenger vehicles in the UK. For the 2-wheeled and bus markets, BEVs are also expected to have a leading share of the market, however with a higher potential for other technologies, they account for less than 1% and 2% respectively of the UK's 2019 transport emissions.

In the commercial segment (including HGVs, bus and coaches, and off-road vehicles) electrification is also expected to be the dominant theme, but this transition will be slower with ICEVs, maintaining a 38% market share by 2030, 8% by 2040 and 2% by mid-century. In terms of the commercial vehicle stock, the share of BEVs will rise to 13% in 2030, 45% in 2040, and nearly 80% in 2050. BEVs are expected to be the preferred solution where the payload and range is not prohibitively large, however with improvements in the energy density of batteries a greater number of heavy-duty applications are expected to utilise BEVs.

The dominant position of BEVs is largely due to their lower cost, and a significant fall in battery costs is assumed in the modelling. In addition, the expansion of public fast charging stations is a key enabling development for the electrification of road transport. The principal advantages of batteries are zero-emissions at the point of use, and the highest well-to-wheel efficiency of any technology. In addition, battery costs have reduced significantly in recent years, making BEVs the lowest cost option in many applications when considering the total cost of ownership (TCO). Further cost reductions are expected, fuelling the expected rapid increase in market share, where purchase price parity with ICEVs is expected to be reached by 2026. Nevertheless, there are challenges with the energy transition, particularly the huge requirement placed on the respective supply chains, with a peak annual battery demand of 240 GWh being reached in 2037.

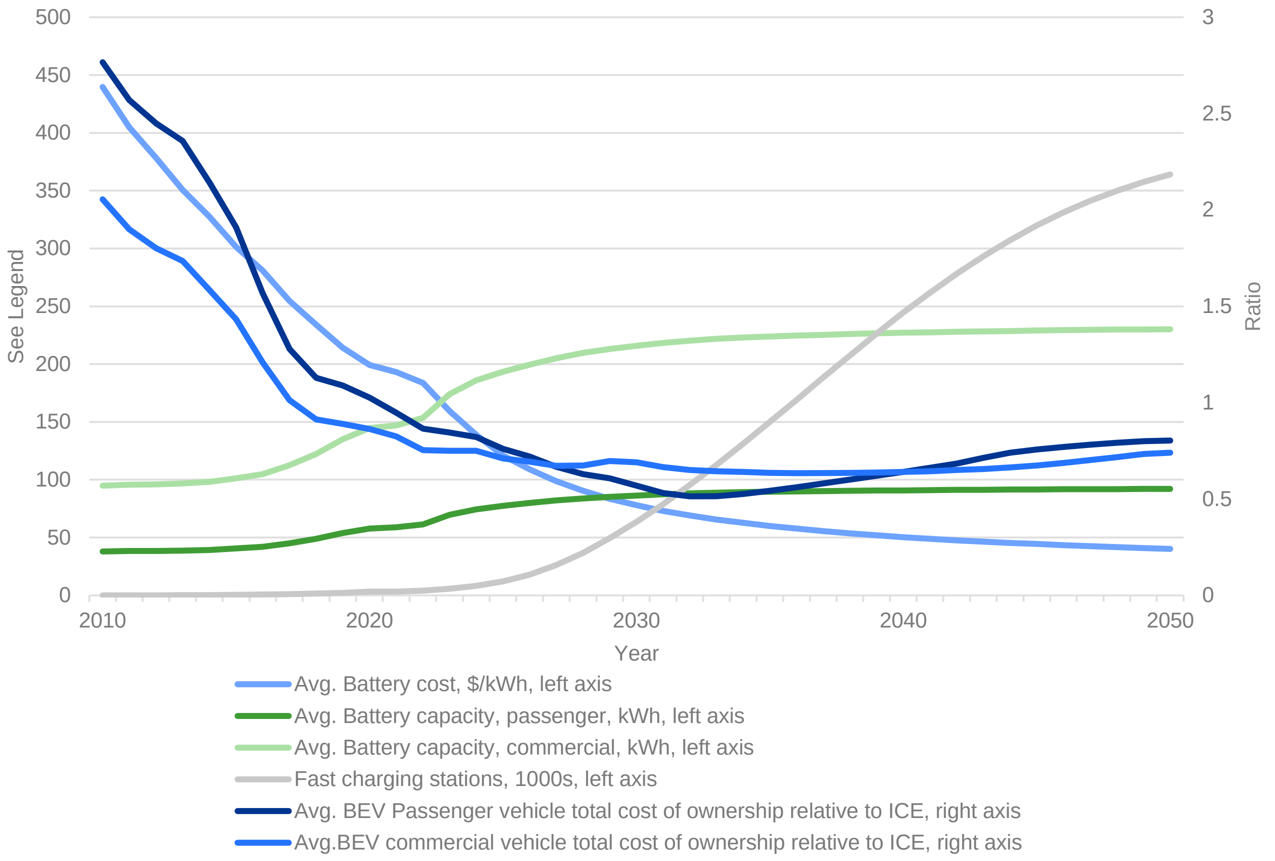

Figure 1-4 Key parameters associated with the rapid expansion of UK battery electric vehicles[106]

Hydrogen Potential

The use of hydrogen in a fuel cell (FC) or in an internal combustion engine (a HICE) is feasible and commercial vehicles are both available and in development today. However, the lower efficiency, higher cost and lack of hydrogen infrastructure are expected to restrict the widespread use of hydrogen in passenger cars and LDVs. Fuel cell demand is, therefore, not expected to have peaked by 2050, at which point 20 GW per year is forecast.

For passenger vehicles, mainly due to the high cost of hydrogen, FCEVs are expected to be much slower in their uptake, with no significant market share until the 2040s, rising to 5% of new vehicle sales by 2050. The use of FCEVs is expected to be concentrated in certain niche applications, for instance vans and larger SUVs where a higher range is required, or where owners need high utilisation and fast refuelling such as emergency service vehicles.

FCEVs are expected to have a higher share of the commercial market than in passenger cars, rising to 8% of new sales by 2050. FCEV uptake is expected to be concentrated in high payload HGVs, some coaches and off-road vehicles, along with some fleet vehicles where high utilisation and rapid refuelling is required. Outside of these areas, the lower costs are expected to drive consumers to BEVs, and therefore FCEVs are expected to have only a more minor uptake in buses and regional HGVs, which will predominantly take a battery electric decarbonization route.

Hydrogen vehicles may take a significant market share of the heavy-duty sectors, such as long-distance high payload HGVs and coach services where battery technology is unable to feasibly meet the performance requirements. In addition to higher energy capacity. Hydrogen vehicles can be refuelled within minutes, making them preferable for applications requiring high utilisation and fast turnaround times, for instance ambulance services.

In many applications, greater long-term potential is seen in FC rather than hydrogen ICE vehicles, however FC costs are currently high. As a result, sectors including construction and agricultural are, in the near-term, investing in hydrogen

ICE vehicles. Hybrid solutions utilising fuel cell as range extenders for BEVs may be the preferred solution in specific applications, however typically the increased cost and minimal refuelling infrastructure is expected to limit the market share for hybrid vehicles.

1.4 Aviation

Aviation is a significant contributor to emissions today, accounting for 3% of global emissions and over 20% of the UK's transport emissions (including both domestic and international travel). Aviation has long been considered a hard-to-abate sector due to its high energy demand and performance requirements. It also requires long design timelines, rapid refuelling and international coordination across its value chain.

Currently, kerosene is the main aviation fuel in use. Biomass or power-to-liquid based synthetic aviation fuels (SAF) are one technology with the potential to reduce emissions, along with the use of pure hydrogen and batteries. The use of petroleum-based aviation fuel is expected to decline to half of the energy mix by 2050. Among low-carbon fuels, biofuels will take the largest share of the total energy required at 22% of the total, with e-fuels and hydrogen following with 14% and 7% respectively. Electric aircraft will account for 5% of the UK aviation energy mix by 2050.

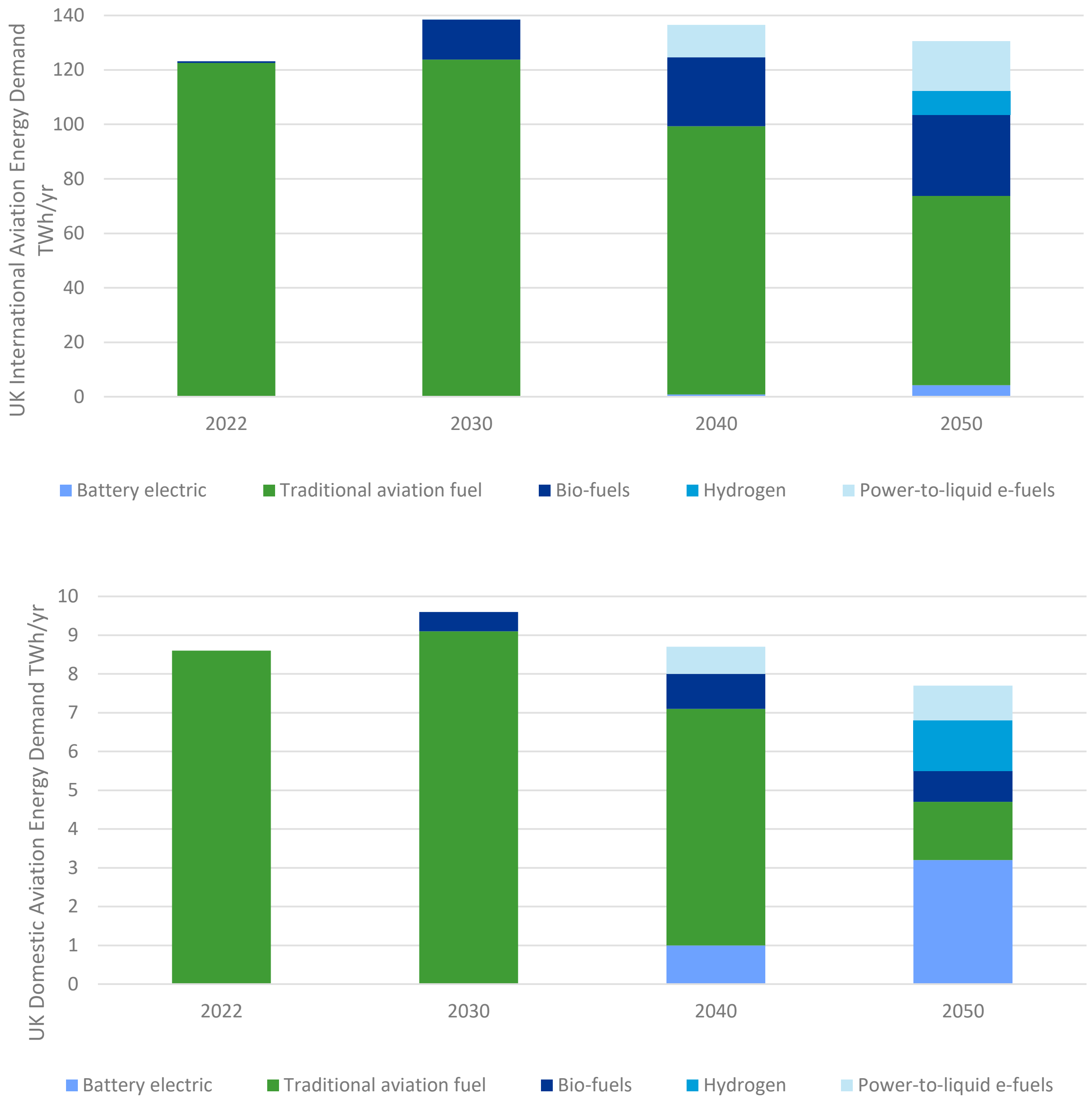

Figure 1-5 UK international and domestic aviation energy demand by energy carrier and year[106]

Battery Potential

Batteries have a lower energy density compared with liquid fuels, and with the high energy requirement for flight, the additional weight of batteries is a significant disadvantage. Nevertheless, the efficiency advantage of batteries is expected to incentivise uptake of battery electric (BE) aviation in the short haul domestic market, powering over half of flights.

Battery powered flight is expected to feature prominently over short haul distances for both general and commercial aviation, where the technology is able to offer cost savings along with reduced noise and local air pollution, with adoption starting in the mid-2030s before reaching over 7 TWh per year in 2050. For BE aircraft to take a larger share of the market, a significant improvement in battery energy density would be required, which based on the analysis today is not considered likely. Due to the greater efficiency of battery powered propulsion, and the focus of battery technology on short haul flights, the aviation market represents a large market for battery capacity, and battery powered flights will make up a significant number of the flights taken in the UK. By 2050, the proportion of person trips undertaken by BE aircraft is estimated to be over 30%. This is not including the large growth of drone aircraft which are expected to primarily be battery electric operated.

For medium and long-haul applications, pure BE aviation is not expected to be viable unless there is considerably technological advancement, however batteries may be used in a hybrid capacity together with hydrogen fuel cells. In hybrid aircraft, batteries can provide additional power during take-off, whilst the energy used for cruising is supplied by hydrogen.

Hydrogen Potential

Hydrogen has the potential to emerge as the primary technology for medium and long-haul aviation, however due to the slow rate of change in the aviation sector, it is not expected to become dominant by 2050, with other technologies such as biofuels and e-fuels retaining a larger share.

Hydrogen powered flight is not expected to develop until the 2040s due to the expected longer development time needed. However, it is expected that from the 2030s, e-fuels using low carbon hydrogen in their production, will begin to be used significantly. Initial hydrogen aircraft are expected to only serve short and medium distances due to the increased fuel tank size and changes to aircraft design needed to account for the lower volumetric energy density relative to conventional fuel. Both hydrogen jet engines and hydrogen fuel cells are expected to be used, however there is uncertainty in the eventual technology choice. DNV expect smaller aircraft to use fuel cells, potentially together with batteries in a plug-in hybrid configuration, and larger aircraft are to be powered by jet engines, which can use a range of fuels. Considering both hydrogen and hydrogen derived fuels, almost 30 TWh per year is expected to be used by 2050, representing the largest market for hydrogen.

Due to the lower energy density by volume, hydrogen aircraft will require significant design changes to accommodate the additional volume of fuel, along with the design of new safety systems to mitigate any explosion risk. Both FCs and hydrogen fuelled jet engines are expected to be used, with the latter required on longer distance flights where higher power is required to lift larger aircraft.

1.5 Maritime

The maritime industry, driven by global trade, contributes approximately 3% of global CO_2 emissions, and 8% of the UK's transport emissions today. As with aviation, the high energy capacity required makes shipping a hard-to-abate sector reliant on oil-based fuels. By the 2050s, the energy derived from oil-based fuels is expected to reduce significantly to approximately 12% of the overall energy demand from its dominant position today. The remaining energy demand is expected to be met by a combination of natural gas, BE propulsion and low-carbon fuels. The maritime market has a large range of vessels that are utilised for specific sub-markets.

Battery Potential

Battery technologies are generally high efficiency and lower cost when compared with other technologies, in addition to having low noise/vibration powertrains. Consequently, battery technology is expected to gain a significant market share in domestic shipping and short distance shipping, including on rivers and lakes, and short distance ferry routes. However, this represents a small portion of the total shipping demand and therefore only 2 TWh of energy per year is expected from electric shipping.

In addition, although not modelled specifically as a separate propulsion technology, hybrid solutions using battery power along with combustion technologies are expected to feature. Therefore, additional battery demand to that presented here can be expected from the maritime sector.

For long distance and deep-sea applications, the energy density of batteries is not expected to be high enough with current technology to allow battery only operation, however batteries are expected to be increasingly used within hybrid shipping, including plug-in hybrid propulsion systems.

Hydrogen Potential

Hydrogen is expected to play a large role in decarbonising international shipping, however not in a pure form but as ammonia and e-methanol. Both ammonia and e-methanol are expected to be cheaper to produce, store and transport than other synthetic fuels and have a higher density by volume than hydrogen. Significant development is needed before either fuel can be in widespread use, leaving some uncertainty in the final energy mix of the sector.

Pure hydrogen is not expected to play a significant role in the future energy mix for the maritime sector. Instead, hydrogen is expected to be used in the production of ammonia and e-methanol, with ammonia expected to be the largest energy source in shipping, with a share of 35% by 2050, and e-fuels including e-methanol contributing 14%. E fuels are expected to be used from 2025 onwards, however the adoption of ammonia as a fuel is expected to be later, from 2035, due to the additional development required. In total 28 TWh of energy from hydrogen derived fuels is expected per year by 2050.

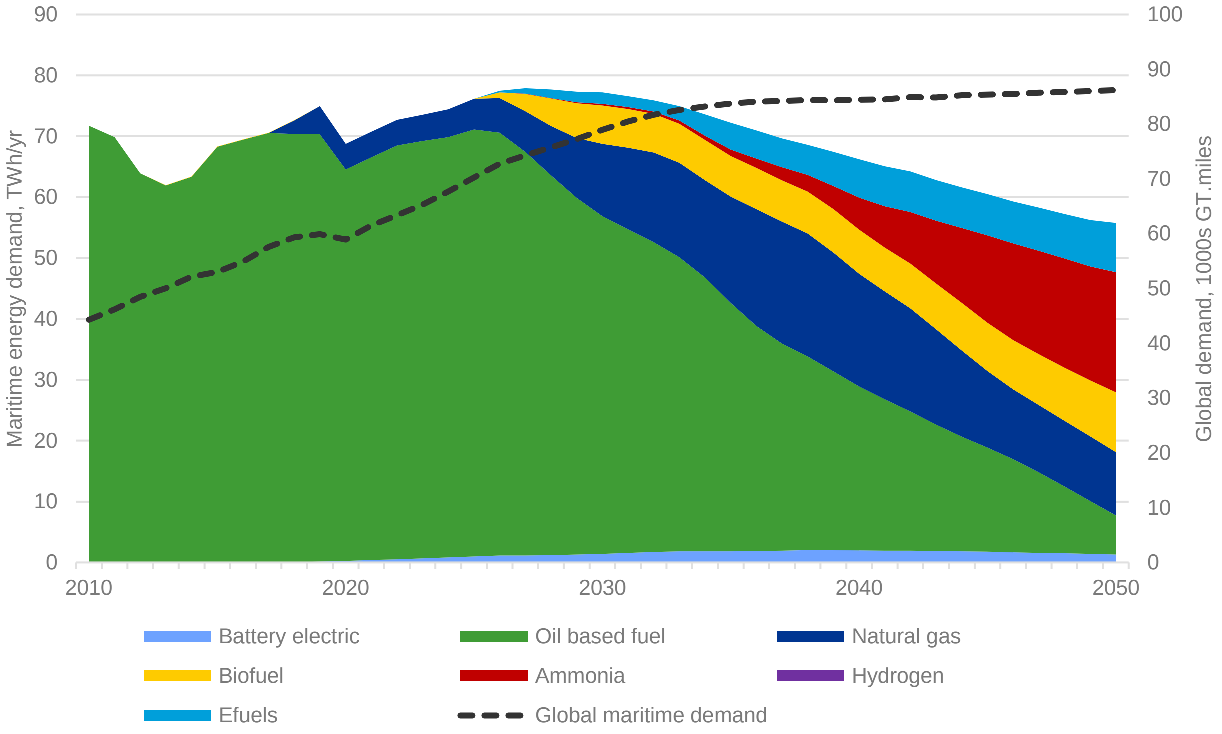

Figure 1-6 UK maritime energy demand by energy carrier, 2010 to 2050

1.6 Rail

Railways typically generate lower emissions per passenger kilometre than competing forms for mass transport. In the UK, the almost 16,000 km network contributes approximately 2% of the UK's transport emissions whilst providing 10% of the distance travelled. Currently, 62% of the UK railways are not electrified, being powered by diesel-electric trains, and the remaining 38% (accounting for over 2/3^{rds} of passenger rail use) make use of electricity via overhead catenary or third rail solutions.

The key to the decarbonisation of the railway network is an increase in electrification, achieved predominantly through the use of overhead lines. As a result, direct electrification dominates the energy use in rail, with only small contributions from BE trains from 2030 onwards, hydrogen from the mid-2030s and a small remaining contribution from diesel. The energy used per year from both BE and hydrogen trains is expected to be less than 1 TWh by 2050.

Battery Potential

Decarbonisation of the rail network is expected to largely be achieved through direct electrification of the network, with plans to electrify 85% of the unelectrified track. In locations where electrification is not possible, battery, hydrogen and hybrid solutions are expected to be utilised.

BE trains offer a higher efficiency compared with hydrogen solutions and are expected to be the preferred solution where the range and/or speed required is not prohibitively large, which must be determined for specific routes. For the widespread use of battery trains, technological and operational solutions are needed to ensure recharging times are fast enough to not restrict operation.

Hydrogen Potential

The use of hydrogen for rail is equally expected only where electrification of the lines is not possible. Hydrogen has advantages over batteries when travelling longer distances, with higher energy density and faster refuelling times. In addition, where the train is operating in remote areas with limited capacity on the electricity grid, installing dedicated refuelling infrastructure may be easier than reinforcing the grid. The share of hydrogen and batteries for rail's yearly energy demand is expected to be similar through to 2050.

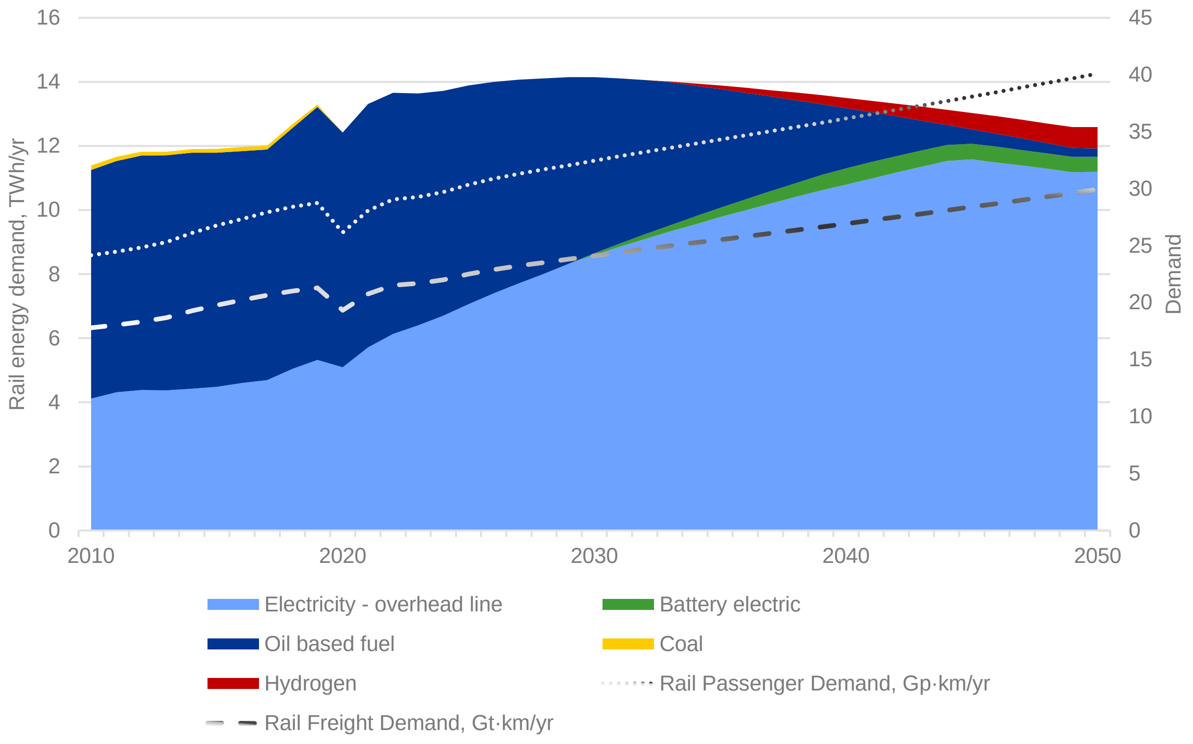

Figure 1-7 Graph showing UK energy demand by different energy carriers in rail along with passenger and freight demand (right axis), from 2010 to 2050 (Gt = Giga tonnes, Gp = Giga passenger)

1.7 Power sector

Electricity generation is a vital part of the energy system, contributing 19% of the final energy demand in the UK and 15.8% of all CO_2 emissions in 2021. Through the rapid expansion of renewable based electricity generation, the GHG emissions of the power sector have decreased rapidly in recent years. However, the increasing share of renewables in the future creates challenges for the network, such as matching supply and demand and ensuring grid stability. Today, the ability to balance the network and ensure stability of the grid is largely achieved through large thermal generation plants, with natural gas supplying a large proportion of the energy whilst being able to quickly ramp up or down its output. Traditionally pumped hydropower has been the principal technology used for short term energy storage.

Battery and hydrogen technology are considered to be complementary technologies in providing energy storage within the power sector, and do not compete directly with one another. Batteries are used extensively within short-term storage, and hydrogen is key potential technology for longer-term seasonal storage.

Battery Potential

As the scale of renewables on the grid increases, along with an increased electricity demand driven by the electrification of different sectors, the requirement for flexibility on the grid will increase.

Battery Energy Storage Systems (BESS) have become a leading provider of grid ancillary services and short-term balancing, and this is expected to continue in the next three decades. Due to the current cost of batteries, BESS are limited in the energy capacity they hold, and typically store up to four hours of energy. As next generation battery technologies are developed, with the potential for further cost reductions, the economic feasibility of longer 8 to 12 hours duration BESS may improve. In addition, flow batteries have the potential to provide energy storage with durations of up to 24 hours, although they currently face a scaling challenge. Utility scale BESS is forecasted by DNV to increase to 24 GW by 2050, with average energy duration of BESS modelled to increase from one hour today to almost four hours by 2050, with an expected energy storage capacity of 190 GWh by 2050 of dedicated BESS and co-located BESS with solar PV, in addition to some other storage technologies. The potential for seasonal storage, with multiple days of energy storage, is not considered viable for current battery technologies.

Vehicle-to-grid (V2G) energy storage is also modelled to play a significant role in providing energy storage, with 45 GW of capacity expected in 2050 based on the availability of 10% of the BEV fleet. This however requires behavioural change from vehicle owners to participate in smart charging that allows the electricity grid to draw from their vehicle batteries.

In addition to the use of around 90 GWh of batteries as dedicated energy storage facilities, 20% of solar PV generation is expected to include batteries in a behind-the-meter configuration to shift the supply of energy away from the solar generation cycle to periods of higher demand. This amounts to a further 93 GWh of battery capacity in 2050.

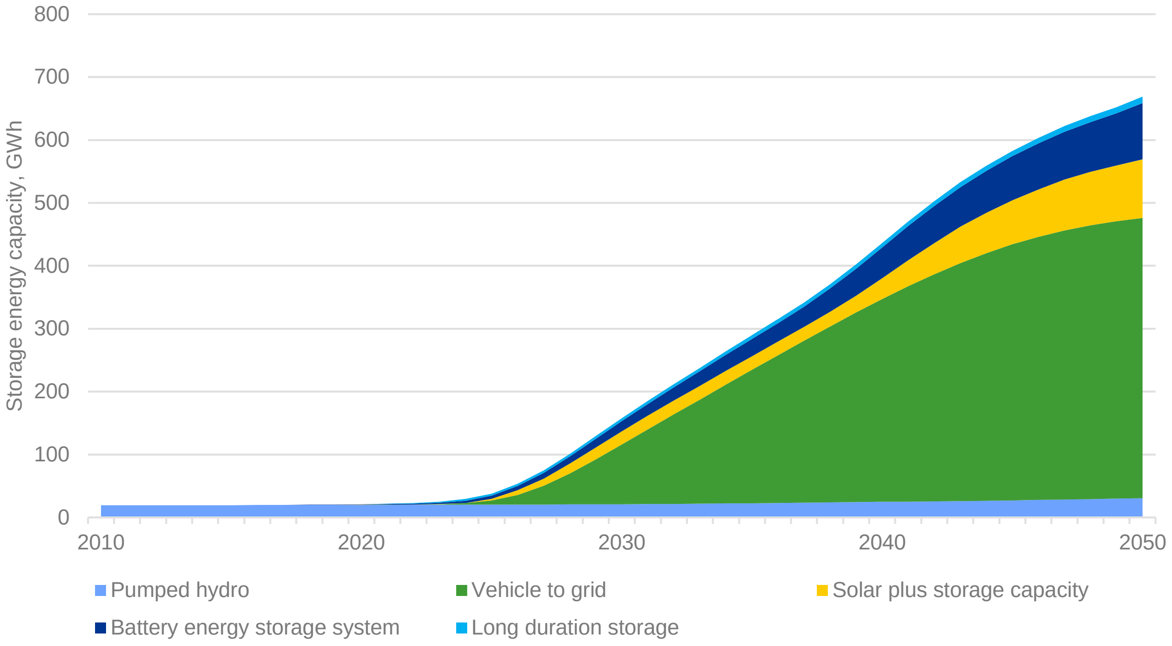

Figure 1-8 UK storage capacity by storage type, up to 2050[106]

Hydrogen Potential

Hydrogen today has only a limited role in the power sector, however as a potential form of low carbon dispatchable generation, this is expected to increase in the coming decades. Hydrogen can be used as a form of seasonal storage by using excess renewable generation in electrolysers, storing compressed hydrogen in underground salt caverns, and converting the hydrogen back to electricity when demand is high. Due to the inefficiencies involved in this process, and the competing demands for low carbon hydrogen, a high price differential will be needed between the cost of energy used to create hydrogen, and the price of energy generated by hydrogen, for hydrogen storage to be used in this way.

Hydrogen's involvement in the power sector is dominated by the production of hydrogen, the majority of which will be via electrolysis, which is modelled to use 63 TWh of electricity by 2050. This is significantly higher than the electricity generated from hydrogen which peaks at approximately 2.3 TWh in 2039. Hydrogen is expected to have multiple applications within manufacturing and for the production of e-fuels, and therefore a higher ratio of hydrogen produced to used is expected. Nevertheless, within the ETO model, hydrogen is converted to electricity within gas fired power stations as a blended fuel, which limits the level with which it can be used. Should sufficient demand for electricity generation from hydrogen exist, it is considered that dedicated hydrogen power stations may be built or gas power stations retrofitted, allowing more hydrogen storage to be used in electricity generation.

1.8 Manufacturing

The energy requirement within industry is high and contributed to 25% of UK emissions and 16% of energy consumption in 2019. Natural gas and electricity currently provide the majority of the energy consumed, with approximately 39% and 34% of energy demand respectively in 2019. Within industry, the greatest demand for energy is for high temperature heat and the operation of machinery. Space heating is generally a much lower energy demand.

Battery Potential

The decarbonisation of industry is expected to be achieved in part through greater electrification, however the demand for battery technology is not expected to be high. Battery technology is not expected to have significant use within manufacturing aside behind the meter solar PV applications which are captured within the power sector.

Where businesses invest in their own electricity generation, through solar PV or wind, batteries may be utilised to balance supply and demand and increase the proportion of self-generation used. Batteries will also be used increasingly for back-up power, but there are cost penalties associated with maintaining battery condition over time.

Hydrogen Potential

For the provision of high temperature heat, the use of electricity is challenging, and therefore hydrogen, as a replacement for natural gas, is expected to play the leading role in the decarbonisation of industry. Hydrogen will also be used extensively as a feedstock for different processes, as it is today. With an existing hydrogen infrastructure, the use of hydrogen to provide heat will require fewer modifications to existing plants, further enabling hydrogen's use. Hydrogen is expected to provide 26 TWh of energy per year by 2050, with the vast majority of this (95%) used for high temperature industrial heat production in place of natural gas as is used today.

1.9 Built Environment

Residential and commercial buildings contribute a significant part of the UK's GHG emissions, with housing accounting for 21% of emissions alone. The principal demand for energy is for both water and space heating, in addition to the powering of appliances. Approximately 85% of UK homes are connected to the gas network and therefore use natural gas for heating and cooking, with the remainder mostly being provided by electricity or "off grid" solutions such as oil. The route to decarbonisation of heating within the built environment through either electrification or hydrogen will predominantly be led by government policy, given the large change to national infrastructure that will be required.

Battery Potential

Battery technology is not expected to have significant use in commercial and residential buildings, and the demand for batteries related to heating is expected to be limited. However, batteries will be an essential component of solar PV systems, as domestic homeowners seek to provide resilience at the home level for electrical power supply. Battery systems could be used in conjunction with renewable generation for off-grid energy systems, and from BEVs through vehicle-to-grid (V2G) capabilities. Removal of Feed in Tariffs in the UK has encouraged the deployment of batteries at the domestic level.

Hydrogen Potential

Hydrogen has a potential for use within the home, making use of the existing gas infrastructure to provide space and water heating. There are significant challenges for the conversion to hydrogen use, along with the high cost of low carbon hydrogen production. Battery technology is however not considered to be a direct competitor to hydrogen for this purpose, with competition instead coming from the use of heat pumps.

Hydrogen has a more limited role within the built environment, based on current policies, providing only 4 TWh or 1% of the energy used per year by 2050. The DNV ETO model still forecasts a significant need for natural gas in domestic heating in 2050, due to the cost differential between natural gas and hydrogen, and the high cost of heat pumps. Though some use of hydrogen within the gas network is expected through blending with natural gas, it is expected that the remainder of the long-term energy for heating will be supplied by electrification and the use of heat pumps.

1.10 Challenges for the UK Battery and Hydrogen Markets

Capacity

Although technical challenges remain and developments for both technologies are required, the largest challenge will be the rapid deployment required to achieve the predicted future demand. Achieving this and the resulting societal and environmental benefits will require collaboration between all stakeholders concerned: government, industry, research institutions and the public.

In the case of battery technology, the required installed capacity of batteries is presented in Figure 1-9, showing a steady increase to 4,500 GWh in 2050 from a very low level today. The challenge of meeting the scale of demand is significant and will require developments in battery manufacturing and recycling, along with performance and cost improvements through the consideration of new chemistries.

Similarly, the biggest challenge for hydrogen is to supply the volumes necessary, and to do so in a relatively low-carbon manner that aligns with the goals of net zero. Green and blue hydrogen are crucial for the UK to meet its commitment to the Paris Agreement goals as they are expected to be key for hard-to-abate sectors. Significant energy will be required for hydrogen production and the energy losses associated with converting it to electricity or in other applications, in addition to being generally more energy intensive to store and transport compared to conventional fuels. Demand is forecasted in DNV's UK ETO to increase from around 0.5 Mth_2/yr in 2020, to 3.8 Mth_2/yr in 2050.

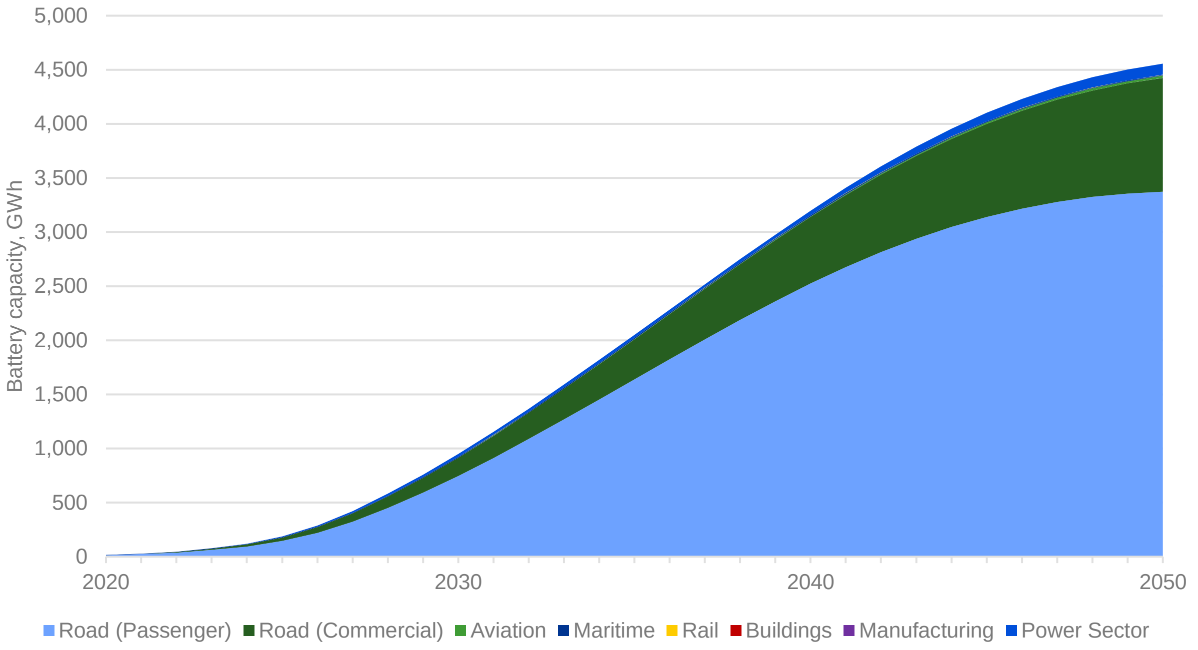

Figure 1-9 Graph showing installed battery capacity across all sectors, 2010 to 2050[111]

Market issues

The rapid expansion of battery technology through the energy transition has significant implications for the industry. The greatest demand for batteries is expected to come from the transport sector, which will therefore drive development. The main challenges for the industry are considered to be energy density improvements, battery cost reduction, supply chain capability and infrastructure deployment. For the power sector, energy density improvements and infrastructure deployment are not significant considerations, however supply chain capability will be important, and cost reductions will be needed to enable battery energy storage systems (BESS) to compete with longer duration storage technologies such as hydrogen, liquid air and compressed air energy storage.

The analysis of the power sector also has implications for the battery industry and its future development. It is useful to recognise that batteries are already very strong technically and provide the most competitive solution for grid stability and short-term balancing services. BESS are therefore expected to dominate the provision of these services without significant competition from other technologies, including hydrogen.

Hydrogen has low initial uptake due to lack of supply meaning the cost of hydrogen is relatively high compared to natural gas, and the lack of certainty and commitment of government policy over the use of hydrogen in heating homes. The main areas of demand of hydrogen by 2050 are transport, specifically aviation and shipping, where hydrogen-based fuels are expected to be used, initially as blended fuels with conventional fuel types in the 2030s, and then greater uptake in the 2040s. Production of blue hydrogen is expected to ramp up into the late 2020s, displacing existing grey hydrogen in industrial clusters, however this depends on the investment and success of Carbon Capture Utilisation and

Storage (CCUS). Policy and business model commitment and implementation is required for hydrogen value chains to develop towards 2050 due to the large-scale investments necessary for hydrogen production, storage, transport and use. Hydrogen is a versatile fuel, in that it can be used in a pure and blended form and converted into derivatives, which allows it to be used across a number of sectors; however, without the necessary policies the UK hydrogen market will struggle to develop. A key finding of DNV's hydrogen forecasts is that hydrogen is likely to satisfy only 5% of global energy demand by 2050 — which is two thirds less than it should be in a net zero pathway. Policies are needed globally to push hydrogen to levels required to meet the Paris Agreement. The forecast did show that European countries, including the UK, have higher proportions with hydrogen likely to be 11% of the overall energy mix by 2050.

Energy Density

The main technical weakness of battery technology, particularly in high energy capacity situations, is its energy density, which is lower than fuel-based propulsion systems. Due to the significant improvements in battery technology over the past decade, an increasing number of vehicle classes are now able to utilise batteries. For sectors such as aviation, to achieve the market share modelled here, a significant further increase in energy density is required. Though energy density of current lithium-ion batteries can be further improved, a step change in density is expected to require next generation battery technologies such as solid-state batteries.

Incremental energy density improvements for batteries can be achieved with current cell chemistries, however a step change in energy density is expected to require next generation battery technologies such as solid-state or lithium-sulphur batteries to be commercialised. Energy density improvement is particularly important for the aviation industry; however the improvement will benefit all sectors.

As explained in this report, hydrogen can be an energy dense fuel that is versatile in how it is used with other fuels and applications. Therefore, hydrogen is seen as a crucial player in decarbonising hard-to-abate sectors that require a dense energy source, such as aviation and shipping. Hydrogen can aid these sectors as it can be produced with electricity generated by renewable energy sources, and be blended with conventional fuels where necessary, therefore reducing greenhouse gas emissions as the sectors transition to new technologies. However, the storage and transport of hydrogen-based fuels can be energy intensive and will require further development in technology and manufacturing for its use, in addition to regulating and implementing its safe application across sectors.

Cost

A second key enabler for both technologies is the decrease in costs over time. Battery costs are expected to fall significantly, halving in the next decade before a more gradual decrease to 2050, however significant work within the industry is needed to achieve this. Similarly, cost of hydrogen production is expected to fall as investment increases, where globally, green hydrogen is forecasted to reach cost parity with blue hydrogen in the next decade, and grid-based electrolysis costs are expected to average at 1.5 USD/kg. Cost reductions are also needed to instil investor confidence and enable more sectors to adopt both technologies in applications ignored thus far. This report does not consider the pathway to achieve the expected cost reductions, which are expected to come from various avenues including improvements in manufacturing, materials, and supply chains. Development in both industries and adjacent sectors is required to map these advancements and ensure the reductions are achieved.

Infrastructure

Charging technology and infrastructure are key enablers for BE transport and both the build-out of public recharging points for electric vehicles and dedicated recharging solutions for the aviation, shipping and rail sectors are needed.

Within the analysis of this report, there are a number of assumptions which underpin the significant market share. Both the build-out of public recharging points for electric vehicles, and dedicated recharging solutions for the aviation, shipping and rail sectors, are needed. Particularly in the case of aviation, shipping and rail, the ability to rapidly charge batteries within the operational schedule available is considered a key requirement. Rapid chargers today are available for numerous applications and delivering the high charging power required will need new procedures and safety systems to ensure this can be done affordably, reliably, and across large fleets of vehicles.

Hydrogen based infrastructure is perhaps a greater challenge when compared to BE applications, due to the broad development of new technologies and scale that is necessary for a range of sectors. This is applicable for the production of hydrogen, with limited production thus far in blue and green hydrogen, in addition to the storage capacities that are to be required for the increasing demand. Moreover, there is infrastructure uncertainty regarding how hydrogen and its derivatives are going to be safely transported and integrated into new applications and systems, many of which are yet to be developed themselves. Hydrogen's role is also expected to be heavily involved in global sectors, such as aviation and shipping, which require considerable collaboration to align infrastructure, regulations and procedures across the global hydrogen value chain.

Grid reinforcement and longer-term storage

It is expected that in some applications, stationary energy storage will be required to lower the grid capacity demand from charging, yet still provide the required peak power.

To accommodate this increased demand, the ability of the grid to supply the required power will need development which may have significant cost implications. It is expected that in some regions, particularly where the electricity grid is not as strong, stationary energy storage will be required to lower the grid capacity demand of a charger yet still provide the required peak power, effectively smoothing the power delivery. Furthermore, smart charging technology can be used to ensure vehicles are able to charge yet avoid times of peak load on the electricity grid. Finally, with such a high delivery of power, the batteries themselves will require development to ensure the rapid charging is not significantly detrimental to the health of the cells.

Battery technology will need to focus on longer duration storage if it is to increase its share of the utility scale energy storage market. At present, the limiting factor for the energy duration of battery storage installations is the cost of storage per MWh. Therefore, cost reduction will enable batteries to compete against technologies such as compressed air and liquid air energy storage in new markets where greater levels of energy storage are needed. These technologies may include flow batteries, or new chemistries that use cheaper materials such as sodium-ion batteries.

The production of hydrogen will require a large amount of electricity, reaching 72 TWh per year in 2050, which may require regional grid reinforcements and also involve long-term storage facilities of hydrogen. Hydrogen's role in the UK is expected to be focused on heating, manufacturing, and hard to abate transport sectors like aviation and maritime, but it can provide grid flexibility as a load, producing hydrogen when electricity supply exceeds demand, up to 20% of the required system flexibility by 2050. Stored hydrogen could be used to generate electricity, especially if heating is electrified as a large amount of dispatchable power will be necessary, however annual demand for hydrogen from other markets such as efuels and manufacturing are expected to be greater.

Supply chain

The implication from the rapid electrification of transport is the volume of batteries required and the supply chain needed to meet this demand. In the 2030s, over 200,000 MWh of batteries will be added to the UK market each year from passenger and commercial vehicles alone, which is considerably more than the total battery capacity of the UK today. Additionally, the use of materials with a lower environmental and social impact is an important related goal for the industry, along with the infrastructure needed to process and recycle used batteries reaching their end-of-life.

Developing the supply chain to meet this demand is a significant challenge, with lead times for BEV purchases currently approaching 12 months. Additionally, the use of materials with a lower environmental and social impact is an important and related goal for the industry, along with the infrastructure needed to process and recycle the used batteries reaching their end-of-life.

As in the transport sector, ensuring the supply chain is able to meet demand for the power sector will be a challenge. Today the battery technology employed in grid connected storage and transport is very similar, however as the markets develop, it may be that the two strands diverge to better represent their specific requirements, particularly in terms of energy density. Due to the dominance of the automotive sector, it may be advantageous for stationary storage applications to find alternative supply chains and technology variants that aren’t dominated by electric vehicles.

Continued innovation

A continual challenge that the energy transition must face and must be considered by industry is that of technology obsolescence. This impacts all sectors of the transition, undermining investor confidence and increasing supply chain risks. Investors require reassurance that they are not investing in “stranded assets” that will lose value in a short space of time, and the supply chain faces the challenge of maintaining competitiveness when faced both with the constant innovation and the threat of disruptive technologies. This is expected to be a major challenge impacting the pace and effectiveness of the energy transition. Technologies will require research and investment to answer fundamental questions of performance, application, and sourcing, whilst needing continued support through technology readiness levels (TRL) to scale up with sustainable infrastructure that enables commercialisation in a completive and dynamic space.

2 INTRODUCTION

As the world embarks upon the transition to a low carbon future, many technological solutions are being considered. The energy transition is not a single transition from one solution to another, but a series of transitions occurring over the next decades that will be characterised by frequent changes to policy, regulations, technology and human behaviour. A wide range of technology options are available to society, and these are being developed and reviewed by both industry and government, in order to find the optimum solutions that provide a reliable, safe and affordable energy system. As the UK has a legal obligation to reach net zero by 2050, the move away from fossil fuels is gaining momentum and numerous studies have been presented showing scenarios and forecasts for the future energy system make-up. However, the DNV UK Energy Transition Outlook (ETO), currently forecasts that the UK will not meet its Net Zero goals for a wide range of factors including government policy, regulation and technology deployment, as well as the required investment not in place; more of the challenges and barriers can be found in the ETO and this report.

A consistent factor in all future energy scenarios is the significant increase in electricity required, and the rapid growth of hydrogen as an energy carrier. With the increased electrification of society, and the increased share of that electricity being provided by variable renewable energy sources such as wind and solar power, the requirement for additional resilience and energy storage is apparent. To meet this need, battery technologies and hydrogen are two technologies expected to play an ever-increasing role. This study looks to compare the use of hydrogen and battery technology across the UK economy, understanding where they are in competition, where one technology will dominate, and where both may be used in a hybrid solution.

As a leading consultancy working across the energy industry, DNV has unique insight on the energy transition and the technologies that will emerge to meet our future energy needs. Utilising experience in the energy storage market, the hydrogen economy and electric vehicles, along with the extensive modelling capability as part of DNV’s ETO, DNV has provided a forecast for the size of the future battery and hydrogen markets; by sector, in the UK, and commented on the key technological developments needed. The results can be used by the Faraday Institution and others in the industry to direct research and development activities to accelerate the transition more effectively to net zero.

The report is based on the modelling undertaken in DNV’s ETO along with DNV’s qualitative analysis of the various technologies. It is noted that this analysis presents DNV’s best estimate of the future battery and hydrogen market size, but there is significant uncertainty in the results particularly due to uncertainty in policy and regulatory developments. DNV’s ETO, and modelling used in the study, is summarised in Section 2.2 along with a brief description of the UK policy framework in Section 2.1.

This report includes an overview of battery and hydrogen technology, presented in Section 3, a review of the Transport, Industry, Built Environment and Power sectors in Sections 4 to 7, and a summary of DNV’s expectations for the battery and hydrogen markets in Section 8. The sectors and subsectors considered in this report are outlined in the schematic below.

Table 2-1 Schematic showing the sectors and subsectors analysed within this report

Sector	Sub-sector	Section number
Road transport	Passenger vehicles	4.1
	2-wheelers	4.2
	Light duty vehicles	4.3
	Heavy good vehicles	4.4
	Buses and Coaches	4.5
	Off road vehicles	4.6
Other transport	Aviation	5.1
	Maritime	5.2
	Rail	5.3
Power sector		6
Manufacturing		7.1
Built environment		7.2

2.1 UK Government Policy

An important influence on the future energy transition in the UK is the policy choices made by the UK and devolved Governments. These decisions have the potential to rapidly increase the development and adoption of a certain technology by giving manufacturers and investors incentives, confidence and regulatory certainty to develop a particular solution. Clarity and consistency from Government is therefore crucial to investor and industry confidence. The current key government policies and targets include those presented in the following figure.

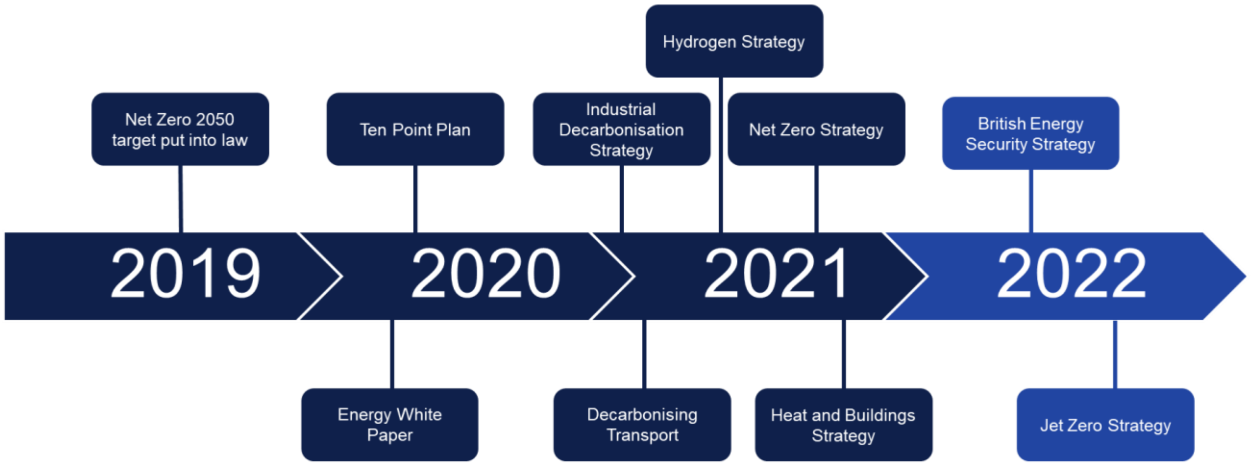

Figure 2-1 Key UK Government policies for decarbonisation

The overarching policy driving the energy transition in the UK is to achieve Net Zero by 2050. It is part of the Climate Change Act 2008, which established the UK government’s responsibility and framework to reduce carbon dioxide and other greenhouse gases. The 2050 target was announced in 2019 and commits the UK government by law to reducing greenhouse gas emission by at least 100% of 1990 levels (net zero) by 2050.

To achieve this target, the UK Government set out its Net Zero Strategy in 2021, developed from its Ten Point Plan for a Green Industrial Revolution. The Net Zero Strategy details the UK's journey to reach net zero by reducing emissions across the economy, and outlines how the transition will be supported. It presents the path the UK Government intends to take to meet its Sixth Carbon Budget (2033 – 2037) and 2030 Nationally Determined Contribution. The target is for the whole of the UK; however, each nation will experience a different transition and therefore each nation has their own target pathway up to net zero.

As well as the Net Zero Strategy, the UK Government have also published multiple strategies outlining the proposed path to decarbonisation for different sectors of the UK: Industrial Decarbonisation (2021), Decarbonising Transport (2021), Heat and Buildings (2021) and Jet Zero (2022). Specific policy and decisions directly affecting the future market potential of both hydrogen and batteries include:

- The sale of new petrol or diesel cars and vans will end in the UK from 2030 onwards, and from 2035 all new cars and vans must be fully zero emission at the tailpipe – Decarbonising Transport Strategy (2021)
- The government is currently assessing different options for the supply of heat to UK homes. In the Heat and Buildings (2021) strategy they have set a deadline of 2026 to make a number of decisions, including the use of hydrogen for domestic heating.

The UK Hydrogen Strategy was published in 2021, outlining an ambition of 5 GW of low carbon hydrogen production capacity by 2030. Following increasing global energy costs and the Russian invasion of Ukraine, the UK Government published their British Energy Security Strategy (2022) setting out the plan to reduce dependence on energy imports. This included an increased ambition of 10 GW of low carbon hydrogen production by 2030, with half of this from electrolytic (green) hydrogen[2].

2.2 The DNV Energy Transition Outlook (ETO)

The projection of the future demand for batteries and hydrogen in the UK presented in this report is based on the DNV Energy Transition Outlook (ETO) UK model. The ETO is an integrated system-dynamics simulation model that reflects relationships between energy demand and supply in several interconnected modules. Each sector of the energy system is modelled for the entire world, representing:

- Final energy demand (buildings, manufacturing, transport, non-energy, and other)
- Energy supply (renewables, nuclear, coal, gas, and oil production)
- Transformations (power generation, oil refineries, hydrogen production, biomethane production)
- Other relevant developments (economy, grids, pipelines, CCUS, energy markets, trade volumes, emissions)

These modules exchange information regarding demand, cost, trade volumes, and other parameters to provide a coherent forecast of the energy system transformation to 2050. The inputs to the models, and the models themselves, are based on the latest datasets available internally and externally to DNV. The figure below presents our model framework.. Policy influences all aspects of the energy system. Energy-efficiency improvements in extraction, conversion, and end use are cornerstones of the energy transition. Further details on the underlying models and principles behind the ETO can be found by downloading the ETO for 2022 here: Energy Transition Outlook - DNV.

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[2] British Energy Security Strategy, HM Government, 2022

For 2022, DNV has produced a UK specific outlook within the ETO framework to give a more focused prediction of the transition from a UK perspective. This considers the energy and material flows impacting the UK, the influence of UK policy, the relative size of the sectors of the UK economy, and the energy mix we see today.

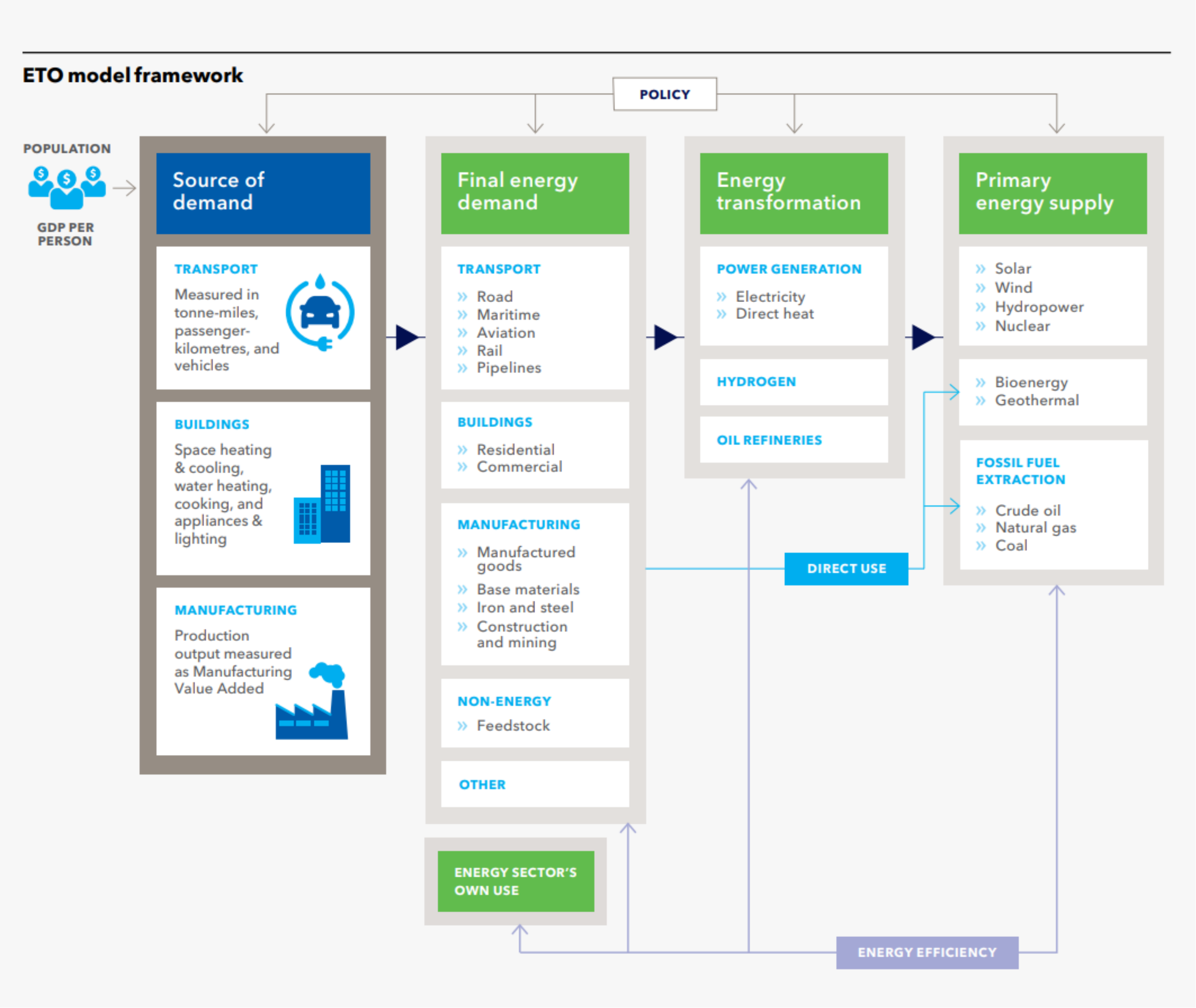

Figure 2-2 DNV ETO Model Framework

In 2022, DNV also issued a specific Hydrogen Forecast[3], based on the ETO model. A key finding of this forecast is that hydrogen is likely to satisfy just 5% of global energy demand by 2050 — two thirds less than it should be in a net zero pathway. Clearly, much stronger policies are needed globally to push hydrogen to levels required to meet the Paris Agreement. In European countries, where gas infrastructure is already widespread, which includes the UK, the forecast did show higher proportions with hydrogen likely to be 11% of the overall energy mix by 2050.

Five percent globally in the forecast, whilst insufficient for a net zero trajectory, still translates into a significant quantity of more than 200 million tonnes of hydrogen required as an energy carrier. One fifth of this amount is ammonia, a further fifth comprises e-fuels like e-methanol and clean aviation fuel, with the remainder being pure hydrogen.

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[3] Hydrogen Forecast to 2050, DNV, 2022

2.2.1 Energy Carriers

The energy carriers used in this analysis are described below. Among the 10 energy carriers that are modelled, seven are also primary energy sources, i.e., they can be used without any conversion or transformation process. The others are secondary forms of energy obtained from primary sources.

Primary energy sources are:

- coal (including peat and derived fuels),
- oil,
- natural gas (including methane, ethane, propane, butane and biomethane),
- geothermal,
- bioenergy (including wood, charcoal, waste, biogases, and biofuels),
- solar thermal (thermal energy from solar water heaters),
- off-grid PV (electricity from solar panels not connected to the grid).

Secondary energy sources are:

- electricity,
- direct heat (thermal energy produced by power stations),
- hydrogen.

3 TECHNOLOGY COMPARISON

Hydrogen and batteries have been commercially available for many years in a range of applications and markets; however, a significant increase in development in recent years, along with the need for low carbon solutions, has increased their potential in the energy system. Further research and development in existing and new markets is driving technological advancements which are expected to continue and accelerate in the coming years.

As outlined, this study is focused on the areas where energy storage is needed, and how batteries and hydrogen may provide this service. Therefore, not all applications are considered, for instance the burning of hydrogen in a boiler for heat production.

Key characteristics of battery and hydrogen technology are presented in Appendix A, showing the fundamentals of their operation along with their potential next generation developments. The comparison presented in this section broadly considers lithium-ion batteries and a generalised consideration of hydrogen-based energy storage technologies. Due to significant variation depending on the specific application, the general comparisons here are expanded upon within Sections 4 to 7 as required.

The performance requirements of energy storage technologies will vary considerably between applications and the price considerations of the user. Key general performance parameters to be considered include specific energy and energy density, energy capacity, charging and discharging rates, cycle life, round trip efficiency (RTE), cost, and the materials used. This section provides an overview of what is important when considering a technology, and some examples of how current technologies compare, and how it is considered in certain use cases and technology fields. The importance of different technical parameters will change depending on the application (e.g., HGV versus a passenger vehicle), in addition to the general demands of a market (e.g., aviation has greater technical demands than grid scale energy storage). Such technical considerations must ultimately factor the cost of production and operation, as well as the sustainability of the materials and supply chain.

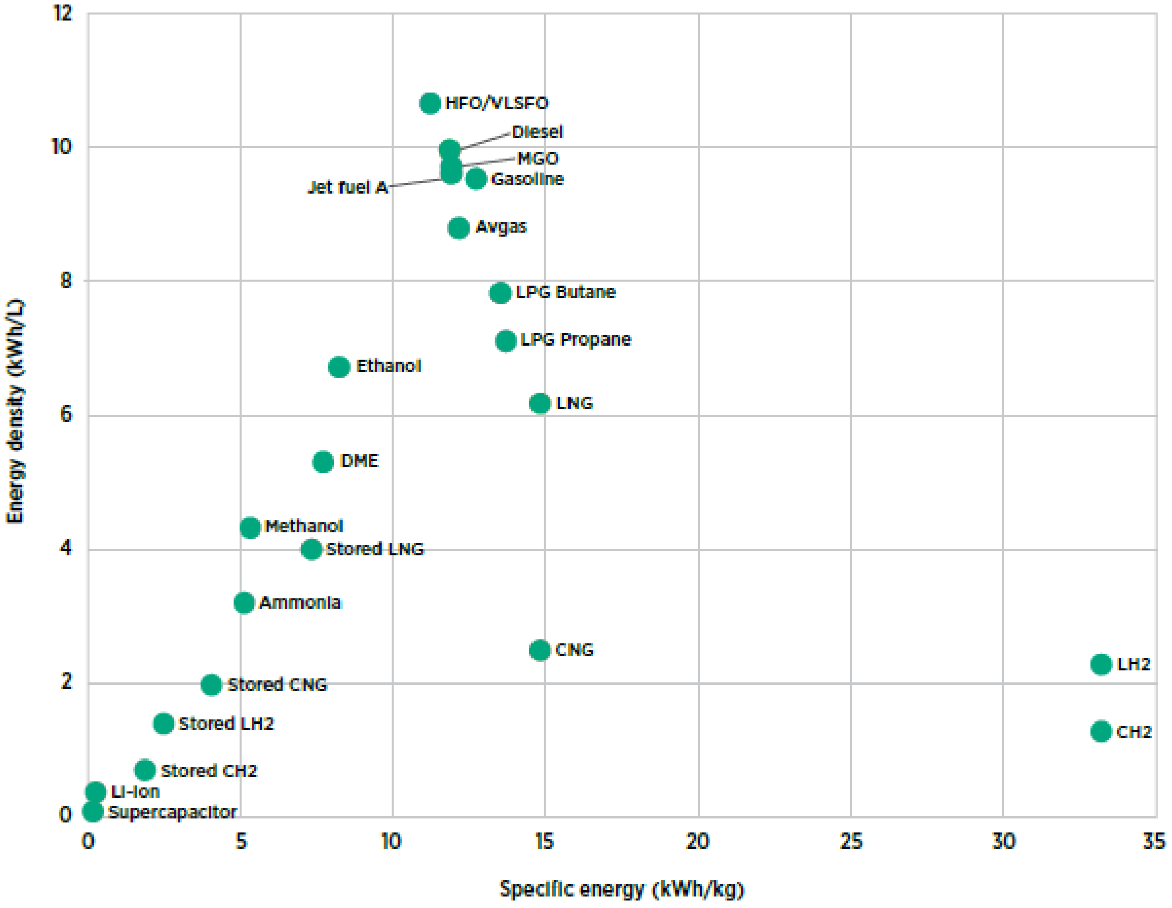
3.1 Specific Energy and Energy Density

Specific energy (Wh/kg) and energy density (Wh/L) provide a value of the amount of energy a battery contains in proportion to its mass and volume respectively. The relationship of these properties can constrain the use-cases of a technology if size or weight are a significant deciding factor. Low energy density tends to mean that larger system volumes and footprints are required to achieve a given energy capacity or power capability; whereas low specific energy means that to achieve a given energy usage the weight of the system increases.

Lithium-ion cells have a specific energy of around 160-275 Wh/kg depending on the chemistry, compared to liquified hydrogen which has a specific energy of around 34,000 Wh/kg (excluding the associated equipment). Even once accounting for the conversion equipment needed, this shows that the use of hydrogen can make an application significantly lighter, which is a key consideration of transport applications (Section 4), but less so for stationary storage installations (Section 6).

Generally, higher specific energy and energy density values are favourable and desired, although not necessarily required for all applications. However, reaching higher values can also have less desirable consequences, such as in the case of NMC cells for lithium-ion batteries which require complex thermal management systems; or in the case of liquefied and compressed hydrogen which require cryogenic temperatures or pressurised containers respectively. This is a consideration for the design of products as higher value energy storage mediums may require greater space or additional equipment to appropriately handle the increased thermal management requirements.

The graph below illustrates the specific energy and energy density of different energy storage mediums. It is clear that at present, the values of liquids are generally higher than batteries and that there is a considerable range available.



Notes: Avgas = aviation gasoline; CH2 = hydrogen compressed at 70 MPa; CNG = natural gas compressed at 25 MPa; DME = dimethyl ether; HFO/VLSFO = heavy fuel oil/very low sulphur fuel oil; LH2 = liquefied hydrogen; Li-ion = lithium-ion battery; LNG = liquefied natural gas; LPG = liquefied petroleum gas; Stored CNG = Type IV tank at 250 bar; Stored CH2 = best available CH2 tanks at 70 MPa; Stored LH2 = current small-scale LH2 on-board tanks; Stored LNG = small-scale storage at cryogenic conditions; MGO = maritime gasoil. Numbers are expressed on a lower heating value (LHV) basis. Weight of the storage equipment is included.
Sources: Energy Transition Commission (2021a); Hurskainen (2019); IEA H2 TCP (2021); Philibert (2020); Royal Society (2020).

Figure 3-1 Energy density and specific energy for various fuels and energy storage systems (IRENA, 2022)

3.2 Energy Capacity and Discharge Time

The suitability of a technology for an application is heavily influenced by the storage capacity and discharge time. For a given power level, the greater the energy storage capacity, the longer the discharge duration is. A graphical comparison between the characteristic energy capacity and discharge time is shown in Figure 3-2. Due to the rapid technological development and the high degree of flexibility available to Li-ion batteries, projects today are being developed with energy capacities of 100s of MWh and discharge times of 1 to 4 hours. Nevertheless, batteries, whether in consumer electronics, electric vehicles or as utility scale storage installations, are typically designed to operate over a period of hours, therefore, have a lower energy capacity than longer-term storage solutions, such as hydrogen which can discharge over multiple days if required. A typical BEV for example can store around 50 kWh of energy using cells with a specific energy of 250 Wh/kg. This means the battery would weigh around 200 kg and provide a range of around 200 miles (at an energy consumption of 250 Wh per mile).

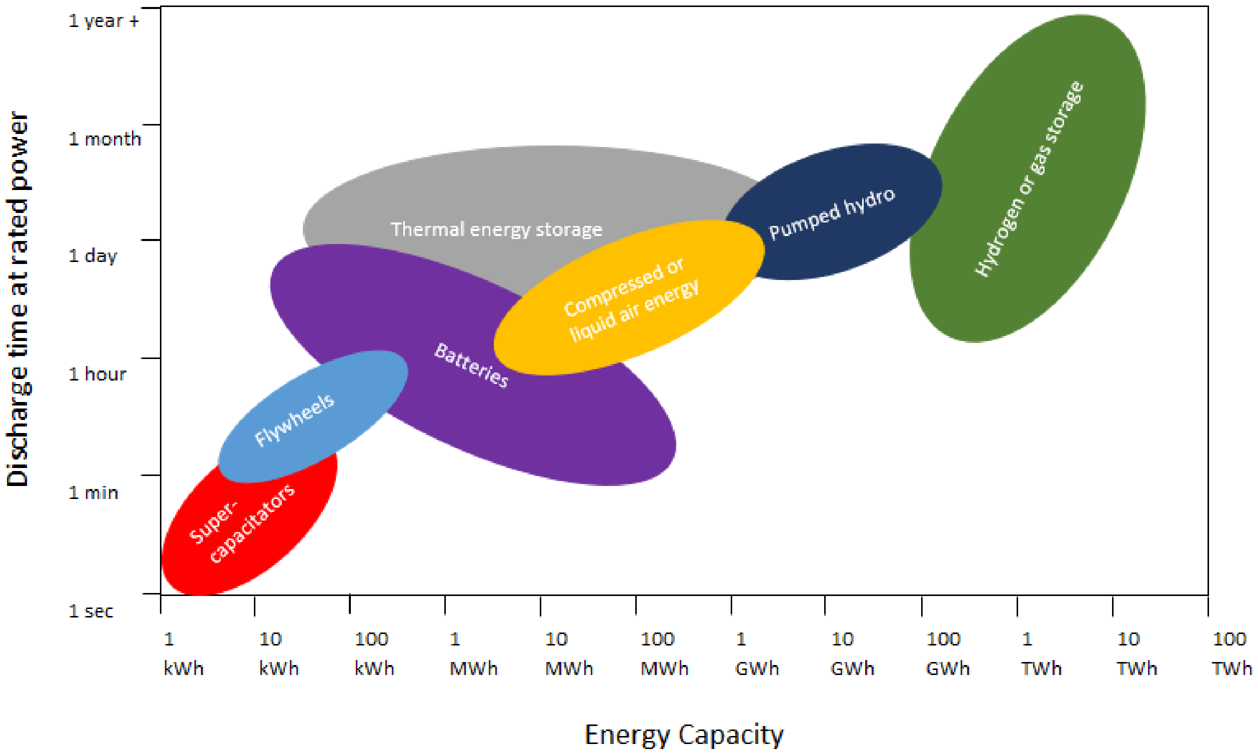


Figure 3-2 Typical energy storage capacities and discharge times for different technologies

The driving force in this relationship is the cost of storage relative to the cost of power production. Hydrogen has the advantage of relatively cheap storage in terms of the equipment used for each kWh stored, storage can be scaled up significantly to increase the discharge time for a given discharge rate. In a utility scale battery storage application, the battery modules themselves make up nearly 50% of the cost, and therefore increasing the capacity has a large CAPEX impact but does mean the £ per kWh decreases.

3.3 Round-Trip Efficiency

Round-trip efficiency (RTE) is the efficiency of an energy storage technology calculated by the percentage of energy that is retrievable in discharging compared to the amount used to charge or store energy. The higher the RTE value the less energy that is lost in the storage process. The RTE value is a consideration to be balanced with other aspects of a technology and an application's technical requirements. For instance, high-performing EVs will require a higher RTE value of its battery, to reduce the necessary weight and volume for the amount of power and stored energy it demands. In contrast, a stationary storage system may not need to have such a high RTE if the cost per cycle is low due to the cost related to the system. A higher RTE value is generally desired by any technology as it means there are less losses in the system and therefore less work is initially required.

One of the strengths of lithium-ion battery systems is their RTE, which for utility scale storage systems can be between 80% and 88%, and for electric vehicles even higher, up to 92% as some of the auxiliary losses are reduced. Hydrogen on the other hand, has a lower round trip efficiency due to the multiple conversion processes that are required. In addition, a greater range is found due to the myriad ways of generating, storing, and converting to electricity. Efficiencies of between 20% and 45% can be found, which is significantly lower than what is typical of most battery technologies.

The efficiencies of other storage technologies such as pumped hydro, compressed air energy storage and flow batteries lie in the range 70% to 85%, 40% to 70% and 60% to 85% respectively[4], with ultracapacitors reaching 92% RTE[5].

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[4] Fact Sheet | Energy Storage, Alexandra Zablocki, 2019

Figure 3-3 presents storage RTE for various technologies in different duration categories; the technologies include Hydrogen (H2), pumped hydro (PSH), pumped thermal electricity storage (PTES), liquid air energy storage (LAES) and compressed air energy storage (CAES), lithium-ion batteries (LIB) and various other battery chemistries.

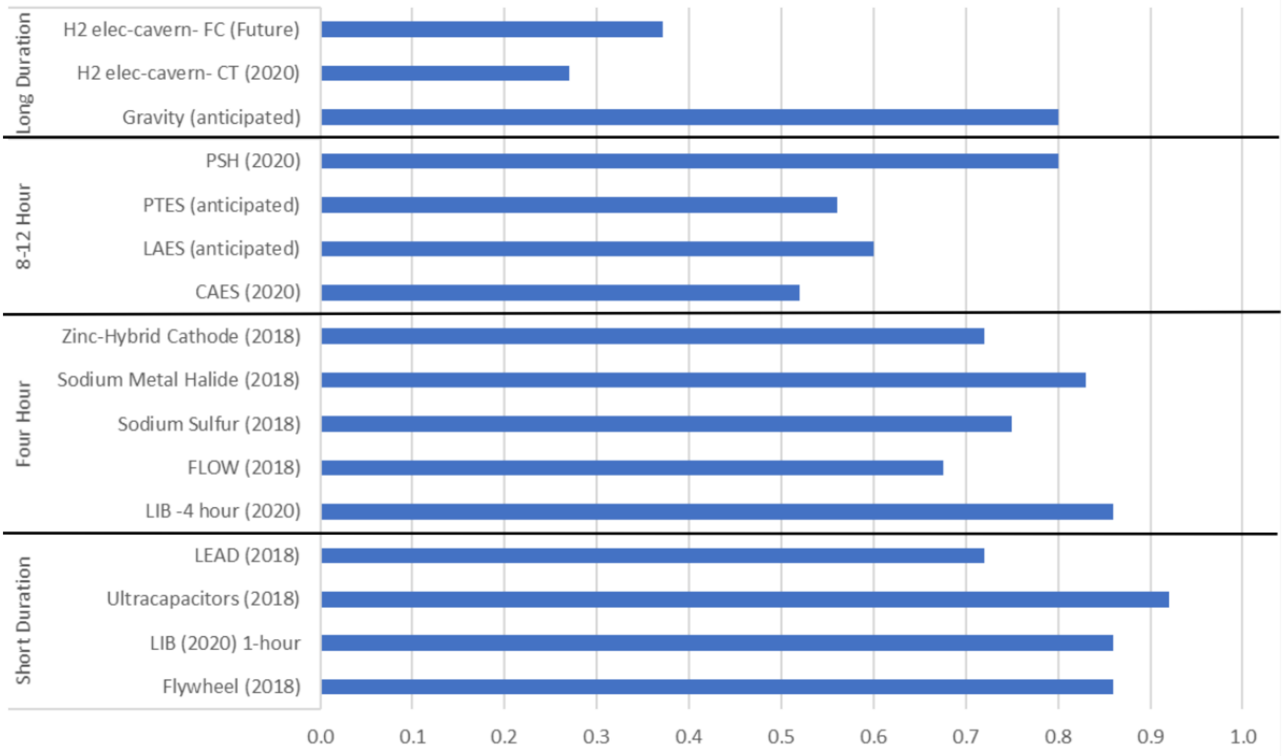

Figure 3-3 Typical energy storage round-trip efficiency values for different technologies (NREL, 2021)

3.4 Lifespan / Degradation

A technology's lifespan and degradation rate of its energy capacity are generally linked. The lifespan designates how long, either in terms of time or cycles, a technology can be used for, and degradation concerns the reduction in performance due to either time or cycling. The State of Health (SOH) indicates the actual energy capacity relative to the initial energy capacity, given as a percentage. For Li-ion batteries, a State of Health (SOH) of 60 to 80 % is often used to indicate the end of useful life depending on the application. For SOH values below a minimum level (as low as 60%), the performance of the cell can be less predictable leading to greater safety concerns, and therefore manufacturers generally do not offer warranties after this point. Under a heavy cycling rate of two cycles per day, the commercial end of life can be reached within 10 years for LFP battery cells; it is common to replace cells after this point is reached as the connected equipment tends to have a longer lifespan. This rate will change depending on the technology and chemistry, how it is operated, and its operating conditions. The lifespan of a system can be extended with considerate operation and maintenance regimes; however, degradation is ultimately driven by chemistry and is therefore difficult to avoid with today's technology. Li-ion cells can be recycled after they have reached their end of useful life, although currently it is a relatively energy intensive process. Efforts are underway to establish a battery recycling industry in many parts of the world today, with an overall metal (Li, Ni, Co, Fe, Mn) recovery efficiency of 60-90% depending on the process used.

The degradation of fuel cell components shortens the life and lowers the reliability of fuel cells[6]. In general, for FCEV's, fuel cell stacks are designed to last the lifetime of the vehicle, about 100,000 – 200,000 miles. Hyundai's Nexo fuel cell

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[5] Energy Storage Futures Study: Storage Technology Modelling Input Data Report, Chad Augustine and Nate Blair, 2021

[6] Degradation in PEM Fuel Cells and Mitigation Strategies Using System Design and Control, Jekan Thangavelautham, 2017

has a lifespan of around 5,000 hours, or 100,000 miles. However, they report that their next generation of fuel cell will be between 50 – 100% better[7]. Fuel cells can be disassembled, and the materials recycled. Fuel cell recycling is mainly focused on the recovery of the expensive precious metal catalysts. In the UK, there is currently no established processes for recovering these high value materials, however it is an emerging area. Companies such as Ballard Power Systems, Inc. state they can typically reclaim more than 95% of the precious metals. They claim that most of remaining components in a fuel cell stack can be recycled using ordinary recycling processes, however key challenges include the collection of the widely distributed fuel cells and scaling any processes[8].

Degradation is a key factor in the levelized cost of storage, which looks at the degradation of a technology over the lifetime of a system. Degradation is generally more impactful for batteries and chemical systems, with mechanical, electromechanical and thermal systems being less sensitive to annual degradation.

3.5 Cost

The cost of supply, installation, and operation are undoubtedly important factors moving forwards. The power (£/kW) and energy (£/kWh) cost component of energy storage technologies can vary between technologies and supports the likelihood that energy storage technologies will become more application specific in the future. Total capital cost comparison of technologies should consider the energy capacity and storage duration of a system in addition to its power output. Furthermore, a comparison of technologies is to consider the lifetime cost of a system, which incorporates the operation and maintenance requirements of a system.

There is a vast range of technologies available to the market, and even more being researched; consequently, it is difficult to predict step changes and future capabilities, and whether they will be successful in scaling up to mass manufacturing. However, the types available do present themselves to have certain characteristics that make them appear more suitable for certain applications which will have different price points. Development of batteries that use inexpensive, high-energy density electrode materials is a key area as they are seen to be critical parameters for the success of EVs. Cost and the speed of build-up of low-emission hydrogen is key for its use as a fuel in sectors that are difficult to electrify.

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[7] 671-HP Fuel-Cell Sports Car Kicks Off Hyundai's Hydrogen Push, Mike Duff, 2021

[8] Recycling PEM Fuel Cells, Ballard

4 ROAD TRANSPORT

In 2019, the transport sector was the largest source of emissions in the UK, contributing 30%[9]. The equivalent energy use was approximately 658 TWh or 38% of the UK's consumption[10]. Decarbonising the transport sector is therefore vital in the UK's ambition to become net zero by 2050.

Within the transport sector, as shown in Figure 4-1, road transport is the largest contributor of emissions accounting for up to 67%, followed by aviation and shipping. Road transport is dominated by passenger cars, with light duty and heavy goods vehicles accounting for the majority of the remaining emissions ahead of buses and a small contribution from mopeds and motorcycles. It is noted that allocating emissions for international aviation and shipping can be done in various ways. The statistics presented here are from BEIS and consider estimated emissions from international aircraft and shipping movements based on the use of fuels from UK international aviation and shipping bunkers.

DNV has undertaken an appraisal of the battery and hydrogen technologies available to the road transport sector, looking at each subsector in turn, and discussing the expected evolution of the market in the UK. The expected vehicle sales by propulsion system out to 2050 are provided based on DNV's ETO modelling, forming the resulting energy usage.

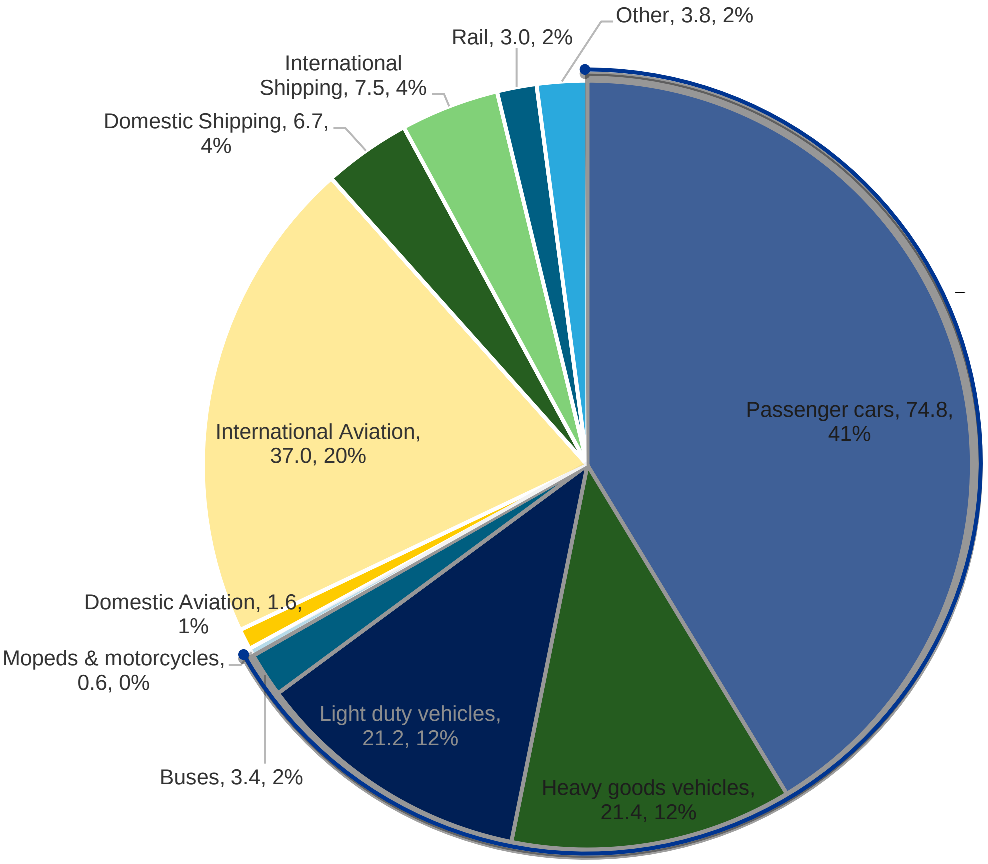

Figure 4-1 UK Transport emissions by vehicle type in million tonnes carbon dioxide equivalent (MtCO2e), 2019. Data from BEIS Final UK greenhouse gas emissions national statistics 1990-2019

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[9] Final UK greenhouse gas emissions national statistics: 1990 to 2020, BEIS, 2022

[10] DUKES 1.1: Aggregate energy commodity balance: gross calorific basis, BEIS, 2022

4.1 Passenger Vehicles

4.1.1 Demand today

Passenger cars are the largest single emitter of CO_2 from transport in the UK and represent the largest market in terms of new vehicle sales per year, with sales of £53 billion in 2021[11,12]. The passenger car is a cornerstone of mobility, and represents, along with taxis and vans, 83-87% of the passenger kilometres travelled within the UK between 1987 and 2019[13]. Though improvements in public transport and changes in consumer behaviour may occur over the next three decades, it is expected that the passenger car market will retain its leading position in providing personal mobility in the UK, and no significant reduction in the total number of vehicles on the road is expected.

The passenger car market today is dominated by petrol and diesel fuelled Internal Combustion Engines (ICEs), accounting for 81.7% of new vehicle sales in 2021[13]. ICEs are cost effective, reliable, have received decades of investment in research and development, and benefit from a global refuelling infrastructure. Despite the dominance of ICEs, alternative propulsion systems are available, and these principally include BE vehicles (BEVs) and hydrogen fuel cell electric vehicles (FCEVs). BEVs have in recent years dramatically increased their share of new car registrations in the UK, from less than 1% pre-2019 to 11.4% in 2021[12]. The sale of FCEVs in contrast remains negligible, with only two passenger car models commercially available in the UK[14] compared with dozens of BEV models. Other alternative technologies exist, such as hydrogen fuelled internal combustion engines, however these are not considered to be viable mass market solutions for passenger vehicles and have therefore not been considered in detail here.

4.1.2 Consumer requirements

In evaluating the future evolution of the passenger car market, the requirements of consumers and society as whole must be considered. In a 2018 survey, consumers ranked fuel efficiency, safety, suitability for everyday use and a low price as being the most important factors when buying a car[15]. Suitability for everyday use encompasses refuelling convenience, range and size. However, in the same survey, environmental friendliness was ranked lowest, suggesting that the importance of fuel efficiency is predominantly driven by operating costs. These consumer requirements are likely to remain similar over the coming decades.

The prospects for the switch to clean road transport is being heavily supported by the UK Government, with the announcement that from 2030, the sale of new petrol and diesel cars and vans must cease, and in 2035, all new cars and vans must be zero emission at the tailpipe (effectively banning petrol/diesel hybrids). This policy offers a huge incentive and opportunity to manufacturers to provide the best clean technology and capture a large share of the market.

4.1.3 Performance characteristics

The technologies with the potential to power low-carbon passenger cars are considered to be BEVs and FCEVs. At a basic level, a BEV consists of a battery pack storing electrical energy, an inverter to convert the DC power from the battery into AC power for the electric motor, which through a transmission drives the wheels. In addition, BEVs include an onboard charger and further ancillary systems. In a FCEV, the energy is contained within hydrogen fuel, stored in a tank either as a compressed gas or cooled to a liquid, which is converted in a fuel cell to electricity. From there the DC electricity from the fuel cell is converted to AC in an inverter, before powering an electric motor in much the same way as a BEV. In addition, FCEVs also contain a battery which is used to provide additional power and act as a store for energy captured through regenerative braking.

In addition to the use of single technologies, hybrid solutions, incorporating two sources of power, can also be considered. Today, hybrid vehicles typically consist of ICEs paired with a battery, however these are not considered a

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[11] Average Car Prices: 2021, Office for National Statistics, 2022

[12] Vehicle licensing statistics data tables, Department for Transport, 2022

[13] Modal comparisons (TSGB01), Department for Transport, 2022

[14] Toyota Mirai and the Hyundai NEXO

[15] Most important factors when buying a car, Martin Armstrong, 2022

low carbon technology and shall no longer be sold from 2035 onwards. An alternative hybrid combines a hydrogen fuel cell with a battery. Though all fuel cell powertrains include a battery in order to improve their variable power output, a hybrid is considered one where the battery can be charged externally from the vehicle. Electric/hydrogen hybrids have been considered at the concept stage by manufacturers, and their prospects are discussed in the following sections as appropriate.

When considering the clean technology of choice, a whole range of factors must be considered, including the consumer requirements but also broader societal factors. Underpinning many of these are the performance characteristics such as efficiency, energy density and safety. These are discussed in the following paragraphs.

4.1.3.1 Efficiency

Efficiency is the consideration of the amount of useful energy available to the vehicle compared with the energy required at its source and is expressed as the well-to-wheel efficiency.

In order to charge a BEV, the energy needed (in this case in the form of electricity) must be transmitted from the point of generation to the vehicle, before incurring various losses from the charging equipment and the conversion processes within the vehicle, until the electric motor converts the electrical energy into motion. This process, as shown in Figure 4-2, results in 77% of the initial energy being used by the vehicle.

For a FCEV, electricity is used in an electrolyser to produce hydrogen. The hydrogen must be transported from its point of generation to a refuelling station, where it is transferred to a vehicle. Within a FCEV the hydrogen is converted in the fuel cell to electricity, before powering the electric motor to turn the wheels. During the conversion process from electricity to hydrogen and back again, significant energy losses are incurred, resulting in 30% of the initial energy being used by the vehicle, as shown in Figure 4-2. The well-to-wheel efficiency of conventional ICEs fuelled by power-to-liquid e-fuels is even lower at 13%.

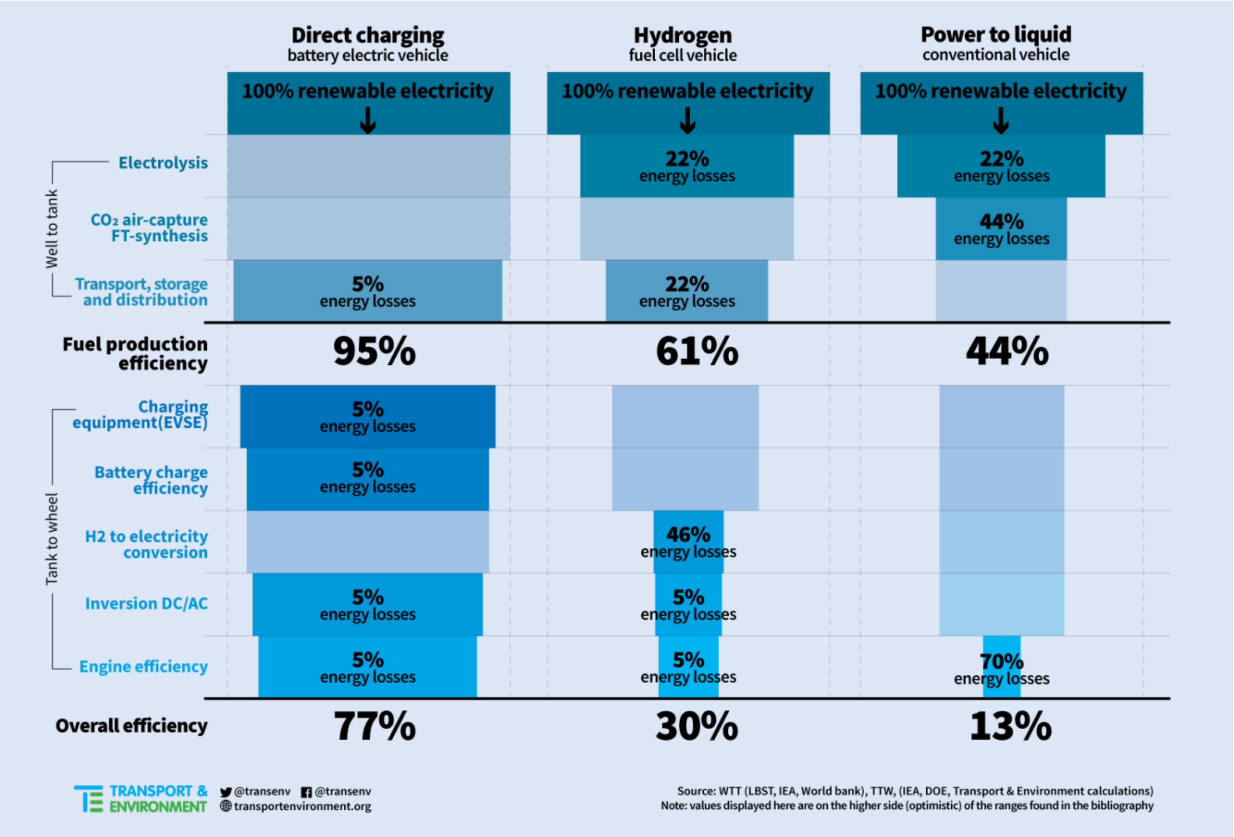

Figure 4-2 Well-to-wheel efficiency comparison for different propulsion systems[16]

The well-to-wheel efficiency comparison shows that BEVs have significantly higher efficiency compared with FCEVs. The implication of this from a system perspective is that the total electricity required to power a vehicle is around three times larger for a FCEV, compared with a BEV (see Figure 4-3). Providing enough electricity to power the passenger car market will therefore be significantly more challenging, costly, and take longer if FCEVs are used in place of BEVs.

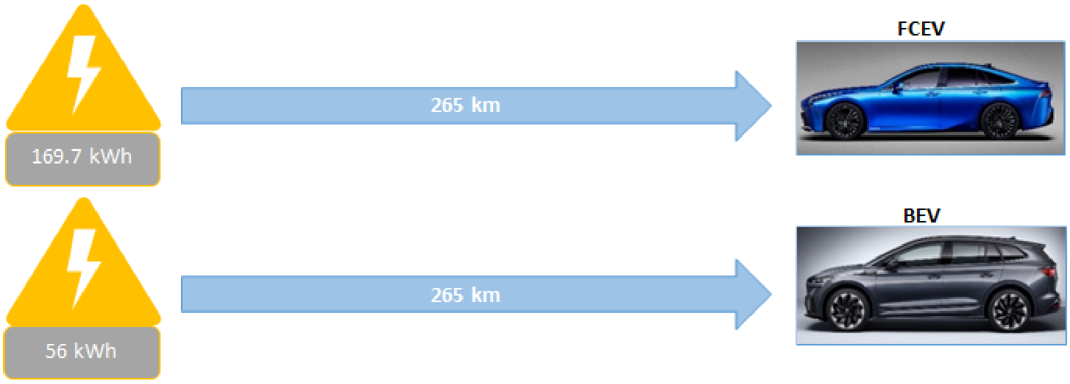

Figure 4-3 Comparison of energy requirements for a hydrogen fuel cell vehicle (the Toyota Mirai) and a battery electric vehicle (the Skoda Enyaq) (Image adapted from Jaroslav Kmet'[17]**)**

The potential for improvements in efficiency over the years to come are expected to be relatively low for both battery and hydrogen fuel cell technologies. Considering the battery vehicle drivetrain, marginal improvements in efficiencies could be expected, however given the high efficiency already achieved, the overall impact is expected to be limited. For

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[16] Roadmap for decarbonising European cars, Transport & Environment, 2018

[17] Comparison of the energy requirements of FCEVs and BEVs when powered by an off-grid energy system, Jaroslav Kmet, 2021

hydrogen, slight improvements in process efficiencies could lead to an overall increased well-to-wheel efficiency. A challenge is the significant amount of energy lost during the production of hydrogen through electrolysis. Electrolyser efficiency can be optimised, with improvements in membrane design and optimised operation. Nevertheless, the level of efficiency improvement available to fuel cells is not expected to significantly change the overall comparison between BEVs and FCEVs.

Other aspects of vehicle efficiency are expected to be similar for BEVs and FCEVs. The efficiency of the vehicle is influenced by factors including vehicle size, driving environment (urban or motorway), and driving style. Furthermore, both FCEVs and BEVs can make use of regenerative braking to increase efficiency and range. In regenerative braking, the electric motor in both BEVs and FCEVs operate as generators, converting some of the kinetic energy of the vehicle back into electrical energy to be stored in the battery. This contrasts with friction brakes, where all the energy is lost as heat. The amount of energy recovered varies depending on the vehicle and driving conditions, however efficiency improvements of up to 40% are considered possible.

4.1.3.2 Energy capacity

Available range is considered an important factor when determining the purchase of a new passenger car. This is influenced by characteristics of the car, such as its size and economy, along with the energy density and capacity of the energy store (fuel tank or battery). A secondary consideration is the convenience of refuelling, which has the ability to compensate for some of the shortcomings of shorter range. ICEs benefit from both a high-density fuel, short refuelling times, and a widespread network of fuel stations. Matching this level of performance and convenience is a challenge for any potential alternative technology.

Today’s battery technology has a significantly lower energy density and specific energy relative to either oil-based fuels or hydrogen. This either limits the range available for BEVs, or adds to the weight of the vehicle, impacting performance. Rapid development of battery technology in recent years has seen a large improvement in BEV range, leading to a fleet wide average of 221 miles in the UK[18]. Ranges of up to 395 miles are available for top of the range vehicles such as the BEV Mercedes EQS 450+. To achieve the highest range, a nominal battery capacity of 120 kWh is included in the EQS 450+, which is approximately twice the capacity of the average BEV available in the UK today. The compromise for this high energy capacity is weight, with an unladen vehicle weight of 2480 kg, which includes over 400 kg of batteries[19]. This is significantly higher than the 144 kg total equivalent hydrogen system weight in the Toyota Mirai.

Of BEVs and FCEVs, the latter has the most similar characteristics and performance with respect to energy density and range compared with ICE vehicles. As discussed in Section 3, hydrogen has a very high specific energy, and although its energy density is lower than oil-based fuels (petrol/diesel), it is higher than battery technology. Therefore, despite a larger fuel tank being required, hydrogen fuelled cars do not suffer a weight penalty relative to ICEs and can achieve a similar range. The range available to the most recent models of hydrogen FCEVs, such as the Toyota Mirai, is up to 446 miles[20] when equipped with 3,700 bar hydrogen tanks with a combined capacity of 141 litres. Due to the high pressure of the hydrogen tank and the safety requirements of storing a flammable gas, the tank itself is large and weighs 82 kg, whilst the fuel cell weighs 56 kg. This gives a total weight of the hydrogen, tank and fuel cell for the Toyota Mirai of 144 kg[21].

The resulting comparison of energy per unit mass is as follows:

- BEV: 120kWh battery with a useable capacity of 108.4kWh[22] and weight of 436 kg gives a usable specific energy of 0.25 kWh/kg

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[18] Range of electric vehicles, Electric vehicle database

[19] Battery weight estimate based on an assumed energy density of 250 Wh/kg.

[20] New Mirai Press Information 2020, Toyota, 2020

[21] Toyota Mirai Fuel Cell Sedan Priced At $57,500, Mark Kane, 2014

[22] The EQS: Effective from December 2022 Production, Mercedes-EQ, 2022

- FCEV: 141 litres of hydrogen with an energy content of 197 kWh[23]. This translates to a useable energy of 107 kWh (54% fuel cell efficiency) and weight of 144 kg, giving a specific energy of 0.74 kWh/kg

This shows that the hydrogen fuel cell vehicle has a specific energy almost three times higher than a BEV, when considering just the components required to provide the electrical energy to the power electronics and motor.

A further consideration for BEVs and FCEVs is degradation of energy capacity over the life of the vehicle. A battery degrades due to the chemical processes within the cells, leading to a decreasing capacity and therefore a range reduction. Nevertheless, with improvements in cell design and battery management, the degree of degradation is decreasing over time. It is typical in existing warranties to guarantee the battery capacity above a threshold for the first 8 years of operation. VW for instance guarantee 70% of battery capacity for the first 8 years or 160,000 km[24]. In the case of FCEVs (as it is with ICEVs), degradation in performance is also observed, however the impact of this is primarily linked to power capabilities, whereas energy capacity degradation is limited.

Finally, though the majority of alternatively fuelled vehicles are either BEVs or FCEVs, a hybrid solution comprising both technologies is also a possibility; particularly where range is a concern. The car manufacturer Renault recently released details of an electric-hydrogen hybrid concept passenger car. This concept would allow a range of up to 800 km without charging a battery[25]. The vehicle contains a 40 kWh battery along with a 2.5 kg hydrogen tank. Though hybrid technology enables a BEV to have a higher range, the number of hybrid vehicles in development is relatively low.

4.1.3.3 Power capacity

Power capacity refers to how quickly a device can discharge its energy (energy flow per unit (mass, area, volume)). In a passenger car, this influences how quickly it can accelerate and what speed it can achieve.

Both battery and fuel cell vehicles use electric motors. In comparison to an ICE, an electric motor has a higher power density by as much as a factor of two[26] and can be scaled up to meet the requirement of the vehicle. In addition to the electric motor, the process of converting the stored energy to electricity must be considered. The inverter included within both a FCEV and a BEV is a key component. The frequency and amplitude of the AC signal determines the torque and speed of the electric motor. Inverters used within electric vehicles are highly efficient, with >95% of the energy retained, and are light weight (typically less than 10 kg for a 100 kW device[27]).

In a BEV, the discharge rate allowed by the battery is determined by its size, design and chemistry. Generally, the higher the discharge rate, the higher the temperature rise within the battery, thereby requiring greater cooling. In addition, higher discharge rates can lead to greater degradation of the cells, which must be considered. Nevertheless, electric vehicles can be designed to have very high-power capacities if required, for instance in sports cars such as the Rimac Nevera.

In a FCEV, the energy conversion consists of the fuel cell which converts the hydrogen fuel into DC electricity as described earlier. Under acceleration, the drive battery used within the FCEV architecture discharges to increase the power available. Proton-exchange membrane (PEM) fuel cells, the type of fuel cells predominantly used in transport applications, can have a range of power outputs depending on the fuel cell size. The latest model of the Toyota Mirai FCEV includes a 128 kW fuel cell with a volume of 24 litres, achieving a power density of 5.4 kW/litre. FCEVs such as the Hyzon Gen3 fuel cell stack used in HGVs achieves a volumetric power density above 6.0 kW/litre and gravimetric power density more than 5.5 kW/kg, which is considered above industry average. It is noted that the fuel cell itself operates most effectively at a constant power output, and therefore the drive battery is an important part of the power capability of the car.

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[23] A conversion of 1.4 kWh/L at 700 bar

[24] High-voltage battery: Warranty and maintenance, Volkswagen

[25] Renault reveals electric-hydrogen hybrid concept car, Anmar Frangoul, 2022

[26] Gen3 is coming, FIA Formula E, 2021

[27] EV power inverter control reference platform Gen 1, NXP

4.1.3.4 Maintenance & reliability

Reliability and vehicle maintenance requirements are important considerations for new technologies and how consumers adopt and utilise them.

An internal combustion engine is a highly complex piece of equipment, with many moving parts requiring frequent servicing. The electric motors and power electronics used in both FCEVs and BEVs are in contrast simpler and require significantly less maintenance during their lifetime. Moreover, the brakes may suffer less wear due to the use of regenerative braking[28] but this is heavily dependent upon vehicle use cycles. The extra weight and higher torque of a BEV tends to produce more wear in tyres.

The maintenance requirements for a BEV are typically limited to inspections during regular service periods and checking oil and coolant levels for the transmission and battery. The battery itself requires no maintenance outside of the scheduled inspections. Inspections are required less frequently than an ICE equivalent, with checks recommended every 30,000 km compared with 20,000 km for a diesel[29]. The lifespan of EVs is not dissimilar to that of conventional cars, with upwards of 10 years or 100,000 miles being of typical expectation.[30]

In a FCEV, there are more components and therefore additional maintenance is required compared with BEVs. In general, fuel cells when used in appropriate environments are highly reliable, due largely to their lack of moving parts. Air filters are a critical component in hydrogen fuel cell vehicles to ensure the air intake is clean, and these therefore require regular replacement. Air filters should be checked every 10,000 miles but usually a replacement is only necessary every 15,000 miles to 30,000 miles depending on driving habits. Other maintenance activities are limited to inspections to ensure all components are in good condition. PEM fuel cells require very high purity hydrogen as contaminants can lead to poisoning of the fuel cell catalyst. Ensuring the purity of hydrogen is however undertaken in the production and distribution stage. As previously stated, the fuel cell stacks are designed to last the lifetime of the vehicle, about 100,000 – 200,000 miles.

To conclude, the maintenance requirements of BEVs can be considered the lowest, followed by FCEVs and lastly ICEs, which have the highest maintenance requirements.

4.1.3.5 Safety

Having excellent safety is a key requirement for any passenger car. BEVs and FCEVs, with their fundamentally different energy storage methods, have different risks and safety considerations. All road vehicles are subject to rigorous regulation and testing before they can be used.

Battery fires suffered by BEVs are well documented in the media and get significant attention. Battery fires typically occur when the battery is damaged either through a collision or when there is a manufacturing fault of some sort. A fault such as this can lead to thermal runaway, in which the chemical reactions within the battery create more heat than the battery can dissipate. Thermal runaway events take a long time to control and require significantly more water to put out than an ICE vehicle fire, which tends to burn out quickly. Nevertheless, the number of battery fires is small; analysis from 2022 shows 25 battery fires per 100,000 vehicle sales compared with 1,530 fires per 100,000 ICE vehicles in the US[31].

Hydrogen based vehicles have different safety considerations to those of battery EVs. Hydrogen gas is flammable and in the right concentrations, explosive. When compared with natural gas, hydrogen has many of the same properties and safety considerations, with the notable difference that it has a greater range of concentrations in air in which it can ignite, and therefore the explosion risk is much greater[32]. The safe storing of hydrogen in a FCEV is therefore crucial.

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[28] Maintenance and safety of electric vehicles, US Department of Energy

[29] All there is to know about electric cars, Renault Group, 2021

[30] How long do electric car batteries last? EV battery recycling, RAC, 2021

[31] Gas vs Electric car fires: 2022 findings, Rachel Bodine, 2022

[32] Hydrogen Forecast to 2050, DNV, 2022

A key risk for hydrogen fuelled vehicles is a hydrogen leak leading to explosion. For this reason, key aspects of the safety design include double walled tanks, sensors monitoring the flow of hydrogen through the system, leak detection sensors, system monitoring and good ventilation around the tanks in case of leaks. The Toyota Mirai has been designed so that leaked hydrogen can easily escape to the outside for quick dissipation, with the tanks and fuel cell unit located outside the passenger cabin.

Additional safety considerations in the production and operation of the battery packs and hydrogen fuel are not discussed here, however from the perspective of operating a vehicle, both BEVs and FCEVs can be considered to be as safe as an ICE vehicle.

4.1.3.6 Usability and performance

Usability and performance attributes can be important considerations in consumers' preferences for vehicles, even if from a system perspective, these factors do not have the same importance as efficiency, supply chain and energy density. Factors including comfort, noise, performance and temperature sensitivity can be considered.

Electric drivetrains have many performance advantages over internal combustion engines. Electric motors provide all their available torque at a very low rpm and are then able to reach a much higher rpm than typical ICEs. This means no heavy clutch and multispeed gearbox is needed within either a BEV or FCEV. Other performance characteristics such as vibrations and noise emissions also show favourably towards both FCEVs and BEVs. The ICE produces significant vibrations through its reciprocating motion, and the combustion process produces significant noise. Therefore, with no moving parts or combustion within their drivetrains, both battery and fuel cell electric vehicles exhibit less vibration and lower noise output, improving the experience for the driver and passengers. It is noted that in the case of noise, road noise becomes the dominant source above very low speeds, and therefore the noise reduction is minimal for much of the time.

For BEVs, increased weight from the battery influences acceleration and stopping distances, along with cornering performance. Nevertheless, these factors can be mitigated through vehicle design and are not considered to be a significant barrier to widespread adoption. Temperature can have various impacts on mechanical and electrical systems, and within a battery, low temperatures can influence electrical resistance, which can substantially impact the range available. To counter this, BEVs include a thermal management system to ensure the battery operates at the correct temperature, although this itself uses some of the available energy. Furthermore, space-heating within the vehicle uses energy from the same source as the energy used to drive the vehicle, the battery, rather than waste heat, as is used in ICEs. Therefore, when driving in cold temperatures, the range available can be up to a third lower than driving during mild temperatures[33] simply to keep the occupants warm. In order to combat this effect, improved heating methods can be used, such as a heat pump. Within the VW ID3, the heat pump installed is able to reduce the heating demand when temperatures become sub-zero by 40%[34].

In a FCEV, weight is typically lower than in a BEV, and therefore good acceleration and handling can be achieved. In respect of temperature, the performance of the fuel cell does not degrade in temperatures between -30°C and +45°C, therefore the cold weather reliability is not a concern for the switch to FCEVs. Furthermore, heat generated from the fuel cell keeps the systems from freezing and can be used for space heating[35].

4.1.3.7 Emissions

One of the key ambitions in the switch to alternatively powered passenger cars is to reduce harmful emissions, and in particular the amount of GHGs released.

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[33] Estimate based on energy use of the Mercedes EQS-450+ during cold temperatures (-10°C) with the heating on, vs mild temperatures (23°C) with no air conditioning: Mercedes EQS 450+, Electric vehicle database

[34] Impressive range: The heat pump in the ID. Models, Volkswagen

[35] Fuel cell electric buses: Cold weather operation, Ballard

At the point of use, both BEVs and FCEVs produce no carbon dioxide or other harmful gases from their drivetrains. Both vehicles will however continue to emit particulate matter (PM) from the brakes and tyres, leading to possible negative health impacts. Due to the extensive use of regenerative braking, the use of friction brakes and therefore the emissions of PM is greatly reduced for BEVs and FCEVs, however tyre wear will continue to have an impact.

The total emissions of different vehicle technologies require a cradle to grave comparison in order to consider all the energy required and emissions caused in the production as well as use of the vehicle, including the production of the hydrogen or electricity used.

Due to the large amount of energy used in extraction of the raw materials for batteries, the emissions in the manufacture of BEVs are higher than that of ICEs. Reuters analysis estimates that a mid-sized BEV creates 8.1 million grams of carbon dioxide in its production, compared with 5.5 million grams from a petrol-powered vehicle. Therefore, depending on the energy mix of the electricity grid, the car needs to be driven either 8,400 miles (100% electricity from hydropower) or 13,500 miles (an electricity mix including 23% coal) before the total emissions of the BEV is lower than an equivalent ICE[36]. Given the typical lifespan of a BEV is 100,000 miles, the total emissions in its life are expected to be significantly lower than those of a conventional ICE vehicle.

When considering FCEVs, lifecycle assessments have shown that the production of the fuel tanks and the cathode catalyst are critical components for the emissions generated in PEM fuel cell manufacture. There is significant potential to reduce emissions from the manufacturing of PEM fuel cells for use in FCEVs. As the technology matures, solutions to mitigate emissions such as the use of secondary platinum from spent catalytic converters and recycled carbon fibre for the storage tanks will go some way to reduce the overall lifecycle emissions[37]. Although no CO_2 is emitted during the operation of a FCEV, the direct emissions associated with the production of hydrogen can impact the overall lifecycle emissions. Where hydrogen is produced through electrolysis and renewable electricity (making green hydrogen), the direct CO_{2e} emissions are negligible. For comparison, methane reforming with CCS (blue hydrogen), can result in 0.5 – 4 kg CO_{2e} per kilogram of hydrogen produced[38]. In the near future, the hydrogen supply mix will likely be a combination of different production technologies with differing emissions intensities and should be considered when conducting lifecycle analyses of FCEVs. Hydrogen production is described further in the appendix.

4.1.4 Costs

The overall financial competitiveness of a vehicle can be best assessed with a total cost of ownership (TCO) analysis. This includes a number of different cost elements including upfront purchase, fuel, maintenance and other operational costs. The upfront cost of the vehicle is often the dominant factor in people's perception, given its impact is felt first.

For a BEV, the dominant upfront cost component is that of the battery. Battery pack costs have decreased significantly over recent years as economies of scale effects have been realised, although due to the rapid uptake in BEVs, supply chain constraints and commodity inflation, the price of batteries increased in 2022[39]. Nevertheless, the overall trend in battery price decrease is expected to resume as the production capacity continues to rise, and in the DNV ETO 2022 model, this is expected to be a long-term rate of 19% price reduction per doubling in annual production capacity. Such reductions are expected to come from further economy of scale effects as production ramps up, along with the adoption of alternative battery chemistries using different materials, such as LFP cathodes and sodium-ion batteries for light vehicles. Historical battery pack reductions and the future projection in the DNV ETO 2022 are presented in Figure 4-4.

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[36] Analysis: When do electric vehicles become cleaner than gasoline cars? Paul Lienert, 2021

[37] Life cycle assessment of fuel cell systems for light duty vehicles, current state-of-the-art and future impacts, Lorenzo Usai et. al., 2021

[38] Hydrogen Forecast to 2050, DNV, 2022

[39] Lithium-ion battery pack prices rise for the first time to an average of $151/kWh, Bloomberg NEF, 2022

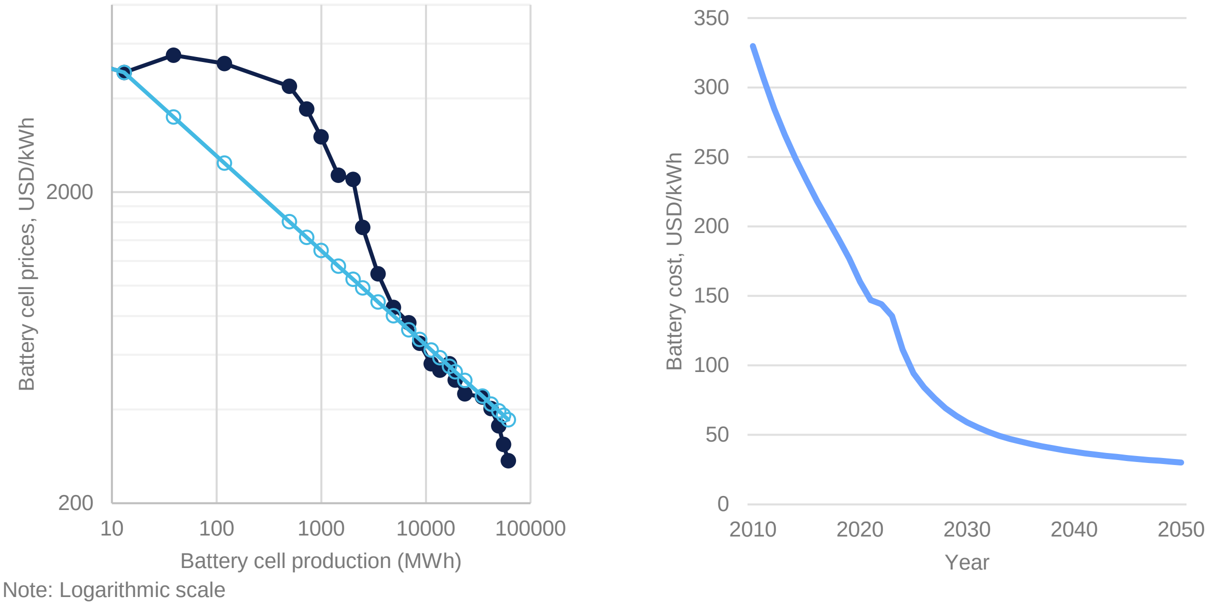

Figure 4-4 Historical global average battery pack cost and future price projection in the DNV ETO 2022[111]

Within a FCEV, the major cost component is the fuel cell system. As the dominant cost element, the expected fuel cell cost development over time is a crucial factor in the final upfront cost of the vehicle. Cost reductions are expected with advancing fuel cell research and development, emphasizing activities that achieve high efficiency and durability with lower material and manufacturing costs for fuel cell stacks. Increased production volumes will also lower the cost of FCEV's. To approach cost parity with other powertrains, passenger FCEVs are believed to require production volumes of around 100,000 units per year, requiring considerable financial support.[40] By 2030, it's thought that the fuel cell system could be at around 85 £/kW, which would be an 83% decrease from 2013[41] and result in a £10,880 fuel cell cost for a vehicle such as the Toyota Mirai. Therefore, the upfront cost of the car is considered a major hurdle for passenger FCEV’s.

After the purchase price, typically the second biggest consideration is the running costs. The estimated fuel cost for ICEs (considering an average of petrol and diesel), BEVs and FCEVs is presented in Figure 4-5.

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[40] The role of hydrogen and fuel cells in the global energy system, Iain Staffell et. al., 2018

[41] An Overview of Costs for Vehicle Components, Fuels and Greenhouse Gas Emissions, Robert Kochhan et. al., 2014

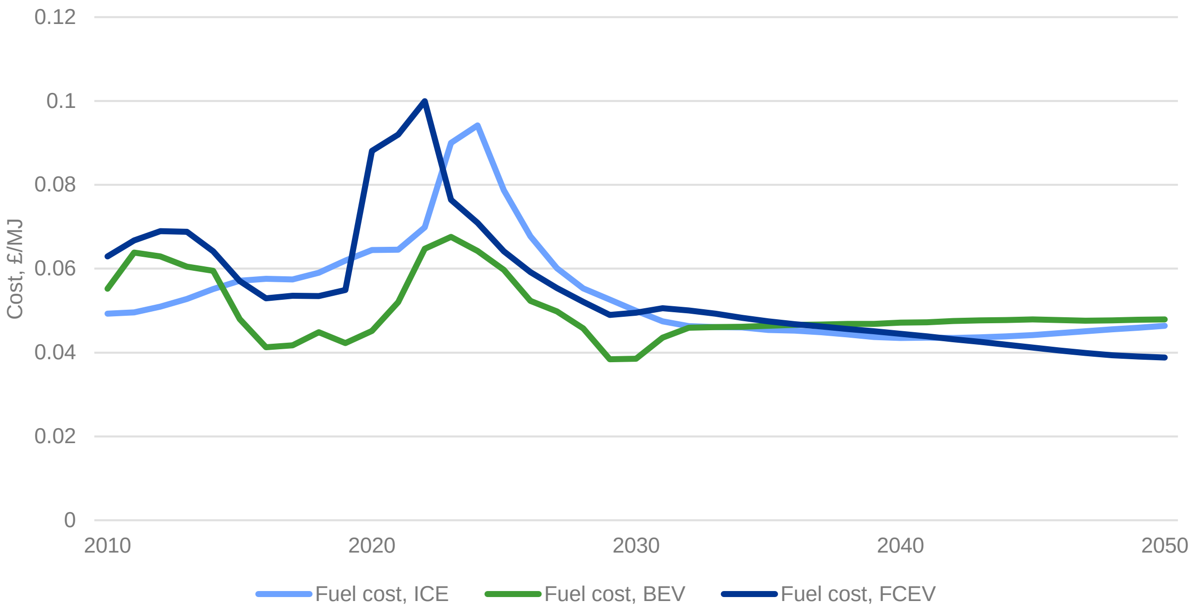

Figure 4-5 Expected UK fuel costs for ICE, VE, and FCE vehicles[42]

The fuel costs in Figure 4-5 are presented per MJ of energy, and therefore this doesn't consider the conversion efficiency of the drivetrain. Using the comparison between the total input energy required for a FCEV and BEV to travel 265 km shown in Figure 4-3, it can be calculated that the FCEV will store approximately 104 kWh of energy in the hydrogen tank (electrolyser, transportation and storage losses of 39%), giving it an efficiency of 0.7 km/MJ at a cost of £0.14/km. The BEV on the other hand stores 53 kWh of energy in the battery, giving it an efficiency of 1.4 km/MJ at a cost of £0.05/km. This makes the energy cost for the BEV almost a third of the cost of a FCEV. By way of comparison, a typical ICE will travel 0.42 km/MJ of fuel (approximately 38 miles per gallon), giving it a cost of £0.17/km. Though the cost of hydrogen is expected to fall significantly as the hydrogen economy develops in the coming decades, the total fuel cost for an owner is expected to remain higher for FCEVs relative to the electricity cost of a BEV.

The remaining costs for the consumer include maintenance costs and costs such as insurance and tax. Maintenance requirements for both BEVs and FCEVs are lower than an equivalent ICEs due to the reduction in moving parts, as described in Section 4.1.3.4. Estimates suggest the maintenance cost of BEVs is at least 30% lower than an equivalent ICE vehicle[43]. Though there is less experience with FCEVs, based again on the reduced number of moving parts, maintenance costs are expected to be similar to those of BEVs, once sufficient volume exists.

The impact of the cost elements described above can be compared and analysed in a TCO assessment. A study performed on behalf of the European Consumer Organisation presents the TCO for different drivetrains for different purchase years [44]. In the early 2020s, diesel, plug-in hybrids (PHEV) and BEVs exhibit the lowest cost at around €73k, while FCEVs show the highest cost by a considerable margin (>€100k). The cost of BEVs is predicted to fall to roughly €67k by 2030, whereas the cost of diesel vehicles is projected to rise to €78k. By 2030, the TCO of the hydrogen fuel cell is forecasted to drastically decrease to €79k, matching the costs of the diesel vehicles but still being significantly higher than battery-powered cars. Therefore, from a cost basis, BEVs are expected to be the most cost-effective form of passenger car transport within the next decade.

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[42] Energy Transition Outlook, DNV, 2022

[43] Cost of running an electric car, John Evans, 2022

[44] Electric Cars: Calculating the Total Cost of Ownership for Consumers, Element Energy, 2021

4.1.5 Infrastructure considerations

The availability of charging and refuelling infrastructure is a key requirement for the adoption of BEVs and FCEVs, as it has a significant impact on the energy capacity and range considerations previously mentioned. Refuelling stations for petrol and diesel vehicles are widespread throughout the UK, enabling users to extend their range wherever they are.

BEVs can be recharged at home, at car parks where recharging infrastructure has been installed, or at rapid charging service stations. The speed of BEV charging can vary significantly depending on the charger type used and the vehicles capabilities. Standard home chargers range from 3 to 6 kW and are commonly used at home for overnight charging and at some workplaces. Fast chargers range from 7 to 22 kW and are used more commonly in public places such as car parks, supermarkets where the vehicle will be parked for more than an hour. Rapid, 50kW, and ultra-rapid chargers ranging from 100-350kW are used at motorway (and some A-road) services and are designed to provide BEVs with up to 80% of their battery capacity within 10-30 mins. The UK Government are prioritising the roll out of charging infrastructure to help reduce consumer range anxiety, with a mandate that all new buildings in England will require the installation of charge points. According to Zap Map, as of November 2022, there are 21,906 public charge points in the UK, with a total of 60,701 connectors[45]. Along England's motorways and major A roads, rapid charge points are available at least every 25 miles[46], allowing drivers to make longer journeys with minimal additional time for charging.

The deployment of more chargers and the increase in their use will have a significant impact on the electricity grid, with transmission and distribution network upgrades required throughout the country to address the overall increase in power and energy demand of the grid. These are part of the wider electricity grid upgrade requirements needed as the economy electrifies over the coming decades. DNV's UK ETO forecasts that electricity demand will increase from 310 TWh/yr in 2021 to 760 TWh/yr in 2050. The largest increase in demand is for transport which increases from 10 TWh in 2021 to 140 TWh in 2050; road vehicles dominate this growth with an expected demand of 120 TWh in 2050.

For hydrogen, only a limited refuelling infrastructure exists, and the roll out of widespread fuel stations represents a significant barrier to widespread adoption. A simple refuelling station consists of hydrogen storage tanks, compressors, a pre-cooling system, and a hydrogen dispenser, which dispenses hydrogen at pressures of 350 or 700 bars depending on the type of vehicle.

At present, there are 11 hydrogen refuelling stations across the UK.[47] The hydrogen refuelling stations built to date have largely been designed to serve the initial low volume of hydrogen vehicles. The poor reliability of these stations is down to their small scale operation, with little-to-no back up system, and their low utilisation, which is not desirable as the stations have many moving parts which tend to suffer from long periods of being idle.[47] The development of hydrogen refuelling infrastructure will require policy development and funding support. Government set targets on the number of hydrogen refuelling stations across the UK would help improve the investment certainty across the transport market. BOC and BP have recently concluded a joint feasibility study, exploring designs for potential distribution and supply networks. The study found that in the near-term, distribution of hydrogen as compressed gas via road trailer is the best option to stimulate the UK market, and in the longer term there is a role for both liquid and gaseous hydrogen[48].

Due to the lower efficiency of hydrogen as a transport fuel relative to electricity, should hydrogen for transport be produced by electrolysis using renewable energy, a greater total increase in electricity capacity would be needed than is needed for a future dominated by BEVs. This would also present a challenge from an infrastructure perspective, whilst reducing the speed at which renewable energy can be available for other sectors of the economy.

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[45] EV Charging Statistics, Zap Map, 2022

[46] Decarbonising Transport: A better, greener Britain, Department for Transport, 2021

[47] Shell has quietly closed down all its hydrogen filling station in the UK, Leigh Collins, 2022

[48] bp and BOC explore UK hydrogen infrastructure network to accelerate the decarbonisation of UK road freight, bp, 2022

4.1.6 Future outlook

Both BEV and FCEVs are available commercially today. The key components within the different drivetrains are mature technologies, and their integration in a passenger car has been successfully achieved. The challenges going forward for both technologies evolve around the need to further enhance performance, expand their supply chains and charging infrastructure to meet the required demand.

BEVs have seen rapid growth in sales in the UK and globally, with major commitments from manufacturers such as VW[49]. Significant research and development in alternative battery and next generation battery chemistries are ongoing. This development is focused on different cell chemistries, such as sodium-ion technology, which will use more abundant materials to lower the cost per kWh[50]. In addition, significant improvements in energy density have also been achieved at the pack level through more efficient pack design. Finally, next generation technologies such as solid-state batteries are being developed to provide a step change in energy density.

For FCEVs, current research is focused on designing PEM fuel cells to reduce overall cost, dimensions, and weight. Significant scaling is required to achieve this, which is threatened by the growing demand and dominance of BEVs in the market. Currently, there are only two hydrogen cars which are commercially available in the UK, and pure fuel cell vehicle models of acceptable maturity in all non-car segments are only likely to appear after 2025. UK right hand drive preference adds an additional challenge to obtaining early market releases of vehicles[51]. The dominance of BEVs is considered a major limitation for FCEVs globally.

The sections above highlight the overall considerations for the passenger vehicle subsector. The table below shows a summary of the different technologies, considering their strengths and weaknesses, and the opportunities and threats to their development.

Battery electric passenger vehicles	**Strengths** Efficiency: Highest well-to-wheel efficiency reducing costs and overall transport sector energy requirements Recharging infrastructure is easier to install given the widespread availability of the electricity network. Currently there are over 21,000 electric charge points available in the UK. Cost: battery costs have dramatically reduced, and the total cost of ownership for BEV passenger cars is already below that of conventional ICE powered cars. Emissions are zero at the point of use Comfort: BEVs are quiet and vibration free, bringing benefits to a range of applications.	**Weaknesses** Recharging times are longer than conventional ICE refuelling and hydrogen refuelling. Cost: The purchase prices of BEV's are currently more expensive than the equivalent ICE vehicle, although light BEVs are expected to be cheaper within the next five years in Europe[52]. Range: The range available of BEVs is currently lower than FCEVs, particularly for entry level vehicles. This is predominantly a function of battery pack energy density and is further exacerbated in cold weather due to passenger compartment heating requirements.
	Opportunities Increase range and recharging infrastructure: Widespread availability of rapid chargers will reduce range anxiety and thereby the need for vehicles to have the largest batteries. This can reduce cost and ease supply chain pressure. Despite this, the range of BEVs is expected to continue to improve. Vehicle-to-Grid technology can provide additional benefits to owners and society (as discussed in Section 6).	**Threats** Battery availability; as demand increases, supply chain pressures and the availability of critical materials may hamper battery availability and lead to cost increases. Rare materials and recycling of batteries has the potential to limit BEV uptake and damage public perception. New materials and improved recycling should be developed to mitigate this.

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[49] Volkswagen Group and SEAT reveal electrification plan for Spain, Volkswagen Group, 2022

[50] Column: Volkswagen powers up for the electric vehicle revolution, Andy Home, 2021

[51] North East Scotland Fleet Review: Hydrogen Demand, Peter Speers, 2021

[52] Hitting the EV Inflection Point, BNEF, 2021

Hydrogen Fuel Cell passenger vehicles	**Strengths** Higher energy density by weight and volume compared with BEVs makes hydrogen vehicles lighter than an equivalent BEV and/or have higher range. Refuelling times are similar to those of conventional ICEVs.	**Weaknesses** Efficiency: FCEVs have a well-to-wheel efficiency of less than half that of BEVs. Costs: FCEV propulsion is more complicated and more costly than that of BEVs. Precious metals: such as platinum, are currently required in hydrogen fuel cells to efficiently catalyse the reactions.
	Opportunities Hydrogen hubs: fleet vehicles may allow early adopters of hydrogen vehicles to install dedicated hydrogen refuelling stations before widespread infrastructure is in place.	**Threats** Refuelling infrastructure build-out is minimal, with only 11 refuelling stations existing across the UK. Build-out depends on the uptake of hydrogen for transport (demand) and demand will be limited if there are insufficient refuelling stations, creating a "chicken and egg" situation. Low carbon hydrogen cost and availability may prohibit uptake, as it is needed in numerous sectors. Fuel costs for FCEVs is expected to remain higher than for BEVs.

Through the analysis undertaken in this section, it is considered that BEV is the most likely technology to replace ICE as the dominant vehicle for passenger vehicles. The high well to wheel efficiency has significant societal benefits along with the zero tailpipe emissions, and the performance characteristics are equal or superior to other technologies, benefiting the driver. With improvements in battery technology and charging infrastructure, the weaknesses of BEVs are not considered to be major and are expected to reduce further as consumers become more comfortable with the existing range characteristics of BEVs, range improvements in the coming years and public charging infrastructure is expanded. The main threat to the expansion of BEVs is considered to lie in the supply chain and the environmental and social implications of battery production. Nevertheless, car makers are rapidly increasing their BEV manufacturing capabilities, with Nissan investing £13bn to accelerate their shift to electric cars and Jaguar Land Rover recently starting the conversion of their Halewood plant near Liverpool to produce BEVs.

FCEVs share many of the same benefits relative to ICEs as BEVs. FCEVs show good performance characteristics such as energy density, however, they have a significant weakness in their overall well-to-wheel efficiency. In order to decarbonise, any hydrogen used within a FCEV must be sourced from renewable electricity or CCUS-enabled fossil fuel technologies and, due to inefficiencies, this capacity will have to be far higher where hydrogen is used expansively within passenger vehicle transport than if BEVs are dominant. Furthermore, for an individual consumer, the cost of fuel cells is currently significantly higher than battery drivetrains, increasing the total cost of ownership of FCEVs, and the lack of refuelling infrastructure is considered a significant barrier to uptake. Therefore, it is not considered that any significant passenger vehicle market share will be captured by fuel cells.

Finally, the combination of both BEVs and FCEVs in a hybrid vehicle is not expected to be an architecture with a significant market share going forwards. Though a hybrid would allow a greater range to be achieved, this benefit is outweighed by the downsides of a fuel cell, being the limited recharging facilities and higher cost.

4.2 2-Wheelers

4.2.1 Demand today

Two wheeled transport, consisting of motorcycles, mopeds and scooters, make up a small share of the total energy use and emissions of the UK. In 2020, 103,665 new 2-wheel vehicles were registered in the UK and of these, over a third have an engine capacity less than 125 cc[53]. As shown in Figure 4-1, in 2019 2-wheelers accounted for less than 1% of the UK's transport emissions.

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[53] Statistical Pocket Guide v1, Motor Cycle Industry Association Limited, 2021

Three wheeled transport, including auto rickshaws, make up a greater share of the total energy use and emissions of Asia passenger road transport.

Motorcycles, mopeds and scooters have historically been powered by ICE, though in recent years, as with passenger vehicles, the share of battery powered 2-wheelers has increased. Though concepts for hydrogen fuel cell motorcycles have been presented by the industry, no hydrogen powered 2-wheelers are commercially available in the UK.

No significant change in demand, as measured by vehicle registrations per year, has been observed in recent years, and the level of current demand is expected to continue in the coming decades.

4.2.2 Consumer requirements

Many of the technical and social considerations of passenger cars apply to 2-wheeled transport. Cost of purchase and cost of ownership, re-fuelling infrastructure, range and overall system efficiency.

The use case for 2-wheeled transport will have a significant impact on the choice of clean technology. Scooters and mopeds are typically used in urban areas, often for commuting or short distance deliveries, and typically only require a short range and power. Motorcycles are more powerful and are most frequently used for commuting[54].

Despite the low contribution to emissions of 2-wheeled transport utilising ICE technology, 2-wheelers must also undergo decarbonisation if the UK is going to achieve its net zero target. This is recognised in policy in that, subject to consultation, all new motorcycles and scooters in the UK are to be fully zero emissions at the tailpipe from 2035.

4.2.3 Performance characteristics

In order to meet the expected requirement for zero emissions at the tailpipe, BE and hydrogen fuel cell motorcycles are the technologies which may meet the demand. ICE powered bikes fuelled by power-to-liquid e-fuels or hydrogen are also potential technologies, however these are expected to only feature in niche applications and are not considered likely for mass adoption.

The considerations for battery and hydrogen power with respect to the different performance characteristics discussed for passenger vehicles in Section 4.1.3 are largely the same. Additional considerations present themselves for characteristics in the areas of energy capacity, which is discussed in more detail below.

4.2.3.1 Energy capacity

The technology employed in both battery and hydrogen fuelled 2-wheelers is largely the same as it is for passenger cars, and therefore the energy density is also comparable. Given the light-weight nature of 2-wheeled transport however, the impact of any additional weight from energy storage has the potential to be higher, providing more incentive for alternative technologies to be used.

With a curb weight of 222 kg and a battery capacity of 15.6 kWh, over a quarter of the weight of a battery powered motorcycle such as the Zero Motorcycles ZF15.6+ is comprised of the battery. With this, the bike can achieve a range of 169 miles in the city and 84 miles at motorway speeds[55]. By comparison, the Kawasaki Z1000SX petrol-powered motorcycle with its 19 litre tank, with a 5.8l/100 km fuel consumption and 235 kg curb weight has a range of 203 miles[56]. For low powered 2-wheelers, electric mobility is also available. The Vespa Elettrica features a 4.2 kWh battery accounting for 20% of the 130 kg total weight and giving it a range of 62 miles[57].

Hydrogen, with the use of a fuel cell, has long been cited as the future technology for 2-wheeled transport, however this has not developed into commercially available bikes and therefore a comparison cannot be made at this stage.

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[54] Motorcycle use in England, Department for Transport, 2016

[55] Zero SR, Zero Motorcycles

[56] Z1000SX, Kawasaki

[57] Vespa Electtrica L1, MSC

Nevertheless, a hydrogen fuelled 2-wheeler has the potential to provide improved energy density and range in comparison with an equivalent BE 2-wheeler.

In addition to hydrogen based options, hybrid motorcycles, using both battery energy and hydrogen fuel cells, are being developed, such as the Segway Apex H2. Details of the relative size of the battery, fuel cell stack and hydrogen storage have not yet been made public.

4.2.4 Costs

As with passenger cars, upfront cost and the total cost of ownership are important considerations when assessing the most suitable technology for 2-wheelers.

The cost elements of 2-wheeler transportation, and the implications of alternative fuels, is expected to be largely similar for 2-wheelers as they are for larger passenger vehicles. With no commercially available hydrogen 2-wheelers, and with limited analysis of the total cost of ownership for different technologies, a full appreciation of costs for low-carbon 2-wheelers is not yet available. Nevertheless, it is expected that the trends from the cost assessment of passenger cars will largely be applicable for 2-wheelers. These can be summarised as follows:

- Battery and fuel cell costs are expected to drive the purchase price of battery and hydrogen powered 2-wheelers, respectively. At current prices, this is expected to make fuel cell 2-wheelers more expensive than an equivalent battery 2-wheeler, and this trend would be expected to remain even with increased uptake and economies of scale.
- Fuel costs will align with those of other transport sectors, meaning that fuel costs for hydrogen 2-wheelers will be higher than for battery powered 2-wheelers.
- Maintenance costs are likely to be low for both technologies.

4.2.5 Infrastructure considerations

The infrastructure considerations for 2-wheeled transport again shows many similarities with those of passenger cars. Further considerations for 2-wheeled transport are discussed here.

For battery powered 2-wheelers, due to the lower energy capacity compared with passenger vehicles, lower powered chargers are more likely to be suitable, reducing the investment needed to install chargers at home or at work. Secondly, where a high utilisation is required, for instance for delivery vehicles, battery swapping technology may be developed. As an alternative to time consuming battery recharging, battery swapping solutions are being developed by some of the leading manufacturers of motorcycles. With a battery swapping solution, rather than waiting for the bike to recharge, the rider can swap the depleted battery for a fully charged alternative, thereby taking only a matter of minutes. The Swappable Batteries Motorcycle Consortium includes manufacturers such as Honda, KTM, Piaggio and Yamaha who are working together to standardise swappable battery technology and design, to enable industry wide swapping of batteries.

Hydrogen powered 2-wheelers are expected to rely on public refuelling infrastructure and therefore the considerations and limitations discussed in Section 4.1.5 are expected to be applicable. This is considered a significant drawback for the uptake of hydrogen fuel cell 2-wheelers.

4.2.6 Future outlook

The development of alternative technologies for 2-wheeled transport has, with the exception of a number of concepts, been exclusively with battery powered bikes. Therefore, no specific development milestones are required and it is expected that performance improvements, in terms of energy density and range, along with cost reductions, will continue over the coming decades, supported by the significant development of BEVs.

For hydrogen fuel cell 2-wheelers, development has been limited so far. Though the key technology is considered viable, this has not translated into commercial development. As discussed below, the key challenges for the investment in fuel cell 2-wheelers is around the cost and infrastructure availability.

The sections above highlight the overall considerations for future low-carbon 2-wheeled transport. The table below shows a summary of the different technologies, considering their strengths and weaknesses, and the opportunities for and threats to their development. This includes the specific considerations for 2-wheelers and should be considered alongside the wider analysis presented in the passenger vehicle section above.

Battery electric 2-wheelers	**Strengths** Overlap with passenger vehicles: Given the comparatively smaller size of the 2-wheeler market, benefitting from the technology development and cost reductions driven by the BE passenger vehicle fleet is a major advantage	**Weaknesses** Range is significantly lower for BE 2-wheelers compared with ICE and potentially FC 2-wheelers. Given the size of 2-wheelers, installing larger batteries to compensate is less practical than it is for passenger vehicles.
	Opportunities Battery swapping particularly for lower powered bikes has the potential to mitigate concerns with range and recharging times. Next generation battery chemistries could provide substantial cost savings and forms of integration.	**Threats** (Same as passenger vehicles) Battery availability; as demand increases, supply chain pressures and the availability of critical materials may hamper battery availability and lead to cost increases. Rare materials and recycling of batteries has the potential to limit BEV uptake and damage public perception. New materials and improved recycling should be developed to mitigate this.
Hydrogen Fuel Cell 2-wheelers	**Strengths** Higher energy density of hydrogen by weight and volume compared with batteries may allow hydrogen 2-wheelers to offer increased range and performance. Rapid refuelling is similar to that of conventional ICE vehicles.	**Weaknesses** Complexity: FC 2-wheelers have more components and are more complex than BE 2-wheelers, limiting their development in a relatively small market.
	Opportunities Hub refuelling: As with passenger vehicles, where rapid refuelling is highly valued for fleet vehicles, dedicated refuelling infrastructure can be installed for early adopters.	**Threats** Development horizon: FC 2-wheelers are not commercially available today and have limited concepts in development. With BE 2-wheelers already growing their market share, hydrogen may be too late.

BE power is considered the most likely technology to lead the 2-wheeled market. Today's battery 2-wheelers are able to achieve reasonable range and performance, making them viable alternatives to ICEs. With the significant strength of the BE passenger car market, 2-wheelers are likely to benefit from increased technological and infrastructure developments, and a greater fall in costs.

Hydrogen fuel cell powered 2-wheelers are in contrast not expected to play a significant role in the UK market. This is due to a number of factors including the lack of infrastructure, expected higher costs and the limited development to date. With BE 2-wheelers increasing their market share, FC 2-wheelers may not develop sufficiently before BE options have a dominant position.

Similarly, hybrid solutions are not expected to have a large market share, due to the same drawbacks facing hydrogen 2-wheelers and the expected development of battery technology making the need for additional energy capacity unnecessary.

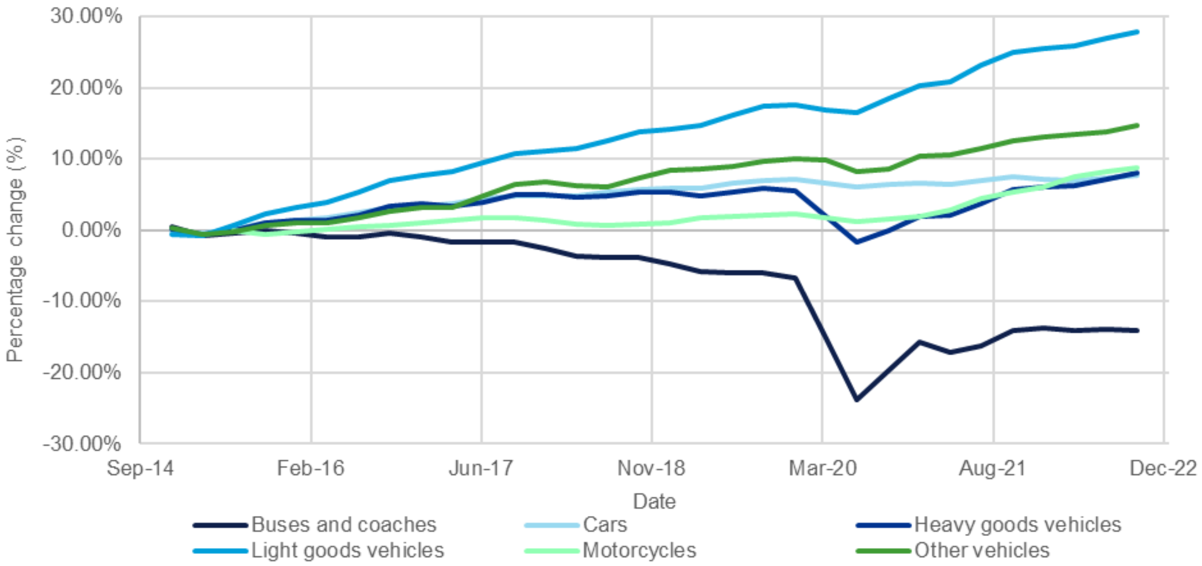
For the highest-powered range of the 2-wheeled sector, some further development is still needed until the technology choice is clear, with BE 2-wheelers today not having sufficient energy density. Nevertheless, this is expected to be a small sector of the market with limited overall impact on energy demand and emissions.

4.3 Light Duty Vehicles

4.3.1 Demand today

There are around 4.5 million light duty commercial vehicles (also known as light goods vehicles, LGVs), such as delivery vans, commercial vans and ambulances licenced in the UK today[12]. The majority of these carry equipment, tools or materials (54%), followed by delivery vans (16%), private use (16%), recreational use (13%) and providing transport for others (1%)[58]. The impact of LDVs on the environment is significant, contributing 12% of the transport sector's emissions in 2019 as shown in Figure 4-1.

LDVs are used extensively across multiple markets, and their use has grown steadily at a rate of approximately 3.3% per annum over the past 8 years[12], as shown in Figure 4-6. This makes LGVs the fastest growing vehicle type today and therefore the demand for new vehicles is expected to remain strong in the coming decades.



Note: Trendlines show moving averages and numbers are compared to the average of Q3 2014 to Q2 2015 values. Data from GOV.UK Vehicle Licensing Statistics.

Figure 4-6 Percentage change in numbers of UK licenced vehicle numbers over time by vehicle type[12]

Of the LDVs licenced in the UK today, 99% are powered by internal combustion engines, only 0.9% are battery powered and <0.1% are powered by hydrogen fuel cells[12].

New battery powered LDV registrations are increasing, with 5% of newly licenced LDVs being BE in Q3 2022[12]. Though at present no fuel cell LDVs are available in the market, Vauxhall have announced plans for a hydrogen fuel cell hybrid version of their Vivaro van.

4.3.2 Consumer requirements

Light duty vehicles are typically commercial vehicles and as such have some different requirements compared with passenger cars. Principally, LDVs are used to transport equipment, tools or materials, and as such the carrying capacity, both in terms of mass and volume is important[58]. Furthermore, with licensed vehicles each driving an average of 77% further than cars in 2021[59], LDVs are used intensively, therefore reliability and low servicing requirements are important.

The higher annual use has an implication on the range requirements. LDVs can be used in a wide variety of applications – in some instances using regular predictable routes or schedules, such as delivery vehicles, and in others the requirements differ from week to week, such as vans used in the building trade. Most frequently, vans are found to

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[58] Final Van Statistics 2019-20, Department for Transport, 2021

[59] Road traffic estimates in Great Britain: 2021, Department for Transport, 2022

return to base after each calling point, however in 17% of instances, vans only return at the end of a day's work[60]. This has implications on the range and refuelling/recharging requirements for prospective low-carbon technologies.

Along with the requirements imposed by consumers, regulations will have an impact on the choice of technology. LDVs shall be subject to the UK government mandate phasing out the sale of petrol and diesel vehicles by 2030, and the requirement for all new vehicles to be zero emission at the tailpipe by 2035. In addition, within a number of UK cities, most notably London, low emission or clean air zones are in existence, in which typically a fee must be paid for vehicles which do not meet the required emissions standards, further encouraging the use of low carbon technologies.

4.3.3 Performance characteristics

As with passenger vehicles, today it is considered that only two low carbon technologies are realistic options for future LDVs, and these are BEVs and hydrogen FCEVs, along with a combination of both in a hybrid solution.

When considering these technologies, factors including efficiency, power, maintenance and reliability, safety, materials supply chain and recycling, development horizon, useability and performance, and emissions are expected to be largely the same for LDVs as they are for passenger vehicles. These factors are therefore not discussed further here. Where some further considerations lie is in the higher load and volume requirements of LDVs and the implication of this on energy capacity and range.

The technology available to battery electric and fuel cell electric LDVs is the same as that available to passenger vehicles. Therefore, the energy density is broadly the same, and in order to meet the required range, the size of the battery or hydrogen tank must be increased.

The Ford E-transit is a fully electric van commercially available in the UK today. The van includes a 68 kWh battery giving it a range of 166 to 196 miles[61]. Other electric vans available such as the Vauxhall Vivaro include options for either a 50 kWh or 75 kWh battery. These capacities are not significantly larger than an average passenger vehicle. One reason for this is the impact a large battery has on the available payload, along with the higher cost. In the UK, the maximum gross weight of a light duty vehicle is 3.5 tonnes, and therefore any additional battery weight reduces the carrying capacity of the vehicle. The Vauxhall Vivaro for instance has either a 143 mile or 205 mile range for the 50 kWh and 75 kWh versions respectively, however the higher battery capacity comes at the expense of a 224 kg reduction in the maximum payload available. Given the inherent disadvantage of battery powered LDVs due to their increased weight, in 2018 the maximum vehicle weight for alternatively fuelled vehicles was increased from 3.5 tonnes to 4.25 tonnes in Great Britain[62]. However an additional training requirement is retained, meaning it is still advantageous to remain below the 3.5 tonne threshold.

The range available to a LDV can be significantly impacted by the payload of the vehicle. The impact on range due to vehicle loading is experimentally researched by Settey et al. however it must be noted that range is also dependent on driving character (speeds, traffic, driving conditions, inclination etc.)[63]. Their experiment used a Nissan Voltia with a payload of 543 kg and emulated the drive of a typical 147 km city-based delivery drive under controlled conditions. The impact of the load on the final battery charge level was a reduction of 6%, which represented a range loss of approximately 15–20 km. It can be understood from fundamental equations that this range impact would be increased especially by hillier conditions, or by an increase in payload (although these effects are minimised by regenerative braking). A reduction in range when carrying heavier loads is not a new phenomenon specific to battery powered LDVs, however the impact is greater given that recharging can take significantly longer than it takes to refuel a diesel van.

Given the greater impact that the lower energy density of batteries has on the range and carrying capacity of LDVs, hydrogen fuel cell LDVs may be more competitive in the market through being able to offer improved performance. As

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[60] Final Van Statistics 2019-20, Department for Transport, 2021

[61] Ford E-Transit, Ford

[62] Changes to license requirements for Alternatively Fuelled Vehicles (AFVs), Department for Transport, 2019

[63] Research into the Impacts of Driving Cycles and Load Weight on the Operation of a Light Commercial Electric Vehicle, Tomas Settey et. al., 2021

previously mentioned, Vauxhall have announced plans for a hydrogen fuel cell hybrid version of their Vivaro van[64]. This version consists of a 45 kW fuel cell and 4.4 kg hydrogen tank, paired with a 10.5 kWh battery, giving it a 249 mile range and a 3 minute refuelling time. With the inclusion of the lithium-ion battery, the fuel cell is able to be lower powered, making it smaller, more efficient and cheaper, with the battery providing additional power under acceleration and enabling the vehicle to make use of regenerative braking. The van will be a plug-in hybrid, allowing the battery to be charged from the grid and undertaking short trips without using hydrogen. As with a battery powered van, an increase in payload will also impact the range available to a fuel cell vehicle, by a similar degree, and therefore fuelling infrastructure is needed to fully benefit from the characteristics of hydrogen. Further fuel cell vans from other manufacturers are also planned for the UK market for 2023.

4.3.4 Costs

The cost considerations for light duty vehicles are similar to those of passenger vehicles. The upfront investment cost as well as fuel costs are expected to be lower for battery electric LDVs compared to fuel cell LDVs. Upfront costs of both are currently higher than an equivalent ICE vehicle, however all passenger and van BEVs are expected to reach parity with ICE vehicles by 2027[52]. For maintenance, the same pattern from passenger cars is expected, with a similar cost of maintenance required for battery and hydrogen fuelled vehicles, both of which would be lower than a diesel powered LDV.

The study also highlights the impact of the congestion zone in cities on the total cost of ownership, in which the diesel vehicles in the study must pay the additional charge, for which the BE and FCEV are exempt. This increases the cost of ownership of the diesel options, making BEVs the most cost effective. A further factor impacting the results of this analysis is the price of diesel, which has increased significantly since the study was conducted. Though hydrogen and electricity prices are also subject to change, the greater volatility of global fossil fuel markets increases the cost risk for conventional light duty vehicles.

Whereas there are no UK government grants available for low emissions passenger cars, for LDVs a grant of up to £5,000 is available where the CO_2 emissions are less than 50g/km and the vehicle is able to travel at least 60 miles without any emissions. Both fuel cell and BE vans are eligible for this grant, helping to offset the increased initial capital cost for the vehicles.

4.3.5 Infrastructure considerations

With regard to BEV charging infrastructure, the requirements of LDVs are much the same as for passenger vehicles. Where vehicles return daily to a central depot, dedicated chargers can be installed to allow overnight charging or rapid charging during the day. In this case, BEV adoption is not constrained by public charging infrastructure or fast charging cost premiums, but rather by the vehicle usage pattern.

As with passenger cars and 2-wheelers, the hydrogen refuelling infrastructure available is a significant barrier to widespread uptake. For fleet vehicles, to combat the infrastructure challenge, hydrogen vehicles can be targeted in the same way as mentioned above, through the installation of dedicated infrastructure. In this solution the business or organisation would need to consider the initial investment cost, along with operating costs, to the cost of the vehicles themselves in their evaluation of the business case. With a total cost of ownership of hydrogen vehicles already being higher than their battery equivalents, it is considered that further benefits of hydrogen vehicles (such as range and refuelling time) would need to be valued highly to make this the preferable business case. Companies, such as NanoSun, have developed a containerised hydrogen refuelling station option for this application[65]. The refuelling station is comprised of nine, type four pressure vessels, capable of holding up to 420 kg of hydrogen at 425 bar[66].

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[64] Vauxhall vivaro e-hydrogen, Vauxhall

[65] Hydrogen facilitates the decarbonisation of diesel vehicles, Nanosun

[66] Mobile hydrogen refuelling station, Nanosun

The requirement for quick refuelling and the ability to use a depot makes vehicles such as ambulances potentially suitable early adopters of hydrogen fuel cell technology. A grant of £460k from Innovate UK has been awarded to Hydrogen Vehicle Systems to develop an electric-hydrogen emergency ambulance.

4.3.6 Future outlook

The analysis in this section shows that many of the considerations for LDVs are the same as they are for passenger vehicles, with both sub-markets currently developing along a similar path. The table below shows a summary of the different technologies, considering their strengths and weaknesses, and the opportunities and threats to their development. This includes the specific considerations for LDVs which should be considered alongside the wider analysis presented in the passenger vehicle section.

Battery electric LDVs	**Strengths** Overlap with passenger vehicles: LDVs are closely related to passenger cars and the strengths of BE powertrains are the same. The combined market size will increase the rate of development benefiting both. Zero-emission vehicles are beneficial in the case of delivery vans and other vehicles that are often idle in urban neighbourhoods.	**Weaknesses** Range is a weakness of current BEVs, and this may be more pronounced in BE LDVs where higher milage and payloads are needed, however this weakness is reducing in severity and isn't a concern for 2050.
	Opportunities (Same as passenger vehicles) Recharging infrastructure and range: Widespread availability of rapid chargers will reduce range anxiety and thereby the need for vehicles to have larger batteries. This can reduce cost and ease supply chain pressure. In addition to continually improving range of vehicles with current systems. Vehicle-to-Grid technology can provide additional benefits to owners and society (as discussed in Section 6).	**Threats** (Same as passenger vehicles) Battery availability; as demand increases, supply chain pressures and the availability of critical materials may hamper battery availability and lead to cost increases. Rare materials and recycling of batteries has the potential to limit BEV uptake and damage public perception. New materials and improved recycling should be developed to mitigate this.
Hydrogen Fuel Cell LDVs	**Strengths** The strengths of FC LDVs are aligned with those of passenger cars. With the higher load and milage of some LDV use cases making these more pronounced, particularly with the total vehicle weight restriction. Rapid refuelling of hydrogen can enable a higher utilisation, which may be required for certain use case, such as emergency vehicles. Zero-emission vehicles are beneficial in the case of delivery vans and other vehicles that are often idle in urban neighbourhoods.	**Weaknesses** (Same as passenger vehicles) Efficiency: FCEVs have a well-to-wheel efficiency of less than half that of BEVs. Costs: FCEV propulsion is more complicated and more costly than that of BEVs. Precious metals such as platinum are currently required in hydrogen fuel cells to efficiently catalyse the reactions.
	Opportunities Hub refuelling: As with passenger vehicles, where rapid refuelling is highly valued for fleet vehicles, dedicated refuelling infrastructure can be installed for early adopters.	**Threats** (Same as passenger vehicles) Refuelling infrastructure build-out is minimal, with only 11 refuelling stations existing across the UK. Build-out depends on the uptake of hydrogen for transport (demand) and demand will be limited if there are insufficient refuelling stations, creating a "chicken and egg" situation. Low carbon hydrogen cost and availability may prohibit uptake, as it is needed in numerous sectors. Fuel costs for FCEVs is expected to remain higher than for BEVs.

The overall outlook for the future market sizes of BE and FC LDVs is similar to that of passenger cars, and BE LDVs are expected to have a leading position in the market. Nevertheless, as highlighted, the impact of energy density and therefore range is higher for LDVs than it is for passenger vehicles, which opens up the possibility of hydrogen vehicles, either as pure fuel cell or range extending hybrid solutions, to have a non-negligible market impact. These are likely to focus on applications which require higher milage and load carrying capabilities, require quick refuelling, and operate from a depot, enabling the installation of dedicated refuelling infrastructure. In these situations, hydrogen FC vehicles may be preferrable despite the increased cost.

4.4 Heavy Goods Vehicles

4.4.1 Demand today

Heavy Good Vehicles (HGV's), defined as lorries with a gross weight of over 3.5 tonnes, are a significant component of the domestic supply chain in the UK, as well as being used extensively in importing and exporting goods. Articulated HGVs are the most common class, with a maximum gross weight of 44 tonnes, and in 2019, articulated HGVs carried 62% of UK road freight (897 million tonnes)[67].

In the UK, diesel fuelled ICE vehicles accounted for almost 100% of heavy-duty vehicle sales. This together with their high milage means that HGVs accounted for approximately 5% of the UK's CO_2 emissions in 2019[68].

4.4.2 Consumer requirements

Heavy goods vehicles are principally concerned with the transportation of goods. The type of goods, their weight and volume, and the trip distances leads to different types of HGVs. An HGV is weight-constrained, however in reality vehicles may be volume-constrained if the density of the goods is not as high, such as when transporting parcels.

The average length of haul for GB-registered HGVs in 2019 was 107 km (66 miles), as calculated by the tonne kilometres divided by tonnes lifted[69], however the vehicles themselves can undertake multiple haulages in a day, leading to increased daily distances. Analysis undertaken by TNO[70] shows the average annual kilometres travelled for rigid and articulated trucks as being 76,996 km and 142,865 km respectively, equating to an average of 296 km and 549 km per day. A typical heavy goods vehicle therefore completes five times the milage of a typical passenger car each year, and as a result, reliability and vehicle lifetime become greater concerns.

Despite the dominance of diesel in the HGV sector, as with the sale of passenger cars, the sale of new diesel HGVs will end at the latest by 2040[71]. In response to the uncertainty in the preferred technology for clean HGVs, the UK government has announced a £200 million, 3-year, comparative study into BE and hydrogen fuel cell powered HGVs. The aim of the study is to gather evidence for the required recharging and refuelling infrastructure, and to help more generally to establish an understanding of the most suitable technology for HGV decarbonisation within the UK[72].

4.4.3 Performance characteristics

For low carbon alternatives to diesel HGVs, BE and hydrogen fuel cell drivetrains are again expected to be the two technologies with the potential for mass market adoption. In addition, concepts for HGVs using hydrogen fuelled internal combustion engines are also in development and must be considered.

The performance characteristics of both drivetrains are aligned with those of other vehicle classes. In order to meet the requirements for long range and high payloads, the focus for HGVs is on the energy capacity of the drivetrain, and the implications this has on the infrastructure required and total cost of ownership.

Battery HGVs have many of the same advantages as has been discussed for passenger cars and LDVs. Due to the high payload, the energy capacity needed is significantly higher than it is for either passenger vehicles or LDVs. With improvements in battery energy density in recent years, a suitable level of capacity can now be achieved, making battery technology viable for many HGV applications. Scania are a leading HGV manufacturer and offer both a rigid and articulated fully electric solution comprising a 624 kWh battery and 410 kW power capability, giving it a 350 km range for a 40 tonne load[73].

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[67] Domestic Road Freight Statistics 2019, Department for Transport, 2020

[68] Final UK greenhouse gas emissions national statistics: 1990 to 2020, BEIS, 2022

[69] Domestic Road Freight Statistics 2019, Department for Transport, 2020

[70] Techno-economic uptake potential of zero-emission trucks in Europe, Dennis Tol et. al., 2022

[71] Decarbonising Transport: A better, greener Britain, Department for Transport, 2021

[72] £200 million boost to rollout of hundreds more zero-emission HGVs, Department for Transport, 2022

[73] Battery electric truck, Scania

A further consideration for battery powered HGVs is the requirement for rests within a journey. In the UK, truck drivers must not exceed 4.5 hours of driving before taking a 45-minute break, and a standard day of driving is 9 hours long. After 4.5 hours, truck drivers could reach up to approximately 270 miles if travelling at an average speed of 60 mph. Provided there is sufficient fast charging infrastructure, battery-electric HGV's could for example be charged during breaks at lorry parks, significantly increasing their range without negatively impacting the business case.

Hydrogen has long been thought of as the preferred technology to decarbonise HGV's, due to its high energy per unit mass allowing for significant power for long range trips without significant additional weight reducing the maximum payload. Nevertheless, no commercially available hydrogen fuelled HGVs are available, limiting the ability to compare the power range and payload capabilities. The HGV manufacturer DAF, together with Toyota and Shell, are in the process of testing a hydrogen fuel cell powered HGVs in the US which has a similar power capability to the Scania and is capable of a 150-mile range[74].

In addition to hydrogen fuel cell HGVs, concepts for hydrogen powered internal combustion engines are in development. DAF is developing a hydrogen fuelled ICE HGV which makes use of the extensive existing knowledge of ICEs and eliminates the requirement for the drivetrain to include a large battery. As discussed, fuel cell vehicles must include a drive battery to provide transient power, allowing the fuel cell to operate at a continuous load. The hydrogen fuel cell trial HGV discussed above includes a 100 kWh battery to provide this function.

In addition, hybrid battery/fuel cell solutions are beginning to be developed to capture the best of both worlds. The Hydrogen fuel cell acts as a range-extender to give up to three times the range of regular battery-electric variants, whilst allowing short journeys to be battery powered to reduce running costs. The battery pack also allows for smaller and cheaper fuel cells to be used. Tevva, a UK-based advanced vehicle developer and manufacturer, have launched a 7.5-tonne hybrid hydrogen-electric truck which has range capability of up to 310 miles[75].

4.4.4 Costs

A full understanding of the costs of different low carbon technology options is associated with some uncertainty given the continued dominance of diesel-powered HGVs in the market, and the limited commercial availability of hydrogen-based technologies. Given the high annual mileage of HGVs, fuel, maintenance and other operational costs have a greater importance than they do for passenger vehicles or LDVs.

A techno-economic analysis undertaken by TNO includes a total cost of ownership calculation for HGVs, covering diesel, battery (with a low and high capacity), and hydrogen fuel cells in four different sub-categories[70]. The study shows that in the 2020's a battery electric HGV is the most expensive option, however significant cost reductions are expected, bringing it almost in line with diesel powered alternatives, and lower than the cost of a fuel cell vehicle (which is also modelled to achieve significant cost reductions in the coming two decades). It is noted that along with significant cost reductions in battery cells, the analysis includes significant battery pack density improvements, going from 184 Wh/kg to 376 Wh/kg from 2020 to 2040. For 2030 to 2035, the total cost of ownership, expressed as the cost per kilometre driven, is lowest for BE HGVs in all cases, with the exception of low daily mileage scenarios in 2030. The fuel cell option stays at a higher price than both BE and diesel options in all scenarios[70]. Nominal battery capacities in the study range from 777 kWh in the 2020's to 616 kWh in 2040 for medium sized trucks and from 1243 kWh in the 2020's to 946 kWh in 2040 for large sized trucks.

A study conducted in the US[76] assesses the most cost effective technology for different cargo types (expressed as being either volume constrained, or weight constrained) and distances travelled. It shows that, as expected, the higher the payload and distance, the greater the need for high energy density. Therefore, where payload and distance are high hydrogen fuel cells are required, and where they are lower, battery technology is the most cost-effective solution. In

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[74] Hydrogen: An interesting option for the future, DAF, 2022

[75] Going the distance: The Tevva hydrogen range extender, Advanced Propulsion Centre UK

[76] Cost-effective technology choice in a decarbonized and diversified long-haul truck transportation sector: A U.S. case study, Lukas Mauler et. al., 2022

addition, the study differentiates between high nickel and LFP battery chemistries, showing a switch to high-nickel as the energy required increases. Ultimately the study suggests hydrogen fuel cell solutions for weight constrained transportation with high range requirements. The results, though not directly applicable to the UK market given the fuel costs and other parameters used, suggests that for high energy scenarios, hydrogen fuel cell technology may also be a viable solution.

4.4.5 Infrastructure considerations

HGVs typically follow established network routes, allowing for standardised refuelling infrastructure in place. The current network provides a template for new recharging and hydrogen refuelling infrastructure.

The development of BE charging infrastructure, led by the passenger car market, is already underway. The charging technology can readily be applied to HGVs if installed at accessible locations at motorway service stations.

The expansion of the network is considered important in the expansion of BE HGVs, as recharging during the statutory 45-minute break may be an important aspect of the business case of battery HGVs.

With the increased capacity of HGV batteries relative to other vehicle classes, the power requirement for charging infrastructure is increased. The Scania battery powered HGV includes a 375 kW charging capability to enable it to recharge fully in 90 minutes. Significant grid infrastructure investment may be needed to allow a service station to recharge multiple HGVs at this power capacity.

Similarly, hydrogen refuelling infrastructure is needed to enable the widespread use of hydrogen HGVs. Though specific businesses may be able to install dedicated hydrogen recharging infrastructure at depots, it is expected that a recharging network will be needed along key freight routes. The limited existing public hydrogen refuelling stations are in many cases not suitable to the size of HGVs.

Further innovative technologies, such as on-road charging, could eliminate the issue of batteries and their range almost entirely. Concepts for on-road charging include Contactless Power Transfer (CPT) systems, providing BEVs with charge using wireless electromagnetic induction without any physical interconnection[77], or pantographs connecting to overhead wires, as used on electric trains[78]. Nevertheless, these options would require significant investment in new infrastructure, and are therefore not a fast solution for decarbonisation and are not included within the modelling to 2050 undertaken in this study.

Finally, according to research undertaken by the University of Oxford, the likelihood of driverless-HGVs within the next 15 years is 79%. In other words, out of 100 lorry drivers, only 21 are predicted to be humans within the next 15 years[79]. The automation of HGV will remove the restriction on driving time; making hydrogen technology more favourable for long-distance goods transportation[80].

4.4.6 Future outlook

The sections above highlight the overall considerations for low-carbon heavy goods vehicles. The table below shows a summary of the different technologies, considering their strengths and weaknesses, and the opportunities for and threats to their development. This includes the specific considerations for HGVs and should be considered alongside the wider analysis presented in the passenger vehicle section.

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[77] On-road charging of electric vehicles, Theodora-Elli Stamati et. al., 2013

[78] Battery strategy goes flat: Net-zero target at risk, House of Lords, 2021

[79] Oxford study: robots will replace freight forwarders before lorry drivers, Polos Zsofia, 2021

[80] Cost-effective technology choice in a decarbonized and diversified long-haul truck transportation sector: A U.S. case study, Lukas Mauler et. al., 2022

Battery electric HVGs	**Strengths** Cost: With development of battery technology in recent years, and the reduction in battery costs, for many applications, BE HGVs are expected to be the most cost-effective solution.	**Weaknesses** Range is expected to be more limited for BE HGVs than alternatives, and the weight of batteries will limit the carrying capacity available, potentially limiting their use in high range and payload applications. Recharging infrastructure specific for HGVs is needed due to their physical size, and the battery capacities. Sufficient rapid chargers are needed at service stations on major freight routes to increase range during drivers enforced 45-minute break.
	Opportunities (Same as passenger vehicles) Increase range and recharging infrastructure: Widespread availability of rapid chargers will reduce range anxiety and thereby the need for vehicles to have the largest batteries. This can reduce cost and ease supply chain pressure. Despite this, the range of BEVs is expected to continue to improve. Vehicle-to-Grid technology can provide additional benefits to owners and society (as discussed in Section 6).	**Threats** (Same as passenger vehicles) Battery availability; as demand increases, supply chain pressures and the availability of critical materials may hamper battery availability and lead to cost increases. Rare materials and recycling of batteries has the potential to limit BEV uptake and damage public perception. New materials and improved recycling should be developed to mitigate this.
Hydrogen Fuel Cell HGVs	**Strengths** The strengths of FC HGVs are aligned with those of passenger cars. The benefit of high energy density is more pronounced for HGVs as it is for passenger cars.	**Weaknesses** (Same as passenger vehicles) Efficiency: FCEVs have a well-to-wheel efficiency of less than half that of BEVs. Costs: FCEV propulsion is more complicated and more costly than that of BEVs. Precious metals: such as platinum, are currently required in hydrogen fuel cells to efficiently catalyse the reactions.
	Opportunities Hub refuelling: New hydrogen refuelling infrastructure is required, which can be focused on depots and key freight routes, making roll out easier than for passenger cars. With fast refuelling times, infrastructure may be simpler to roll out than large installations of high-capacity battery chargers.	**Threats** (Same as passenger vehicles) Refuelling infrastructure build-out is minimal, with only 11 refuelling stations existing across the UK. Build-out depends on the uptake of hydrogen for transport (demand) and demand will be limited if there are insufficient refuelling stations, creating a "chicken and egg" situation. Low carbon hydrogen cost and availability may prohibit uptake, as it is needed in numerous sectors. Fuel costs for FCEVs is expected to remain higher than for BEVs.
Hydrogen ICE HGVs	**Strengths** Rapid refuelling is similar to that of conventional ICE vehicles. Reuse of existing technology lowers development costs and time. High performance: ICEs have good power capabilities, and with sufficient hydrogen tanks, a high energy capacity can be achieved. Hydrogen purity requirement is lower than for FCEVs, potentially lowering fuel costs and increasing availability of suitable fuel.	**Weaknesses** Efficiency: Hydrogen ICE's have a lower efficiency than batteries and fuel cells. Emissions: Hydrogen ICEs produce NO_X upon combustion and are therefore not zero-emission. Engines can run lean and thereby produce significantly less NO_X than current petrol/diesel ICE's, however this results in lower power output.
	Opportunities Hub adoption, as with fuel cell HGVs. Transition technology: Hydrogen ICEs can be a transition technology given the lower development required and the ability to accommodate fuel switching between diesel and hydrogen-diesel mixes.	**Threats** Low carbon hydrogen cost and availability may prohibit uptake as with FCEVs. Refuelling infrastructure is currently limited limiting update of hydrogen fuelled vehicles. Government support: The UK government has launched a 3 year comparative study into batteries and fuel cells, within which hydrogen ICE's are not included.

In the medium term, it is considered that there is no clear technology frontrunner for HGVs, and both battery-electric and hydrogen-based technologies may provide a solution to decarbonise the sector. In addition, efficiency gains and the use of biofuels will also contribute to decarbonisation.

With improvements in battery technology, BE-HGVs are now considered viable and with a number of BE-HGVs commercially available, their share of the sector is expected to increase. Improved technology and the decrease in costs enables BE-HGVs to offer significant range which will be sufficient for many applications. Where the load and range required is within the performance window of BE-HGVs, they are expected to provide the most cost-effective solution.

Hydrogen fuel cell HGVs are expected to provide a viable solution and may be the most economic option for high range and payload applications. Nevertheless, there is significant uncertainty in their development due both to the limited models commercially available and the lack of suitable refuelling infrastructure. These factors and the potential rapid increase in BE-HGVs may further limit the market share available to hydrogen fuel cell HGVs.

Hydrogen ICE HGVs have also been discussed and may compete with fuel cell technology for market share in high range and payload applications. Nevertheless, many of the limitations facing fuel cell vehicles are also applicable to hydrogen-ICEs, which will limit their development, and the emission of NOx may restrict the level of government support in their development.

Given the size and breadth of the HGV market and the myriad of challenges in finding the best clean technology, it is expected that both BE and hydrogen fuelled vehicles will play a significant role in the UK to 2050.

4.5 Buses and Coaches

4.5.1 Demand today

In 2019, buses and coaches made up 2% of GHG emissions in the UK transport sector. Current technology is largely based on ICEs, however driven by the need to improve air quality in urban areas, several FCEVs and BEVs bus fleets are already successfully in operation throughout the country. Go-Ahead Group, a UK public transport operator, has a 15-year hydrogen supply deal in place, with an ambition for a fossil-fuel-free fleet of buses in the UK by 2035[81]. Aberdeen has a fleet of 15 double decker hydrogen fuel cell buses, these have recently clocked up one million miles of service since they were launched in 2021[82]. Equally, the All-electric Bus scheme has already replaced fleets with BE buses and Coventry has been awarded with £50m to fund up to 300 electric buses and associated charging infrastructure[83].

As of March 2020, 2% of the approximately 32,000 buses in operation were zero-emissions[84], with BE buses being the most popular zero emission technology. In 2021 560 BE buses were newly registered, representing 48% of new bus registrations, compared with 55 new hydrogen fuel cell vehicles[85]. Coach travel, with its higher energy demand owing to their increased speed and varied routes, has limited uptake of either BE or hydrogen fuel cell vehicles.

As shown in Figure 4-6, the number of registered buses fell slightly from 2014 to 2019, before a drop from March 2020 due to the impact of the COVID pandemic. Following the easement of COVID restrictions, passenger numbers on public transport have been recovering and it is expected that no significant long-term change in demand will occur over the next three decades.

4.5.2 Consumer requirements

The requirements for buses and coaches align with those of other transport sectors, including safety, reliability and cost. In addition, the performance characteristics of a bus or coach must allow the operator to use the vehicle for its intended use. This in particular requires that the energy capacity of the vehicle is suitable to service the designated route in an efficient and reliable manner. Buses are typically focused on urban areas operating routes with frequent stops and low average speeds. Coaches on the other hand are typically used over longer distances on major roads.

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[81] Go-Ahead forges ahead with plans to launch hydrogen buses in the UK this summer, Sarah George, 2022

[82] Hydrogen bus fleet launched in Aberdeen reaches million mile landmark, Erikka Askeland, 2022

[83] Decarbonising Transport: A better, greener Britain, UK GOV, 2021

[84] Annual bus statistics: England 2019/20, Department for Transport, 2020

[85] Zero Emission Bus Guide, Daniel Hayes et. al., 2022

Particularly in the case of buses operating in urban areas, there is a strong drive to achieve zero emissions at the tailpipe, both from a GHG perspective, and from an air quality perspective. To this end, the UK Government has committed to investing in zero emissions buses, supporting at least 4,000 new vehicles by 2025 along with the required infrastructure[86]. In this role-out both battery-electric and hydrogen fuel cell buses will be considered.

4.5.3 Performance characteristics

To decarbonise the bus and coach sector, BE and hydrogen fuel cell technologies are considered viable. The critical performance characteristic in determining the most suitable technology is the energy capacity and therefore the ability of the vehicle to meet its operational requirements.

BE buses are typically fitted with batteries of capacities up to 500 kWh. The resulting range of up to 250 km is dependent on the particular route, the temperature, and the size/weight of the bus [85]. Owing to their frequent acceleration and deceleration, regenerative braking is an important capability and provides a boost in range of up to 30%[87].

Hydrogen fuel cell buses have the potential to benefit from increased range relative to battery only solutions thanks to the energy content of hydrogen. The fuel cell system used in buses is similar to those of passenger vehicles, however, they have a number of differences. Typically, hydrogen is stored at a lower pressure relative to passenger vehicles, 350 bar rather than 700 bar, and have lower powered fuel cells in the range of 30 kW to 50 kW, instead relying on batteries to provide the peak power requirements. With a hydrogen consumption of 6-7.5 kg/100km and storage tanks with 25 kg to 50 kg of hydrogen, ranges of up to 500 km are achieved[87].

The Alexander Dennis Enviro400, a double-decker bus, comes in both BE and hydrogen fuel cell versions, with key parameters presented in the following table.

Table 4-1 Comparison of key parameters associated with the Alexander Dennis Enviro400 battery and fuel cell buses

Alexander Dennis Enviro400EV[88]	Alexander Dennis Enviro400FCEV[89]
375/382 kWh LFP battery	45 kW or 60 kW fuel cell NPROXX composite pressure vessels, 29.4kg at 350bar 30 kWh LTO battery
Max power of 300 kW (2x150 kW motors)	350kW peak and 250kW continuous power
Up to 257 km (160 miles) on a single charge	Up to 482 km (300 miles) on a single fill

The most significant difference is, as expected, the range available. Whether this is important will depend on the specific route required, and the possibility of charging throughout a day. The total cost of ownership of both solutions should be assessed for selected routes to determine the optimum solution and a local transport provider.

Intercity coaches travel long distances typically on regular routes, and therefore have requirements more akin to HGVs than they do to urban buses. In addition, with a lower weight relative to an HGV, up to 19.5 tonnes in the UK, the energy required is lower, increasing the possibility of BE and hydrogen operation.

With a lower uptake of low carbon technologies, the number of commercially available BE coaches is limited. The Yutong TCe12 is the first full electric coach available in the UK, with capacity for 50 passengers. The TCe12 consists of

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[86] UK on track to reach 4,000 zero emission bus pledge with £200 million boost, Department for Transport, 2022

[87] Zero Emission Bus Guide, Daniel Hayes et. al., 2022

[88] Enviro 400 EV, Alexander-Dennis

[89] Enviro 400 FCEV, Alexander-Dennis

a 281 kWh LFP battery connected to a single 350 kW drive motor. With a top speed of 100 km/h (62 mph) it has a quoted range of up to 250 miles on a single charge. The TCe12 also has an option for a larger 350 kWh battery[90].

Though not available yet in the UK, the Hyzon high floor FCEV coach is a 50+ seat coach consisting of an 80 kW fuel cell, 141 kWh battery and 195 kW power capability. With a 35 kg, 350 bar hydrogen storage capacity, the vehicle has a quoted driving range of 250 miles[91].

4.5.4 Costs

A total cost of ownership study was used to compare the costs for battery and fuel cell buses[92]. It included total ownership costs for each technology type for 2023 and 2030, including the total capital expenditure (CAPEX), total operational expenditure (OPEX) and maintenance costs.

The CAPEX cost of a BE bus was approximately double that of a diesel bus, with the BE bus saving significantly on operational costs, comprising predominantly of fuel costs. The maintenance cost for the BE bus is comparable to those of the other technologies[92].

FCEV buses currently have higher CAPEX costs than BE buses, as well as intermediate operational costs, giving them the highest total cost of ownership in 2023 at 1.46 EURO/km in the best-case scenario. By 2030, this is predicted to change as the CAPEX costs of FCEV buses show the greatest reduction (from 0.89 EURO/km to 0.58 EURO/km), however the TCO remains above that of BE buses (1.09 EURO/km FCEV compared to 1.05 EURO/km for BEV)[92].

Current predictions for the total cost of ownership show both BEV and FCEV buses becoming better economic options than diesel buses by 2030, with BE bus costs comparable to diesel bus costs today. This study highlights the uncertainty in TCO predictions and sensitivity to different input assumptions, with cost predictions overlapping such that either BEV or FCEV buses may have the lowest cost of ownership.

Due to the sparse availability of zero emission coaches today, no reliable data comparing the TCO between conventionally fuelled and zero emission coaches is available. Based on the available assessments for buses and HGVs however, it is expected that the total cost of ownership for BEV and FCEV coaches will reduce over time, with FCEV coaches being more competitive for higher range applications. The timeframe before zero emissions coaches become better economic options than diesel coaches, however, may be longer than this timeframe for buses, with National Express targeting their UK coach fleet to be zero emissions by 2035, 5 years after their UK bus fleet target[93].

4.5.5 Infrastructure considerations

The availability of suitable charging and refuelling infrastructure is crucial to the adoption of battery and fuel cell buses and coaches.

Charging infrastructure for buses and coaches can be tailored to the specific requirements of the operator and will involve the installation of a depot of chargers to enable overnight charging. In addition, the use of opportunity charging during the day may be adopted to enable increased range. Concepts including pantographs as shown in Figure 4-7 can also be used. As with HGVs, given the size of bus and coach batteries, chargers used for opportunity charging will need to be high powered which will have implications on the local electricity grid.

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[90] Yutong TCe12 Full electric, zero emission coach, Pelican Yutong, 2021

[91] Hyzon high-floor coach, Hyzon motors

[92] Development of a Total Cost of Ownership Model to Compare BEVs, FCEVs and Diesel Powertrains on Bus Applications, Giacomo Di Vece et. al., 2022

[93] Our strategy, National Express

Figure 4-7 Pantograph opportunity charging as used at Birmingham airport[94]

For hydrogen powered buses and coaches, through returning to key hubs or having a regular depot, widespread refuelling infrastructure may not be required, and fleet operators may be able to install dedicated refuelling infrastructure at their facilities. This will remove the requirement for widespread public refuelling infrastructure to be available before fuel cell vehicles can be adopted.

4.5.6 Future outlook

The sections above highlight the overall considerations for low-carbon buses and coaches. The table below shows a summary of their strengths and weaknesses, opportunities and threats. This includes the specific bus and coach considerations and should be considered alongside the analysis presented in the passenger vehicle section.

Battery electric Buses & Coaches	**Strengths** Speed: For buses, the average speed is low, reducing the energy required, making BE buses more competitive with other technologies, particularly with the benefit of regenerative braking. For Coaches, this is not applicable. Opportunity charging can in many situations be incorporated into the schedule of both buses and coaches.	**Weaknesses** Range: With the high weight and speed of coaches, the lower energy density of batteries has a greater impact on coach travel, making BE coaches unsuitable for certain existing routes.
	Opportunities (Same as passenger vehicles) Increase range and recharging infrastructure: Widespread availability of rapid chargers will reduce range anxiety and thereby the need for vehicles to have the largest batteries. This can reduce cost and ease supply chain pressure. Despite this, the range of BEVs is expected to continue to improve. Vehicle-to-Grid technology can provide additional benefits to owners and society (as discussed in Section 6).	**Threats** (Same as passenger vehicles) Battery availability; as demand increases, supply chain pressures and the availability of critical materials may hamper battery availability and lead to cost increases. Rare materials and recycling of batteries has the potential to limit BEV uptake and damage public perception. New materials and improved recycling should be developed to mitigate this.

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[94] ABB brings its Mission to Zero to Birmingham airport, Smart Transport, 2019

Hydrogen Fuel Cell Buses & Coaches	**Strengths** The strengths of FC HGVs are aligned with those of passenger cars. Energy density: The benefit of high energy density is more pronounced for coaches as it is for passenger cars. Rapid refuelling: For sectors requiring high utilisation, rapid refuelling can keep vehicles in services for longer each day.	**Weaknesses** (Same as passenger vehicles) Efficiency: FCEVs have a well-to-wheel efficiency of less than half that of BEVs. Costs: FCEV propulsion is more complicated and more costly than that of BEVs. Precious metals: such as platinum, are currently required in hydrogen fuel cells to efficiently catalyse the reactions.
	Opportunities Hub refuelling: FC buses are currently in commercial use, providing valuable experience and helping to drive development.	**Threats** (Same as passenger vehicles) Refuelling infrastructure build-out is minimal, with only 11 refuelling stations existing across the UK. Build-out depends on the uptake of hydrogen for transport (demand) and demand will be limited if there are insufficient refuelling stations, creating a "chicken and egg" situation. Low carbon hydrogen cost and availability may prohibit uptake, as it is needed in numerous sectors. Fuel costs for FCEVs is expected to remain higher than for BEVs.

Unlike the other road transport sectors, both BE and FC drivetrains are in use today within the UK bus fleet. Though both technologies have been demonstrated to be suitable, through the analysis presented here, it is expected that BE buses will take a larger share of the market due to their suitable performance, expected lower cost and overall improved system efficiency. Hydrogen fuel cell buses are expected to provide services in areas where the route requirements limit the ability of battery vehicles to operate economically, for instance when the range is higher and opportunity charging infrastructure is not installed.

For coaches, neither technology has a significant market share today and both are expected to play a role in the future. BE coaches benefit from many of the advantages discussed for other road transport sectors, however, may be limited in the range they can economically offer. Hydrogen fuel cell coaches may be able to offer increased range, but will be limited by the availability of refuelling infrastructure, which is a significant risk.

In addition, due to the expected dominance of battery powered passenger cars and the resulting significant investment and development in battery technology, the ability of battery powered buses and coaches to develop more quickly may give batteries the advantage.

4.6 Off-road Vehicles

4.6.1 Demand today

Offroad vehicles includes a whole range of specialist equipment, for instance warehouse material handling forklifts, agricultural vehicles (such as tractors), and construction and mining machinery.

Within national statistics, off-road vehicles are considered part of the manufacturing or agricultural sectors, and their emissions are therefore not included in Figure 4-1. Data from the Climate Change Committee shows that in 2018, manufacturing and construction contributed 12% of the UK's CO_2e emissions and of this, 10% (6 $MtCO_2e$) were from off-road mobile machinery (ORMM), with the majority being in construction[95]. Within agriculture, combustion of fuels, including both in stationary and mobile equipment, accounts for 4.7 $MtCO_2e$ of emissions, or 9% of total agricultural emissions[96]. Taken together, these sectors are a significant contributor to GHG emissions in the UK.

There is a wide variety of different applications for off-road vehicles, the technology choice used today varies depending on the application and user. Forklifts used for material handling in warehouses are in many cases already LPG or battery powered to reduce emissions, and manufacturers are advanced in considering alternative technologies to further reduce these. Toyota for example have 90% of their range being either battery or hydrogen fuel cell[97]. Nevertheless,

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[95] The sixth carbon budget: Manufacturing and construction, Climate Change Committee, 2020

[96] Agri-climate report 2021, Department for Environment Food and Rural Affairs, 2021

[97] Hydrogen fuel cell technology, Toyota

despite the success of lower carbon technologies in some applications within the sector, the dominant energy source in the sector as a whole is diesel, which is used extensively in construction and agricultural equipment. Therefore, to achieve the UK's decarbonisation ambitions, new cleaner products are needed to address these harder to abate applications. A number of other construction and mining equipment OEMs are developing or have announced BE equipment, some of which is already available commercially.

4.6.2 Consumer requirements

The requirements for vehicles in the sector are specific to each use case. Heavy machinery used within construction or agriculture have many of the requirements of HGVs, including high energy and power capacities, good reliability and low costs. In other sectors such as forklifts, indoor operation may be required which can make emissions as well as noise important considerations, with energy and power capacities less so. For indoor applications, supporting infrastructure can be readily installed, however for remote operation in agricultural or construction applications, the infrastructure requirements are an important consideration and constraint, as vehicles are utilised across different sites throughout the UK, and are not necessarily near infrastructure, let alone charging infrastructure. It is noted that the UK Government ban on selling new ICE vehicles in 2030 does not appear to apply to off-road vehicles at present.

4.6.3 Performance characteristics

The performance characteristics required depend on the specific application and therefore a variety of technologies can be suitable within off-road vehicles.

In the smaller scale of the off-road vehicle sector, forklift trucks represent a technology which has shown some development into low carbon technologies. Forklifts today use either battery technology (both lead acid and lithium-ion), LPG or diesel, with the latter being used for heavy duty applications, and the former being more suited to warehouses where low noise and emissions is valued. Hydrogen fuel cell forklifts have limited market share today; however, they can be suitable in a number of applications. Fuel cells can be suitable for indoor applications, as they are also low noise and don't produce harmful emissions, and with their high-power capacities they can be an alternative to heavy duty use cases. For outdoor based use, hydrogen also presents a potentially easier refuelling scenario for remote applications.

Construction vehicles are large and heavy-duty, making their energy capacity a key consideration. Diesel is the typical energy source at present, however low carbon technologies including BE, FC and hydrogen-ICE (HICE) are all considered viable solutions. For heavy machinery used in construction, given the similarity with HGVs, many of the aspects discussed in Section 4.4 are applicable here. As discussed, battery technology has many advantages where the energy capacity required isn't prohibitively large including lower operating costs, low maintenance, low vibration and noise, and high well-to-wheel efficiency. Komatsu recently announced a 20-tonne battery powered hydraulic excavator which is set to be commercially available in 2023[98]. The PC 210E is fitted with a 451kWh capacity battery and has a 123 KW motor, making it capable of operating for 8 hours when fully charged. Several other construction and mining equipment OEMs are developing or have announced BE equipment, some of which is already available commercially.

The operational period required is considered a significant challenge for BE construction, mining or agricultural vehicles. For instance, during busy periods such as harvesting, tractors may need to operate continuously for 16 hours. It is not expected that this level of performance can be achieved with current technology, meaning that businesses will need to use other technologies with a higher energy capacity or quicker refuelling times to meet the operational requirements. Furthermore, particularly in the case of agricultural vehicles, weight can also be an important consideration and limiting factor for BE drivetrains. A report from the Royal Agricultural Society of England[99] suggests battery powered tractors greater than 50 horsepower would require large batteries to provide the required energy and the added weight of the batteries may damage the soil. Current commercial BE tractors are more suited to small scale farming applications.

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[98] Accelerating to achieve safe, highly productive, smart and clean workplaces of the future, Komatsu, 2022

[99] Decarbonising Farm Vehicles and Future Fuels, Nick McCarthy and Keith Budden, 2022

FarmTrac have developed an electric tractor with a 22 kW battery pack (equivalent to a 25-horsepower diesel engine), with a 6-hour runtime[100]. The charging time from 0 – 100% takes 8 hours.

Hydrogen powered construction vehicles are also in development, with both fuel cell and hydrogen-ICEs being considered. In 2020, JCB announced a 20-tonne excavator prototype powered by a hydrogen fuel cell. The prototype has undergone significant testing; however, no performance characteristics are available in the public domain[101]. Since the announcement, JCB has turned its attention to the developed a hydrogen-ICE which has been tested in a backhoe loader and telehandler[102]. JCB state that the HICE is more able to match the varying loads required in its vehicles than a fuel cell, which is more suited to continuous operation. Liebherr are also developing a hydrogen combustion powered 20-tonne excavator, to be fitted with their H966 13.5 litre 6-cylinder hydrogen engine[103]. Full details of the engine and excavator are not available at present; however the overall performance is expected to be similar to that of conventionally fuelled alternatives.

Off-road vehicles can operate in a range of environments, from snow and storms to inside of warehouses. Though the general maintenance and reliability considerations of the battery and hydrogen fuel cell vehicles is discussed in Section 4.1.3.4, the different environments off-road vehicles operate in must be considered. Fuel cells in dusty high-vibration environments may require more frequent maintenance of the air filtration system. This is also leading to greater development of hydrogen combustion engines which are more tolerant of such environments, as hydrogen has the advantage of being able to be used in conventional diesel engines in a hydrogen-diesel mixture. The H_2 Dual Power tractor for instance is based on a standard diesel engine with additional hydrogen storage tanks (5, 11.5 kg, 350 bar cylinders). The engine can operate on 100% diesel or a hydrogen-diesel mix, lowering CO_2 emissions in proportion to the amount of hydrogen used and reducing NOx to negligible levels[104]. Dual-fuel technologies such as this enable hydrogen to be used to reduce emissions without significant development and upfront purchasing costs and help build understanding in using hydrogen ahead of future 100% hydrogen-ICE solutions.

4.6.4 Costs

As commercial vehicles, the total cost of ownership of different off-road vehicle technologies is a key consideration for businesses, particularly as many operate on minimal margins and require a predictable outlook.

Due to the sparse availability of low carbon off-road vehicles today, few direct comparisons of the total cost of ownership between different technologies are available, and therefore higher uncertainty exists in the eventual costs. Nevertheless, similar cost trends as seen in other vehicle sectors, particularly HGVs, are expected to be applicable and can be used as proxies. This suggests that for vehicles with lower energy requirements, batteries are likely to be the most cost-effective solution, whereas hydrogen is predicted to become more cost-effective for higher energy requirement applications.

BE powertrains will be the most cost effective in many applications, particularly with the expected decrease in battery pack costs over time. This is expected to be the case for forklifts and other lower powered vehicles as used in construction and agriculture. The dominant cost for these vehicles compared to diesel equivalents is expected to be upfront purchase cost, with maintenance and fuel costs comparatively lower. As the energy capacity of the vehicles increases however, the additional cost of batteries is proportionally higher than the cost of additional hydrogen storage, making battery technology less attractive. This is expected to be the case for medium- and heavy-duty off-road vehicles, fuelling the interest in HICEs.

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[100] Farmtrac FT25G: A viable alternative to a diesel compact tractor, Farmtrac

[101] JCB leads the way with first hydrogen fuelled excavator, JCB, 2020

[102] Hydrogen campaigns, JCB

[103] H966, Liebherr

[104] H2 Dual Power, Blue Fuel Solutions

For fuel cells vehicles, the total cost of ownership is driven by the upfront capital cost of the fuel cell, this is in many instances prohibitively large at present. If production volume is sufficient going forwards, cost reductions may be achieved, but as noted above, some technical challenges with fuel cells remain, potentially limiting this. Hydrogen fuelled ICEs show good promise with regards to CAPEX due to parallels with conventional ICEs. Although, with lower efficiency relative to BE or FC technology, fuel costs for HICE vehicles would be expected to be higher, as would maintenance costs due to the additional complexity of off-road ICEs. These factors must be considered once vehicles are commercially available.

It is expected that the purchase cost of battery and hydrogen off-road vehicles will reduce, broadening the use-cases of zero emission solutions. The current market trajectory points towards HICE and battery construction equipment instead of fuel cell options, which may prove a cheaper development option given the potential for retrofitting existing ICE fleets. Greater use of other fuels such as biomethane in existing ICE powered vehicles is expected as a transitionary fuel.

4.6.5 Infrastructure considerations

As with other sectors, the limiting factor may be the availability and logistics of refuelling and recharging infrastructure.

BE operations would in many situations require similar infrastructure to that of other transport technologies. The required infrastructure will need be built into the operations of the vehicle, for instance with overnight charging together with fast chargers to provide opportunity charging. Particularly for smaller vehicle classes such as forklifts, an alternative to opportunity charging or where a higher utilisation is need, is to make use of battery swapping or on the go charging.

For remote and temporary BE vehicle operation, ensuring suitable infrastructure is expected to be more of a challenge, which may make other technologies more suitable in these situations. Whereas mobile refuelling trucks can be used for diesel or hydrogen operations, with the weight and size of battery packs, mobile recharging vehicles are considered less likely to become a viable option.

Hydrogen refuelling operations will need to be installed at operations where hydrogen is in use. The dedicated infrastructure will add to the capex cost, however, it means vehicles and the sector will not rely on widespread refuelling stations being installed and accessible. The use of hydrogen will enable quick refuelling and high utilisation. For remote and temporary operations, temporary refuelling stations could be facilitated with containerised systems such as NanoSUN’s mobile hydrogen refuelling solution[105].

Agriculture is often characterised by remote locations, a further consideration for both battery and hydrogen options are off-grid generation of energy from wind or solar combined with a battery or electrolyser installation. Self-sufficiency is already the case for some users, who source biomethane from upgraded biogas from on-site anaerobic digester plants. As discussed, due to the higher well-to-wheel efficiency of BEVs, more own generated energy is required for hydrogen solutions than an equivalent BE one.

4.6.6 Future outlook

The sections above highlight the overall considerations for low-carbon off-road vehicles. The table below shows a summary of their strengths and weaknesses, opportunities and threats specific to off-road vehicles, and should be considered alongside the analysis presented in the passenger vehicle section.

Battery electric off-road vehicles	**Strengths**	**Weaknesses**
	Emissions are zero at the tailpipe, making BE vehicles suitable for indoor applications. Noise emissions are also greatly reduced compared with ICEs making indoor and urban applications more comfortable. Vibrations are lower, reducing operator fatigue over long shifts.	Lower energy density results in higher weight and shorter operating times without recharging. For certain applications this makes BE off-road vehicles unsuitable. Remote & temporary operation is often required, in which case supplying recharging infrastructure is more challenging.

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[105] Hydrogen construction, Nanosun

	Opportunities Where businesses are able to generate their own electricity, further fuel savings can be made.	**Threats** (Same as those for passenger vehicles) Battery availability; as demand increases, supply chain pressures and the availability of critical materials may hamper battery availability and lead to cost increases. Rare materials and recycling of batteries has the potential to limit BEV uptake and damage public perception. New materials and improved recycling should be developed to mitigate this.
Hydrogen Fuel Cell off-road vehicles	**Strengths** Energy density is higher than BE vehicles allowing extended operation before refuelling. Rapid refuelling: For sectors requiring high utilisation, rapid refuelling can keep vehicles in services for longer each day.	**Weaknesses** Transient loads are less well managed by FCs, reducing efficiency Environmental factors such as vibrations and dust have a greater impact on fuel cells than on BE or HICE powertrains
	Opportunities Hub refuelling: dedicated refuelling infrastructure can be installed for fleet vehicles.	**Threats** Refuelling infrastructure build-out is minimal, with only 11 refuelling stations existing across the UK. Build-out depends on the uptake of hydrogen for transport (demand) and demand will be limited if there are insufficient refuelling stations, creating a "chicken and egg" situation. Low carbon hydrogen cost and availability may prohibit uptake, as it is needed in numerous sectors. Fuel costs for FCEVs is expected to remain higher than for BEVs.
Hydrogen ICE off-road vehicles	**Strengths** In addition to those of FC off-road vehicles: Dual-fuel technology can allow existing ICEs to be used, reducing development time and cost. Transient response is better than FC technology, allowing vehicles to meet the varying power demands required. Environmental conditions such as vibrations and dust due not pose a significant issue for HICEs, making them suitable for many applications Purchase costs are expected to be lower than a BE or FC alternative due to the use of existing technology without the use of expensive materials.	**Weaknesses** Efficiency of ICEs is expected lower than FCs and BE vehicles, increasing fuel costs and the total energy required for the sector. Emissions: though the emission of CO$_2$ is eliminated, NO$_x$ emissions are still expected. Noise emissions is higher than for FC or BE alternatives, making it less suitable for indoor or urban operation.
	Opportunities In addition to those of FC off-road vehicles: Early development: Significant investment and development is going towards HICE solutions. If sufficient early commercial success can be achieved, a leading market position may be possible, further improving the case for HICEs.	**Threats** (Same as those for passenger vehicles) Low carbon hydrogen cost and availability may prohibit uptake, as it is needed in numerous sectors. Fuel costs for HICEs is expected to be higher than for alternative technologies.

The technology choice in the off-road sector is expected to be a mixture between several different technologies. Battery technology has many advantages and is expected to dominate where the energy required is not prohibitively high and where recharging infrastructure can be installed. This is therefore applicable to most forklifts and other material handling equipment, and to some smaller vehicles in the construction and agriculture sectors. For larger applications in construction and agriculture, particularly where operations are remote, BE vehicles are not expected to be suitable and therefore FC and HICE solutions will be used. With the higher level of development and investment and lower upfront costs, HICE are expected to take a significant market share in the near term, with FC solutions requiring further development to improve the transient performance and reduce costs.

4.7 Future market evolution

Following the appraisal of the road transport sectors and the modelling undertaken as part of the DNV ETO, a projection of the future market size and technology choice is presented below. The split of sub sectors and propulsion systems is the same as those in the DNV ETO, and is a balance between market size relative to the total energy system, prediction confidence and computational efficiency.

The sectors considered are as follows:

- Passenger vehicles: Includes cars, SUVs, pickups, vans and taxis, with vehicles seating 3 to 8 people.
- Commercial vehicles: Includes HGVs, buses, coaches and utility vehicles.

Due to the low energy use across the 2- and 3-wheeler sector, these are not included separately within the model.

The propulsion systems considered for both Passenger and Commercial vehicles are as follows:

- combustion: any engine that produces mechanical energy by combustion of a fuel, which in this context refers to internal combustion engines.
- electric: any engine that produces mechanical energy without combustion of a fuel, which in this context refers to batteries or fuel cells.

The results for electric propulsion systems are further broken down to BE and hydrogen fuel cell electric.

It is considered that hydrogen fuelled ICEs will be applicable to only niche applications and are not currently commercially available today. Therefore, hydrogen fuelled ICEs are not included within the future forecast.

The number of new car sales and total vehicle numbers by propulsion system is presented in Figure 4-9 and Figure 4-10 respectively, along with Table 4-2.

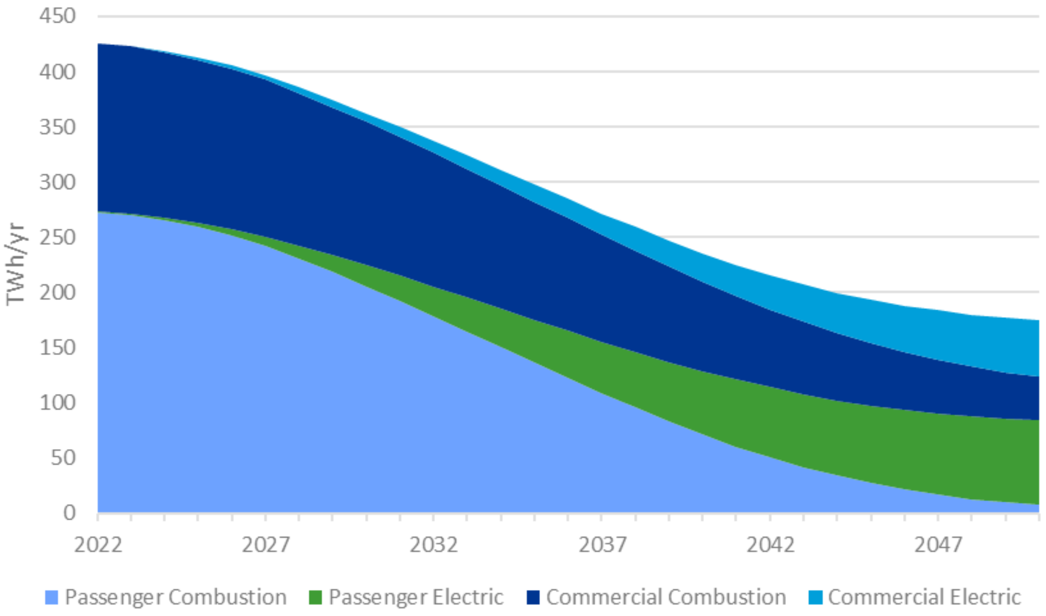

Figure 4-8 UK vehicle annual energy demand by vehicle and engine type, up to 2050[106]

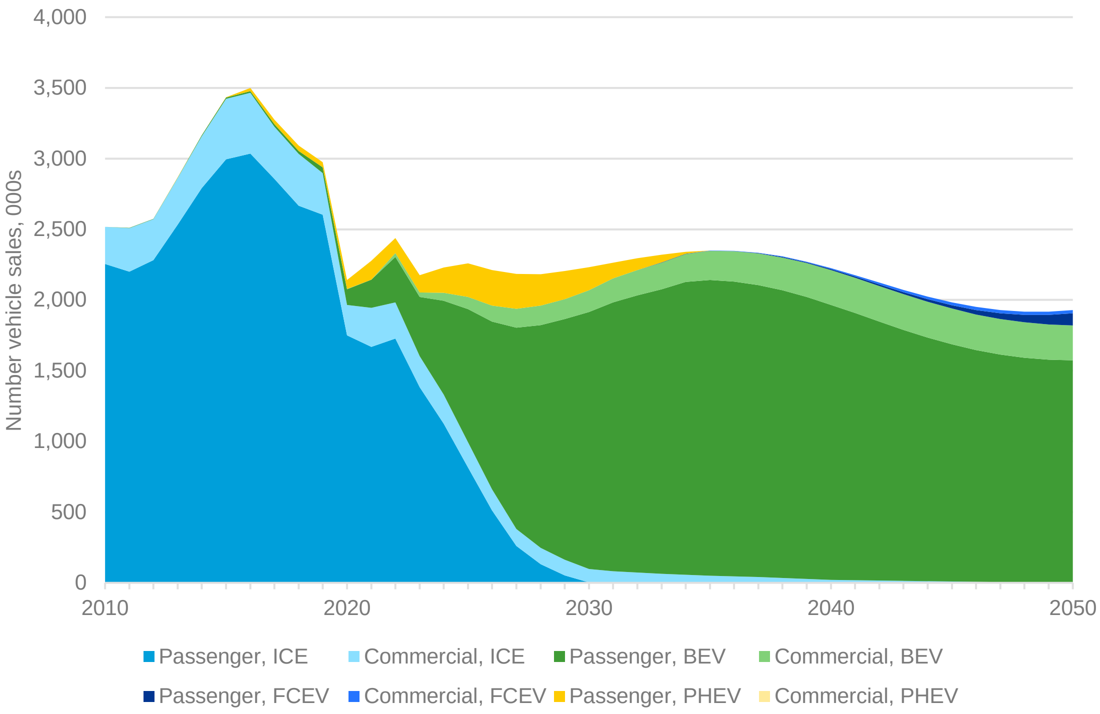

Figure 4-9 Road vehicle UK sales by engine type, in 1000s[106]

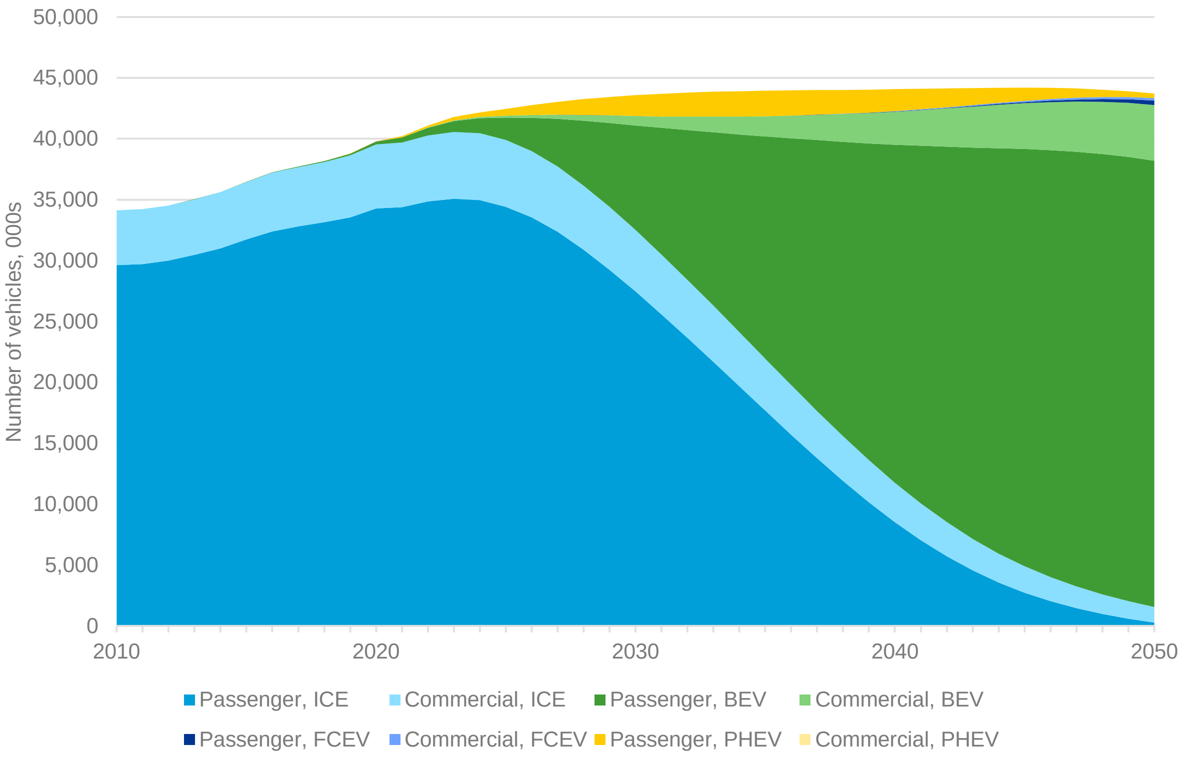

Figure 4-10 Total numbers of road vehicles in use in the UK by engine type, in 1000s[106]

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[106] Energy Transition Outlook, DNV, 2022

Table 4-2 Projection for annual new vehicle sales and total fleet size by propulsion system in thousands[106]

	Propulsion system	2022	2030	2040	2050
Passenger vehicle sales	ICE	1,728	-	-	-
	BEV	321	1,817	1,944	1,568
	FCEV	0	0	6	87
	PHEV	105	163	0	-
Commercial vehicle sales	ICE	255	95	21	5
	BEV	29	155	247	247
	FCEV	0	0	7	23
	PHEV	-	-	-	-
Total vehicle sales		2,438	2,230	2,225	1,930
Passenger vehicle fleet	ICE	34,869	27,387	8,470	264
	BEV	612	8,646	27,790	36,648
	FCEV	0	1	22	366
	PHEV	167	1,724	1,817	369
Commercial vehicle fleet	ICE	5,412	5,045	3,248	1,295
	BEV	32	780	2,709	4,566
	FCEV	0	0	21	205
	PHEV	-	-	-	-
Total vehicle fleet		41,092	43,583	44,077	43,713

The total number of vehicles is expected to grow slightly from 41.1 million today to 43.6 million by 2030, remaining stable thereafter. For passenger cars, both the number of sales and total number of vehicles shifts dramatically from ICEV dominated to BEV dominated between today and 2050. By 2030, BEVs account for over 92% of passenger vehicle sales, with PHEVs accounting for the remaining 8%. This is in line with the upcoming ban on new sales of petrol and diesel cars in the same year. In terms of existing stock, BEVs are expected to account for up to 27% of the passenger vehicle stock by 2030, rising to more than three quarters by 2040, and 99% by 2050. Mainly due to high cost of hydrogen, FCEVs are expected to be much slower in their uptake, with no significant market share until the 2040s, and rising to 5% of new vehicle sales by 2050. The use of FCEVs is expected to be concentrated in certain niche applications, for instance vans and SUVs where a higher range is required, or where owners need a high utilisation and fast refuelling.

Due to the requirement for greater power and range and the slower pace of development from manufacturers, the commercial segment will lag somewhat behind in electrification, maintaining a 38% market share for ICEVS by 2030, 8% by 2040 and less than 2% by mid-century. Nevertheless, BE commercial vehicles are expected to have a leading position within the market by mid-century, with a 90% share of new vehicle sales and in terms of the commercial vehicle stock, the share of BEVs will rise to 13% in 2030, 45% in 2040, and nearly 80% in 2050. The greater energy density needed in certain commercial vehicles increases the share of FCEVS, which rises to 8% of new sales by 2050. FCEV uptake is expected to be concentrated in high payload HGVs, some coaches and off-road vehicles, along with some fleet vehicles where high utilisation and rapid refuelling is required. Outside of these areas, the lower costs are expected to drive consumers to BEVs, and therefore FCEVs are expected to have only a more minor uptake in buses, which will predominantly go down the battery electric decarbonization route. In addition, though modelled as fuel cell powered vehicles, hydrogen may also be used within internal combustion engines, particularly in the off-road segment (for instance construction and agricultural vehicles). The use of hydrogen will be heavily dependent on the availability of refuelling stations, which is not expected to be widespread but instead concentrated on specific uses (with dedicated refuelling infrastructure) and freight routes.

For consumers, a leading consideration when purchasing a new vehicle is cost. BE options have already fallen through the fossil fuel total cost of ownership line, however buyer behaviour lags cost developments, as other considerations such as range and ease of charging are considered important. In addition, it is expected that buyers of passenger vehicles in particular will consider purchase price to be the main factor, putting less emphasis on the lower running costs. Therefore, efforts to reduce the cost of batteries, and therefore the purchase cost of BEVs, and expand the public recharging network is crucial to the success of BEV uptake. Though direct financial support from the Government for the purchase of BEV passenger cars is not expected, support for commercial vehicles is currently available, helping uptake. Government support for a charging network build-up is considered important in the near term, until momentum is sufficient that further support is not needed.

Based on the market share of each technology and the expected number of kilometres driven each year, the total energy demand by fuel type is presented in Table 4-3 and shown graphically in Figure 4-11. Total mileage (passenger and commercial combined) will increase by about 10% by mid-century compared with today, however, even with this vehicle growth and the overall demand for vehicle-miles driven rising, the UK will experience a decline in road sector energy demand thanks to widespread electrification bringing significant improvements in overall energy efficiency. Despite recent improvements in fuel efficiency of ICEs, they are considerably less efficient compared to BEVs, therefore they require a greater initial energy prevision which is illustrated in Figure 4-11, where the bulk of energy prevision pre-2030 is from oil-based fuels for ICEs. Even with the limited uptake of hydrogen within the road transport sector, 15 TWh/yr of hydrogen is expected to be required per year in 2050, or 9% of the total demand.

Table 4-3 Total annual UK road transport energy demand by fuel type, in TWh/year[106]

	2022	2030	2040	2050
Electricity	2	29	84	115
Oil	406	309	136	42
Natural gas	1	1	0	0
Hydrogen	0	0	2	15
Bioenergy	16	17	8	2
Total	**425**	**356**	**230**	**174**

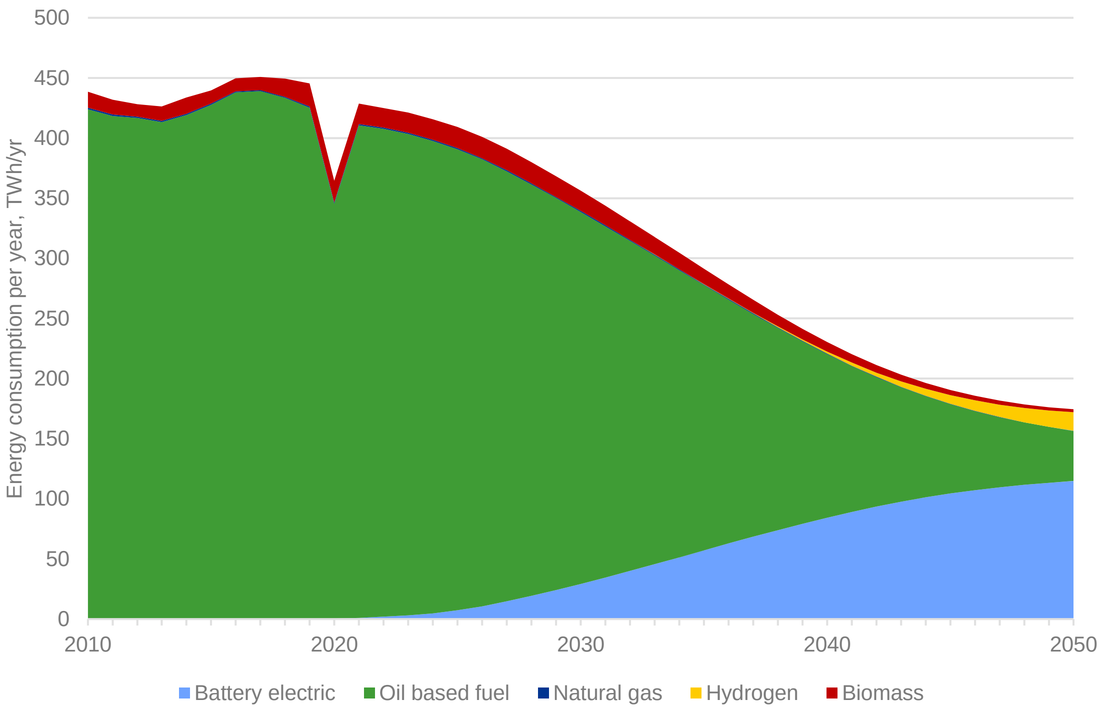

Figure 4-11 All UK road transport energy demand by carrier[106]

Given the significant uptake of BEVs, across all parts of the road transport segment, the key requirements and characteristics of the BEV fleet are presented in Figure 4-12. They show a rapid decrease in the cost of batteries, from approximately $200/kWh today to approximately $40/kWh in 2050. This is a primary driving force in reducing the total cost of ownership of BEVs to approximately 60% of the cost of an ICE vehicle at its minimum. After the 2030s, the relative total cost of ownership of BEVs increases slightly due to an increase in ongoing operating costs. This occurs mainly as a result of an assumption that in the longer term there will be an increased usage of fast charging stations, and there is a cost premium associated with using fast chargers relative to regular home charging, in addition to some form of taxation that will be applicable to EV users.

The reduced battery price also allows the average battery capacity to increase by 57% between today and 2050, which leads to improved range of EVs, reaching average values of over 600 km and 700 km for passenger and commercial vehicles respectively. Finally, the infrastructure required is summarised by the expansion of the network of fast chargers, from a small number today to over 350,000 by 2050.

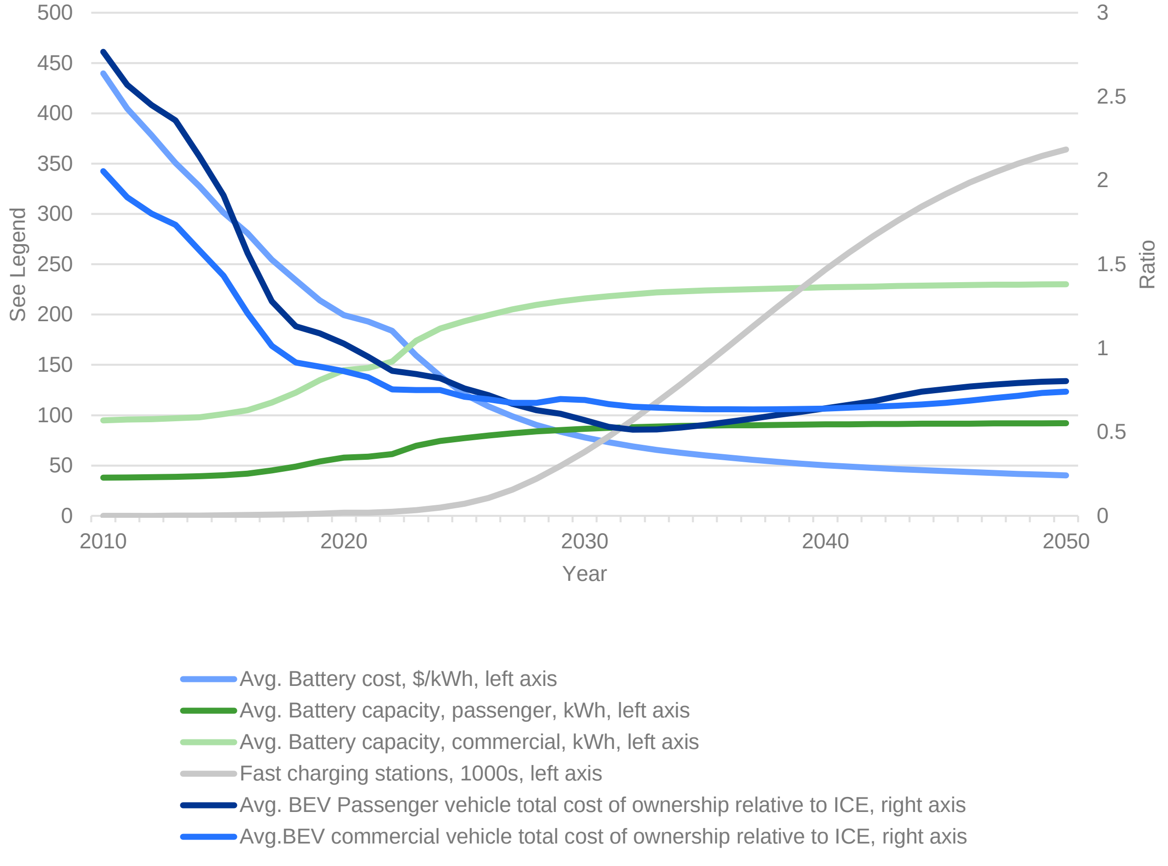

Figure 4-12 Key parameters associated with the rapid expansion of UK battery electric vehicles[106]

All in all, the road transport sector represents a large market for battery technology. The battery capacity contained within the UK road transport fleet in each year is presented in Figure 4-13, along with the annual additions sold into the market. At its maximum, occurring in 2037, the road sector has a requirement for almost 240,000 MWh of additional battery capacity per year, which is 10 times the annual new capacity requirement of today.

Figure 4-14 shows an estimate of the total fuel cell capacity and capacity additions per year. An assumed average fuel cell capacity of 130 kW per passenger vehicle and 350 kW per commercial vehicle is used. Total fuel cell capacity rises to about 120 GW in total by 2050, at which point annual capacity additions will be still rising at just below 20 GW/yr.

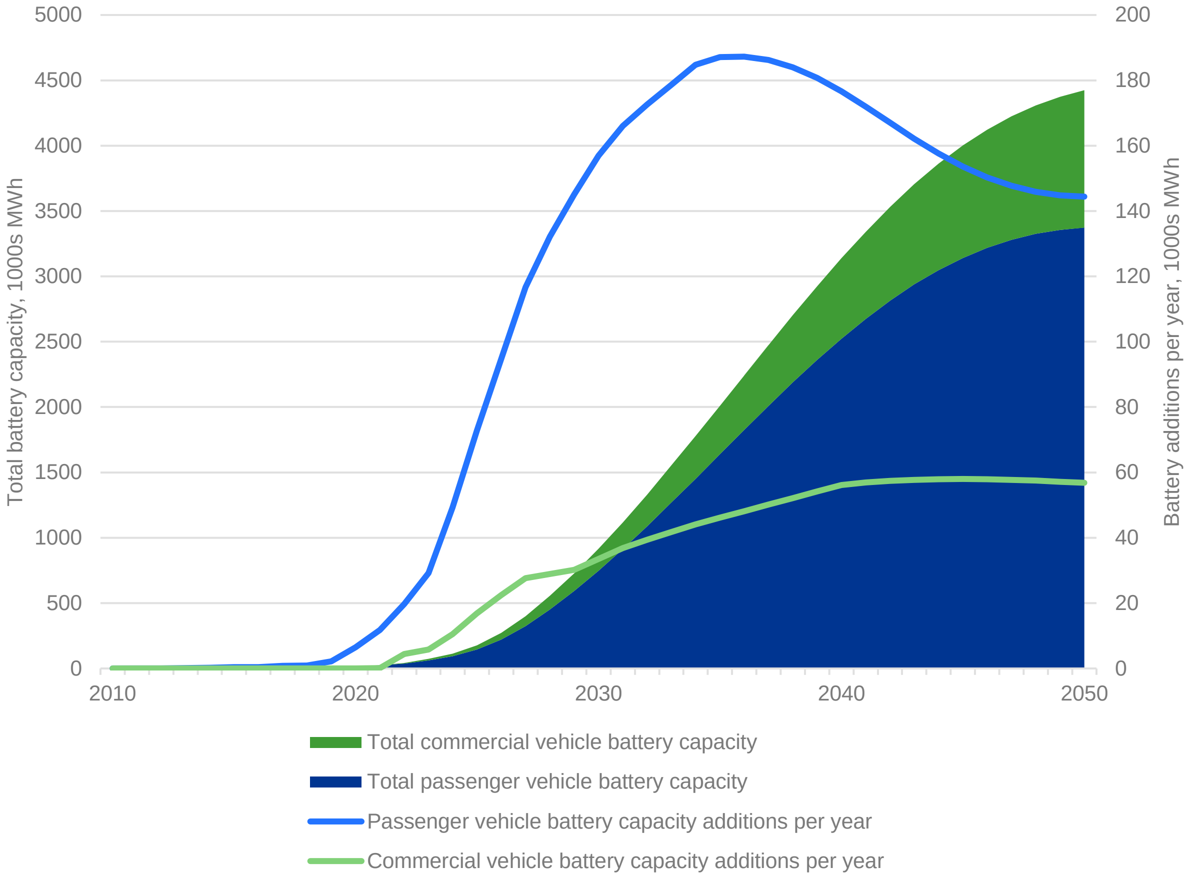

Figure 4-13 Total UK fleet wide battery capacity and annual capacity sold in road transport

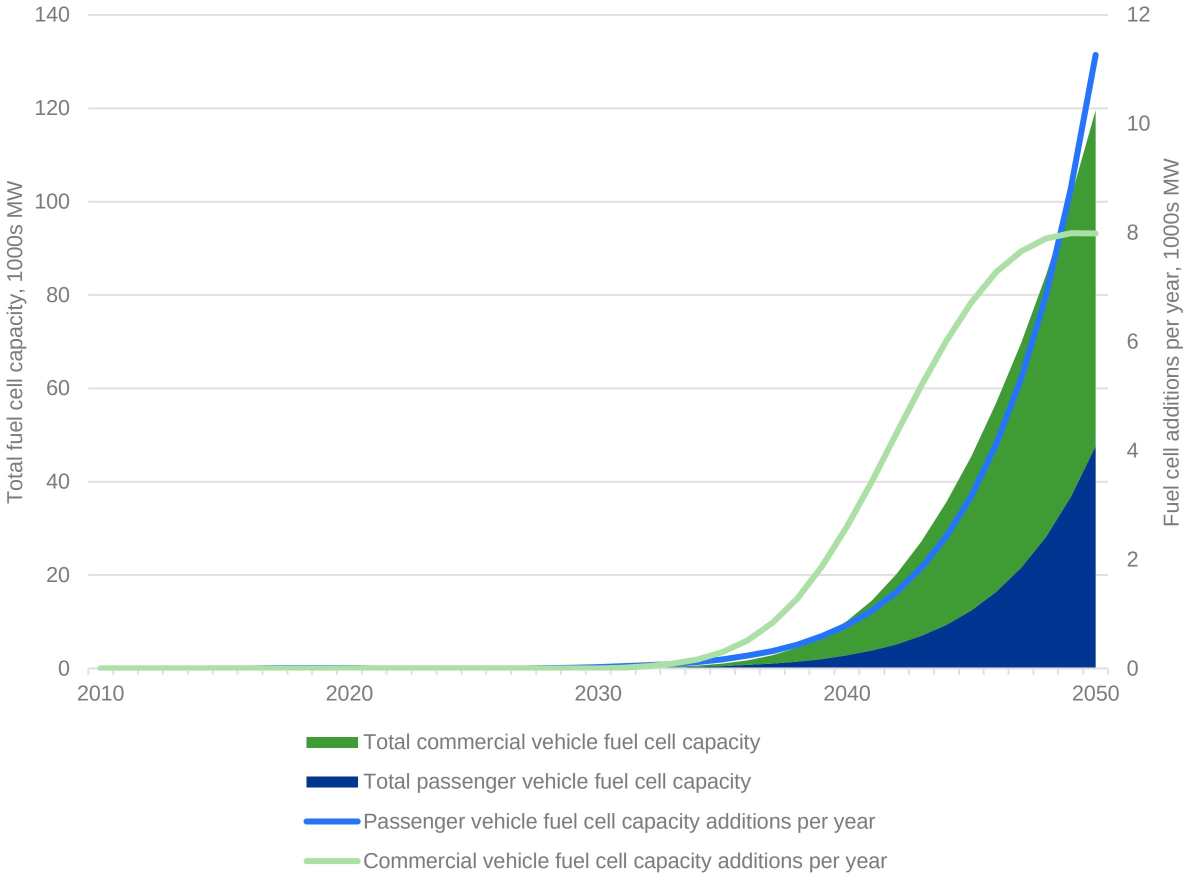

Figure 4-14 Total UK fleet wide fuel cell capacity and annual capacity sold in road transport

5 AVIATION, MARITIME AND RAIL

Following the analysis of the road transport sector, it is also important to consider the aviation, maritime and rail transport sectors which together contribute 1/3rd of the emissions from the transport sector.

5.1 Aviation

5.1.1 Demand today

Aviation accounted for approximately 3% of global CO2 emissions in 2019[107]. In the UK, domestic aviation contributed 1% of transport emissions, combined with international aviation this grows to approximately 21% of UK transport emissions. It is important to note that there is no globally agreed method to allocate emissions from international aviation, and these estimates are made based on refuelling in the UK. According to the International Air Transport Association (IATA), the UK air transport sector contributes $120 billion gross value to the UK's GDP, with 1.6 million jobs. Europe and North America are the UK's largest markets in terms of air transport connectivity, with a share of 79% and 7.5% of passenger flows respectively[108].

The aviation industry today predominantly operates using jet fuel, a refined kerosene, together with a small number of light aircraft using aviation-grade petrol (AVGAS). In addition, there are some bio-based synthetic aviation fuels (SAF) which when blended with aviation fuel are used as a drop-in fuel requiring no modifications to existing equipment. The limits on SAF blending varies from 10% to a maximum of 50% depending on the production process. Emission reductions to date has largely been achieved through efficiency improvements and, other than the small use of SAFs, the use of low carbon technologies has been negligible. Thanks to improvements in efficiency over the past two decades, energy intensity of domestic and international aviation has been decreasing, however these improvements are slowing[109]. With the limited progress in decarbonising to date, aviation is considered a hard-to-abate sector.

The advanced air mobility industry (eVTOLs - electric vertical take-off and landing) is growing, with $7 billion of new investment in 2021, more than doubling the total disclosed investment over the previous decade. The market for advanced air mobility is expected to continue growing, with five of the ten largest aerospace OEMs and four of the largest airlines actively engaged in it[110]. As shown in Section 5.1.7, passenger demand is expected to increase, as is the number of new aircraft brought into service. eVTOLs are small electric aircraft that are targeting a new taxi and delivery market of people and high value goods over short distances. eVTOLSs do not require significant runways or hangers due to their vertical capabilities and small size but are generally not designed for over 10 passengers at present. They are expected to open up new markets and routes for aircraft.

Unmanned Aerial Vehicles (UAVs) or drones are rapidly becoming an important part of various industries beyond military applications. The UK drone market is expected to increase by 14% between 2022 and 2028[111]. This is driven by an increasing range of applications in the commercial and government sectors, such as utilities, agriculture, and emergency services and control response. In a best-case drone adoption scenario, the UK drone market is estimated to be worth £45 billion to the economy and support 650,000 by 2030[112]. Key challenges for the UK drone market include industry and public perception, skills, technology, and regulation.

5.1.2 Consumer requirements

Aviation has three primary sectors, commercial (passenger and cargo), general aviation (public services, personal and business use) and military (combat, cargo, and reconnaissance). Generally, flights are categorised as international,

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[107] Tracking Aviation, IEA, 2020

[108] The Importance of Air Transport to United Kingdom, IATA, 2018

[109] Tracking Aviation, IEA, 2022

[110] Future Air Mobility, McKinsey, 2022

[111] Aerospace (September 2022). The Study of Electrical Energy Power Supply System for UAVs Based on the Energy Storage Technology

[112] PWC (2022). Skies without Limit. The potential to take the UK's economy to new heights

national, or regional, with business models generally based on full-service, low-cost, chartered or cargo/freight markets. Short-haul flights are seen to be less than 3 hours, with long-haul flights being greater than 6 hours.

The global fleet of aircraft is primarily commercial, with over half of the world's aircraft used for passenger and cargo flights. Demand for cargo has increased since the pandemic, and business travel has reduced. Passenger planes are forecasted to account for over 36,000 of the globe's nearly 40,000 aircrafts operating in 2030[113]. Commercial aircraft bodies are historically divided into three categories: regional, narrow body and wide body. Narrowbody, midsize, widebody segments collectively accounted for 93% of CO2 emissions in 2019 and are projected to account for 96% of CO2 emissions in 2050.

The requirements placed on aircraft by airlines depends on their purpose and the load, distance, and specific business case. As the industry looks to decarbonise, airlines require aircraft that can provide a similar service to those of today while adhering to the stringent international safety regulations that aircraft are certified to.

Long-haul aviation has many of the same challenges as those for short-haul, however this is exacerbated by the greater energy and power required. In addition, the decarbonisation of the long-haul aviation sector, even more so than for short-haul operations, requires international collaboration to ensure the infrastructure requirements for a given technology is available at all airports served by a fleet. Therefore, short-haul aircraft are expected to be the first to see alternative technologies implemented, initially in general and then commercial aviation sectors.

Current and near-future low-emission aircraft are expected to target the commuter and regional turboprop sections of the market, which have a median stage length of 160 km and 386 km respectively. These sections account for 4% and 9.3% of today's global aviation departures respectively[113]. For commercial aircraft, the categories have the suggested requirements as displayed in the following table.

Table 5-1 Suggested aircraft categories and their suggested range, passenger numbers, and mass[114]

Aircraft Type	Mission Lengths (km)	Passenger Numbers	Mass (kg)
Regional	~930	~30 – 75	~50,000
Narrow body	~1900	~100 – 200	~100,000
Wide body	~>3700	~200 – 400	~250,000

The decarbonisation of the aviation industry is being supported by the UK Government as well as the industry as a whole. As set out in the recently published Transport Decarbonisation Plan and Jet Zero Consultation, the UK Government is committed to achieving net zero aviation by 2050, with domestic flights to reach net zero by 2040. A target is to have zero emissions routes in the UK by 2030. Under the current strategy's plans, the UK aviation sector will not reach net zero by 2050 without carbon offsetting. The plans expect passenger numbers to increase by 70% from 2021 to 2050[115].

5.1.3 Performance characteristics

Aviation is considered a "hard-to-abate" sector due to the high energy and power required. Nevertheless, a range of technologies are being considered including synthetic aviation fuels (SAF's or e-kerosene), hydrogen fuel cells, hydrogen gas turbines and batteries. SAF's can be bio-based or they can be produced through power-to-liquid techniques with hydrogen as a feedstock. The eventual aim is to develop 100% sustainable "drop-in" fuels which do not require blending with fossil fuels, and can be used in present aircrafts and infrastructure, preventing changes in fleets and infrastructure for alternative aviation technologies. The UK government has voiced its commitment to increasing the

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[113] Performance Analysis of Regional Electric Aircraft, The International Council on Clean Transportation, 2022

[114] Performance Metrics Required of Next-Generation Batteries to Electrify Commercial Aircraft, ACS Energy Letter, 2020

[115] Jet Zero Strategy, Department for Transport HMG, 2022

amount of SAF used in the aviation sector to start to make an impact on the emissions reductions from the existing aircraft fleet.

SAFs, as will be discussed, are expected to be an expensive solution, and therefore only used where other low carbon technologies are not suitable, for instance for long-haul flights. The sections below will therefore primarily compare the capabilities, requirements and advancements of hydrogen and battery-based aircraft technologies. Battery-electric aircraft consist of the same basic elements as electric road vehicles – a battery connected through an inverter to an electric motor, which in the case of an aircraft drives a propeller. Hydrogen-aircraft can either make use of fuel cells providing electrical energy or can use combustion within a jet or turboprop engine to provide propulsion.

5.1.3.1 Efficiency

The overall efficiency of an aircraft depends on its size and design to a greater degree than it does on road transport, given the high speeds and aerodynamic lift required. This is in addition to the efficiency of the propulsion system and energy source. Reducing the empty mass fraction (fraction of aircraft mass with no payload or energy storage to the total take-off mass of the aircraft) of an aircraft is desirable in all cases, but especially with respect to battery-based aircraft as it directly increases its battery mass fraction for a constant payload and maximum take-off mass.

Battery-electric aircraft typically have the highest efficiency of all the technologies available. BE aircraft are more efficient at converting their stored energy into propulsion when compared with jet engines, and a high proportion of the electrical energy used to charge a battery remains available to the aircraft, giving it a high well-to-wake efficiency. Generally electric motors are more efficient than combustion processes, with an efficiency of approximately 75% to 90% or better, as demonstrated by the NASA X-57 aircraft, compared with fossil fuelled engines that are around 30% efficient. During cruise, the resulting difference can be a factor of 2.1 to 3.2[113]. This difference is more pronounced when comparing electric motor aircraft with those of smaller commuter aircraft that use piston-based engines. Overall, compared to aircraft flown on e-kerosene, an electric aircraft could be 4.5-6.9 times more energy efficient.

Hydrogen fuel cell powered aircraft would use the same electric motor and propeller combination as in a battery aircraft, however the conversion of hydrogen fuel to electricity involves greater losses from a well-to-wake perspective, as described in Section 4.1.3.1. Jet engines have a lower fuel conversion efficiency compared with fuel cells; however, they are required by the high-power demand of larger aircraft. Nevertheless, due to the lower efficiency, where possible it is advantageous to use fuel cell technology to reduce the amount of hydrogen fuel required.

SAFs are a significantly denser way of using energy from hydrogen. The drawback of SAFs however is the requirement for significantly more input energy in their production and distribution, compared to liquid hydrogen (for use in fuel cells or gas turbines). Figure 5-1 shows a breakdown of the efficiency losses for the required processing steps. The production of SAFs includes the Fischer-Tropsch process, which significantly lowers the overall efficiency.

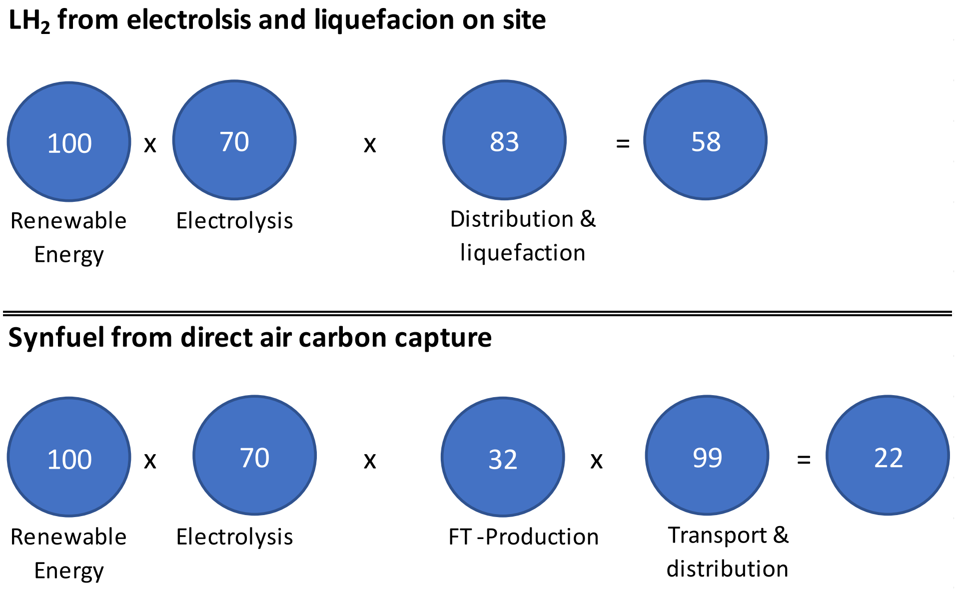

Figure 5-1 Well-to-tank efficiency of Synfuel (a form of SAF) and liquid hydrogen for use in aviation[116]

5.1.3.2 Energy capacity

Aircraft operate at higher speeds and travel significantly greater distances than other forms of transport. In order to achieve this, significant energy is required, which is greatly influenced by the energy density of the propulsion system.

As discussed in Section 3, battery technology today has a lower energy density compared with fossil-based fuels. This is a significant limitation in their ability to be used in aviation. Nevertheless, battery technology is expected to provide viable solutions to the aviation industry, starting with smaller aircraft. Commuter and eVTOL (electric vertical take-off and landing) aircraft are generally smaller in size and fly short distances. Commuter and eVTOL aircraft are initially looking for batteries with an energy density of around 300 to 350 Wh/kg[117], this is nearly achievable at present with advanced cells[118] and using next generation battery chemistries such as lithium-sulphur[119], along with potential further developments[120].

The battery pack specific energy required varies for different aircraft types. Regional aircrafts have an average specific energy of 600 Wh/kg, Narrow Body aircrafts have an average specific energy of 820 Wh/kg and Wide Body aircrafts have an average specific energy of 1280 Wh/kg[114].

A specific energy of 500 Wh/kg is viewed as an important benchmark for achieving commercial flights, however even at this specific energy only 25% of the current average range of regional aircraft would be met. A higher value is likely to be required for commercial aircraft that addresses the regional market. The increase in specific energy with aircraft size is primarily due to the longer-range use cases of the larger aircraft and their higher cruising altitudes. High specific energy is required to address ranges flown by larger aircrafts.

Current scaled technology has an energy density of around 250 Wh/kg. This is expected to increase to 300 Wh/kg by 2030 and potentially with further advancements to 500 Wh/kg by 2050[113]. To achieve this significant development, lithium-sulphur and lithium-air batteries are seen as contenders for the aviation sector due to their high specific energy characteristics. Along with the chemistry itself, ensuring safety is of paramount importance, and safety requirements are

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[116] Hydrogen-powered aviation by 2050, Fuel Cells and Hydrogen Joint Undertaking, EU, 2020

[117] Zenlabs eVTOL Battery Technology, Vertical Mag, 2022

[118] Amprius Technologies, 2022

[119] Faraday Battery Challenge Funded Projects Booklet, UKRI, 2021

[120] Technology Roadmap Electrical Energy Storage, 2020

a potential barrier to battery aircraft. Current commercial aircraft lithium battery pack requirements are so strict that the batteries that provide backup power on airliners have an energy density of 64 Wh/kg, due to the safety packaging that encases each cell[121].

A further consideration, particularly for long-haul aviation where the energy required is significantly higher, is that the battery weight is borne for the duration of the flight, unlike for liquid fuelled aircraft within which the weight of the fuel decreases as it is burnt. As a result, batteries would have a significant penalty for long-haul flights, especially on maximum take-off and landing loads. With today's technology, an aircraft would need to carry more than 50 kg of battery weight to replace 1 kg of kerosene[122], and therefore, based on the review of battery technology, battery only flight has limited-to-no potential in the long-haul aviation sector.

Hydrogen-powered aircraft have the benefit of greater energy density by mass of hydrogen fuel; however, the volumetric energy density of hydrogen is much lower than traditional aviation fuel. Liquified hydrogen has an energy density by mass of around 34,000 Wh/kg (excluding the associated equipment) and contains about 2.5 times more energy per kilogram compared with kerosene, however, requires approximately four times as much space for fuel in comparison to kerosene[123]. Hydrogen powered aircraft are targeting 12,000 Wh/kg, including equipment[116] and the architecture of aircraft would therefore have to change considerably to adapt to the larger tanks required for hydrogen flight.

New aircraft designs may allow ideas such as blended-wing body aircraft to be developed, with associated aerodynamic advantages. Nevertheless, it takes time and significant investment to develop a new fleet of hydrogen aircraft, therefore they are likely to come only later in the 2040's. Airbus has three different architectures for their ZEROe program of hydrogen-based aircraft that all use a liquid hydrogen system, they are a turboprop, a narrow-body and blended-wing body. The turboprop is to carry <100 passengers and have a range greater than 1,800 km, and the other two types are to carry <200 passenger with a range greater than 3,600 km. At present longer ranged hydrogen-based aircraft are not expected to occur by 2050.

Hybrid hydrogen-electric aircraft may also be used to decarbonise aviation. Utilising a high specific energy fuel during the low power cruise phase of a flight would reduce the weight issue batteries currently present, whilst using battery power during take-off to boost the aircraft's performance will allow smaller cheaper fuel cells to be used[124]. Nevertheless, aircraft concepts with a hybrid propulsion system are limited and therefore significant further development is needed before this becomes a viable mass market option.

Finally, all aircraft are mandated to maintain emergency reserve energy for contingencies, as per the CAA's Skyway Code, these depend on the length of flight and the aircraft used and for less dense energy systems such as battery and hydrogen, the impact can be significant. A proposed value based on the USA's FAA commercial reserve requirements is 30% of the battery state of charge or of the hydrogen system[125].

The energy requirements of drones depend on the type and its associated payload. High-altitude long-endurance and medium-altitude long-endurance drones have different energy requirements than octocopter drones for example. Like all aircrafts weight is a critical constraint for drone use, with the propulsion system consuming the majority of the power and with battery life typically less than 60 minutes. Drones typically use lithium-polymer (LiPo) and nickel-cadmium batteries, similar to those in consumer electronics, as they offer high energy density, low self-discharge, long cycle life and are relatively lightweight.

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[121] Faith in batteries, Aerospace America AIAA, 2021

[122] How airlines can chart a path to zero-carbon flying, McKinsey, 2020

[123] Fact Sheet: Hydrogen, IATA, 2019

[124] Power management control and delivery module for a hybrid electric aircraft using fuel cell and battery, Pia Hoenicke et. al., 2021

[125] Technical and environmental assessment of all-electric 180-passenger commercial aircraft, Albert Gnadt et. al., 2019

5.1.3.3 Power capacity

Power capacity is a key parameter for aircraft design and determines the maximum take-off loads that can be achieved.

Commuter and eVTOL aircraft have a relatively low power requirement due to their smaller size, and current battery research is likely to address this market which is expected to be the first commercially viable market within the sector. Advancements in battery technology in recent years, driven through the development of high-performance electric vehicles, has led to significant improvements in discharge rates and power capacities. The Rolls-Royce Spirit of Innovation racing electric aircraft has a 400 kW powertrain including a 1,600 W/kg battery.

For the commercialisation of hydrogen fuel cells in aviation, it is considered new fuel cell technology will need to achieve up to two to three times more system power density than current fuel cell systems, with an improved density of 1.5 - 2 kilowatts per kilogram (kW/kg). Current fuel cell power density is around 0.75 kW/kg.[116] Therefore, from a power perspective, hydrogen fuel cells are considered suited to the short-haul aviation sector, however it is expected that larger aircraft requiring more power would utilise hydrogen jet engines. In this case, fuels cells could still be incorporated to power auxiliaries and be fuelled from boil off from the main hydrogen storage tanks. Hybrid systems of hydrogen turbines and fuel cell systems could optimize the higher power densities of turbines with the higher efficiencies and lower emissions of fuel cell systems.

The gas turbine is the most power dense propulsion solution, making it most suitable for long-haul, large aircrafts. The power density of hydrogen gas turbines is currently around 4 kW/kg, however the Aerospace Technology Institute forecast this to increase to 6.5 kW/kg by 2025, and to 7.6 kW/kg by 2050[126].

5.1.3.4 Maintenance & reliability

General maintenance and reliability for hydrogen and battery systems in the aviation sector is expected to be similar to those of other transport sectors. Nevertheless, there has been limited research into understanding the aging process of batteries in aircraft application, with much of the focus being on passenger cars.

Battery usage in aircrafts differs from passenger cars, with aircraft batteries expected to go through multiple cycles per day and the intense power demand from take-off meaning that discharge rates will be high. These two factors impact the aging process of batteries and more development is needed to fully understand this. It is thought that a typical lifespan for the battery in an aircraft would be around 3,000 duty cycles, or four flights daily for four years, after which the battery would need replacing[127]. As a result, battery replacement is a factor that must be considered in designs, given an aircraft life is typically 30 years. Electric motors are beneficial with respect to reliability and maintenance compared with jet engines as they have far fewer moving parts, with less friction, filtration, fluid changes and so forth. The eFlyer 2's electric motor is expected to last 10,000 hours[128].

Similar to battery technology, commercial hydrogen power aircrafts are not yet realised, and therefore a deep understanding of the maintenance requirements has not yet developed. The integration of liquid hydrogen storage on-board, hydrogen fuel distribution systems, and fuel cell-based propulsion drive trains or direct combustion of hydrogen will need to be fully researched including operational, maintenance, and certification aspects. If they become operational, maintenance schedules will be more frequent, at least in the initial years of deployment. It is predicted that the increased complexities of the fuel and propulsion system will increase maintenance costs initially, in addition to the considerable training regime that will be required across the sector. The integration of the systems into the fuselage, especially for blended-wing bodies, will increase costs for maintenance and the frequency of checks necessary.

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[126] Hydrogen gas turbines & thrust generation, ATI, 2022

[127] Performance analysis of regional electric aircraft, Jayant Mukhopadhaya and Brandon Graver, 2022

[128] Bye aviation's e-flyer 800, Mark Huber, 2021

5.1.3.5 Safety

Safety is paramount to aviation and any new technology must undergo stringent testing before being used commercially. Lithium-ion batteries are used in current battery-electric aircraft designs due to the high energy density compared with other chemistries. As discussed in Section 4.1.3.5, Lithium-ion batteries can be pushed into a thermal runaway event which could be disastrous in an aviation context. Given the requirement to achieve higher energy density for aviation batteries, as more energy is stored into smaller volumes, the greater any exothermic event will be during thermal runaway. Therefore, new aircraft certification policies will be required to ensure safe operation of battery powered aircraft.

Similarly, to battery-electric technology, hydrogen-powered aviation will require the development of new aircraft certification policies. The behaviour of cryogenic hydrogen, when tanked in a commercial aircraft, is not well understood. Substantial further work is needed in this area and global collaboration on safety standards will be required[129]. In addition, though the primary energy comes from hydrogen, as with other fuel cell drivetrains, a fuel cell aircraft will require significant battery capacity in order to smooth the delivery of power and improve fuel cell efficiency. Therefore, any new certification policies for battery aircraft may also be required for hydrogen fuel cell aircraft.

Aside from safety considerations during aircraft operation, new regulatory framework to guarantee safe handling and refuelling with liquid hydrogen would be required. Currently, aircraft refuelling can take place simultaneously with other servicing operations. It’s unknown whether the safety case will allow this to occur under hydrogen refuelling, if not, then current airport logistical operations would need to be adapted[130]. This could have a huge knock-on impact to the day-to-day operations of how airports operate currently. Hydrogen has characteristics such as diffusivity and a high auto-ignition temperature that make it safer than kerosene, and other characteristics such as a lower minimum ignition energy and a greater flammability range of its concentration in the air that make it less favourable, meaning new hydrogen specific systems need to be designed and tested.

5.1.3.6 Usability and performance

An aircraft’s ability to carry sufficient loads, fly at altitudes of 36,000 ft, cruise at speeds of 460 – 575 mph, and travel long distances is essential for commercial airlines. A combination of aircraft architectural design and chosen powerplant dictates these performance factors, which must also be able to operate safely within different environmental conditions. At present battery and hydrogen aircraft are unable to meet all these performance characteristics. In addition, aircraft operations on the ground must be efficient in order to be usable for airlines, including their refuelling/recharging operations. To ensure this, aircraft designs must consider airline and airport operations. Given the nascency of battery and hydrogen aircraft, further development in these aspects is needed to ensure they can be adopted fully.

Noise emissions are an important consideration at many airports. Through not relying on jet engines, battery and fuel cell aircraft emit reduced noise, improving conditions in the surroundings, along with those for passengers. The electric aircraft manufacturer, Ampaire, projects a 60% reduction in noise levels during takeoff and landing for their 15-passenger aircraft, with others suggesting a reduction of up to 85%[136].

5.1.3.7 Emissions

As a drop-in fuel, power-to-liquid SAF has a good potential for adoption in aviation within a relatively short time horizon. SAF does however still produce emissions, roughly the same amount of carbon dioxide as conventional jet fuel, and the extent of decarbonisation depends on the full life cycle of the fuel. It is considered within the industry that a reduction of up to 80% in overall CO_2 lifecycle emissions compared to fossil fuels can be achieved[131].

Hydrogen fuel cells don’t emit carbon dioxide; however, water vapour is released. Research has shown that the use of hydrogen fuel will generate 2.6 times the amount of water emissions whether from fuel cells or jet engine propulsion

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[129] FlyZero: Our Vision for Zero-Carbon Emission Air Travel, ATI, 2022

[130] Hydrogen infrastructure and operations, ATI, 2022

[131] Beginner’s guide to sustainable aviation fuel, ATAG, 2022

units. Further research is required on the impact this has on contrail formation and the balance between their atmospheric cooling and warming effects[132]. For fuel cells, a design where water is held on board could be a possible solution, but research in this area is insufficient and would have significant weight implications. This is not an issue with battery-electric aircraft where no emission release occurs from the aircraft itself.

In hydrogen jet engines, combustion produces NOx, however this is less than traditional combustion as hydrogen can burn lean. Lean operation can significantly reduce the power output due to the reduction in the heating value of the air/fuel mixture so there is a limit as to how lean the engine can be run. Studies have estimated that NOx emissions are between 50 – 70% lower for hydrogen than kerosene fuels (fossil or SAF)[133].

5.1.4 Costs

Costs for future aircraft are uncertain given the advances in technology expected to occur as research and development increases.

BE aircraft today and in the near term are limited in their size and range. As a result, studies comparing their costs with conventional aircraft or aircraft with alternative fuels are limited. Heathrow’s 2022 NAPKIN Project’s cost model for instance does not include BE aircraft. Within small aircraft for alternative uses, some comparisons exist. Bye Aerospace’s eFlyer 2 is intended to replace small aircraft used for pilot training and expects operating costs to be a fifth for the current 11,000 training fleet. With its larger aircraft, eFlyer 4 and 800, the company aim to reach USD $20 and USD $200 per hour respectively (these are predicted values for aircraft with less than 10 seats)[134]. The eFlyer2 is similar to the operational Pipistrel Velis Electros fleet in the UK, which have reduced training costs from £30 to £3 per hour due to lower operational costs and similar upfront costs relative to their gasoline-fuelled cousins[135]. As a further example, Ampaire projects a decrease of fuel costs by 90% and reduced maintenance costs of 50% for its 15-passenger aircraft.[136]

According to the FlyZero study, hydrogen aircraft operations are forecast to be cost competitive by early 2030’s and by 2050, the cost of liquid hydrogen is expected to fall below that of fossil kerosene.[137] The economics of hydrogen aircraft are largely dependent on this CAPEX value and what the cost of hydrogen will be, both of which have significant uncertainty. However, the CAPEX for hydrogen aircraft is expected to be significantly higher than conventional aircraft, largely due to the liquid hydrogen tank, increased aircraft size and the complex fuel distribution system. Ongoing maintenance costs may also be higher because of an increased frequency of checks and the complexity of the fuel distribution, though this may reduce in the longer term as learnings are considered and implemented.[116] An EU research project into hydrogen powered aviation provides an estimated increase in cost of 25% for a short-range hydrogen aircraft compared to conventional kerosene, as illustrated below in Figure 5-2.

Also shown is the equivalent cost of SAF fuelled aircraft, which are expected to be 32% higher than conventional kerosene in 2040. This highlights the major drawback of SAFs and the high cost is expected to restrict market growth and will necessitate policy interventions to be introduced if SAFs are to be adopted at scale.

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[132] Academic programme research findings and recommendation, ATI, 2022

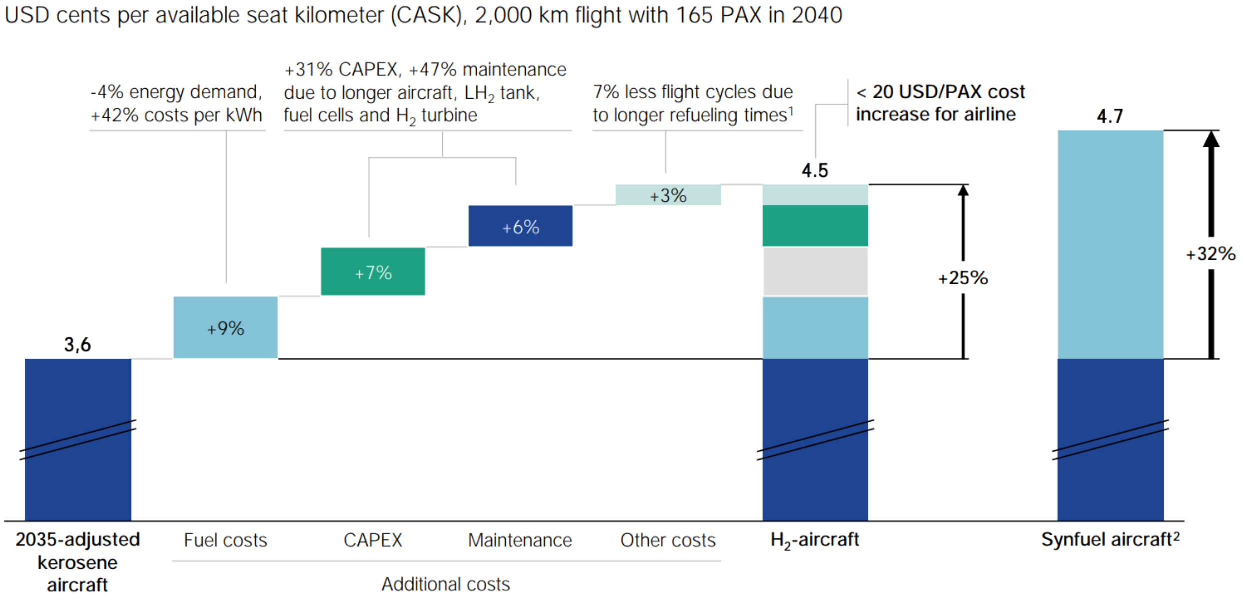
[133] Sustainability report: The lifecycle impact of hydrogen-powered aircraft, ATI, 2022

[134] George Bye - Bye Aerospace, Business Jet Online, 2021

[135] UK flight schools hire instructors for electric aircraft as fuel prices bite. The Guardian, 2022

[136] Electrification of Aircraft: Challenges, Barriers, and Potential Impacts, NREL, 2021

[137] Fly Zero – Key Findings, Aerospace Technology Institute, 2022



1. As the number of flight cycles decrease, CAPEX and crew costs will increase. Other costs also cover increased fees due to higher MTOW
2. Synfuel from green hydrogen with carbon from direct air capture

Figure 5-2 Cost comparison of hydrogen short-range aircraft versus kerosene and synfuel aircraft[138]

5.1.5 Infrastructure considerations

The development of new infrastructure will be required for both battery and hydrogen powered aircraft, including the refuelling, re-charging and servicing of the aircraft.

The introduction of battery-electric aviation would require airports to expand their existing electrical infrastructure to meet aviation recharging needs. This upgrading would require significant investment and coordination within the industry and the grid operators. The use of battery swapping could allow faster turnaround times for commercial operations as an alternative to fixed or mobile charging infrastructure. Currently, battery swapping maturity in aviation is much lower than for other transport modes. The complex safety standards for aircraft means that models for battery management and ownership need to be developed[139]. There are currently no economic charging solutions for medium and large range aircraft, given the additional time taken to charge the higher capacity batteries needed. Development of rapid chargers, which can safely and quickly charge high-capacity aircraft batteries, will be key to further penetration of electric aircraft.

Currently, the regulations needed to bring hydrogen aircraft into service are insufficient, and global cooperation will be required for their development. Refuelling services are seen to be manageable in the initial ramp-up years of limited routes and airports, but an overhaul of airport infrastructure would be required to accommodate hydrogen-powered aircraft on a wider scale. The supply of hydrogen would be a new consideration for this sector, with airports either having a dedicated on-site electrolyser, or more likely being served by dedicated pipelines to on-site storage systems[140]. Hydrogen refuelling procedures will also need to be developed. According to the Hydrogen Council, if liquid hydrogen aircraft accounted for 40% of all aircraft by 2050, they would require 10 million tonnes of hydrogen per annum, equating to 5% of the projected total global hydrogen demand.[116]

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[138] Hydrogen-powered aviation: a fact-based study of hydrogen technology, economics, and climate impact by 2050, McKinsey, 2020

[139] Blueprint for Zero Emission Flight Infrastructure, Catapult, 2022

[140] Blueprint for Zero Emission Flight Infrastructure, Catapult, 2022

5.1.6 Future outlook

Electric aviation is still in its infancy, with only one electric aircraft company having received full certification from the European Union's Aviation Safety Agency and the UK Civil Aviation Authority. The Velis Electro, by Pipistrel, is a two-seater with an enclosed cockpit. The aircraft's battery takes around 90 minutes to charge and lasts about an hour[141]. Further battery aircraft are in the development stage, such as the Heart Aerospace ES-30 with a 30-seat capacity and 200 km all electric range[142]. Airbus is also developing battery-electric and hybrid-electric propulsion, and in 2017 launched the E-Fan X. This hybrid aircraft had one of its four jet engines replaced with a 2 MW electric motor and provided key learnings on the possibilities and limitations to the technology. The demonstrator ended in April 2020[143], however Airbus continues to play a role in battery-electric aircraft sector. Airbus have developed a prototype for an all-electric, 4-seater aircraft; it has an 80 km range and is capable of cruising at 120 km/h[144]. There are over 170 electric aircraft projects underway worldwide[145], from the dominant aircraft players (Rolls-Royce, Boeing etc.) in addition to airlines like EasyJet, new entrances (Ampaire, Heart Aerospace, Eviation), and national organisations like NASA. They are almost uniformly targeting short-haul flights, with the National Renewable Energy Laboratory of the USA's Department of Energy predicting the first 50 to 70 seaters in 2028.

Airbus' ZEROe demonstrator programme will test a variety of hydrogen technologies both on the ground and in the air. Technologies to be tested include the hydrogen tanks, hydrogen combustion engine and liquid hydrogen distribution system. The first flight is expected to take place in the next five years[146]. ZeroAvia are focussing on hydrogen-electric powered aircrafts. In 2020, ZeroAvia's first hydrogen fuel cell powered commercial-grade aircraft, a Piper M-class six-seater, completed a full flight including taxi, take-off, circuit and landing at Cranfield Airport[147]. Later in 2021, 19-seat aircraft testing was undertaken. ZeroAvia have an ambition to offer first commercial aircraft of 9 to 19 seats at 300 nautical miles in 2024, following this they envisage a scale up of both seats and range out to 2040[148]. Despite this progress, for hydrogen fuel cells, as discussed, a significant increase in power density is thought to be needed in order for the technology to be viable to large scale commercial flights. This will require significant development in the next decade, alongside development of hydrogen fuelled jet engines.

Hydrogen gas turbines have a low technology readiness (TRL2-3) and are in early concept formulation and combustion trial work[149]. Currently there is no UK supplier of liquid hydrogen burning gas turbines for aerospace applications. The UK does however have extensive capability in the design and manufacture of combustor components for kerosene powered aeroengines through Rolls-Royce, where skills will be transferable. There is also strong capability in hydrogen combustion within the UK research community, for example in Cardiff, Loughborough, and Cranfield.

For SAFs, one of their main advantages is the potential for reduced development timescales, given the limited changes to existing aircraft that is needed, particularly when a blended fuel mix is used. With global warming being impacted by cumulative emissions, technologies that can be deployed fast are greatly needed. Therefore, the adoption of SAFs is limited by the supply, cost and the implementation of any industry/governmental emissions reduction mandates.

In general, aircraft are large complex engineering systems with stringent international standards and testing requirements. As a result, bringing new technologies to market is a lengthy process and this is expected to slow development, encouraging retrofitting of existing aircraft designs as an intermediary solution. New markets, which may be able to more easily adopt low carbon technologies such as the eVTOL air-taxi services and autonomous/remote-

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[141] UK Flight schools hire instructors for electric aircraft as fuel prices bite, Oliver Holmes, 2022

[142] Learn more about the ES-30, Heart Aerospace

[143] E-Fan X: A giant leap towards zero-emission flight, Airbus

[144] CityAirbus NextGen: Safe, sustainable and integrated urban air mobility, Airbus

[145] Electric Planes Take Off, John Fialka, 2022

[146] The ZEROe demonstrator has arrived, Airbus, 2022

[147] Decarbonising Transport: A better, greener Britain, Department for Transport, 2021

[148] ZeroAvia, 2022

[149] Hydrogen gas turbines & thrust generation, ATI, 2022

piloted cargo planes, will need to navigate this regulatory environment. For large scale adoption, new training will need to be undertaken for new aircraft designs and operations, which will encourage developments in domestic markets first.

The appraisal above highlights the overall considerations for the decarbonisation of the aviation sector. Below is a summary of the viable technologies, considering their strengths and weaknesses, and the opportunities for and threats to their development.

Battery electric	**Strengths** Zero emissions during flight. Higher efficiency leading to reduced total energy usage and operating costs. Noise emissions and vibrations minimised, improving the comfort of passengers and those living near to airports.	**Weaknesses** Weight: Current battery technology is not sufficiently energy dense and therefore a high weight penalty exists for battery powered aircraft, particularly over longer distances. Power is limited with current technology, and therefore less suited for heavier payloads. Range is limited with current technology, and long-range applications pay the cost of not reducing fuel weight during flight, increasing landing weight affecting both aircraft and runways.
	Opportunities Technology development: Battery technology has good potential for improvement due to the investment from the road transport sector, opening up possibilities for higher energy densities and therefore ranges. Hybrid battery and hydrogen fuel cell powered aircraft can be used to minimise the weight penalty of batteries.	**Threats** Charging infrastructure: the build out of high-power chargers will be needed to service aircraft efficiently, which may be difficult for smaller airports. Competing technologies: Development of infrastructure may be limited if hydrogen is the only viable solution for long haul aviation. Certification: The time involved in certifying radical new aircraft is significant, along with potentially substantial costs and changes to operational infrastructure.
Hydrogen fuel cell	**Strengths** Energy density: Hydrogen fuel cells benefit from the greater energy density of hydrogen fuel, meaning larger ranges can be achieved. Efficiency: Fuel cells are typically more efficient than jet engines, reducing the amount of fuel required and therefore the cost. Noise emissions and vibrations are lower for fuel cells compared with jet engines, improving the comfort of passengers and those living near to airports.	**Weaknesses** Fuel volume: The architecture of the aircraft would have to change to accommodate the larger tanks required for hydrogen flight, particularly for longer distances. Power: Fuel cells have a lower power density than gas turbines, so there is more weight for a given power output. This makes fuel cells, as the sole onboard technology, less suitable for larger aircraft.
	Opportunities Competition: due to the limitations of battery technology for anything other than short-distance flights, hydrogen solutions have the opportunity to develop and become the dominant technology.	**Threats** Water is released from the hydrogen fuel cell to a greater degree than traditional aviation fuel. The extent of the impact is not well known. Certification: The time involved in certifying radical new aircraft is significant, along with potentially substantial costs and changes to operational infrastructure. Hydrogen availability: the large requirement for green hydrogen throughout the economy risks hydrogen economics. Competition with SAF: Investment in SAF could mean airports don’t invest in hydrogen infrastructure. Safety perception: The ability to refuel simultaneously with other airport operations in a safe way must be proven.
Hydrogen Jet Engine	**Strengths** Based on known technology reducing the development time and costs. Power: Benefits from the high power capacity of combustion engines, making it suitable for longer distance, higher payload situations. Energy density: As with fuel cells, hydrogen jet engines benefit from the greater energy density of hydrogen fuel, meaning larger ranges can be achieved.	**Weaknesses** Emissions: Combustion produces NOx, however this is less than traditional combustion as hydrogen can burn lean. Lean operation can significantly reduce the power output due to the reduction in the heating value of the air/fuel mixture so there is a limit as to how lean the engine can be run. Efficiency: Combustion has lower efficiency compared with conversion in a fuel cell, requiring more fuel to be carried.

	Opportunities Similar to those outlined in hydrogen fuel cell.	**Threats** Similar to those outlined in hydrogen fuel cell.
Hydrogen-derived SAFs	**Strengths** Drop-in fuel limiting disruption to operations and the requirement to design new aircraft, and reducing the need for international collaboration. Energy density is high and comparable to conventional jet fuel, enabling long distance flights.	**Weaknesses** Emissions: When burned, SAFs create the same amount of CO_2 (and other pollutants) as conventional jet fuel. The life cycle emissions therefore depend on the method of production, and may not be net zero, particularly when the increased impact of emissions at high altitudes is considered. Cost: Producing SAFs costs twice as much as traditional aviation fuel and therefore will need significant subsidising on an international basis. Energy efficiency: the production of SAFs involves significant efficiency losses, and it has the lowest well-to-wheel efficiency of the potential technologies.
	Opportunities Speed of adoption: given the drop-in nature of the fuel, with the ability to blend with conventional fuel, SAFs can be adopted much more quickly, enabling an earlier impact on **CO_2**emissions. Regulation: The use of SAFs blended with conventional kerosene may be mandated by Governments, ensuring the market picks up and cost reductions can be found.	**Threats** Availability of fuel: Power to liquid SAFs requires a significant amount of renewable electricity to produce enough SAF to meet demand. In addition, feedstock availability concerns and price fluctuations may restrict market growth. Dependent on CCS: Power to liquid SAF relies on developments of carbon capture and storage technologies, for CO_2 feedstock.

The direction of low carbon aviation is associated with higher uncertainty than many other transport sectors. In order to efficiently transition to new technologies, and to do so at scale, will require substantial international collaboration across the public and private sectors.

There is currently a large focus on SAF in the aviation industry to address near term demands to reduce emissions, however, it is critical that for the longer-term transition, hydrogen and electric aircraft technologies remain a prevailing research and development area. This must include the consideration of technology developments, operational and planning needs, and the commercial and regulatory requirements.

SAF are currently the most likely technologies for long-haul aviation. The UK government are aiming to have a mandate in place by 2025 ensuring that at least 10% of the fuel used by aircraft is SAF by 2030, this may rise to 75% by 2050. Airbus, Boeing and others, are aiming for 100% SAF certified aircraft to be delivered by 2030, as safety regulators only allow a maximum of 50% blend at present. This is reportedly partially due to conventional jet fuel aiding older engines with fuel leaks, as components of jet fuel allow seals to swell; newer engines generally do not have this concern but testing and production volume of different SAFs also need to advance for greater usage and blend percentages.

Commuter and eVTOL (electric vertical take-off and landing) aircraft are expected to be the initial adopters of electric aviation. This is due to the relatively low flight durations and the use of new electric aircraft such as Heart Aerospace ES-19 expected in 2025, and the Wright Electric’s 100 seat Spirit aircraft expected in 2026. These are targeting 1-hour flights, and hope to utilise more regional and smaller airports. It is expected that by 2050, over half of domestic flights in the UK will be battery powered.

In the longer-term, researchers and manufacturers are mainly looking to hydrogen-based solutions, particularly for medium duration flights. The Fly Zero project, led by the Aerospace Technology Institute and funded by BEIS, has set out a vision for a new generation of aircraft, powered by liquid hydrogen. Hydrogen is considered to be most suited to medium range flights principally due to its higher energy density relative to electric aviation and lower cost relative to SAFs. Nevertheless, due to the slow rate of change in the aviation industry, the proportion of hydrogen fuelled aircraft is expected to remain low through to 2050.

Hybrid solutions consisting of BE and predominantly fuel cell systems are considered to have a number of technical advantages and are expected to be used in medium-haul flights.

5.1.7 Future market evolution

Based on the modelling undertaken as part of the DNV Energy Transition Outlook, a projection of the future market size and technology choice for aviation is presented below. Table 5-2 presents the total energy demand by energy carrier, and this is also shown graphically in Figure 5-3.

Table 5-2 Projection for UK annual energy use by energy carrier in the aviation sector

		2022	2030	2040	2050
UK Domestic Aviation Energy Demand TWh/Yr	Battery electric	0.0	0.0	1.0	3.2
	Traditional aviation fuel	8.6	9.1	6.1	1.5
	Bio-fuels	0.0	0.5	0.9	0.8
	Hydrogen	0.0	0.0	0.0	1.3
	Power-to-liquid e-fuels	0.0	0.0	0.7	0.9
UK International Aviation Energy Demand TWh/Yr	Battery electric	0.0	0.0	0.8	4.2
	Traditional aviation fuel	122.6	123.8	98.5	69.5
	Bio-fuels	0.6	14.7	25.3	29.8
	Hydrogen	0.0	0.0	0.0	8.8
	Power-to-liquid e-fuels	0.0	0.2	11.9	18.3
Total UK aviation energy demand TWh/Yr		**132**	**148**	**145**	**138**

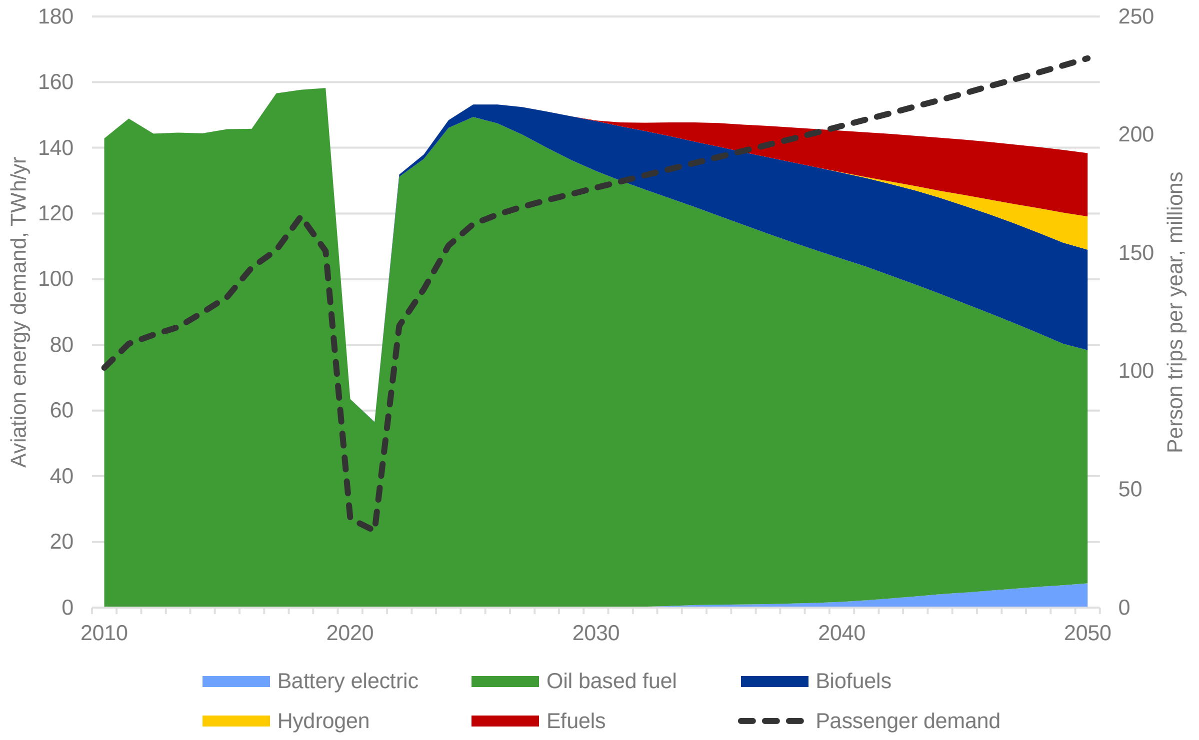

Figure 5-3 UK aviation energy demand by energy carrier

Apart from an exceptionally dramatic 70% fall in 2020–21 due to the COVID-19 pandemic, demand for air travel in the UK has grown strongly in recent decades and is expected to continue to grow. Despite continuous growth in air travel demand, aviation energy demand in the UK peaked at 160 TWh/yr in 2019, the last pre-pandemic year. After 2025, aviation energy demand is expected to start a slow decline from 150 TWh/yr to 140 TWh/yr in mid-century. This is driven primarily by an increase in load factors and improvements in aircraft design, including aerodynamics, as well as electrification of a share of the fleet covering short-haul flights, which together all add up to significant energy-efficiency gains. Aviation energy demand is driven mainly by international flights (with medium and long-haul flights dominating the energy use), with short haul domestic flights holding a small 7% share.

Until now, there has essentially been no fuel mix: all the energy demand has been met by oil-based aviation fuel. This is expected to change over the next three decades, with the share of petroleum-based aviation fuel expected to decline to half of the energy mix. With 51% of energy coming from oil, emissions are expected to remain at 48% of the 2019 levels.

The decarbonisation of aviation is expected to start with the adoption of drop in fuels, either biofuel based or power-to-liquid e-fuel SAFs. This is principally due to the quicker adoption possible without the need for substantial redesign of aircraft or airport operations. Battery powered flight is expected to feature prominently over short haul distances, where the technology is able to offer cost savings along with reduced noise and local air pollution, with adoption starting in the mid-2030s. For BE aircraft to take a larger share of the market, a significant further improvement in battery energy density would be required, which based on the analysis today is not considered likely.

Hydrogen powered flight is expected to take off from 2040 onwards due to the expected longer development time needed. Initial hydrogen aircraft are expected to serve short and medium distances due to the increased fuel tank size and changes to aircraft design needed to account for the lower volumetric energy density relative to conventional fuel. Hydrogen is used in both jet engines through combustion and fuel cells for conversion to electricity. Given the nascency of the technology and the significant time horizon, there is uncertainty in the eventual technology choice, however DNV expect smaller aircraft using hydrogen to do so using fuel cells, potentially together with batteries in a plug-in hybrid configuration, and larger aircrafts to be powered by jet engines with a greater range of fuels.

By 2050, among low-carbon fuels, biofuels will take the largest share of the total energy required at 22% of the total, with e-fuels and hydrogen following with 14% and 7% respectively. Electric aircraft will account for 5% of the UK aviation energy mix by 2050. It should be noted that, at present, there is still significant uncertainty around which sustainable fuel or mix of fuels will dominate in the aviation industry as the alternatives are currently fairly evenly poised in terms of cost and availability.

Despite the small proportion of the final energy consumption in aviation being provided by battery technology, due to the greater efficiency of battery powered propulsion, and the focus of battery technology on short range flights, the aviation market still represents a large market for battery capacity, and battery powered flights will make up a significant number of the flights taken in the UK. By 2050, the proportion of person trips undertaken by BE aircraft is estimated to be over 30%.

The total battery capacity required by aircraft operating in the UK is shown in Figure 5-4. The estimate is based on an assumed 700 flights per aircraft per year and a battery capacity equal to twice the energy used in an average BE flight. The battery capacity reaches 21,000 MWh by 2050 with year-on-year additions of up to 1800 MWh. Note the annual change in capacity considers both the impact of new batteries joining the market and the decommissioning and recycling of others, and therefore does not fully represent the demand for new batteries.

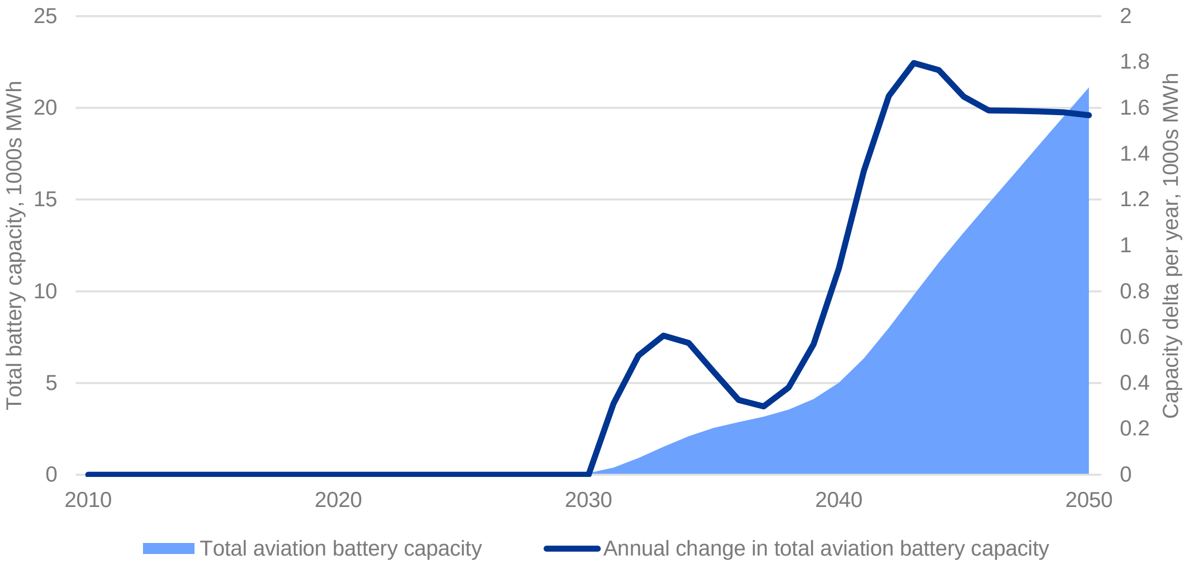

Figure 5-4 UK aviation battery demand from 2010 to 2050, including fleet total and annual additions, excluding battery replacement due to decommissioning

5.2 Maritime

5.2.1 Demand today

Domestic shipping contributed 5% of the UK's transport emissions in 2019, rising to 8% with the addition of the UK's contribution to international shipping[9]. It is noted that accounting for the UK's contribution to international shipping can be done in various ways, with this figure taken from BEIS based on the use of fuels from UK international shipping bunkers. Therefore, the total of the UK's contribution to emissions from international shipping may be higher. Considering global shipping, at present, the ships primarily used for international freight shipping consume roughly 3% of the world's final energy demand, including 7% of the world's oil. [32]

International shipping is one of the cornerstones of the modern globalised economy, and over 80% of the volume of international trade is carried by sea[150]. Though the efficiency per kg per km is better than other modes of transport, due to the high volume of goods shipped each year and the use of heavy fuel oil (HFO) and marine gas oil (MGO), the total emissions impact is significant, accounting for approximately 3% of global GHG emissions[151].

The International Maritime Organization (IMO) recently released a report detailing the fuel consumption by ships of 5,000 gross tonnage or more. The data was reported for 28,171 ships which consumed 212 million tonnes of fuel and it was demonstrated that Heavy Fuel Oil, Light Fuel Oil, and Diesel/Gas Oil account for almost 93% of the fuel used in 2021[152], with 5.95% being LNG, and other fuels (LPG Propane, LPG Butane, Methanol, Ethanol, Ethane, Biofuel) accounted for 0.11%. Alternative propulsion systems including BE and hydrogen have currently little-to-no impact on the overall maritime energy demand.

International shipping is dominated by the trade of goods and raw materials, including the transportation of fossil fuels. Though the trade in fossil fuels may decrease in the coming decades as the world decarbonises, the overall impact on trade volumes is not expected to be significant, particularly if alternative, less dense, low-carbon fuels are transported in place of crude oil.

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[150] Review of Maritime Transport 2021, UNCTAD, 2021

[151] Climate Regulations Are About to Disrupt Global Shipping, Willy Shih, 2022

[152] Energy efficiency of ships, International Maritime Organisation, 2022

For domestic shipping, the driver for demand is offshore vessels and smaller contributions from inland waterways and leisure craft, ferries, and the fishing industry. As the UK offshore oil and gas sector reduces in line with the country's decarbonisation ambitions, the demand for vessels servicing the market is expected to reduce. This will result in a reduction in the demand for and emissions from domestic shipping and will need to be considered by any alternative technologies looking to enter the market.

5.2.2 Consumer requirements

The requirements for commercial shipping focussed on safety and the total cost of ownership, which considers factors such as maintenance, energy capacity and payload capability. In addition, following the Paris Agreement, the IMO established goals to reduce the GHG emissions from the shipping sector. By 2050, the IMO hopes to have cut yearly GHG emissions overall by at least 50% compared to 2008 levels[153]. The UK is establishing its own rules and incentives to lower carbon and other GHG emissions, as by mid-2020, it plans to incorporate domestic shipping into its emission trading system (ETS) [154].

5.2.3 Performance characteristics

In order to achieve decarbonisation of the shipping industry, alternative methods of propulsion are needed. LNG and low-carbon fuels such as ammonia, hydrogen (fuel cell) and eMGO (Marine Gas Oil) are expected to replace the current reliance on HFO and MGO[155]. Fuels such as ammonia and e-methanol are derivatives of hydrogen and their widespread use in shipping will also create a significant demand for low-carbon hydrogen.

Methanol is the simplest alcohol with the lowest carbon content and highest hydrogen content of any liquid fuel. E-methanol, or "green" methanol, is methanol derived from renewable hydrogen and carbon dioxide. Ammonia is also considered as a viable carbon free marine fuel. In a 'green' ammonia plant, the hydrogen feedstock is produced from renewable electricity and electrolysis.

The rate at which new vessels that can run on alternative fuels are being purchased is encouraging, with LNG being dominant for the time being. The figure below shows the fleet's current uptake of alternative fuels – as well as the order book as of June 2022.

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[153] Greenhouse Gas Emissions, IMO

[154] Britain proposes to bring shipping sector into carbon market, Susanna Twidale, 2022

[155] Energy Transition Outlook, DNV, 2022

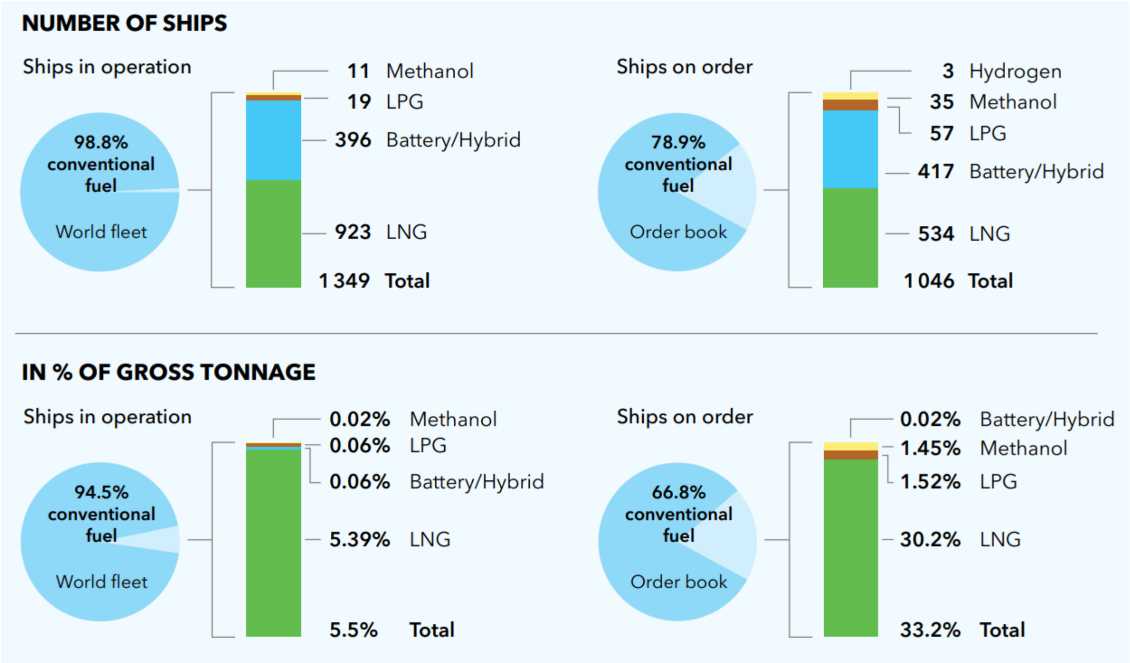

Figure 5-5: Current status on the uptake of alternative fuels in shipping[156]

Figure 5-5 shows that despite the continued dominance of conventional fuels, LNG is making a significant impact in the order book for new vessels. Nevertheless, LNG is not a low carbon fuel and is subject to the problem of methane slip, and therefore this can only be considered a bridging solution before true low carbon solutions can be employed.

BE and hydrogen solutions are included in the order book, however only on small vessels as reflected by the 0.02% share of the gross tonnage being served by these technologies. Due to their low energy density relative to fossil fuels, they are not regarded as practical alternatives for long-distance shipping. Despite the limited application of BE and hydrogen fuel cell solutions, these are considered viable for smaller vessels, and within larger power systems in the form of hybrid solutions, as discussed further below.

5.2.3.1 Efficiency

The efficiency of different fuels for the shipping industry is similar to those of other transport types. The use of batteries enables the highest overall efficiency to be achieved, with hydrogen-based fuels suffering the penalty of multiple conversion processes, assuming the hydrogen is derived from renewable electricity.

For ammonia and e-methanol, an additional conversion step is added, further reducing the overall efficiency. The conversion process of electricity to ammonia is expected to have a higher efficiency than the conversion to renewable methanol[157]. Converting hydrogen to ammonia requires energy equivalent to between 7% and 18% of the energy contained in the hydrogen. Therefore, significant additional electricity capacity would be required to produce both e-methanol and ammonia[158].

Pure BE solutions are considered to have limited applicability for large scale shipping due to the total energy content required. Nevertheless, batteries are expected to play an increasing role within shipping as a means to improve the efficiency of the fuel-based propulsion system, as well as being suitable for standalone propulsion systems for smaller sized boats. The marine technology company Wärtsilä has a range of hybrid propulsion systems which utilise batteries alongside diesel or dual fuel engines. Through using the battery, the combustion engine is able to operate closer to its

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[156] Maritime Forecast to 2050, DNV, 2022

[157] Ammonia as a marine fuel, DNV

[158] The future of hydrogen, IEA, 2019

design point, with the battery able to meet transient load requirements. Further benefits include improved manoeuvrability in port due to the improved system response, and in some circumstances emission free propulsion in coastal regions[159].

5.2.3.2 Energy density

The key requirement for larger ships, typically travelling further, is the density of the energy source, which must be sufficient to propel their large weight over long voyages without refuelling. A container ship typically carries in the region of 1 million to 3 million litres of fuel, with an energy content of 40 to 120 GWh. Therefore, batteries are not considered a feasible technology for long distance shipping, as the energy density of batteries both today and in the future is likely to remain too low.

Figure 3-1 shows the energy density and specific energy for different fuels. Although neither ammonia nor methanol have the density of traditional maritime fuels, they are superior to compressed or liquid hydrogen, and are therefore considered most likely to serve the international shipping market. The lower density by volume and mass will require ships to dedicate more space for storage and will reduce the payload that can be transported.

For smaller scale ships, such as ferries operating from the UK to either Ireland or France, the potential for battery and hydrogen is higher. With shorter, predictable routes, ferries can be sized with appropriate battery technology. Recently, the largest hybrid powered ferry was ordered by Brittany ferries to operate between Britain and France[160]. The ferry consists of an 11.5 MWh battery paired with an LNG fuelled combustion engine. The battery used within this solution employs similar technology to other transport modes, with NMC lithium-ion cells and liquid cooled racks for maximum energy density[161]. In addition, ABB is developing electric-diesel hybrid ferries for the 31-mile Dover-Calais channel crossing, allowing emission free manoeuvring in port[162].

Vessels featuring hydrogen fuel cells are also entering the market, both as hybrid solutions (paired with fossil fuels) to provide low speed cruising within ports and for auxiliary loads, and also as the main energy source for the vessel. The Viking Neptune cruise ship produced by Fincantieri includes a 100 kW fuel cell, which is to be used within the ship and tested for future further expansion. The second step in the development is to increase the size of the fuel cell in order to produce a 6-7 MW of power from hydrogen, enabling it to operate at slow speeds in ports without using the main engines[163].

The world's first hydrogen fuel cell hybrid ferry is to be launched in Norway, built by LMG Marin[164]. Operating on a short route taking 12 minutes and capable of carrying 80 cars and 290 passengers, the vessel is a hybrid and uses battery technology to use the fuel cell more efficiently; it includes fast charging to enable it to operate part of the journey in battery mode and uses liquid hydrogen contained within an 80 cubic meter tank. Liquid hydrogen enables a higher energy density to be achieved, reducing the space required relative to a compressed hydrogen solution.

5.2.3.3 Power density

The power density of different alternative fuels for the shipping industry is typically similar to that of other transport sectors. The electric motors used in BE, or hydrogen fuel cell drivetrains are expected to have the same performance characteristics, and the fuel cells themselves would align with the technology employed elsewhere. In the case of fuel cells, though they are modular and can be scaled up to meet higher power outputs, the cost may limit their size. As a result, the use of an ICE may also be required to meet power requirements when hydrogen is used as the fuel.

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[159] Hybrid Solutions, Wartsila HY

[160] Wartsila and Stena to build the world's largest hybrid vessels, Wartsila Corporation, 2022

[161] E-Marine, Leclanche

[162] XALT Energy Selected by ABB Marine & Ports for New Ferries Operating between Dover, England and Calais, France, Elaine Arnold, 2020

[163] Viking Neptune delivered in Ancona, Fincantieri, 2022

[164] Hydra, LMG Marin

For ammonia and methanol, both fuels are expected to be used within internal combustion engines, and therefore have sufficient power for their application. In addition, both fuels may also be converted within a fuel cell, however the development of this is still in its relative infancy.

5.2.3.4 Maintenance & reliability

Reliability for vessels is important given the long distance travelled and time away from port. In addition, any downtime for domestic vessels operating on shorter routes will have an impact on revenues and the business case and should therefore be minimised. The reliability of battery and fuel cell drivetrains are discussed in detail in Section 4.1.3.4 and it is considered that they are suitable for shipping applications without the need for over-onerous maintenance requirements. Internal combustion engines have decades of operating experience, however versions suitable for the combustion of ammonia or e-methanol are still in development and so the maintenance requirements are more unknown.

5.2.3.5 Safety

The safety considerations for battery and hydrogen technologies to be used on vessels is similar to those of other transport sectors, however given the location on a ship potentially far from assistance, the hazards associated with any issues are more severe. A recent comparative safety assessment for high-speed passenger ferries found that both hydrogen and battery powered ferries are feasible in terms of safety, so long as suitable safeguards are in place to mitigate potential issues[165].

Alternative fuels such as methanol and ammonia contain their own set of hazards and the risks of these must be considered. The toxicity of methanol and ammonia, along with the flammability of hydrogen, will require the development of international regulations for their safe use, both onboard ships, but also in their transportation and bunkering. Given the international nature of shipping, this is a key requirement for the development and decarbonisation of the sector.

Ammonia is hazardous to handle, however is considered less so than hydrogen, and although it is stored at low temperatures (-33°C), this is not as low as hydrogen, which requires -253°C in liquid form. As outlined in the Control of Major Accident Hazards regulations (COMAH), there are two levels of COMAH site: Lower Tier sites, holding a smaller hazardous inventory; and Upper Tier sites, holding larger hazardous inventories, and as such are more potentially hazardous (requiring more stringent requirements). Ammonia is classified by the COMAH regulations as a dangerous substance, and can be harmful to aquatic life and would require rigorous safety procedures such as double wall piping.

Methanol has hazards associated with it toxicity, in terms of ingestion and inhalation, and from fire. Both risks are increased by the lower boiling point of methanol relative to diesel, increasing the risk of higher concentrations developing in confined spaces. This necessitates the increased use of sensors and monitoring equipment, particularly within the engine room. One advantage of methanol is its solubility in water and that it biodegrades relatively fast, reducing the negative environmental impact of a spill[166].

5.2.3.6 Materials, supply chain and recycling

The considerations around materials, supply chain and recycling of batteries and hydrogen used within shipping are largely the same as those in other transport sectors.

When considering alternative fuels such as ammonia and methanol, the vessel-based technology is not expected to be a constraint, and suitable engines and associated infrastructure is expected to be derived from existing technologies. Instead, the fuel production, storage and distribution infrastructure will be the area subject to the most development. These aspects are discussed in detail in DNV's Maritime Forecast to 2050[167]. Today's ammonia and methanol production is mostly fossil based and has a total yearly production of 176 Mt and 98 Mt respectively. Though this is not all available for shipping, the quantity equates to 45% of shipping's annual energy needs. Therefore, as with the supply

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[165] Hydrogen vs. Batteries: Comparative Safety Assessments for a High-Speed Passenger Ferry, Foivos Mylonopoulos et. al., 2022

[166] Challenges in the use of hydrogen for maritime applications, Lauren Van Hoecke et. al., 2021

[167] Maritime forecast to 2050, DNV, 2022

of pure hydrogen, to supply global shipping with either of these fuels, a huge increase in renewable energy capacity would be required. Once the production of fuel is achieved, an additional consideration is the infrastructure required for distribution and bunkering. The cost for this is expected to be significantly different depending on whether non-cryogenic liquids such as methanol are used compared with compressed or liquid hydrogen, or ammonia (stored at -33°C).

5.2.3.7 Usability and performance

Electric propulsion, using batteries on their own or in a hybrid solution comprising hydrogen fuel cells or combustion engines, have a number of performance benefits. Given the size of marine combustion engines, their transient response is poor, whereas electric propulsion systems offer fast response times and accurate control. Fuel cells are typically more efficient when operating at a constant load factor, and benefit from having a significant battery capacity to enable hybrid operation. Therefore, the ability of electric propulsion systems to improve control is seen as a benefit for increased hybridisation within shipping, along with battery only operation for small vessels.

5.2.3.8 Emissions

The emissions from battery and hydrogen-based shipping are similar to other forms of transport, with no harmful emissions from batteries or hydrogen fuel cells at the point of use, though there remains the potential for NOx emissions from hydrogen when using ICEs.

The low emissions of both battery and hydrogen solutions are a major advantage in urban contexts. London, like many major cities, considers air pollution to be a significant environmental and health risk, and therefore decarbonising barges and passenger transport on rivers is important. Danfoss Power Solutions have developed a high-speed hybrid-electric passenger ferry for the London area. The hybrid technology allows for BE propulsion in central London and biofuel operation outside of this area. The ferry will be able to carry up to 230 passengers, with plans to be in operation in Autumn 2022. Danfoss claim that not only batteries but also hydrogen fuel cells can be integrated into its DC system[168].

For the alternative fuels, it is considered that green ammonia could in theory be free of CO_2 emissions, however, there still are challenges related to NO_x and N_2O emissions from the combustion process. When considering E-methanol, CO_2 emissions can be cut by 95% compared with traditional fuels[169].

The GHG emissions from alternative fuels must consider those emitted during fuel production, distribution and use onboard the ship in order to determine a fuel's true impact on climate change. These are known as well-to-wake emissions. This can be divided further into the well-to-tank emissions, and tank-to-wake. In general, e-fuels have the lowest emissions levels for alternative fuels[170].The source of hydrogen has a fundamental effect on the well-to-wake emissions of pure hydrogen and hydrogen-based fuels, and therefore the decarbonisation of hydrogen production is key to achieve decarbonisation in the shipping industry. The energy required to make these fuels is not considered here, however as discussed in Section 5.2.3.1, the energy required for e-fuels is higher.

5.2.4 Costs

Price is a key parameter that operators have to consider when investigating new vessels, and a total cost of ownership model consisting of purchase price, fuel costs and other running costs is needed. Given the nascent nature of many of the alternative fuels and their associated infrastructure costs, a total cost of ownership study is subject to significant uncertainty. Nevertheless, Figure 5-6 presents a comparison of costs for various marine fuels, both today and in the future. As illustrated, ammonia is shown to be the lowest cost option both at present and in the long-term scenario of the low carbon technologies. In addition, pure hydrogen is shown in the short-term using an ICE, before switching to a fuel cell once their costs come down. In the case of synthetic fuels, though the costs drop significantly over time, they remain higher than ammonia, but reaching parity with a pure hydrogen solution.

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[168] UK's First High-Speed Hybrid-Electric Passenger Ferries Coming Later This Year, Otilia Dragan, 2022

[169] Renewable methanol, Methanol Institute

[170] Alternative Fuels Outlook for Shipping: An overview of alternative fuels for a well-to-wake perspective, Bureau Veritas, 2022

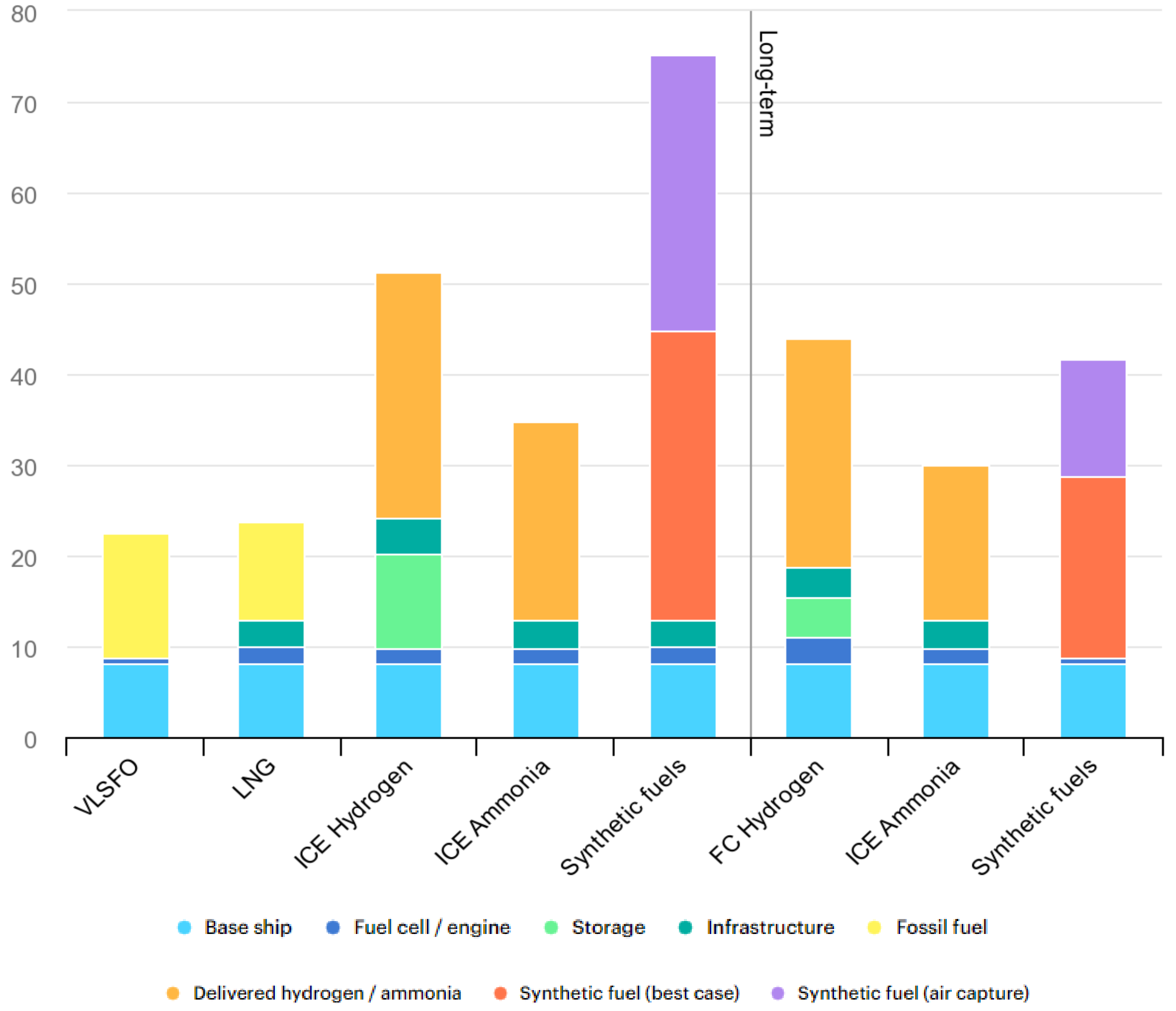

Figure 5-6 Current and future total cost of ownership of fuel/powertrain alternatives in a bulk carrier ship USD/km [171] (VLSFO = very low sulphur fuel oil)

For short distance shipping, both batteries and hydrogen fuel cells can be a viable option.

With regards to battery powered vessels, the high capacity of batteries required has a significant impact on the purchase price. Nevertheless, with prices expected to fall thanks to the high BEV uptake, battery ships are expected to be become increasingly competitive. Though complete TCO studies of ferries have not been reviewed, recent research compared the financial viability of a battery-powered neo-panamax container ship to that of a two-stroke, slow-moving ICE running on very low sulphur fuel oil. The opportunity cost of forfeiting twenty-foot equivalent units (TEUs) to the battery system was accounted for in the calculations. With current technology, the total cost of propulsion of a battery-electric ship was shown to be lower than the current ICE vessel (larger than 8,000 TEU) for shorter distances of approximately 1,000 km. In the near future, this number is shown to climb up to 3,000 km with advancements in battery technology and rising HFO costs[172]. Though not directly related to the domestic shipping market in the UK, the results of this study are encouraging and shows that BE propulsion can be cost competitive with other technologies. This is also in line with cost comparisons from other transport sectors.

In a recent study, the annual operating costs of a hydrogen fuel cell-powered passenger ferry was compared to those of a traditional fossil diesel-powered solution. At the current technology, the overall annual cost of a fuel cell-powered

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[171] Current and future total cost of ownership of fuel/powertrain alternatives in a bulk carrier ship, IEA, 2022

[172] Rapid battery cost declines accelerate the prospects of all-electric interregional container shipping, Jessica Kersey et. al., 2022

passenger ferry was found to be 28% more expensive than diesel. The hydrogen-powered ferry was determined to be cost competitive with the diesel alternative under future scenarios that incorporated minor improvements to hull efficiency and fuel cell lifetime, as well as modest price reductions for the hydrogen and fuel cell systems and increases in CO_2 taxes [173]. This further demonstrates that a fuel cell-powered propulsion system can soon become a practical choice for short-haul excursions with numerous port calls, such as passenger ferries.

5.2.5 Infrastructure considerations

For plug-in battery solutions in the shipping industry, the ability to deliver sufficient energy to the vessel within the timeframe available for its activities is the key challenge. Depending on the local conditions, the size of the vessels and the length of time in port, grid reinforcements may be required to be able to deliver the power required. Alternatively, or in addition, stationary batteries onshore may be required to charge at relatively lower power, ready to discharge at high power to the ship whilst in port. Charging operations, using either approach, can be automated and installed as part of the docking procedure, making the operation efficient and cost effective. For example, the Tycho Brahe passenger ferry is capable of transporting 240 cars and 1250 passengers between Helsingborg in Sweden and Helsingor in Denmark. The ships battery system consists of a 6.4 MWh battery charged by an automated system delivering 6 MW of power for a short period each time the vessel docks. This, together with an overnight charge enables the vessel to make the 4 km journey 46 times per day[174] [175].

For the development of hydrogen fuelled shipping, new hydrogen infrastructure will be required. Facilities for hydrogen refuelling are currently limited to trials and would therefore need to be installed at ports at which hydrogen vessels are to operate. It was recently announced that Portsmouth marina will accommodate a 137-bar hydrogen compressor, 400-bar booster/refuelling compressor and hydrogen refuelling nozzles to refill hydrogen tanks used by a dual-fuel hydrogen engine. The scope of the project includes a comprehensive assessment of the regulatory environment for hydrogen generation, storage and use as a marine fuel[176].

With the different use cases of vessels, and, within the short sea shipping segment, the use of regular ports, the requirement to install widespread hydrogen refuelling stations is reduced, and the feasibility of installing specific refuelling stations for specific applications is greater. This reduces some of the barriers to hydrogen-based shipping which are more apparent in road transport settings.

The source of hydrogen has an impact on the infrastructure required. Where significant demand for hydrogen is identified, local hydrogen production in the form of an electrolyser may be considered, as an alternative to transportation via road.

For both battery and hydrogen-based shipping, these technologies are not considered viable for deep sea international shipping. For these segments, alternative fuels such as ammonia and methanol are considered more likely, and this will require significant changes to international bunkering facilities in order to become viable. The considerations around bunkering for different fuels is discussed in the DNV Maritime Forecast to 2050[167].

5.2.6 Future outlook

For battery and hydrogen technology in the shipping sector, the fundamental aspects of the technology are in existence today and used on other transport sectors. For BE technology, no specific development milestones are required before their deployment can accelerate, and the significant use in road transport will help drive development that is applicable to the maritime sector. For hydrogen fuel cell vessels, though the technology is available and in use, an overall increase in fuel cell production is required in order to improve the technology and bring costs down.

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[173] Energy and cost analysis of a hydrogen driven high speed passenger ferry, Fredrik Aarskog, 2020

[174] Charging infrastructure for near-shore electric vessels, Cenex, 2022

[175] ForSea to upgrade Tycho Brahe with the world’s largest battery pack, extending the vessel lifetime and cutting emissions, ForSea

[176] Tests Start with UK First Hydrogen Powered Outboards, Hydrogen Central, 2022

Engines suitable for methanol are available and tankers carrying methanol as cargo have successfully been using dual-fuel 2-stroke methanol engines for propulsion since 2017, and interest in methanol fuelled 4-stroke engines is increasing. For ammonia, neither 2-stroke nor 4-stroke engines using ammonia as fuel are currently commercially available, with manufacturers facing challenges around nitrous oxide (N_2O) emissions and potential ammonia slip[167].

It is noted that due to the long service life of ships, typically 25 years, in comparison with road transport vehicles, the time taken to upgrade a fleet is significantly longer, and therefore the impact of new technologies is expected to be slower.

The appraisal presented in the preceding sections covers the factors influencing the future technology choice for shipping. As discussed, a clear distinction can be made between deep sea international shipping, and shorter distance and domestic shipping. For deep sea international shipping, no potential for BE based solutions is seen, and hydrogen is also considered unlikely to feature significantly. For shorter distances, and within domestic shipping, there is a potential for both battery and hydrogen technology to play a role in the market.

Below is a summary of the viable technologies, considering their strengths and weaknesses, and the opportunities for and threats to their development.

Battery electric	**Strengths** Efficiency: The use of renewable energy stored in batteries has the highest well-to-wake efficiency. Comfort: Reduced noise and vibration levels will make travelling or sightseeing via ferry more comfortable. Opportunity charging can be implemented into docking infrastructure where ferries use regular routes to boost range.	**Weaknesses** Low energy density limits the distance that can be travelled, excluding battery power from most international shipping.
	Opportunities Hybrid: Battery technology can be utilised in hybrid solutions with conventional fuels. This helps reduce emissions, develop charging infrastructure and increase the rate of development in maritime environments.	**Threats** Grid/charging infrastructure is needed to successfully operate a fleet of battery powered vessels. High powered chargers will be needed to minimise turn-around time, along with coordination across different harbours and ports.
Hydrogen fuel cell	**Strengths** Energy density: Hydrogen fuel cells benefit from the greater energy density of hydrogen fuel, meaning larger ranges can be achieved. Energy efficiency is higher for hydrogen than for e-fuels, reducing the total energy demand from the sector. Note it is however lower than battery technology. Comfort: Reduced noise and vibration levels will make travelling or sightseeing via ferry more comfortable.	**Weaknesses** Cost of using hydrogen fuel cells is currently significantly higher than conventional diesel-based propulsion. Though further research is needed, based on other transport sectors, it is expected that in particularly shorter distance applications, BE ship costs are also likely to be lower than FC ships.
	Opportunities Hybrid: Fuel cells can be used in a hybrid configuration with conventional powertrains allowing for demonstration and infrastructure build-out, reducing risk.	**Threats** Development of infrastructure: Challenges exist for the successful build out of hydrogen infrastructure to support maritime applications.
Hydrogen derived marine fuels (ammonia, methanol)	**Strengths** High energy density compared with liquid hydrogen and batteries, enables vessels to transport heavy payloads over large distances.	**Weaknesses** Emissions: Some fuels still produce CO_2 emissions at the point of combustion, for example methanol, and Ammonia can also produce NO_X. Efficiency: The conversion process means well-to-wheel efficiency is lower than pure hydrogen or battery technology. Technology readiness is lower for ammonia combustion engines.
	Opportunities Existing infrastructure: many of the potential hydrogen	**Threats** Availability of low carbon ammonia, derived from

	derived marine fuels have existing infrastructure in place and existing markets, which will enable early adopters to access fuel supplies. Dual-fuel: Many of the potential hydrogen derived marine fuels can be used in dual fuel applications or be blended conventional fuels, assisting in the technology development.	renewable energy, will be a significant challenge for the scaled use of hydrogen derived marine fuels, due to the total electricity capacity required.

For short distance shipping, the potential for alternative low carbon technologies is good. Battery powered vessels over shorter distances are considered viable, as the weight penalty of battery packs is less significant, releasing the benefits discussed in other transport sectors, such as the high well-to-wheel efficiency and zero emissions. Though hydrogen fuelled vessels are in use today, the widespread use of hydrogen in shipping is expected to be limited as alternative technologies provide a more competitive solution. Hydrogen may be preferable where battery technology is not yet able to meet energy requirements, or the operational schedule requires fast refuelling times. In these scenarios, hydrogen may be used in a hybrid configuration as a range extender.

For long distance applications where the majority of the global demand lies, neither battery nor hydrogen technology is expected to be suitable, principally due to the energy capacity required, and therefore alternative fuels will be needed instead, such as ammonia and e-methanol. For these fuels however, significant development is needed before their widespread use, with key barriers including increased capital investment, limited fuel availability, lack of global bunkering infrastructure, high fuel prices, and the additional demand for onboard storage space. Safety is also a primary concern, with the absence of prescriptive rules and regulations complicating the implementation of the required onboard technology. With these challenges and their lower well-to-wake efficiency and higher costs, these technologies are not expected to have a significant market share in the short distance sectors where batteries provide a viable alternative.

Battery technology is expected to be increasingly used within larger power systems of deep-sea ships. When used in conjunction with ICEs, the batteries can enable vessels to control load variations and improve engine performance and allow larger ferries to operate in battery mode when in port. Where charging facilities are developed, these vessels will also be able to operate as plug-in hybrids, charging using renewable energy from the grid. Therefore, it is expected that batteries, in many forms will become increasingly used within the maritime sector with both conventional and alternative low-carbon fuels.

5.2.7 Future market evolution

The projections for the future energy demand from different maritime fuels is shown in Table 5-3 and Figure 5-7. Also shown in Figure 5-7 is the global maritime demand, which shows a steady increase before remaining steady in the 2030s and 2040s. In 2021, the total energy demand was 71 TWh/yr, 85% of which was energy sold to international marine bunkers and assigned to the UK within the ETO model. The proportion of international compared with domestic shipping is constant within the model.

At present, driven by international shipping, oil-based fuels provide over 90% of UK maritime energy demand. This is based around the existing bunkering infrastructure developed internationally over years. The majority of the remaining energy is supplied by natural gas, with a small fraction of electricity. By the 2050s, the amount of oil-based fuels used is expected to reduce significantly to approximately 12% with the remaining energy demand expected to be met by natural gas, BE propulsion and low-carbon fuels. With the increase in low carbon fuels along with efficiency improvements, the total emissions from maritime are expected to reduce by over 75% by 2050.

BE propulsion is expected to be a significant source within domestic shipping over short distances, however a significant increase in energy density would be required in order for batteries to be used as the main energy source for international shipping. Therefore, the total share of the energy mix for batteries in shipping is small.

The use of hydrogen fuel is not expected to be significant within the maritime sector, with a negligible contribution to 2050. Instead, hydrogen is expected to be used in the production of ammonia and e-methanol, with ammonia expected to be the largest energy source in shipping, with a share of 35% by 2050, and e-fuels including e-methanol contributing

14%. Initial pilot projects for H_2-derived fuels within the maritime sector will start to build from the late 2020s. From 2035 to 2050 the maritime sector is expected to transition rapidly with conversion of international and domestic fleets to low carbon fuels. The delayed update is due to the significant development still required for the use of these fuels, particularly the deployment of technologies to manage the hazardous challenges they contain, and the large investment in new renewable energy needed to ensure enough low carbon hydrogen is available. It is expected that the accelerated development is aligned with the conversion of established bunkering and port facilities globally, which is needed to provide confidence to ship operators to convert stock. During this period new LNG fuelled ships are expected to approach the end of their operational life.

Though not modelled specifically as a separate propulsion technology, hybrid solutions using battery power along with combustion technologies are expected to feature along with dual fuel technologies, as early adopters look for flexibility in both performance and logistics. Many of these are not expected to have plug in capabilities, and therefore do not increase the share of electricity used within the ETO model. Therefore, additional battery demand to that presented here can be expected from the maritime sector.

Table 5-3 Projection for total maritime energy demand from the UK

		2022	2030	2040	2050
Maritime energy demand TWh/Yr	Battery electric	0.5	1.4	2.0	1.3
	Oil based fuel	67.9	55.4	26.9	6.4
	Natural gas	4.2	11.9	18.5	10.4
	Biofuel	0.0	6.3	7.3	9.8
	Ammonia	0.0	0.2	5.2	19.7
	Hydrogen	0.0	0.0	0.0	0.0
	E-fuels	0.0	1.9	6.3	8.1
Total Maritime energy demand TWh/Yr		**72.7**	**77.2**	**66.3**	**55.8**

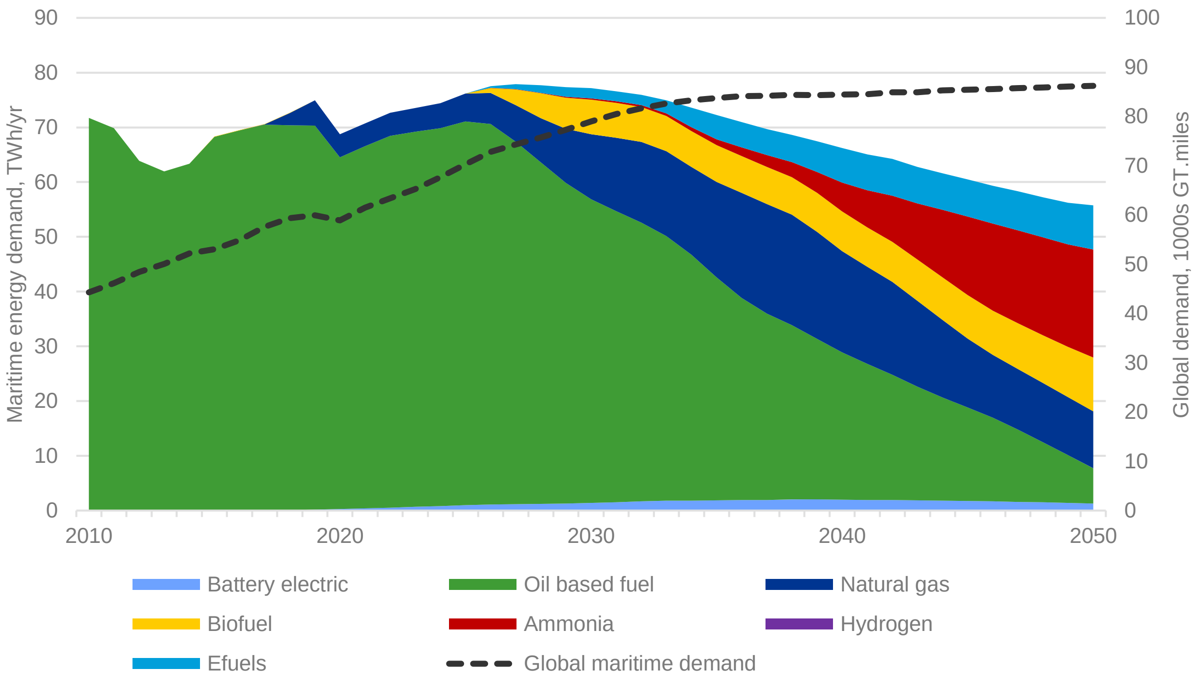

Figure 5-7 UK maritime energy demand by energy carrier, 2010 to 2050

The figure presented above is based on energy used, rather than number of vessels, tonne-kilometres transported, or revenues earnt. Much less energy is required for BE propulsion given the high efficiency of battery power, and the typically shorter distances and lower payloads transported. Nevertheless, the market for shorter range battery powered vessels is still expected to be significant, with peak annual increase in battery capacity of approximately 900 MWh per year in the 2020s. The battery capacity is estimated based on a single charge and discharge each day, and a capacity twice the average energy required in an average journey. Within the ETO model, the year-on-year change in battery capacity becomes negative from 2039 onwards, indicating that more battery capacity it the maritime sector is decommissioned each year than that which is added. Given the resolution of the ETO model, and the small overall contribution to the maritime sector of battery technology, there is additional uncertainty in this result.

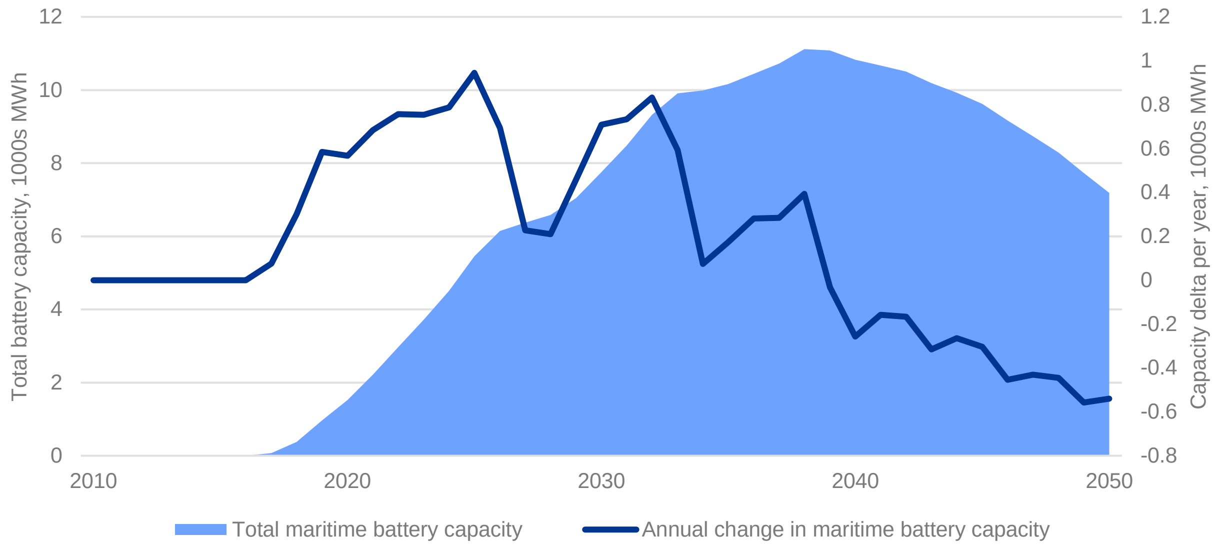

Figure 5-8 The annual change in and fleet wide battery capacity for the UK maritime sector from 2010 to 2050

5.3 Rail

5.3.1 Demand today

Railways provide fast and efficient mass transport for both passengers and goods over significant distances. In 2019, rail accounted for 10% of passenger distance travelled in England, from 2% of the trips made[177]. Rail was used for 2.3% of journeys in Scotland[178], and shows lower use in Wales[179]. As presented in Figure 4-1, the emissions at the point of use from rail in the UK are 2% of the total transport emissions.

The UK rail network is currently made of electrified tracks comprising 38% of the network, with unelectrified track operated by diesel electric trains accounting for the remainder[181]. Despite being the smaller share of the total network, 70% of the passenger stock fleet in the UK is pure electric.[180]

The total number of journeys undertaken by rail is expected to steadily increase in the coming decades, both for passenger and freight transport.

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[177] Rail factsheet 2019-20, Department for Transport, 2020

[178] Transport and travel in Scotland 2019, Transport Scotland

[179] Rail station usage in Wales 2020-21, Welsh GOV, 2022

[180] Rail Infrastructure and Assets April 2021 to March 2022, ORR, 2022

5.3.2 Consumer requirements

Rail, as a form of mass public transport, must be safe, reliable and provide value for money. Moreover, the sector has the target to achieve significant decarbonisation and the Department for Transport has set the challenge for the UK rail industry to remove all diesel trains by 2040[181].

The Network Rail Traction Decarbonisation Network Strategy considers the technological, operational and economic methodologies to identify the optimum application of decarbonised traction technologies. It shows that there are 15,400 single track kilometres that remain unelectrified in the UK, and of these, around 85% should be electrified. The remaining routes are not considered suitable for electrification due to having limited usage, or where modification to tracks to accommodate electrification would be too expensive. Other than electrification, the task force recommended 8% should be hydrogen and 5% should be battery powered, leaving around 2% of the remaining unelectrified track with no clear plan, and additional work at a local level is recommended.[182]

This is further supported by the Network Rail Traction Decarbonisation Network Strategy, which sets out ambitions to achieve emissions reductions primarily through increased electrification, however for those areas where electrification of the tracks is not possible, new propulsion technologies are needed, with battery and hydrogen both viable options. [182]

5.3.3 Performance characteristics

The route to decarbonisation of the rail sector is dominated by direct electrification of the network. Through electrification, renewable energy available on the electricity grid is able to provide low carbon energy reliably and at low cost. Where direct electrification of the track is not possible, both hydrogen fuel cells and battery power are expected to be viable technologies.

In assessing the most suitable technology for a particular route or application, the considerations must include the range and weight of the payload, the speed required, the available infrastructure to support the chosen option, and ultimately the price of the solution. Other important requirements including safety and maintenance factors are expected to be similar to those of other transport sectors and are not expected to be decisive in determining the future technology for unelectrified rail routes. Much like the other sectors discussed, for rail, there are limited-to-no standards for the design, installation, and operation of the necessary infrastructure for energy storage, refuelling or charging systems. These will need to be developed alongside developing technologies so that the new systems can maintain high safety standards.

5.3.3.1 Energy capacity

Current battery technology has relatively low energy density, resulting in a requirement for more batteries, impacting cost and weight, or operating with lower range.

Vivarail's BE trains consist of 200 kWh of capacity on each vehicle, although they are designed to have a reserved capacity of between 30 – 40% which means around 130 kWh of useable energy. Typically, Vivarail trains consume around 2.75 – 3.5 kWh per vehicle mile. Energy consumption varies depending on operating conditions however the useable energy results in a range of up to 80 miles (up to 80 mph) on a single charge. Current designs allow for up to 136 seated and 161 standing passengers.[183] Development of batteries with greater energy density will improve the viability of BE trains, additional improvements and usage could include incorporating batteries into the design of train carriages themselves.

Hydrogen fuel cells, benefiting from the higher specific energy of hydrogen, offer an alternative solution with the potential to reach higher ranges. Nevertheless, due to hydrogen's low volumetric energy density in comparison to diesel, large hydrogen storage tanks are required. At 350 bar, the volumetric energy density of hydrogen is 4.6 MJ/litre, compared with 35.8 MJ/litre for diesel. Locating these within the train's architecture is considered a challenge and

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[181] Let's raise our ambitions for a cleaner, greener railway, Department for Transport, 2018

[182] Traction Decarbonisation Network Strategy, Network Rail

[183] Flexible power systems for rail vehicles, Vivarail

potential downside due to the restrictive loading gauge in the UK. Locating the hydrogen tanks on the roof of the train, as can be done in other countries, may not be possible, and therefore the tank may have to be in a portion of the main passenger carriage, reducing its passenger capacity. Alternatively, smaller hydrogen tanks could be used with more frequent refuelling taking place.

The Alstom hydrogen train in Germany is the world's first hydrogen train and has a passenger capacity of up to 300. The fuel cell and hydrogen storage tank are located on the roof of the train, and the traction equipment and battery are in the base. The design allows for the hydrogen fuel cell to be supplemented by traction batteries to boost power output for acceleration, and to store and reuse energy from regenerative dynamic braking[184]. The hydrogen tanks have a storage capacity of 260 kg at 350 bar, this equates to 8671 kWh of energy being fed to the fuel cell (based on 33.35 kWh/kg hydrogen). The powertrain has an energy storage battery capacity of 110 kWh.[185] The train has a range of 620 miles (at speeds of up to 90 mph) which reduces the frequency of refuelling required. Although hydrogen powered trains use batteries as part of their traction system to allow flexible power output, the battery is only chargeable via the hydrogen fuel cell and regenerative breaking.

Depending on range requirements and recharging or refuelling availability, the importance of the energy capacity of the train will vary. Both battery and hydrogen solutions are complementary, with each of them catering to different needs. Battery solutions are generally more suitable for short and medium-length routes without electrified track, while hydrogen solutions are better suited to long-distance travel.

5.3.4 Cost

For successful mass transit rail operations, low costs and reliability are essential, and any future technology must meet the economic expectations of users.

Given the expected dominance of overhead electrified rail, limited cost information and comparisons are available for battery and hydrogen powered trains. Nevertheless, a study funded by the German government found that battery trains are 35% less expensive to buy and operate in comparison to hydrogen fuel cell trains.[186] The study assumes the hydrogen fuel will be more expensive than electricity, accounting for about 40% to 50% of a train's total cost of ownership (20% to 30% by 2030). This is the main cause of the price difference. The future development of costs, particularly for hydrogen fuelled systems is subject to high uncertainty, and cost reductions will require significant early uptake to achieve economies of scale. With the expected dominance of battery technology in many of the different transport sectors, achieving the fuel cell demand required is considered to be at risk.

5.3.5 Infrastructure considerations

Developments in the rail sector are by their very nature large infrastructure projects. In considering the adoption of either hydrogen or battery powered trains, the required charging infrastructure will need to be developed.

Charging infrastructure will need to be installed to enable BE trains to charge overnight, however it is unlikely that one charge per 24 hours would be sufficient given the range trains usually travel in a day. As a result, fast charging infrastructure at stations will be essential for the advancement of BE trains. The technology used may share similarities with opportunity charging installed for public buses, with the potential for even higher power requirements. Depending on the area of uptake, local electricity grids may be constrained or require upgrading. Limitations to battery range and the grid capacity available can be mitigated by Vivarail's next generation battery and patented Fast Charge system – able to recharge the train in around 10 minutes[187]. The system employs a stationary battery to charge at relatively lower power from the grid, before discharging rapidly to a train as required. Nevertheless, in areas of significant grid constraint,

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[184] Intelligent Power Solutions to Decarbonise Rail Hyd-Energy: Feasibility and Concept Design of Future Hydrail Enabled Railway Depots, Stephen Kent, 2020

[185] Study on the use of fuel cells & hydrogen in the railway environment, Roland Berger, 2019

[186] VDE study finds battery trains 35% cheaper than hydrogen, International Railway Journal, 2020

[187] Battery trains, vivarail

hydrogen fuel cell trains may be the only viable option. Network Rail envisage Norfolk and Suffolk as areas that will have a significant uptake of hydrogen trains[188].

Similarly, to battery charging infrastructure, hydrogen refuelling infrastructure for the rail sector is not yet developed. For the Alstom hydrogen train in Germany, refuelling was initially undertaken by a mobile fuel tanker, however a hydrogen refuelling station has now been developed in cooperation with Linde[189]. The roll out of hydrogen infrastructure will therefore need to be planned along with the adoption of hydrogen train routes. However this will reduce the need for widespread refuelling infrastructure, which is a significant barrier to road vehicles.

5.3.6 Future outlook

BE and hydrogen fuel cell trains are commercially available. For example, Alstom's hydrogen train and Vivarail's battery-electric train. Hitachi Rail have also recently announced their tri-mode battery-hybrid train. This operates on electrified track, but also can use both battery and diesel power whilst on non-electrified track. The battery can recharge while the train is in operation, both in diesel and electric mode[190]. Plug-in hybrid battery and fuel cell concepts are not currently being developed.

In general, improvements in both battery and fuel cell performance, for example efficiency increases, would benefit the rail sector. Gains in fuel cell efficiency would reduce the hydrogen volume required to be stored on the train. Advances in battery recharging times would mitigate range constraints of current battery technology, equally improvements in battery energy density are also expected. With increased range and the efficiency and price advantages of battery technology, battery powered rail is expected to be competitive in applications that are usually viewed as only viable for hydrogen-based technology, such as longer journeys with short downtimes.

As detailed in the decarbonisation strategy, electrification of railways is the preferred route to decarbonisation. Where decarbonisation isn't technically or economically viable, both hydrogen and batteries are considered potential solutions and are expected to play a role in the decarbonisation of the rail sector. Below is a summary of the viable technologies, considering their strengths and weaknesses, and the opportunities for and threats to their development.

Battery electric	**Strengths** Technology development: Battery technology is more advanced than hydrogen, with many lessons that can be taken from parallels in road transport. Performance: many of the advantages of battery technology in road transport apply, including well-to-wheel efficiency and cost.	**Weaknesses** Low range compared with existing trains limits the ability to serve all routes
	Opportunities Fast charging technology reduces the issue of limited range available for batteries, and together with stationary batteries at stations, may alleviate issues with weaker electricity grids in remote areas.	**Threats** Charging infrastructure: battery trains will require upgrades to electricity grids and the installation of charging infrastructure at stations.
Hydrogen fuel cell	**Strengths** Range: significant range is achievable with hydrogen technology. Decentralised operation: Hydrogen is suitable where existing infrastructure is more limited and suitable grid capacity is not able to support battery recharging.	**Weaknesses** Fuel tank size: large fuel tanks may be required to travel longer distances; height restrictions may mean fuels tanks will be placed in passenger carriages reducing overall passenger capacity.
	Opportunities Hub refuelling: new hydrogen refuelling infrastructure is required, which can be focused on depots and key routes, making roll out easier than for passenger cars.	**Threats** Development of infrastructure: The UK's restrictive loading gauge for trains limits the placement of the larger hydrogen tanks. Hydrogen supply and the cost of securing low carbon

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[188] Comment: why hydrogen trains will be a rare sight in the UK, The Engineer, 2021

[189] Alstom Coradia iLint – the world's first hydrogen powered train, Alstom

[190] Hitachi Rail unveils tri-mode battery hybrid train (RailUK), London Reconnections, 2022

		hydrogen limit the business case for hydrogen.

Overall, based on the Network Rail Traction Decarbonisation Network Strategy, both batteries and hydrogen are expected to play a small part of the future rail network, supporting overall electrification. The exact technology used is expected to be driven by the local infrastructure available and the requirements of the specific route in terms of distance, speed, utilisation and refuelling/recharging. As with other transport sectors, where battery technology is feasible from an energy capacity perspective, BE trains are expected to be the lower cost option and therefore preferrable.

Due to some restrictions in the available infrastructure and the high power and energy required, some rail-freight transport is expected to remain fuelled by conventional fuels based on current technology, as their needs are not yet able to be met by either hydrogen or battery options. Nevertheless, the overall emissions from the rail sector are expected to be significantly reduced by 2050 and represent a small proportion of the overall transport emissions for the UK.

5.3.7 Future market evolution

Based on the modelling undertaken as part of the DNV Energy Transition Outlook, a projection of the future market size and technology choice for rail is presented below. Table 5-4 presents the total energy demand by energy carrier, and this is also shown graphically in Figure 5-9.

Table 5-4 Projection of the total UK railway energy demand

		2022	2030	2040	2050
Railway Energy Demand TWh/Yr	Electricity - overhead line	6.1	8.6	10.8	11.2
	Battery electric	0.0	0.1	0.5	0.5
	Oil based fuel	7.5	5.5	1.9	0.3
	Coal	0.0	0.0	0.0	0.0
	Hydrogen	0.0	0.0	0.3	0.7
Total railway energy demand TWh/Yr		**13.7**	**14.1**	**13.5**	**12.6**

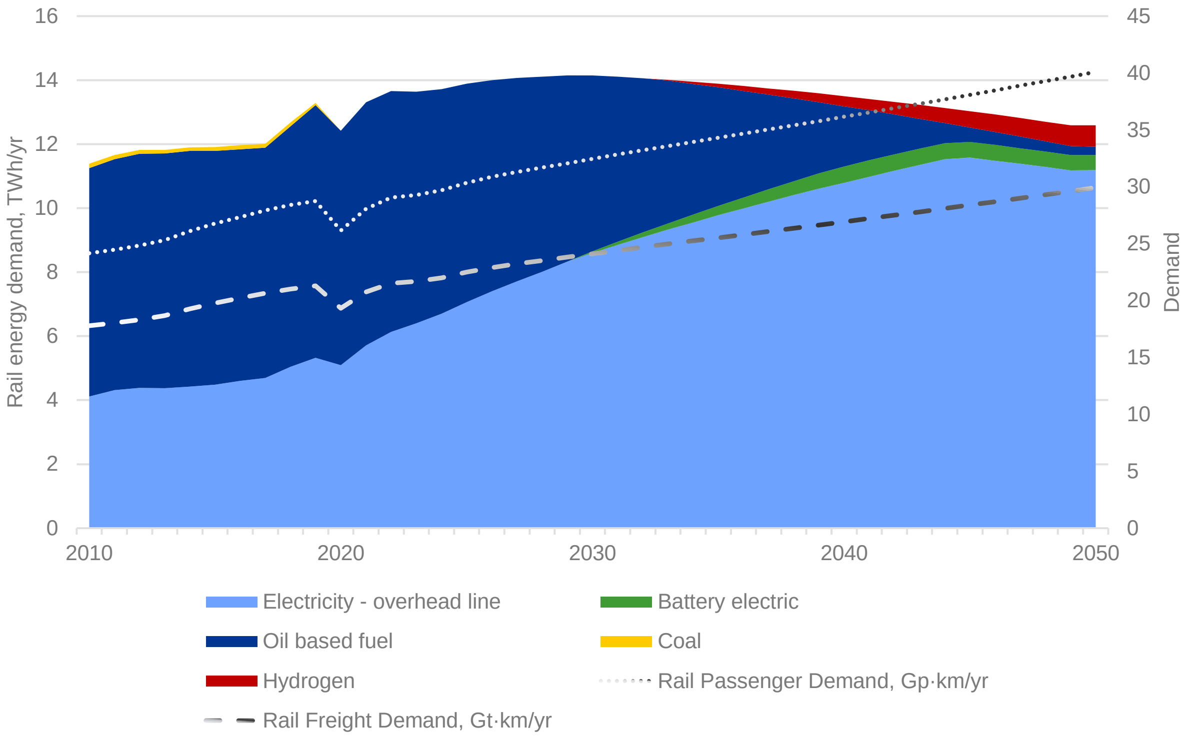

Figure 5-9 Graph showing UK energy demand by different energy carriers in rail along with passenger and freight demand (right axis), from 2010 to 2050

The key to the decarbonisation of the railway network is an increase in electrification, achieved predominantly through the use of overhead lines. As a result, direct electrification dominates the energy use in rail, with only small contributions from BE trains from 2030 onwards, hydrogen from the mid-2030s and a small remaining contribution from diesel. Due to the increased efficiency of electrification, the total energy required decreases over time, despite the demand from both passengers and freight being projected to increase.

With the limited requirement for battery trains, the demand for batteries in rail is the lowest of the transport sectors, with a total estimated capacity of 1,370 MWh by 2050 and a peak growth of 140 MWh per year. This is estimated based on an assumed two charges per day, operation over 350 days per year and a capacity twice the average use per charge/discharge cycle.

6 POWER SECTOR

6.1 Demand today

A key focus for the decarbonisation efforts in the UK and the rest of the world to date has been in the power sector. UK GHG emissions from electricity generation have reduced significantly, from 0.71 kgCO$_2$e/kWh to 0.21 kgCO$_2$e/kWh between 1990 and 2019 as shown in Figure 6-1. The power sector contributed to 19% of the UK's final energy consumption in 2021, with power stations accounting for 15.8% of all CO$_2$ emissions in 2021. Nevertheless, further reduction in GHG emissions from electricity generation is required to achieve net zero, and this is expected to be accompanied by a large increase in total electricity demand as the transport, industry and home heating sectors electrify.

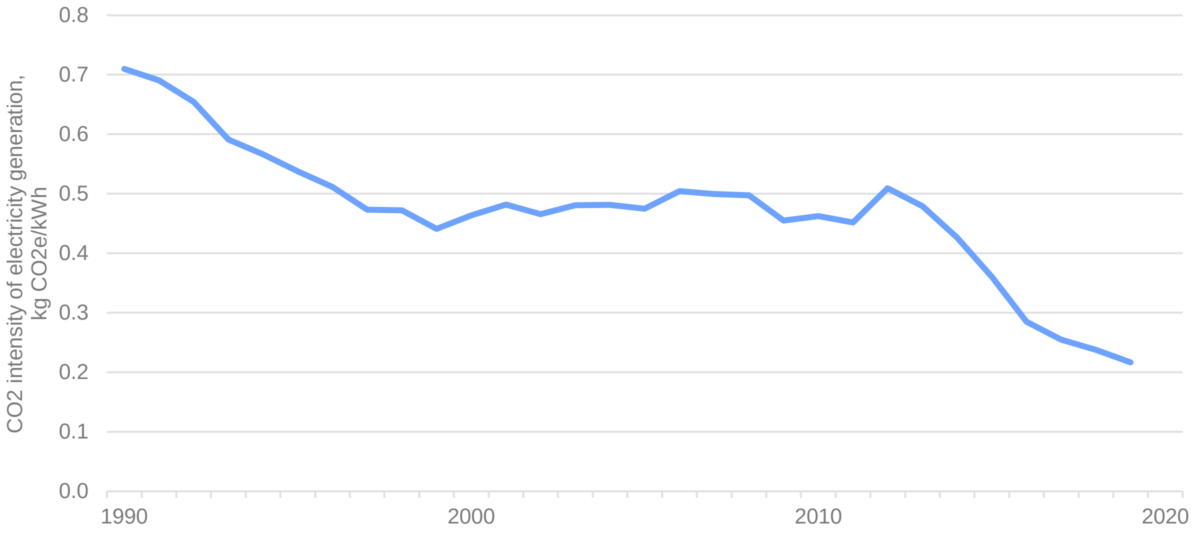

Figure 6-1 CO$_2$ intensity for UK electricity production, 1990 to 2019[191]

6.2 Market requirements

A major challenge for the electricity network is balancing variable demand and supply. Imbalance can occur on both a short-term basis, i.e. within a day, and longer-term seasonal or annual basis, and in each case due to both variations in demand and the changing output of supply. With an increased utilisation of renewable energy sources on the grid, the need for both short-term and seasonal storage is expected to increase significantly.

The seasonal nature of the energy system is illustrated in Figure 6-2. It shows the monthly energy demand from natural gas and electricity relative to the long-term demand, for the period 2005 to 2022. What it shows is a significantly greater seasonal spread in demand from gas relative to that of electricity (71% vs 27% respectively). This additional variation seen in gas is due to its dominant use in home heating (approximately 85% of UK households as discussed further in Section 7.2), which is by its nature seasonal, whereas electricity, used to a greater extent for powering appliances, has a more consistent demand profile over the year.

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[191] Greenhouse gas reporting: Conversion factors 2021, BEIS, 2022

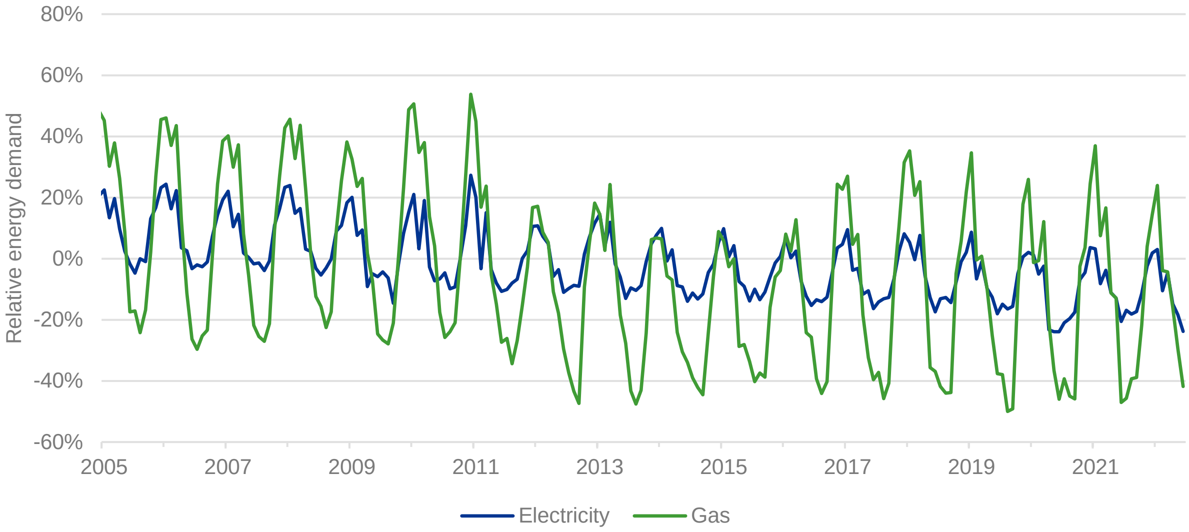

Figure 6-2 Seasonality in both natural gas and electricity demand in the UK, 2005 to 2022. [192] **Monthly demand relative to the long-term average**

Today, a large part of this seasonal variation is managed through storing natural gas, which is converted to heat in people's homes, or electricity in power stations, as required. Though power stations fitted with CCS is a potential solution to limit the emissions of GHGs, an energy system increasingly based on electricity will require new methods for balancing this seasonal demand.

Though historically matching demand has been the principal challenge for National Grid, in a future dominated by variable renewable energy generation, an equal challenge will be to utilise the large amounts of energy supply which is not matched by demand, and which without a suitable solution would need to be curtailed. Energy storage solutions will therefore be a key part of a decarbonised world, and both hydrogen and battery technology have the potential to meet this need, along with options such as more active demand management and technologies such as compressed or liquid air energy storage.

The causes and solutions for supply and demand imbalance are presented in the following figure, with timescales broadly split into two groups: short-term (hours) and seasonal (from days up to multiple months).

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[192] Natural Gas consumption data: BEIS energy trends, Table 4.2 Natural gas production and supply, monthly data (GWh). Electricity consumption data: BEIS Energy Trends, Table 5.5 Availability and consumption of electricity, monthly data (TWh)

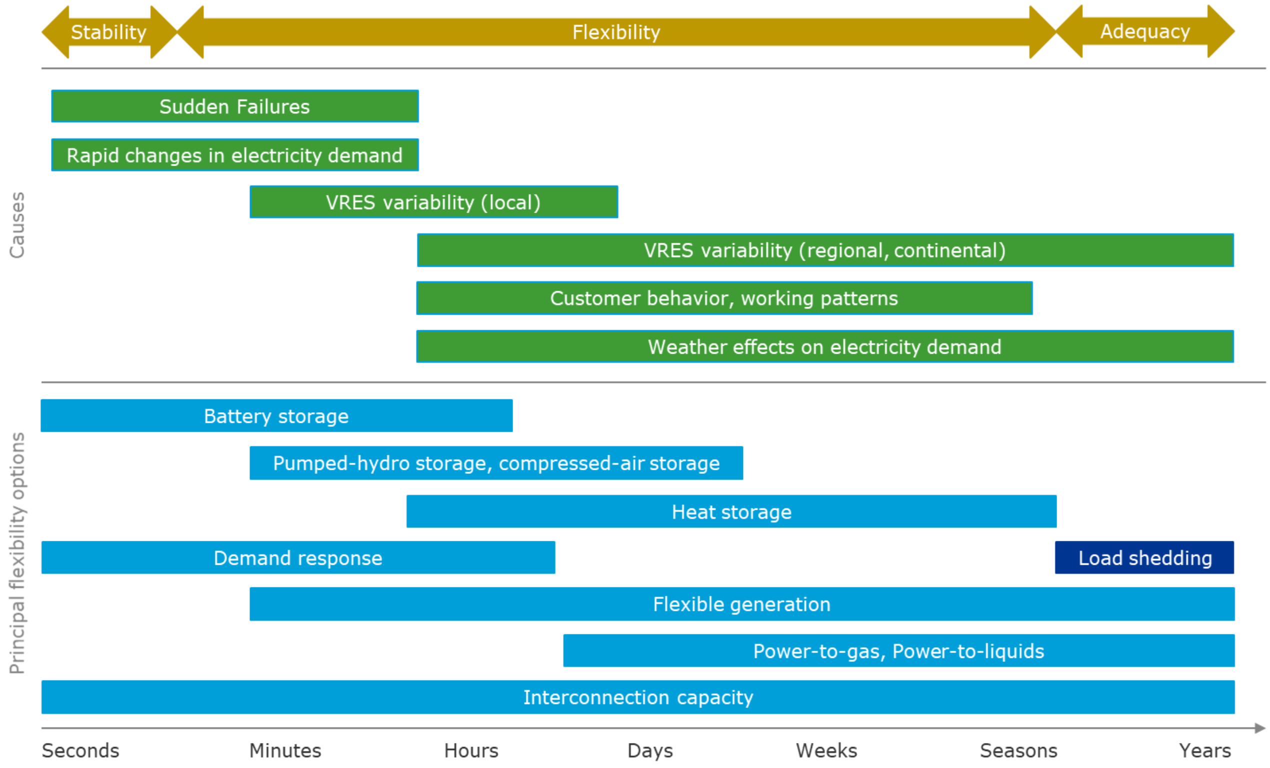

Figure 6-3 Overview of flexibility needs and solutions in the electricity system[193]

6.2.1 Short-term storage

The need for short-term storage, typically a few hours at most, can be broadly split into two categories as follows:

1. ensuring grid stability, and
2. providing energy balancing.

The key to ensuring grid stability is in maintaining the frequency and voltage of the system within acceptable limits. This requires solutions which can rapidly export power to the grid or remove it by importing power. Since the introduction of Enhanced Frequency Response (EFR) as a service in 2016 by National Grid, utility scale Battery Energy Storage Systems (BESS) have grown to dominate the frequency response sector, due to the favourable performance characteristics and business case of lithium-ion based BESS. BESS have provided all of the required power for Dynamic Containment, which has been the leading frequency response service of the past year.

The second requirement for short-term storage, is to balance the demand of energy against when that energy is produced. Energy demand is characterised by a daily profile, being lowest at night and higher during the day. In addition, solar PV, whose contribution to energy is expected to rise significantly to over 57 TWh by 2050 from 12 TWh in 2021, has a distinct generation curve, with peak production occurring across midday and no production at night. These two mechanisms create the need for intraday energy storage that can shift energy from when it is produced to when it is needed.

Furthermore, in recognition of the distinct seasonal nature of solar PV, it is expected that behind-the-meter batteries will be used at several solar PV plants, and in domestic applications, in order to shift the supply of energy from the midday peak to more profitable times when demand is high, and generation is low. This creates an additional market for short-term energy storage.

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[193] The Promise of Seasonal Storage, DNV, 2020

Following from these, the requirements of short-term energy storage solutions include having a fast response time, high cycle efficiency, an energy capacity of typically 1-4 hours, and high reliability.

6.2.2 Medium-term and Seasonal

Beyond the need to balance short-term differences in supply and demand, storage technologies will increasingly be required to balance longer periods with durations in excess of 4 hours up to multiple days. Where short-term energy storage has a well-defined daily cycle for both demand and supply, multiday profiles are less clearly defined, with only a small weekend/weekday influence on demand seen before the broader seasonal winter/summer patterns are found. Nevertheless, periods of low renewable generation and high energy demand covering multiple days occur and will need to be balanced within the future energy system, and the overall seasonal variation in electricity demand is expected to increase significantly from what it is today due largely to the electrification of heating.

In reality there is no defined cut-off between short-term, medium-term and seasonal storage needs and technologies, however the longer the period of storage the greater the importance of the following parameters:

- the energy capacity of the storage technology increases, relative to the power capacity,
- self-discharge must be minimised due to the longer period the energy will need to be stored,
- the storage cost must be minimised.

In addition, medium-term and particularly seasonal storage has the characteristic that fewer cycles of charging and discharging will be desired and thus, less availability to generate revenue. This may drive the creation of new business models and perhaps necessitate the creation of alternative markets to provide investor confidence and long-term revenue security.

6.3 Performance characteristics

6.3.1 Short-term storage

With the decrease in battery prices seen over the past 10 years (shown in Figure 4-4 and Figure 4-12), battery technology is considered to be the preferred solution for short-term energy storage due to its fast response time, high cycle efficiency, reliable operation and low operational costs. UK BESS has rapidly grown to a capacity of over 1.5 GW in 2022 and is expected to increase to between 18 GW and 35 GW by 2050 based on the National Grid Future Energy Scenarios[194].

For both grid stability services and energy balancing, over a short time period, hydrogen is not considered a viable solution, this is primarily due to the lower cycle efficiency and resulting higher cost in relation to batteries. For hydrogen storage to be economic, a larger price differential is required between the price of energy that is bought and stored, and the price that the energy can be sold for in the future.

Sharing many of the same technical characteristics as stationary storage, the expansion of electric vehicles offers the possibility of BEV owners using their battery capacity as a storage asset and participating in energy balancing services. The technological solutions for vehicle-to-grid (V2G) battery storage are available, it is expected that the required regulation will be developed in the near term along with the smart meters and smart grids needed. This will enable a significant number of BEV owners and fleets to use their energy capacity for short-term energy storage. In DNV's ETO, it is expected that by the mid-2030s, around 10% of all BEV batteries will be available to provide grid flexibility at any time through V2G. There are a number of challenges of V2G with personal vehicles, such as public perception, battery degradation, and new business models being required.

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[194] Future Energy Scenarios, National Grid ESO

Competing technologies for short-term storage include pumped hydro, however this is geographically constrained, and, in the UK, no significant expansion of capacity is expected. Other novel technologies are being developed but scaling these to an economical position will be a challenge.

6.3.2 Medium-term and Seasonal storage

With the intrinsic storage capability of fossil fuels, the development of specific medium-term and seasonal storage technologies has been limited. Flow batteries, liquid air energy storage and compressed air energy storage are technologies suited to medium-term or longer storage applications, however their commercial development to date has been limited. For seasonal storage, a greater potential is seen through the use of power-to-gas or power-to-liquid molecular storage using hydrogen or related fuels such as ammonia and methane.

The potential for lithium-ion batteries as part of a BESS to provide seasonal storage is considered to be limited. This is primarily driven by the high cost per kilo-watt hour of battery technology, which therefore requires more frequent cycling in order to recoup the initial investment. As the price of batteries reduces, particularly with alternative chemistries, the economic duration of BESS is expected to increase, increasing its potential for medium-term storage applications.

As mentioned, for seasonal storage, the more promising technologies are based on the conversion of electricity to a fuel and then re-conversion of that fuel to electricity when required. In this case compressed or liquid hydrogen is one of a number of concepts, along with the creation of hydrogen-based fuels such as ammonia. The RTE of ammonia as an energy storage technology is largely dictated by the hydrogen production route. Ammonia from steam methane reforming has an efficiency of between 20 to 25%, whereas green ammonia has an efficiency of 40 to 72%. Ammonia has a relatively low energy installation cost, typically between 0.11 USD/kWh and 0.24 USD/kWh, again, depending on the production route[195].

In creating a fuel to store energy, the overall process is quite different to that of battery technology. In this case, production (charging), storage and use (discharging) can be undertaken by different entities and in different locations, as required. With a growing hydrogen sector supplying industry and some transport sectors, production of clean hydrogen is expected to develop first, with little large-scale storage until a number of years later. In addition, initially the hydrogen used for electricity production is likely to be blended with natural gas, and used within combined cycle gas turbines, reducing the investment needed in new technologies. Later, as well as gas turbines, hydrogen can be converted in a fuel cell to provide electricity.

Hydrogen as an energy storage technology will also be in competition with new and existing users for clean hydrogen, leading to potential price volatility. This in effect means hydrogen's use in the power sector will only be as a last resort, after other options such as interconnectors, demand response and dispatchable generation, including natural gas, are used.

6.4 Cost

The analysis of the performance characteristics of battery and hydrogen as a form of energy storage shows that they are suitable for different markets within the power sector and are therefore not in direct competition.

Lithium-ion BESS are already the dominant technology for new short-term energy storage assets. They are able to operate remotely and, with few moving parts, have low maintenance requirements, leading to low OPEX costs. Furthermore, the high cycle efficiency that can be achieved (typically greater than 80%), reduces the cost of energy needed to run the facility.

The dominant cost for lithium-ion BESS is their CAPEX and specifically the cost of battery modules. As shown in Figure 4-4, the cost of batteries is expected to fall in the next decades with the development of new chemistries and improved

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[195] Ammonia as a storage solution for future decarbonised energy systems, The Oxford Institute for Energy Studies, 2020

production techniques, driven by EV demand. This will further increase the competitiveness of lithium-ion BESS and may allow installations with increased energy durations to be installed, bringing it into the medium-term storage market.

For medium-term and seasonal storage, the nascency of the market makes cost estimates, particularly for hydrogen-based solutions, less certain. Analysis undertaken by Jacobs models the unit cost of firm generation for a series for technologies from one hour up to six days of duration. For durations up to four hours, BESS is shown the be the lowest cost, from 4 hours to 12 hours liquid air energy storage has the lowest cost, after which Hydrogen using gas cavern storage and a combined cycle gas turbine (CCGT) has the lowest cost[196].

Analysis presented by DNV looking at various hydrogen based seasonal storage solutions also finds compressed hydrogen using subsurface storage to be the most economical solution, with lower costs than using liquified hydrogen, methane or ammonia as the energy storage medium.

6.5 Infrastructure considerations

The infrastructure requirements for energy storage systems are closely linked with the electricity grid itself. Technologies such as BESS, flow batteries, CAES and LAES are limited by the availability of suitable grid connections, along with securing land and obtaining planning permission.

For seasonal storage using hydrogen, though some producers of hydrogen may opt for using dedicated renewable energy, grid connected installations shall be constrained by grid capacity to the same extent as other technologies. In addition, the most economic seasonal storage solution with hydrogen relies on the availability of underground salt caverns suitable for hydrogen gas storage, requiring installation in certain locations. The stored hydrogen could be used with hydrogen gas turbines. Siemens Energy have plans to run 100% hydrogen for power generation applications by 2030, with successful demonstrations on some systems today. GE Gas Power are also developing hydrogen gas turbines.

Hydrogen storage installations are expected to be large scale infrastructure projects, with longer construction times than other technologies. Significant development from a technical and commercial perspective is needed before an investment decision can be made. These factors are expected to slow the development of hydrogen seasonal storage enabling other technologies to develop first.

6.6 Future outlook

The appraisal above highlights the overall considerations for the decarbonisation of the power sector and the areas where battery and hydrogen technology may be used. Below is a summary of the viable technologies, considering their strengths and weaknesses, and the opportunities for and threats to their development.

Battery energy storage systems	**Strengths** Fast response makes battery technology ideally suited to frequency response services. High efficiency minimises the energy lost from the system, reducing costs.	**Weaknesses** Battery degradation decreases the life of the asset and limits the number of charge/discharge cycles that can be undertaken. Cost of energy capacity is high, meaning batteries need frequent cycling to recoup the initial investment. This, and self-discharge rates, limits the duration of batteries to hours, rather than days.
	Opportunities Vehicle-to-grid: Batteries as part of electric vehicles offer the potential for short term storage in a symbiotic relationship, in which each offers the other additional capacity and revenue, accelerating uptake. Technology development: Due to the significant interest in electric vehicles, the rate of development in battery technology is high.	**Threats** Battery availability; as demand increases, supply chain pressures and the availability of critical materials may hamper battery availability and lead to cost increases. Rare materials and recycling of batteries has the potential to damage public perception. New materials and improved recycling should be developed to mitigate this.

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[196] Strategy for Long-Term Energy Storage in the UK, Jacobs, 2020

	Flow batteries and next generation battery technologies may be used to provide a longer storage duration than is economic with current lithium-ion batteries.	
Hydrogen	**Strengths** High energy capacity can be achieved, through having large hydrogen storage facilities. De-coupled: Hydrogen can be transported from point of production to multiple storage and use locations, increasing flexibility. Compatibility with natural gas enables hydrogen to be blended and used with lower initial investment costs for both heating and electricity production.	**Weaknesses** Efficiency of the overall process is low adding to cost, and the overall amount of energy required. Storage costs: Above ground storage requires significant amounts of CAPEX, far greater than subsurface storage. Location suitability Cost effective storage options such as salt caverns are limited by the available geology. Technology development of subsurface storage in depleted fields and reservoirs is currently unproven.
	Opportunities Multiple uses: clean hydrogen production has many potential markets, which can increase demand and investment. Existing infrastructure from natural gas networks can be used to kick-start development of a hydrogen economy.	**Threats** Competition from other users of hydrogen may increase prices, making investment in electricity generation infrastructure from hydrogen unattractive

The appraisal of hydrogen and batteries within the power sector shows that the overlap between the two technologies is expected to be limited, with batteries taking a dominant share of the short duration requirements for storage, and hydrogen being used to balance demand over a longer seasonal period. The two technologies therefore complement each other, enabling the UK to achieve significant decarbonisation within the power sector whilst also ensuring grid stability and security of supply.

6.7 Future market evolution

Based on the modelling undertaken as part of the DNV ETO, a projection of the future market size and technology choice for energy storage within the power sector is presented in the graphs below. Battery technology is considered within short-term storage applications, presented in Figure 6-4 to Figure 6-6, and hydrogen is considered as seasonal storage in Figure 6-7.

Figure 6-4 presents the installed power capacity in the UK for different technology options. Little change in the capacity of pumped hydro, which historically has been the dominant storage technology, is modelled due to the geographical constraints in its deployment. Instead, a rapid increase in the capacity of utility scale battery storage is forecasted, leading to 24 GW by 2050, along with 45 GW of V2G energy storage from EVs. The amount of capacity provided by long-duration storage technologies is expected to remain low through to 2050. In modelling the amount of V2G available, DNV expects that at any time 10% of the fleet will be available for the electricity grid to use. By mid-century, V2G systems in the UK will provide a third of the total throughput from battery storage, equivalent to 3.7 TWh per year.

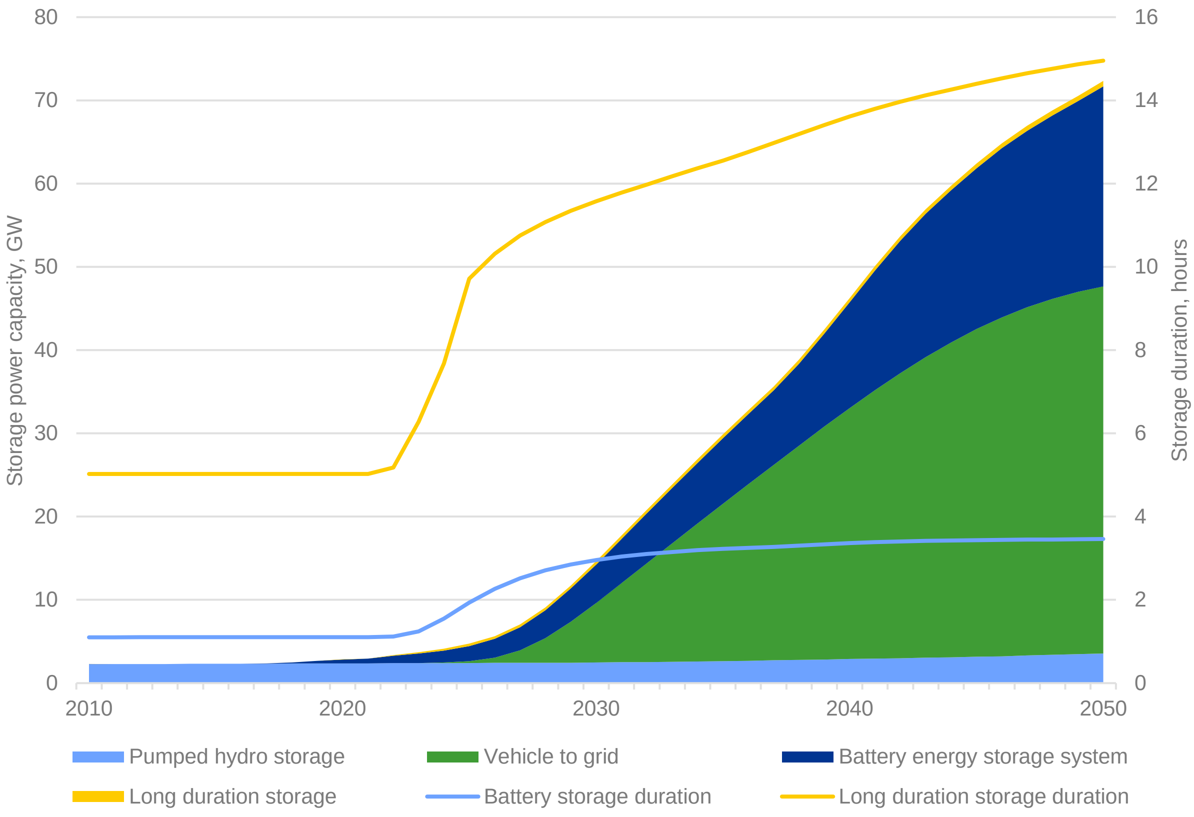

Figure 6-4 Graph showing power capacity of different short term storage technologies, along with the average storage duration of each technology, 2010 to 2050

As well as the energy capacities, the average energy storage duration is presented above, which for both battery storage and long-duration energy storage, shows an increase from the durations today to approximately 4 and 15 hours respectively. For pumped hydro and V2G storage, the durations are 8.4 hours and 10 hours respectively throughout the analysis period.

The total energy storage capacity of different technologies for use in balancing the electricity grid is shown in Figure 6-5. In terms of energy capacity, the energy contained within EVs is expected to be the largest source due to the 10-hour duration of BEV batteries, however it is not expected that this full capacity is used. Following EVs, utility scale batteries are expected to be the dominant provider of energy capacity with 90 GWh installed and 93 GWh of co-located BESS with solar PV, with smaller contributions from pumped hydro and long-duration storage technologies, totalling 190 GWh of storage facilities by 2050 excluding capacity from EVs and pumped hydro.

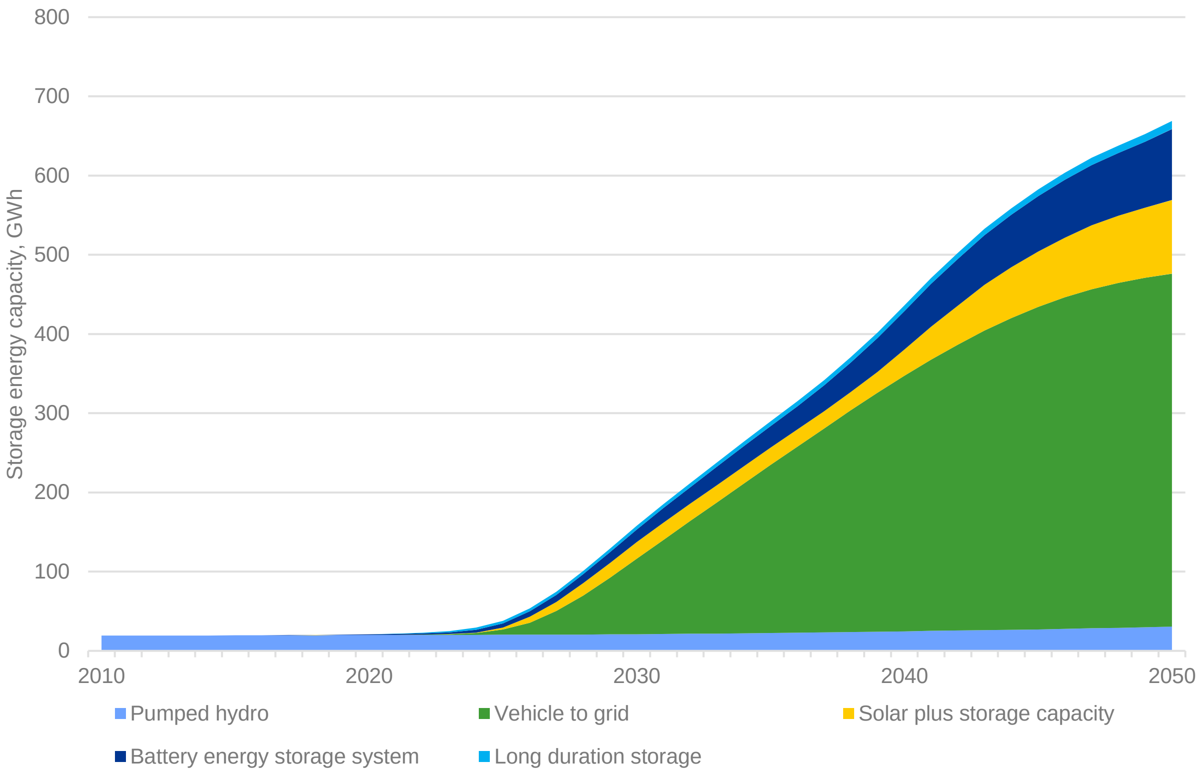

Figure 6-5 Graph showing energy storage capacity for different storage technologies, from 2010 to 2050

Batteries are expected to be used together with solar PV in order to shift the supply of energy away from the solar cycle to periods of high demand. As shown in Figure 6-6, the expansion of solar PV generation in the UK is significant, and within that, approximately 10% is co-located with BESS, amounting to 93 GWh of battery capacity in 2050.

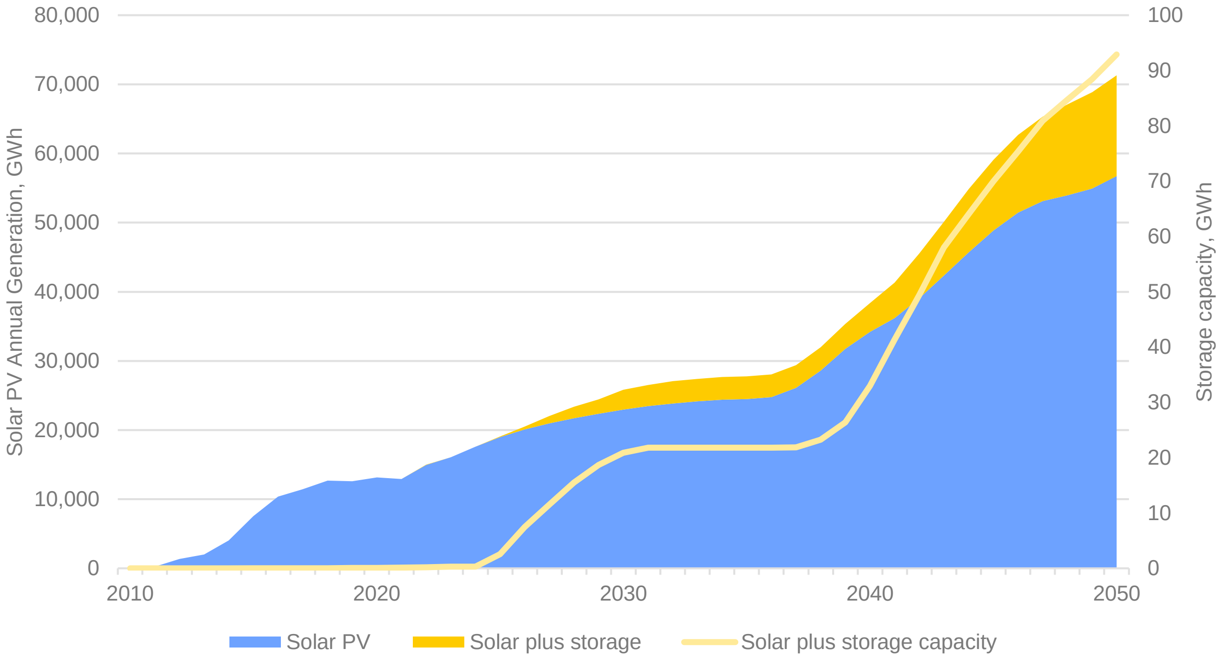

Figure 6-6 Graph showing Solar PV generation and sociated dedicated battery storage capacity, 2010 to 2050

The use of hydrogen as a seasonal storage technology is not explicitly modelled within the ETO, which aligns with the expected hydrogen market, which as discussed is expected to be decoupled with multiple competing uses of green hydrogen.

Nevertheless, the use of hydrogen with the ETO model can be derived and is presented below, showing the electricity produced from hydrogen, the use of electricity to produce hydrogen and the total power capacity of grid connected electrolysers producing hydrogen for use within the merchant market. It is noted that further electrolysers are expected to be in use, however not connected to the electricity grid, and therefore they will be unable to utilise excess renewable generation from the grid.

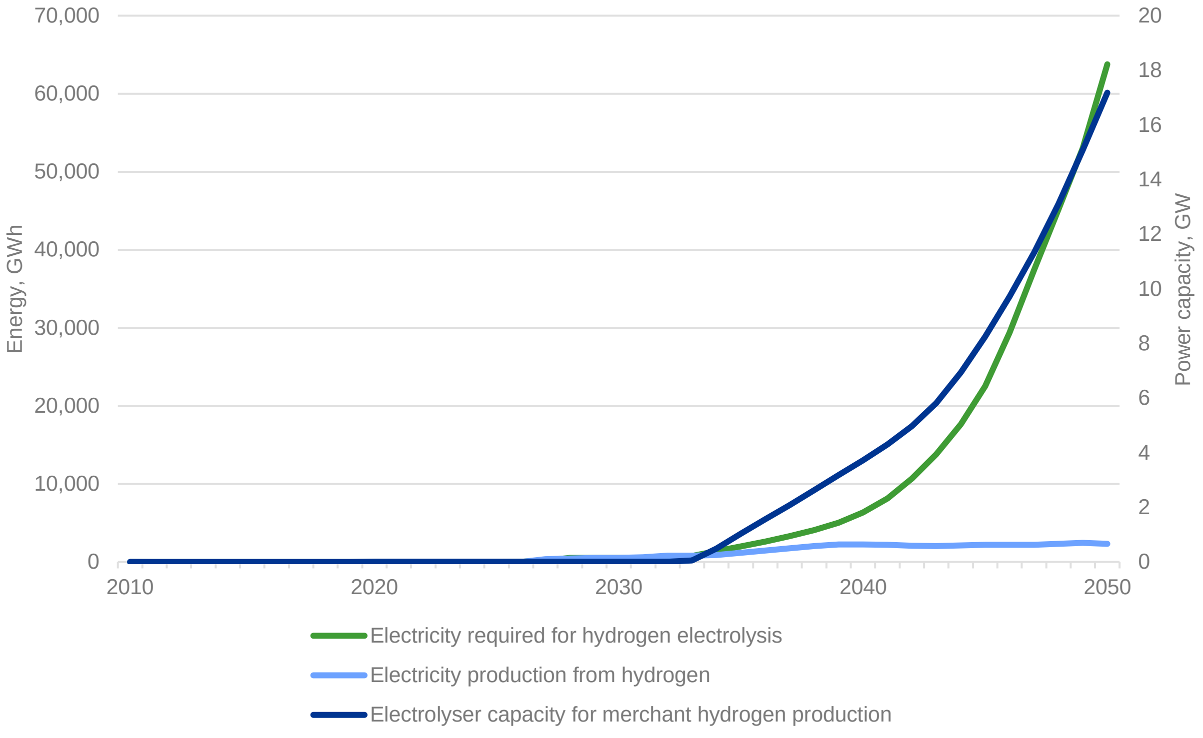

Figure 6-7 Graph showing hydrogen within the power sector, including energy production and use, and electrolyser capacity, from 2010 to 2050

The total electricity generated from hydrogen is significantly below that which is used to produce hydrogen, and peaks at approximately 2,300 GWh in 2039, whereas the production of hydrogen continues to rise through to 2050. Within the ETO model, electricity is produced from hydrogen by being blended with natural gas for use in gas turbine power stations. Therefore, as the fleet of gas fired power stations are removed from the grid, the ability of hydrogen to produce electricity is greatly reduced. From this point, hydrogen can still be used as an energy store within the ETO model, however only in its ability to absorb excess renewables on the grid, rather than in adding power during times of peak demand. Should sufficient demand for electricity production from hydrogen exist, it is considered that dedicated hydrogen power stations may be built or gas power stations be retrofitted, allowing hydrogen storage to be used for electricity production.

7 MANUFACTURING AND THE BUILT ENVIRONMENT

7.1 Manufacturing

The UK has significant amounts of industry, contributing approximately 25% of UK emissions and 16% of energy consumption in 2019. Natural gas and electricity met approximately 39% and 34% of energy demand respectively in 2019[197], with the remainder provided by oil, coal and biomass.

Accurate figures are not available, however estimations as part of DNV's ETO modelling research suggest across the manufacturing sector, industrial heating processes and energy for machines, motors and appliances account for the largest amount of energy consumption at 61% and 32% respectively. The remainder is accounted for by iron ore reduction processes and energy use for onsite industrial vehicles.

Electrification of industrial process where possible has many benefits for the decarbonisation of industry. However, for industry, electrification is expected to be achieved without widespread use of high-capacity battery technology. Where batteries may provide value, is in increasing the power available for short periods within an electrified industrial setting. By charging at low power for a longer periods and delivering high power for short periods of time throughout the day, batteries may enable lower power, more cost effective, grid connections to be secured. Nevertheless, this approach is not anticipated to be widespread, and instead by reserved for more specialist applications, or where a factory has a significant amount of own power generation, through for instance solar PV.

Industrial processes requiring high temperatures such as steel works and glass manufacturers tend to achieve this through natural gas combustion. Electrification of these industries is unlikely to be an option due to the high energy demand required. Instead, replacement of natural gas with hydrogen is considered to be the most likely low carbon alternative for high temperature heat in the manufacturing industry.

Today, UK hydrogen production is already concentrated in the steel, chemicals and refinery industry. Hydrogen is used as a feedstock and can be used to produce further products in conjunction with crude oil. The production and usage of hydrogen is typically integrated at the facility. Currently this is dominated by grey hydrogen; hydrogen produced from natural gas, without carbon capture and storage.

The existing use of hydrogen in industry provides some benefits for the wider use of low carbon hydrogen in industry as an energy source. Hydrogen facilities, safety awareness and an existing market will help early producers of low-carbon hydrogen to find suitable markets and provide investor confidence.

Therefore, the overlap between battery and hydrogen technology within industry is anticipated to be limited. The future energy demand by energy carrier is shown in Figure 7-1. Hydrogen is expected to rise from negligible today to over 10% in 2050, however the dominant energy carrier is predicted to be grid connected electricity. Though batteries will be present in the manufacturing industry, in comparison with the transport and power sectors, this is expected to be negligible and has not been modelled in this report.

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[197] Aggregate energy commodity balance: gross calorific values basis, BEIS, 2022

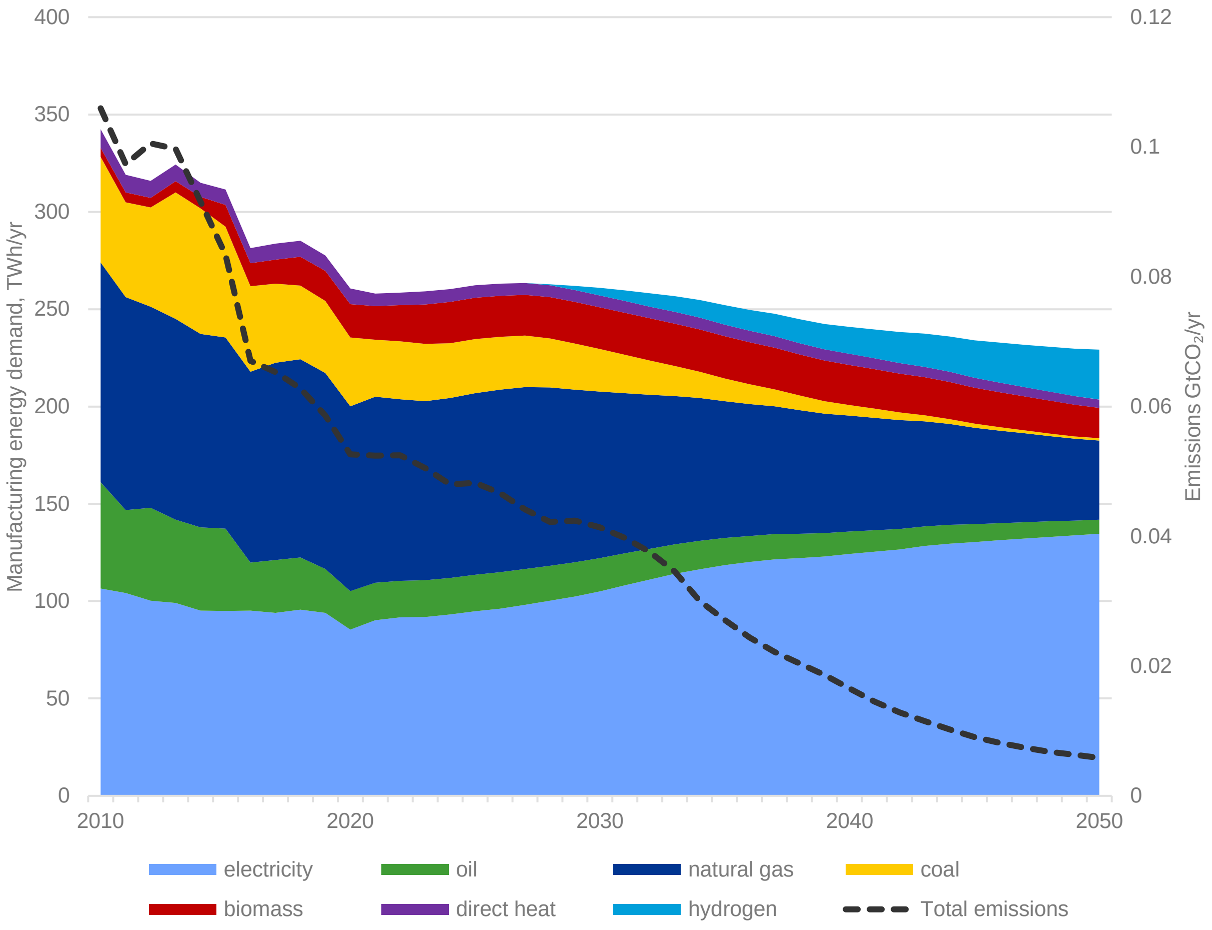

Figure 7-1 Energy demand by energy carrier for manufacturing industry from 2010 to 2050, including total emissions after consideration of CCS

7.2 Built Environment

The built environment refers to energy use in residential and commercial buildings, typically for water and space heating, cooking and appliances, and lighting. In 2019, energy use in buildings was dominated by space heating (59%), water heating (9%) and appliances and lighting (22%)[198] as shown in Figure 7-2. This trend is broadly expected to remain, except for space heating energy demand which reduces, due to improvements in building efficiency and the use of heat pumps.

Residential buildings alone accounted for 21% of UK emissions in 2019[199], and hence the built environment is a sector in significant need of decarbonisation. Approximately 85% of residential properties in the UK are connected to the gas network[200], and use natural gas for cooking, space and water heating. For buildings not connected to the gas grid, the main heating fuel comes from oil and liquid petroleum gas (LPG) or they make use of electric heating. As a result of this, most of the energy demand in the UK is delivered from natural gas, electricity and oil. In 2019, natural gas covered up to 57% of energy demand, with approximately 32% and 7% from electricity and oil respectively. Solar thermal, biomass and combined heat and power (CHP) systems also contribute small amounts in meeting the energy demand for the built environment sector.

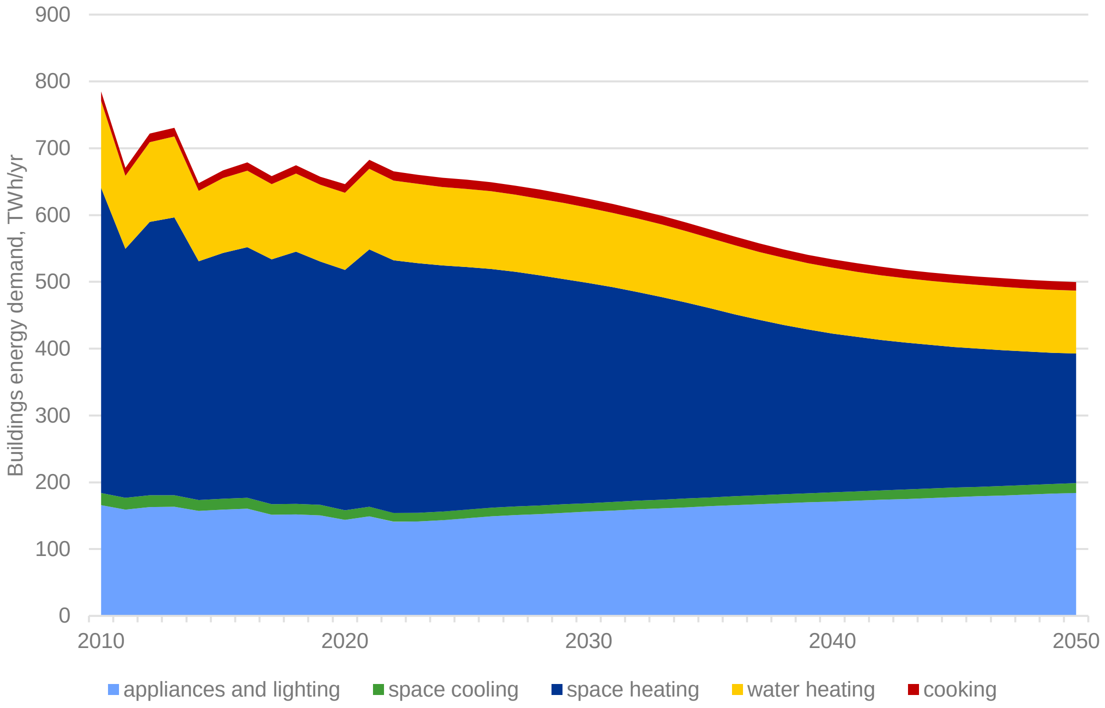

Figure 7-2 Building energy demand by type of use from 2010 to 2050[201]

Low-carbon hydrogen could play a key role in decarbonising energy for hard to abate sectors such as heating within the built environment.

Fuel switching to low-carbon hydrogen is one option for reducing emissions from domestic heat, currently responsible for some 21% of UK GHG emissions. The UK Government will make the decision on hydrogen for heating in 2026, meanwhile boiler manufacturers have developed "hydrogen ready" boilers which means the boilers will only require minimal alterations for the fuel switch to hydrogen. Industry, regulating authorities and gas network operators across the

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[198] Energy Consumption in the UK (ECUK): End Use Tables, BEIS, 2022

[199] Final UK greenhouse gas emissions national statistics 1990-2019, BEIS, 2021

[200] Heat in UK Buildings Today, CCC, 2016

[201] Energy Transition Outlook, DNV, 2022

UK are undertaking numerous studies and trials to provide the evidence base to prove hydrogen can be delivered safely and securely to all UK customers through new and re-purposed gas pipelines; and safely used in appliances.

Figure 7-3 shows a summary of the forecast consumption increase between 2030 to 2035. There is currently significant uncertainty related to the use of hydrogen for heating, and as a result, the DNV ETO model only forecasts up to 2035. If this is the case, wide-spread electrification will be required to decarbonise domestic heat. There is also potential for a hybrid mixture of electrification (including heat pumps), district heating and hydrogen in the UK.

Figure 7-3 Forecast hydrogen demand in the UK (TWh), adapted from BEIS 2021

Aside from political decisions, the suitability of a solution is largely dependent on factors including regional geography, house type, the heating systems currently in use, and whether existing homes are connected to the gas grid. Other aspects that need to be considered are the required changes in the home to install low carbon heating systems, for example, changing pipework, radiators or installing additional equipment.

The potential electrification of heating, using heat pumps, is not expected to increase demand for batteries as power will be used directly or stored as heat. Batteries today already play a small role within the built environment where home or business owners have their own electricity generation and use batteries in combination particularly with solar PV to enable them to use more of their own generation. As the cost of solar PV and batteries continue to come down, the number of businesses and individuals investing in own generation is expected to increase, particularly as wholesale electricity and gas prices continue to be volatile. As of 2020, self-generation capacity in the UK was around 6.8 GW [202]. Due to the lower RTE of hydrogen production as an electricity store, it is not expected that hydrogen will complete with batteries for this purpose.

DNV's future fuel mix forecast for the built environment sector can be seen in Figure 7-4, with <1% attributed to hydrogen by 2050, and the vast majority of the remaining through continued use of natural gas or direct electrification. The negligible share of hydrogen demand in 2050, is expected to be associated with blending and reflects the overall lack of committed policy support by 2050[106]. The decarbonisation route for the built environment is not anticipated to include battery technology, and therefore limited competition or overlap between battery and hydrogen is expected in this sector.

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[202] UK Energy in Brief, BEIS, 2021

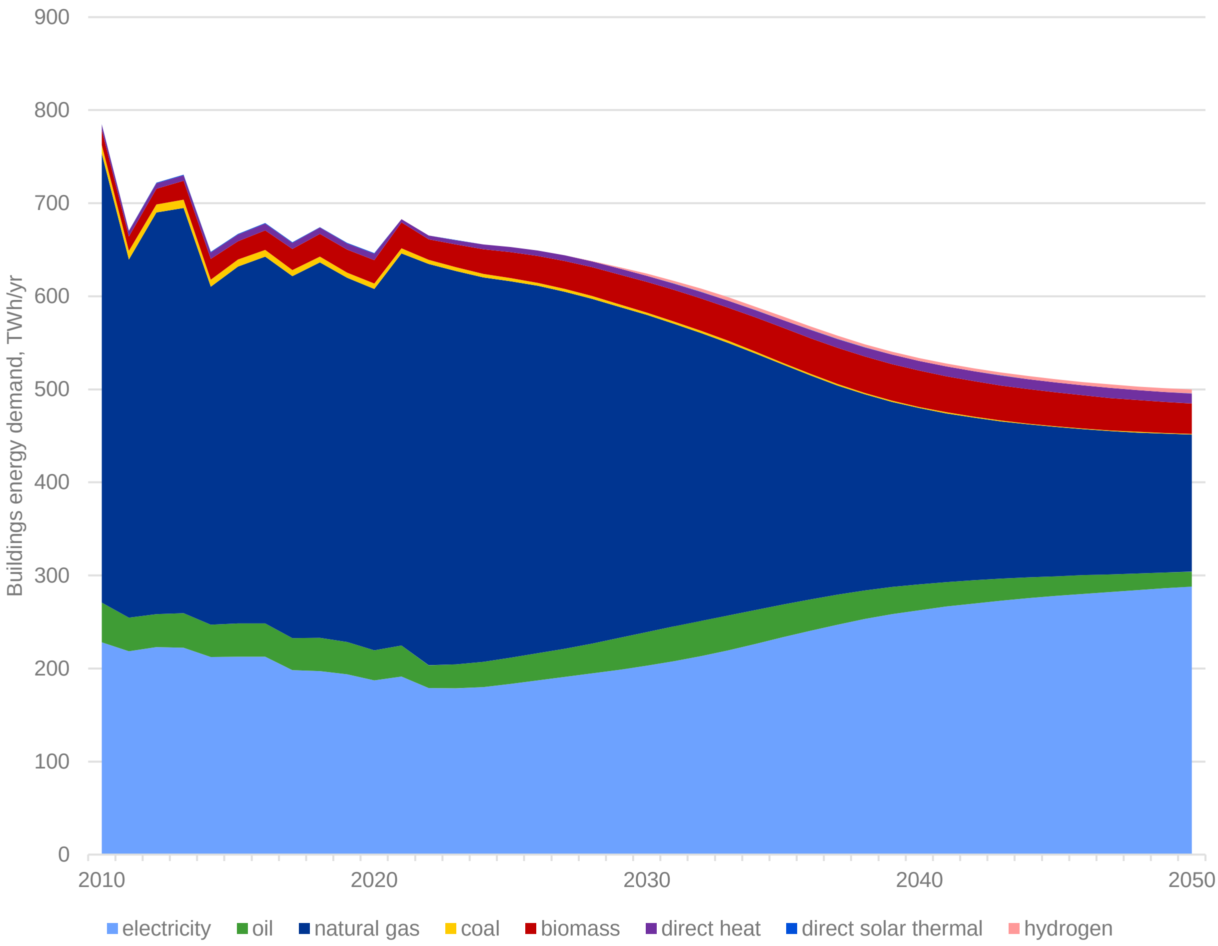

Figure 7-4 Predicted building energy demand by energy carrier, 2010 to 2050

8 CONCLUSIONS

This report presents an analysis of the different sectors within the UK and the expected role that both hydrogen and batteries are likely to play as the UK transitions to a low carbon future. Analysing the potential for batteries and hydrogen within the transport, manufacturing, built environment and power sectors, DNV has considered where a single technology is expected to dominate, where multiple technologies are expected to complement each other and even offer hybrid solutions, and where both are in direct competition.

The review of different technologies is based on DNV's knowledge and experience within both the battery and hydrogen industries, as well as a review of different studies available in the public domain. This review has been incorporated into the DNV's Energy Transition Outlook model, an integrated system-dynamics simulation model covering the energy model and providing an independent view of the UK and global energy outlook from now until 2050. The modelling undertaken is cost based and enables the non-linear interdependencies between different parameters to be considered so that decisions made in one sector influence the decision made in another. Therefore, a comprehensive picture of the future UK energy system, embedded within the global economy, is formed, and shows DNV's view of the most likely market share for hydrogen and battery technology.

In general, the review of the different sectors shows that the instances of direct competition between batteries and hydrogen are limited, and instead one of the two technologies is typically more suited to a particular application. For instance, battery technology is expected to dominate passenger vehicles, leaving little room for hydrogen, whereas in both the built environment and manufacturing sectors, the demand for batteries is expected to be low, as any electrification will be achieved directly through the electricity grid. Therefore, for these sectors, the demand for hydrogen is in competition with grid connected electricity, rather than batteries.

Both hydrogen and battery technology are expected to operate in the power sector. In this instance, the characteristics of the two technologies lend themselves to different areas of the sector. Batteries are expected to dominate in providing short term energy storage solutions, improving grid stability and balancing supply and demand within the daily cycles of renewable electricity generation and changing demand. Hydrogen on the other hand is expected to play a role as a form of dispatchable generation, which allows for the seasonal storage of energy – producing hydrogen in seasons with excess electricity generation from renewables, to then convert it back to electricity during periods with reduced wind and solar availability. In this sense the two technologies complement each other and help to ensure a secure supply of electricity to an electrifying economy.

The main area of competition for battery and hydrogen technology is in the transport sector where there is a high demand for power and energy. This includes aviation and maritime sectors, rail where it is not possible to directly electrify the tracks, and heavy-duty applications in road transport. With its higher efficiency and lower cost, battery technology is generally considered the preferred solution for transport applications. The areas in which battery technology can operate is increasing due to the rapid uptake of electric vehicles over recent years advancing the capabilities of battery technology. Heavy goods vehicles, buses and coaches can be served by batteries in many instances with today's technology, whereas previously these applications were considered to be too onerous. In addition, short range travel in aviation and shipping are areas where batteries have the potential to meet demand, where previously only liquid fuels were thought to be suitable. With further improvements in battery technology, more areas of transport may be able to be served by battery technology.

The analysis undertaken as part of this report shows that hydrogen is in many applications expected to be more expensive and overall less efficient compared to direct electrification and should therefore be thought of as the low-carbon energy carrier of last resort. Electrification on the other hand is typically the most efficient energy carrier, with battery technology used where storage is required. Therefore, renewables should ideally first be used to reduce the use of fossil fuels in the electricity mix, with hydrogen production via electrolysis being deployed later in the transition.

The graphs shown in Figure 8-1 and Figure 8-2 present the total energy carried by battery and hydrogen technology (including hydrogen derived fuels) respectively in the future UK energy system. In both cases, the energy throughput shows a rapid increase over the next three decades reaching approximately 130TWh and 105 TWh per year by 2050 for each technology respectively.

In the case of battery technology, the requirement from road transport dominates, using 88% of the energy in 2050, with aviation and the power sector making up most of the remaining energy use. Only limited use of batteries is expected in the rail and maritime sectors, and no significant use in manufacturing or the built environment, with vehicle-to-grid and behind-the-meter solar PV applications captured within the power sector.

For hydrogen, the use of energy is more evenly distributed with aviation, maritime, and manufacturing providing the largest demand, along with contributions from road transport and the power sector.

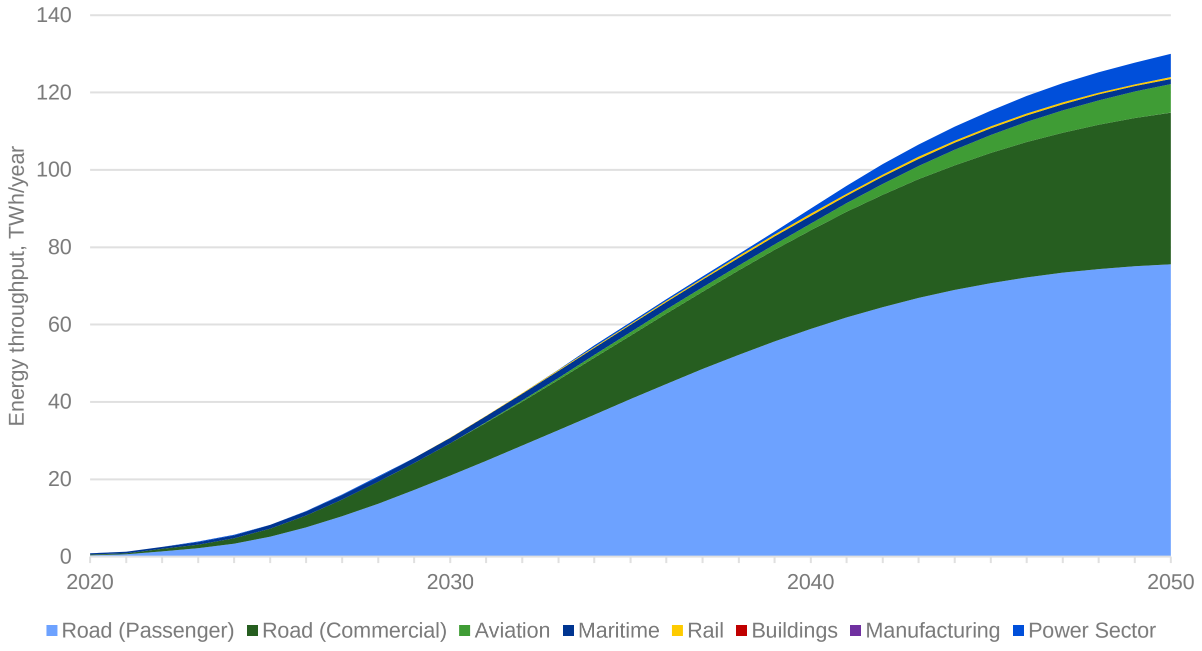

Figure 8-1 Graph showing total battery energy throughput across all sectors from 2010 to 2050

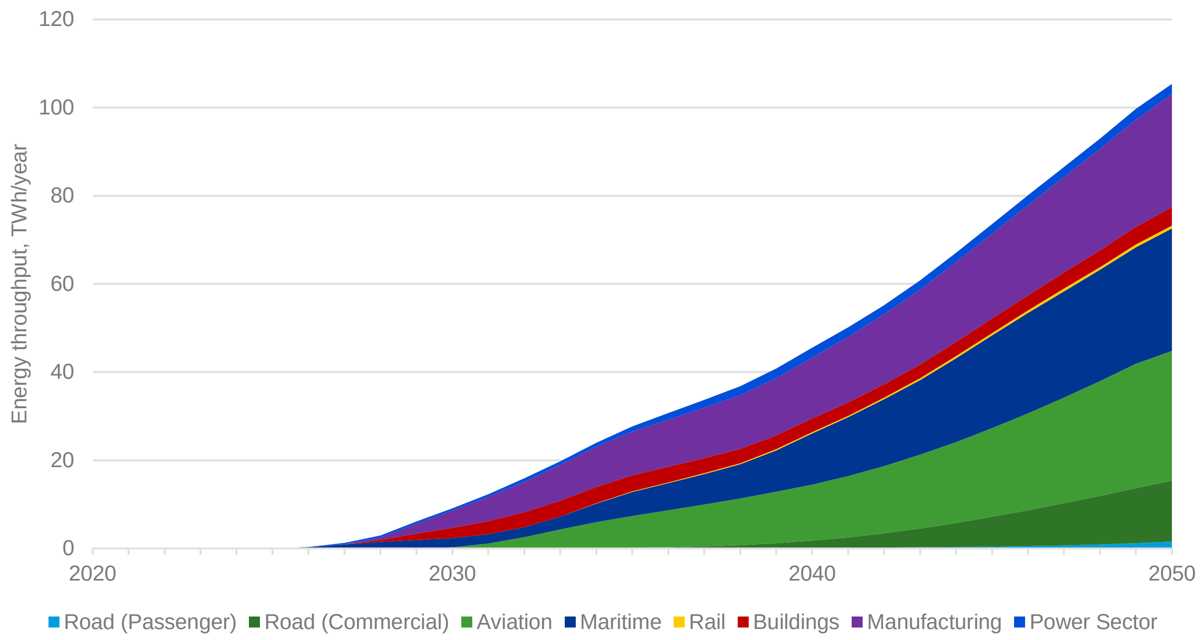

Figure 8-2 Graph showing total hydrogen and hydrogen derived fuels energy use as an energy carrier across all sectors from 2010 to 2050

The results show a very rapid rise in both technologies, which presents a significant challenge for the UK as well as other countries undertaking similar transitions. In the case of battery technology, the required installed capacity of batteries is presented in Figure 8-3, showing a steady increase to 4,500 GWh in 2050 from a very low level today. The challenge of meeting the scale of demand is significant and will require developments in battery manufacturing and recycling, along with performance and cost improvements through the consideration of new chemistries.

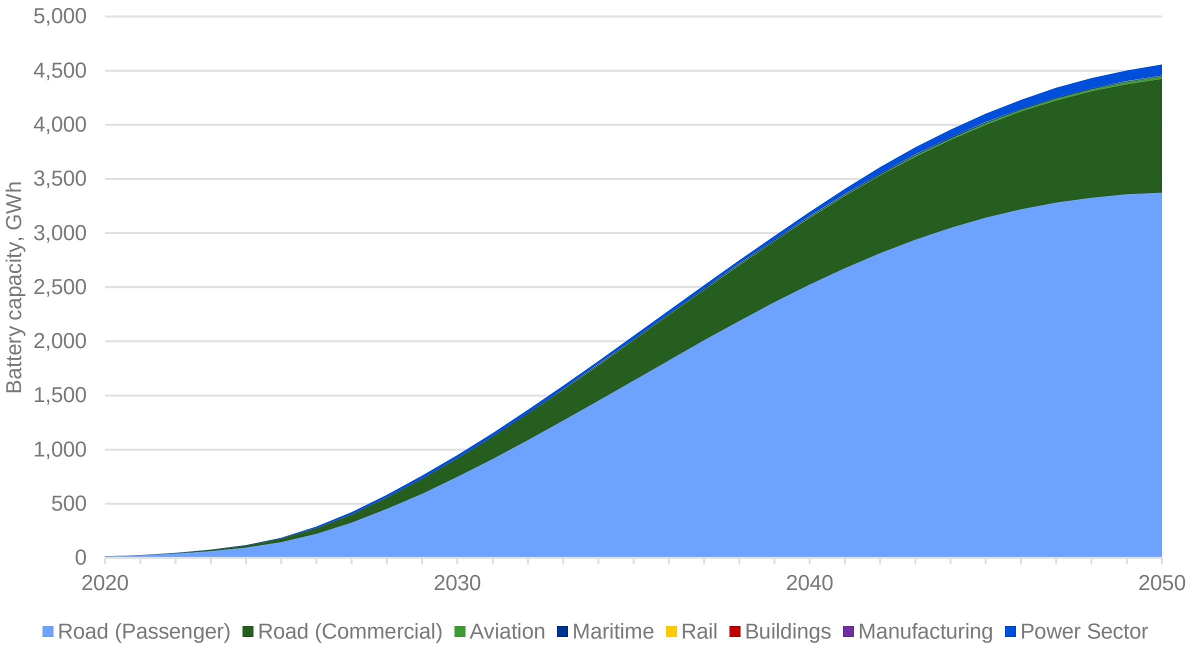

Figure 8-3 Graph showing installed battery capacity across all sectors, 2010 to 2050

8.1 Implications for battery research in the UK

The greatest demand for batteries is expected to come from the transport sector, which is therefore expected to drive development. The main challenges for the industry in meeting the rapid deployment of batteries shown in this report are considered to be energy density improvements, battery cost reduction, supply chain capability and infrastructure deployment.

The main technical weakness of battery technology, particularly in high energy capacity situations, is its energy density, which is lower than fuel-based propulsion systems. Due to the significant improvements in battery technology over the past decade, an increasing number of vehicle classes are now able to utilise batteries. For sectors such as aviation, to achieve the market share modelled here, a significant further increase in energy density is required. Though energy density of current lithium-ion batteries can be further improved, a step change in density is expected to require next generation battery technologies such as solid-state batteries. Though improvements in energy density will have the greatest benefit for aviation, these will also benefit other transport sectors.

Charging technology and infrastructure are key enablers for BE transport and within the analysis of this report, there are a number of assumptions which underpin the significant market share. Both the build-out of public recharging points for electric vehicles, and dedicated recharging solutions for the aviation, shipping and rail sectors, are needed. Particularly in the case of aviation, shipping and rail, the ability to rapidly charge batteries within the operational schedule available is considered a key requirement. Rapid chargers today are available for numerous applications, and delivering the high charging power required will require new procedures and safety systems to ensure this can be done affordably, reliably, and across large fleets of vehicles.

To accommodate this increased demand, the ability of the grid to supply the required power will need development which may have significant cost implications. It is expected that in some regions, particularly where the electricity grid is not as strong, stationary energy storage will be required to lower the grid capacity demand of a charger yet still provide the required peak power, effectively smoothing the power delivery. Furthermore, smart charging technology can be used to ensure vehicles are able to charge yet avoid times of peak load on the electricity grid. Finally, with such a high delivery of power, the batteries themselves will require development to ensure the rapid charging is not significantly detrimental to the health of the cells.

A second key enabler for BE transport is the decrease in battery costs over time. Battery costs are expected to fall significantly, halving in the next decade before a more gradual decrease to 2050, however significant work within the industry is needed to achieve this. Cost reductions are also needed to instil investor confidence and enable more sectors to adopt battery technology in applications ignored thus far. This report does not consider the pathway to achieve the expected cost reductions, which are expected to come from various avenues including improvements in manufacturing, materials, and supply chains. Development in the industry and adjacent sectors is required to map these advancements and ensure the reductions are achieved.

The third implication from the rapid electrification of transport is the volume of batteries required and the supply chain needed to meet this demand. In the 2030s, over 200,000 MWh of batteries will be added to the UK market each year from passenger and commercial vehicles alone, which is considerably more than the total battery capacity of the UK today. Developing the supply chain to meet this demand is a significant challenge, with lead times for BEV purchases currently approaching 12 months. Additionally, the use of materials with a lower environmental and social impact is an important and related goal for the industry, along with the infrastructure needed to process and recycle the used batteries reaching their end-of-life.

The analysis of the power sector also has implications for the battery industry and its future development. It is useful to recognise that batteries are already very strong technically and provide the most competitive solution for grid stability and short-term balancing services. Battery energy storage systems (BESS) are therefore expected to dominate the provision of these services without significant competition from other technologies, including hydrogen.

Battery technology will need to focus on longer duration storage if it is to increase its share of the utility scale energy storage market. At present, the limiting factor for the energy duration of battery storage installations is the cost of storage per MWh. Therefore, cost reduction will enable batteries to compete against technologies such as compressed air and liquid air energy storage in new markets where greater levels of energy storage are needed. These technologies may include flow batteries, or new chemistries that use cheaper materials such as metal air batteries.

As in the transport sector, ensuring the supply chain is able to meet demand for the power sector will be a challenge. Today the battery technology employed in grid connected storage and transport is very similar, however as the markets develop, it may be that the two strands diverge to better represent their specific requirements, particularly in terms of energy density. Due to the dominance of the automotive sector, it may be advantageous for stationary storage applications to find alternative supply chains and technology variants that aren’t dominated by electric vehicles.

In addition, one technology challenge that the energy transition must face and must be considered by industry is that of technology obsolescence. This impacts all sectors of the transition, undermining investor confidence and increasing supply chain risks. Investors require reassurance that they are not investing in “stranded assets” that will lose value in a short space of time, and the supply chain faces the challenge of maintaining competitiveness when faced both with the constant innovation and the threat of disruptive technologies. This is expected to be a major challenge impacting the pace and effectiveness of the energy transition. Technologies will require research and investment to answer fundamental questions of performance, application, and sourcing, whilst needing continued support through technology readiness levels (TRL) to scale up with sustainable infrastructure that enables commercialisation in a completive and dynamic space.

DNV’s analysis and modelling shows that the demand for both batteries and hydrogen technology and their importance in the decarbonisation efforts of the UK is expected to grow rapidly from today to 2050. Batteries and hydrogen are key enabling technologies which will allow abundant renewable energy sources to be harnessed and provide society with reliable, affordable and sustainable energy. Batteries and hydrogen have very different characteristics, making them suitable for different applications, and are therefore primarily seen as complimentary technologies, rather than competitors. Although technical challenges remain and developments for both technologies are required, the largest challenge will be the rapid deployment required to achieve the predicted future demand. Achieving this and the resulting societal and environmental benefits will require collaboration between all stakeholders concerned: government, industry, research institutions and the public.

APPENDIX A INTRODUCTION TO BATTERY AND HYDROGEN TECHNOLOGIES

Batteries

Li-ion Batteries

A “lithium-ion” battery is the umbrella term referring to any electrochemical energy storage system which uses lithium-ions as the charge carrier. Lithium -ion batteries are the current market leaders for applications ranging from personal electronic devices, BEVs, and stationary grid scale storage installations. The leading position stems from lithium-ion’s combination of high energy density, high system efficiency, longevity, and ease of manufacturing, in addition to its high flexibility with regards to system sizing, usability, and fast deployment. Demand for lithium-ion batteries and better performance has driven successive iterations of improved capabilities from a range of chemistries.

Changes in the chemistry of the cathode and anode gives rise to variations in properties such as specific energy, specific power, cycle lives, cost, safety and thermal stability. The most common anode (negative) material is graphite but there are alternatives such as lithium-metal, silicon, hard carbon and lithium titanate. The cathode material is often a metal oxide and some of the most common cathode types include; NMC (lithiated nickel manganese cobalt oxide), NCA (lithiated nickel cobalt aluminium oxide), LCO (lithiated cobalt oxide) and LFP (lithiated iron phosphate). The anode and cathode are separated by a porous film, the separator, which consists of several layers of polymers. The electrodes and separator are soaked in an electrolyte that provides the lithium ion with a means to pass between the electrodes. The electrolyte usually consists of organic solvents with dissolved lithium salt (LiPF6).

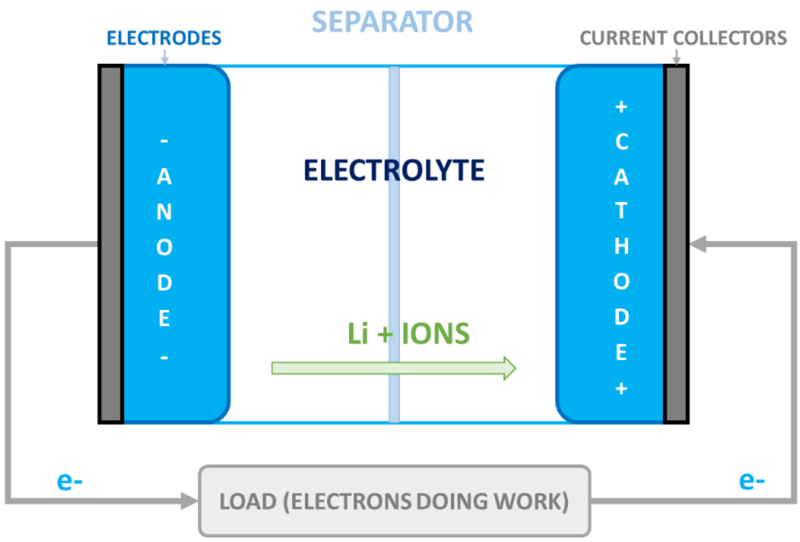

Figure A-1 Diagram showing schematic of a battery (DNV)

A major concern for current lithium-ion chemistries is the reliance on resource constrained raw materials such as cobalt and nickel, whose production and disposal often come with a significant environmental and social impacts in some production locations, along with human rights concerns[203]. Recent price increases in commodities used in NMC cells has accelerated the use of lithium-iron phosphate (LFP) cells, in addition to increasing the proportion of nickel where NMC is used. The greater use of nickel relative to cobalt is beneficial for energy content, however it comes at higher manufacturing costs and reduced cycle times. Finding alternative materials and improving the recyclability of batteries is a major consideration for the overall social and environmental impact of battery technologies and must be a focus area

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[203] Towards the battery of the future, European Commission, 2018

for future development. In addition, technical challenges in lithium-ion's safety are still apparent, as the use of a pressurised flammable electrolyte can result in fire if the battery is pierced or short circuited.

The lithium-ion market has seen technical improvements of cells year on year, with improved performance characteristics and reduced costs. This has been achieved by using new materials and refining its manufacturing and control processes. The theoretical limit for energy density has not been reached for lithium-ion cells, and further development is expected to increase the energy density of cells by 30%, an increase in power in the range of 300%, and costs decreasing by 60% - 80% over the next decade[204]. However, this introduces a key consideration in the manufacturing of lithium-ion cells and whether current processes can adapt and incorporate future variations and alternative chemistries with minimal change of assets, such as solid-state batteries, lithium-sulphur and sodium-ion (discussed further below). Investing into engineering a mass-scale manufacturing process for a new battery form will compete against falling prices of existing technologies and their ecosystem, in manufacturing, application and decommissioning processes.

Flow Batteries

Redox flow batteries are an alternative form of electrochemical storage. The energy capacity of the battery is a function of the volume of electrolyte that is stored externally in tanks; therefore, by changing the size of the electrolyte tanks, the energy capacity of the system can be increased or decreased. Redox flow battery technology is less developed than lithium-based chemistries, however there are a number of promising grid-scale trials and initial commercial systems.

The ability to scale the energy capacity of the system independent of the power capacity, at a relatively low cost, is a key advantage of flow batteries if long duration services are required. Moreover, the ability to perform a very high number of cycles at essentially 100% depth of discharge with limited degradation, combined with a 25-year life, could make the cost per cycle very competitive with competing technologies. Leading flow batteries are not as energy dense as lithium-ion but are marketed towards energy storage duration of 2 to 12 hours, specifically targeting the market of 6+ hours of storage. Electrolyte costs are relatively low, in addition to low overall maintenance, storing, and shipping considerations.

The limited number of utility scale operational installations increases project risk which could also make project financing more difficult. This is not aided by the widespread difficulty of flow batteries to scale in terms of manufacturing output, especially when compared to lithium-ion cells. Unlike current lithium-ion cells that are typically in the form of small cylinders or pouches, flow batteries are larger and require electrolyte tanks, this limits their suitability for mobile applications and means they are predominantly utilised as stationary storage.

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[204] Aerospace Technology Institute – written evidence (BAT0021), UK Parliament, 2021

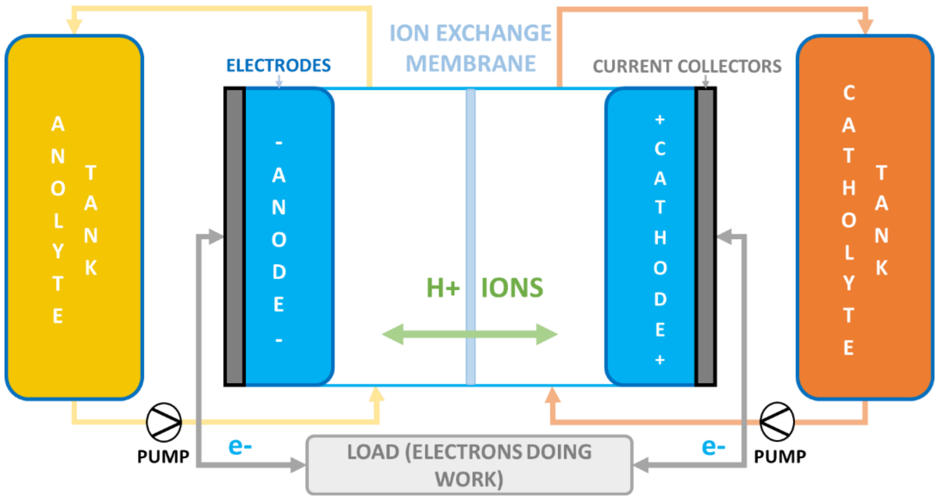

Figure A-2 Diagram showing schematic of a flow battery (DNV)

Next Generation Battery Technology

Next generation battery technologies are difficult to determine due to the significant increase in research and development in batteries, combined with the vast array of mediums and potential services they can provide. Nevertheless, battery technologies will continue to evolve, and in the near term the most promising include solid-state lithium, lithium-sulphur (Li-S) and sodium-ion (Na-ion) batteries.

Despite the potential for new battery variants, the dominance of NMC and LFP cells is expected to continue in the near future, with new iterations of both chemistries being implemented into EVs and other applications, with a greater focus on aligning cell types to applications (e.g., HGV specific cells). The near-term focus of innovation is likely to be in module design and anode chemistry, with silicon and lithium metal entering the market. These new NMC and LFP iterations are expected to use existing manufacturing processes and applications, easing their implementation.

Solid-state batteries

Solid-state batteries (SSBs) are similar to typical lithium-ion battery cells, however the electrolyte within the cell is solid as opposed to the liquid or gel electrolyte currently used. The intention is to have a cell that has improved safety, lifetime, and energy density characteristics, where a cell could potentially have a 50% improvement in energy density compared to current technology. The primary challenge at present is to align advanced materials used in SSBs to competitive manufacturing processes, in order to maintain costs at a reasonable level. SSBs are likely to be non-combustible, which reduces the risk of thermal runaway events, allowing for greater design flexibility and volumetric density. SSBs could be key in improving the offering of electric transport, as they would reduce the size of battery packs required for a similar performance, in addition to improved safety.

Currently, SSBs are yet to reach commercial use and be manufactured at scale, with leading companies providing batteries for testing to automakers for near-future manufacturing. Further in the future, cell-to-chassis technology integrated with SSBs could lead to a near complete redesign of battery packs and how they integrate into an EV.

Lithium Sulphur

Lithium-sulphur cells are relatively mature in their development, and they are lighter, more energy dense, and potentially cheaper than the current generation of lithium-ion cells, however they face challenges in longevity and safety. Lithium-sulphur cells use sulphur which is a relatively cheap material in comparison with the cobalt and nickel used in lithium-ion batteries, and this abundance is aimed at reducing the cost and volatility of cell prices. As mentioned, the primary challenge for lithium-sulphur cells is longevity, where lithium-sulphur cells are inhibited by their very low cycle rates, in addition to a high rate of degradation impacting the power and safety of the cells. Further research and development are required to optimise the materials within a lithium-sulphur cell; theoretically lithium-sulphur cells can store up to five times of the energy of a lithium-ion cell by mass, however they require greater volume as they expand during cycling. Research is looking at solidifying the lithium-sulphur electrolyte and tackling its current challenges so it can be used in large EVs; the near-term use cases are generally for smaller scale and niche technologies such as drones or applications where space is not a priority. The EU's research into the use of lithium-sulphur technology for use in passenger EVs (LISA) is to end by 2023, following from their 2020 ALISE programme (Lithium-sulphur for EVs).

Sodium Ion

Sodium-ion batteries are perhaps the most developed of these future technologies, with cell manufacturers now offering Sodium-ion products for stationary energy storage solutions with production expected to be underway in 2023/2024. Greater interest in lithium alternative cells has been due to the increased demand in lithium raising its price and importance of its supply, in addition to ESG concerns of its extraction and refinement. Sodium is more abundant than lithium, with a lower cost of extraction and purification. In addition, sodium-ion batteries do not require copper or cobalt. Sodium-ion cells have a lower energy density at present; however, this is expected to increase (though not to the level of lithium-ion), and in general sodium-ion has a relatively high-power density. A further advantage for sodium-ion cells is that they can often use the same manufacturing lines and equipment as lithium-ion, and therefore are seen as a complementary technology which manufacturers can produce alongside lithium-ion and integrate into the same applications. Moreover, sodium-ion technology will likely take up market share in market segments where performance or size are less important, such as industrial vehicles and some stationary storage, in addition to more price conscious forms of EVs.

Metal Air

Metal-air or metal-oxygen technologies are batteries that use a reactive metal as the anode and air as the active cathode. Oxidation of the anode and reduction of oxygen at the cathode generates a current for discharging, and charging reverses the reaction. Candidates for such batteries include lithium, zinc, iron, and magnesium. An advantage of metal-air technologies is the potential low cost and reduced environmental impact. Metal-air batteries can theoretically have a far higher specific energy than lithium-ion batteries (up to five times), meaning they could store more energy in the same sized product. However, research and development are still required to tackle challenges with their cycle efficiency, rate of charge/discharge, and method of manufacturing. Metal-air batteries are likely to be best suited to utility scale stationary energy storage, complementing the use of faster acting lithium-ion cells; however, commercial products are not expected to be available for another 5 to 10 years.

Materials supply chain and recycling

BEVs have seen significant growth in demand in recent years and this has placed a spotlight on the source of materials used to manufacture batteries and the capability to recycle them. While other industries are predicted to see significant growth in demand for batteries, the recovery of precious metals in BEVs will potentially be addressed before it becomes a major issue for other industries, due to the timeline of adoption. Issues surrounding materials supply chain and recycling will be similar between industries, with the main difference being the exact battery technologies used. The IEA report entitled Global Supply Chains of EV Batteries[205] goes into detail on the challenges facing the industry. It highlights the dominance of China in the global supply chain, producing 75% of all lithium-ion batteries and having 70% of the production capacity for cathodes and 85% for anodes. China also dominates the processing of raw materials with over 50% of global lithium, cobalt and graphite processing and refining capacity. Figure A-3 presents a summary of the global BEV supply chain. As shown, Europe has a small footprint.

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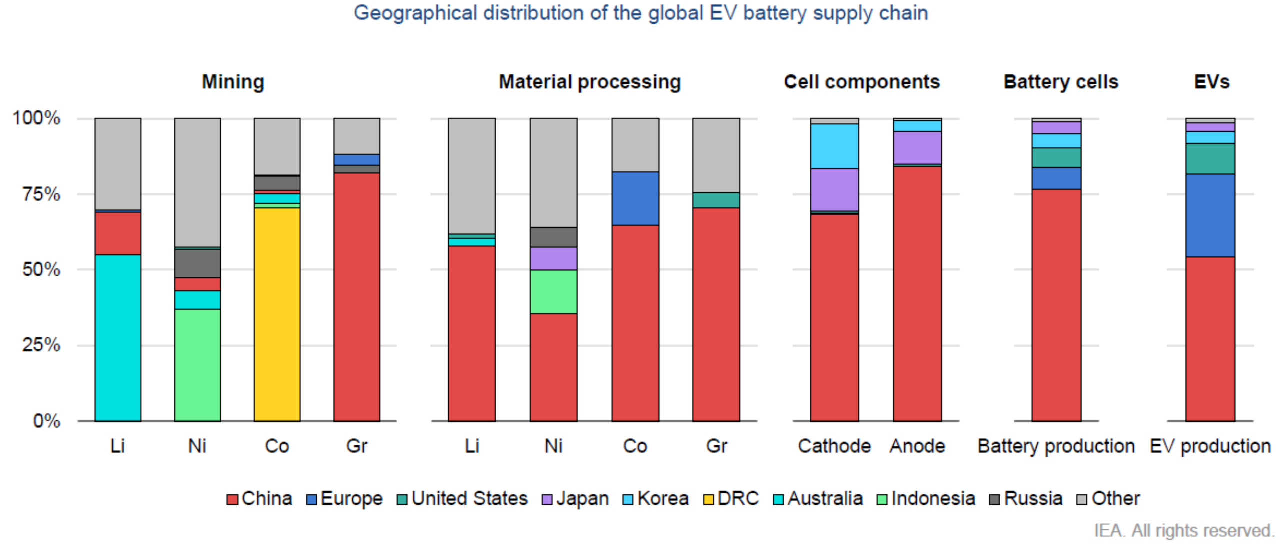
[205] Global Supply Chains of EV Batteries, IEA, 2022

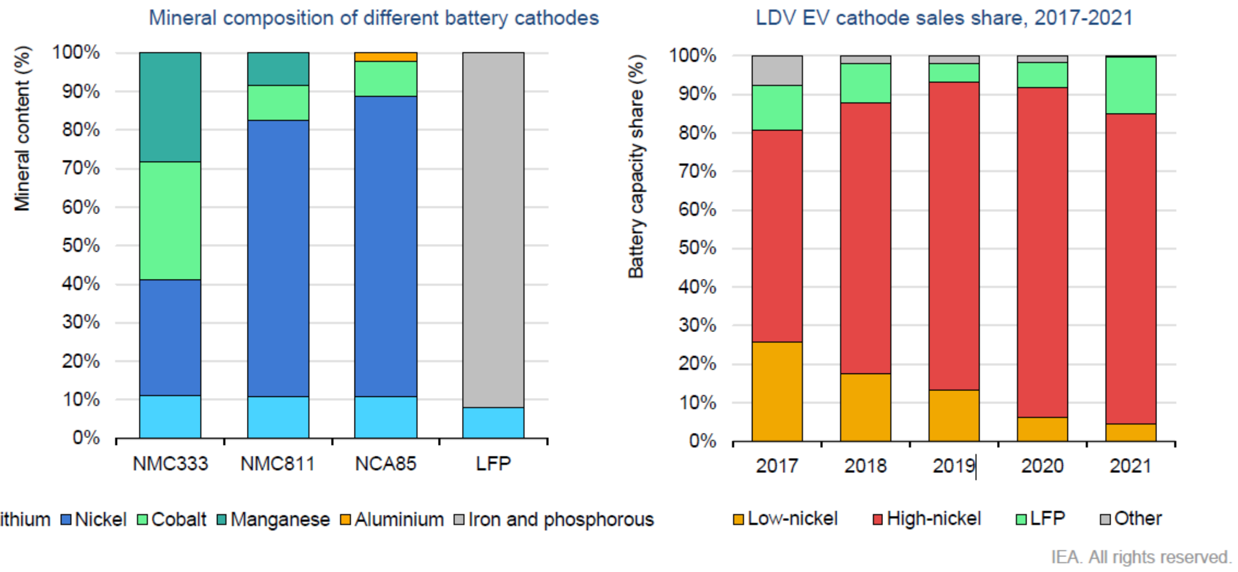

Geographical distribution of the global EV battery supply chain

Notes: Li = lithium; Ni = nickel; Co = cobalt; Gr = graphite; DRC = Democratic Republic of Congo. Geographical breakdown refers to the country where the production occurs. Mining is based on production data. Material processing is based on refining production capacity data. Cell component production is based on cathode and anode material production capacity data. Battery cell production is based on battery cell production capacity data. EV production is based on EV production data. Although Indonesia produces around 40% of total nickel, little of this is currently used in the EV battery supply chain. The largest Class 1 battery-grade nickel producers are Russia, Canada and Australia.

Sources: IEA analysis based on: EV Volumes; US Geological Survey (2022); Benchmark Mineral Intelligence; Bloomberg NEF.

Figure A-3 Geographical distribution of the global EV battery supply chain, IEA 2022

Within the lithium-ion umbrella, different battery chemistries are used, with the cathode chemistry being key in determining energy density, safety characteristics and material demand. The mineral composition of different cathodes is presented below. It shows an overall dominance of high nickel-based chemistries with a significant increase in 2021 of the use of LFP.


Mineral composition of different battery cathodes

LDV EV cathode sales share, 2017-2021

Notes: LDV = light-duty vehicle; LFP = lithium iron phosphate; NMC = lithium nickel manganese cobalt oxide; NCA = lithium nickel cobalt aluminium oxide. Low-nickel includes: NMC333. High-nickel includes: NMC532, NMC622, NMC721, NMC811, NCA and NMCA. Cathode sales share is based on capacity.

Sources: IEA analysis based on EV Volumes.

Figure A-4 Cathode material composition for BEV batteries, IEA 2022

Despite the advantages of LFP cells from a cathode perspective (lower cost primarily), they too require lithium, which is associated with its own challenges. Lithium is predominantly extracted from its mineral found in igneous rocks (chiefly spodumene) or from lithium chloride salts found in brine pools, which requires 250 tonnes and 750 tonnes respectively to produce 1 tonne of lithium[206]. This extraction has significant environmental impacts, along with a significant energy requirement. As shown in Figure A-3, the majority of lithium is mined in Australia before being processed in China.

To ease pressure on material extraction, and to reduce the lifecycle impact of batteries, there is an increasing focus on the ability to recycle batteries. Today, a number of efficient and viable battery recycling processes exist, however new methods, such as direct recycling are being developed[207]. While the volume of end-of-life batteries is currently low, the number is going to rapidly increase in the 2030s and 2040s in line with the energy transition.

Hydrogen

Hydrogen as an energy storage system differs from battery technology in a number of fundamental ways. Whereas batteries are typically self-contained with charging, storage and discharging happening within the same unit, these functions are separated when using hydrogen for energy storage.

Hydrogen production can be achieved in a variety of methods, including from fossil fuels (“grey” hydrogen) through coal gasification or natural gas fuelled steam methane reforming (SMR), and these can be low carbon with the addition of carbon capture and storage (CCS) (making “blue” hydrogen). Hydrogen production from electricity is achieved through electrolysis of water, with a number of different technologies variants available including Alkaline, Proton Exchange Membrane (OEM), Solid Oxide Electrolysis (SOE) and Anion Exchange membrane (AEM). Where the electricity used for electrolysis is renewable, the hydrogen is considered “green” hydrogen.

Initial supplies of hydrogen are expected to be from blue hydrogen production at the UK’s industrial clusters due to the required volumes and continuous supply required by industrial processes. Green hydrogen is expected to supplement this initial growth in the 2030’s. As cost competitiveness increases, greater volumes become more available alongside wider infrastructure and storage.

Storage of hydrogen can also be achieved in a multitude of ways, including subsurface gas storage, compressed hydrogen tanks, liquid hydrogen tanks, ammonia tanks and Liquid Organic Hydrogen Carrier (LOHC) tanks. In each case, the state of hydrogen is converted through either compression, liquefaction or chemical reactions. The advantages and disadvantages of each depends on several factors, including the method of transportation and distance between its production and end use, the duration of storage, the storage capacity and the response time to market.

Finally, the conversion of hydrogen back into energy can also be achieved in a variety of ways. Hydrogen can be burnt directly in a boiler, or combined cycle gas turbine (CCGT), used as a fuel in an internal combustion engine or gas turbine, or converted to electricity in a fuel cell.

The combination of production, storage and conversion to energy of hydrogen will depend on the end purpose and on the structure of the hydrogen economy. Producers of hydrogen will have customers using hydrogen as an industrial feedstock, direct fuel for heating, input to produce synthetic aviation fuels, as well as conversion to electricity.

Today, UK hydrogen production is concentrated in the steel, chemicals and refinery industry. Hydrogen is used as a feedstock and can be used to produce further products in conjunction with crude oil. The production and usage of hydrogen is typically integrated at the facility. Currently this is dominated by grey hydrogen; hydrogen produced from natural gas, without carbon capture. This reflects the potential for early adopters of low-carbon blue hydrogen with the build out of industrial clusters.

As a form of energy storage, the focus area of this report, hydrogen would be produced using electricity, either from the grid or from dedicated renewable generators, and converted back into electricity or used within the transport sector. The key technologies involved in this process are discussed in the following sections.

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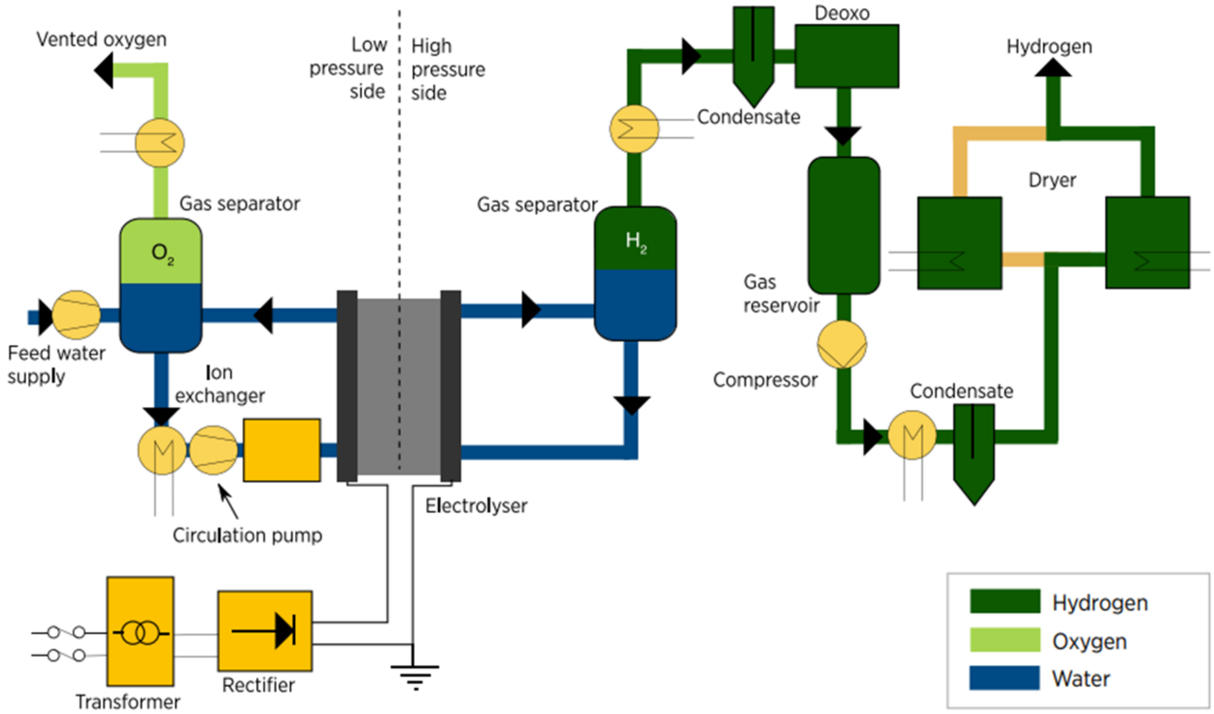
[206] Extraction of lithium from primary and secondary sources by pre-treatment, leaching and separation: A comprehensive review, Pratima Meshram et. al., 2014
[207] Recycling lithium-ion batteries from electric vehicles, Gavin Harper et. al., 2019

Hydrogen Electrolysis

Hydrogen Electrolysis is the process by which water (H_2O) is split into its component molecules, H_2 and O_2, when an electric current is passed through the fluid. There are 3 main types of electrolysers, Polymer Electrolyte Membrane (PEM) electrolysers, Alkaline water electrolysers (AEL) and Solid Oxide electrolysers (SOEC).

PEM electrolysers – Capable of rapid start up and shut down, the process consists of water reacting over an anode to form oxygen and positively charged hydrogen ions with the hydrogen ions selectively moving across the PEM for capture at the cathode. The technology is still in the development phase for large scale deployment, but currently PEM have higher power density than alternatives, leading to lower footprint requirements.

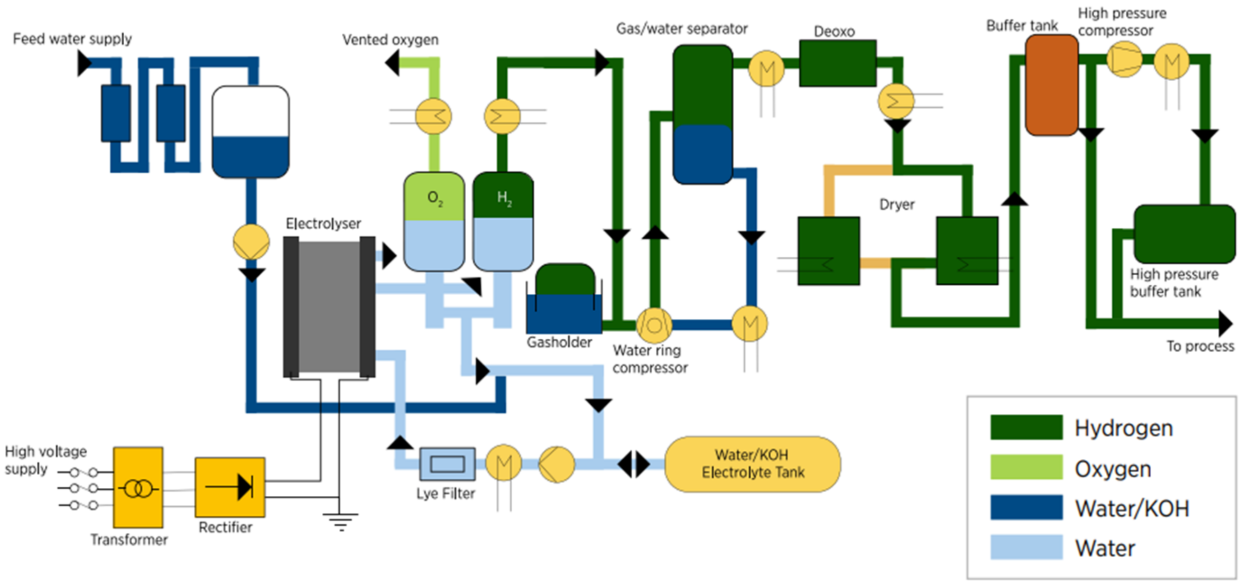


Note: This configuration is for a generic system and might not be representative of all existing manufacturers.

Based on IRENA analysis.

Figure A-5 Diagram showing schematic of a Polymer Electrolyte Membrane electrolyser

AEL electrolysers – Existing and established technology with supply chains capable of scale without reliance on precious metal supplies as needed for PEM deployment. The process involves a cathode and an anode submersed in a liquid electrolyte, typically potassium hydroxide (KOH), separated by a diaphragm permeable to hydroxide ions and water molecules. At the cathode, water is split to form H_2 and releases hydroxide anions which pass through the diaphragm and recombine at the anode to form O_2.



Note: This configuration is for a generic system and might not be representative of all existing manufacturers.

Based on IRENA analysis.

Figure A-6 Diagram showing schematic of an alkaline water electrolyser

SOEC electrolysers – Using a solid ceramic material as the electrolyte, SOEC operate at much higher temperatures (above 500°C) giving rise to higher process efficiency. Electrons (from external circuit) combine with water at the cathode to form hydrogen gas and negatively charge anions. Oxygen then passes through the solid ceramic membrane and reacts at the anode to form oxygen gas and generate electrons (through the external circuit).

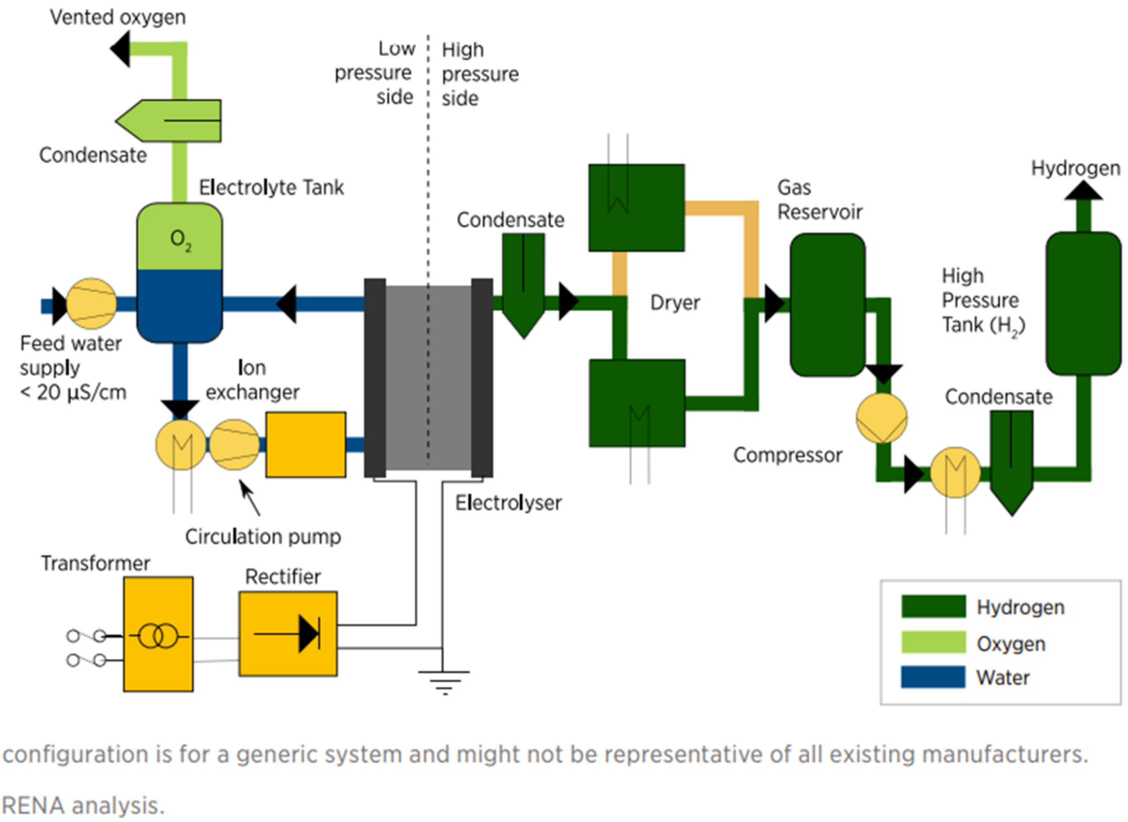


Figure A-7 Diagram showing schematic of a solid oxide electrolyser

Hydrogen Fuel Cells

Hydrogen fuel cells convert hydrogen into electricity, heat, and water. This technology is clean, efficient, and reliable; providing a steady supply of power when the fuel source is provided. There are several types of fuel cells, however they all share a similar mode of operation. A fuel cell is an electrochemical device, consisting of an anode, cathode, and an electrolyte membrane. Hydrogen is passed over the anode where a catalyst splits the hydrogen molecules into electrons and protons. Electrons are forced through an external circuit which generates an electric current and excess heat. The protons pass through the electrolyte membrane, where, at the cathode, they combine with oxygen to produce water molecules.

Hydrogen fuel cells are scalable due to their modular design. They are highly efficient (~60%) compared to a combustion engine and they have advantages such as quiet operation and low-to-zero emissions. There is ongoing research aimed at improving fuel cell lifespan and achieving cost reductions. Technological advances can be achieved through modifying the materials that are used in fuel cells to be more efficient, longer lasting, and cheaper to acquire and produce. Research areas include alternative catalysts, limiting degradation, efficiency of manufacturing processes and provision of ancillary equipment[208].

Hydrogen in Gas Turbines

Hydrogen fuelled gas turbines can drive generators to produce electricity or generate thrust for propulsion.

To produce electricity, first the gas turbine compresses the air and mixes it with fuel, this ignites and creates hot gas. The hot gas moves through the turbine blades, causing them to spin quickly and rotate the turbine drive shaft and in turn the generator, producing electricity.

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[208] Battery strategy goes flat: Net-zero target at risk, House of Lords, 2021

A combined-cycle gas turbine (CCGT) uses a gas turbine to drive an electrical generator and recovers waste heat from the turbine exhaust to generate steam. The steam from waste heat is run through a steam turbine to provide supplemental electricity. In this way, a CCGT is significantly more efficient than an individual gas turbine operating in an open-cycle gas turbine (OCGT), where this excess heat isn't captured. Waste heat can be also used to provide heating for local buildings to further increase the efficiency.

The flexibility of the gas turbine makes them well-suited to frequent starts and fast response; characteristics required to meet variable electricity demands.

Existing gas turbines are typically fuelled by natural gas for electricity production, and are likely to require significant retrofitting to allow for the increased volumetric flow and temperature requirement of hydrogen. General Electric (GE) are one of the largest gas turbine manufacturers globally. Expectations are that GE's 100% hydrogen fuelled turbines will be ready and available by 2030. Siemens' Zero Emission Hydrogen Turbine Centre (ZEHTC) research project also hopes to fulfil Siemens' current roadmap of 100% hydrogen availability across their entire range of gas turbines by 2030. DNV are leading a European workgroup on hydrogen use in gas turbines.

Hydrogen in Jet Engines

A jet engine is another form of gas turbine, which in this application is optimized to produce thrust from the exhaust gases, or from ducted fans connected to the gas turbine's output shaft. The jet engine is the dominant technology used within the aviation industry.

From an aviation perspective, there are several challenges in the use of pure hydrogen in jet turbines over longer distance, due primarily to its lower energy density (and larger storage volumes as a result). Therefore, sustainable aviation fuels (SAFs) are in development which can be either biomass-based, or hydrogen-based power-to-liquid- / e-fuels. There is significant uncertainty in the development of hydrogen and SAF fuelled commercial aircraft given the significant higher costs and long development time of new aircraft.

Hydrogen in Internal Combustion Engines

Hydrogen-fuelled internal ICE's share similar components to traditional ICE's, with hydrogen fuel replacing some or all the fossil fuel counterpart. The combustion of hydrogen in air releases energy, however unlike hydrogen fuel cells, the process also produces NO_X emissions. As hydrogen has a wide flammability range, it can run on a "lean" mixture which reduces the amount of NO_X compared to conventional ICE emissions. Exhaust treatment is required to remove excess NO_X, and this is an established technology. When a vehicle is run on a lean mixture, the combustion reaction is more complete and fuel economy greater. However lean operation can significantly reduce the power output due to the reduction in the heating value of the air/fuel mixture[209]. Hydrogen also has a high auto-ignition temperature, allowing for higher compression ratios resulting in increased thermal efficiency[210]. Compared to hydrogen fuel cells, hydrogen fuelled ICE's can operate with lower grade hydrogen.

Materials supply chain and recycling

PEM fuel cell technology is expected to be the most significant hydrogen technology within the transport sector, and therefore the supply chain considerations are discussed here. Internal combustion engines and gas turbines may also be significant technologies, however, use variations on existing technology with well-established supply chains. PEM fuel cells have only limited use today, and therefore the global manufacturing supply chain is also limited.

Platinum is a key catalyst in fuel cells and is an extremely rare metal, with global production only around 200 tonnes per year. Platinum supply is highly concentrated, with South Africa supplying over 70% of global platinum[211]. Such highly concentrated supply is likely to put strain on the environment in these countries. Rapid growth of fuel cell production will

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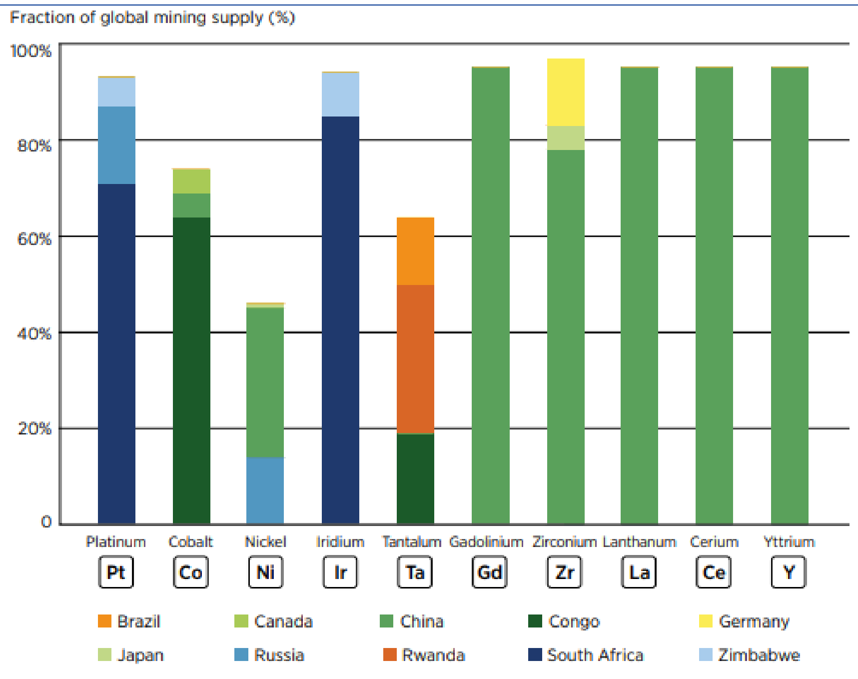
[209] Module 3: Hydrogen Use in Internal Combustion Engines, College of the Desert, 2001

[210] Hydrogen combustion, explained, Airbus, 2020

[211] Geopolitics of the Energy Transformation: The Hydrogen Factor, IRENA, 2022

underpin the rising demand for platinum-group metals. The decline in catalysts for internal combustion engines, one of the main uses of platinum group metals today, is thought to potentially offset platinum demand. Newer FCEV generations are already reducing the amount of platinum material required in their designs. Toyota's first-generation Mirai car (2014) used around 40g of platinum, whereas its second-generation Mirai, released in 2020, reduced this by roughly a third for the same power output. Developments are in place to reach 5g per car in 2040[212].



Source: IRENA (2020a).

Figure A-8 Top producers of critical materials[213]

Key countries for the supply of fuel cell components include the US, Germany, and Japan. Current UK fuel cell production capacity is limited, with small-scale assemblies and two reporting a production capacity of 150MWh with ambitions to increase future capacity to over 1.2GWh[214]. There are several leading fuel cell technology companies in the UK working throughout the value chain, from specialist materials to fuel cell technology. Johnson Matthey has announced that a plant capable of producing enough membranes to create 3 GW worth of fuel cell stacks annually at maximum capacity will be opening by the first half of 2024. This move will contribute to the reduction in fuel cell production costs through economies of scale[215].

Fuel cells can be disassembled, and the materials recycled. Fuel cell recycling is mainly focused on the recovery of the expensive precious metal catalysts. In the UK, there is currently no established processes for recovering these high value materials, however it is an emerging area. A Canadian company (Ballard Power Systems, Inc.) state they can typically reclaim more than 95% of the precious metals and that most of the remaining components in a fuel cell stack can be recycled using ordinary recycling processes. Similarly, to the recycling of battery cells, increased automation of recycling systems of these technologies is key and is something that is being increasingly targeted.

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[212] The Role of Critical Minerals in Clean Energy Transitions, IEA, 2022

[213] Geopolitics of the Energy Transformation: The Hydrogen Factor, IRENA, 2022

[214] UK hydrogen fuel cell electric heavy-duty vehicle supply chain review, National Composites Centre, 2021

[215] Johnson Matthey announces new hydrogen gigafactory to accelerate the transition to a decarbonised transport economy, Johnson Matthey, 2022

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