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Energy technologies for net zero

An IET Guide

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Foreword

In November 2021, the UK will host the 26th Conference of Parties (COP26), the most important event in international climate change negotiations since the 2015 Paris Agreement. COP26 will determine each member state's Nationally Determined Contribution (NDC) in eliminating net greenhouse gas emissions and limiting the effects of global warming. Amongst other things, this means weaning ourselves off fossil fuels.

In 2019, 78% of UK final energy demand was derived from burning fossil fuels. While this is the lowest proportion it has been since the Industrial Revolution, it demonstrates the scale of the challenge ahead.

The transition to Net Zero greenhouse gas emissions will rely on people and technology. Technology enables us to drastically reduce our dependence on fossil fuels by shifting our energy demand to sustainable *energy carriers* such as electricity from renewable sources and low-carbon hydrogen. However, the success of technology depends on people and their active involvement in making low-carbon choices in how they travel, how they heat their homes, what they buy and what they eat. The UK Climate Assembly in 2020 has shown that if people understand what is needed and why, if they have options and can be involved in decision-making processes, then they will support the transition to Net Zero.

This highlights the vital importance of a *just transition*. To succeed, a Net Zero transition must be fair, without adverse effects on peoples' jobs and quality of life. People, places and communities must be well-supported.

The roles of societal and technological changes in achieving Net Zero are uncertain, though analysis of seven published Net Zero pathways towards the end of this guide (§5.2) allows us to conclude that:

- A pathway to Net Zero that relies on *less* behavioural change relies on *more* significant changes in technology.
- A pathway to Net Zero that relies on *more* behavioural change relies on *less* significant changes in technology.

However, no matter the level of behavioural change that is assumed to be achievable, technology plays a pivotal role. A third concluding message is therefore:

- *Significant changes in technology are required to meet Net Zero.*

This guide serves as a comprehensive reference to the technologies that we can use to decarbonise the UK *energy* system, that can shift our energy demand from fossil fuels to a low-carbon supply.

As we continue the run-up to COP26, it is critical that policymakers, stakeholders and the public have a base level of fluency in these technologies – what they are, how they work, how they interact with the rest of the energy system and to what extent they can (or can't) help us to get to Net Zero. This guide is designed to provide that fluency.

As evidenced from this guide, there is an abundance of technology options for a Net Zero energy system. However, some are more suited to the UK – in terms of its renewable resources, existing infrastructure and evolving energy demand 'culture' – than others. After going through these options sector by sector, this guide presents comparative analysis of a set of seven published Net Zero pathways to uncover what our decarbonised energy system – both supply and demand – in 2050 will probably look like (§6).

This guide is designed to make it easy to flick to a specific Net Zero energy technology for the key facts (see the Technologies A-Z), but those who want a thorough explanation of Net Zero technology options for the energy sector may benefit from reading from cover to cover. Any terms and abbreviations used are defined at the first point of use and in a glossary (§8) at the end of this guide.

Technologies A-Z

Chapter 1 – Introduction

1.1 What is Net Zero?

Net Zero is a greenhouse gas (GHG) emissions target binding the UK to bring all GHG emissions to Net Zero by 2050 [1.1]. This means that certain sectors (such as aviation and agriculture) can have positive emissions in 2050 – so long as others have negative emissions to result in a zero emissions balance overall [1.2].

In November 2021, the UK will host the 26th Conference of Parties (COP26) in Glasgow. This represents the most significant meeting of United Nations Framework Convention of Climate Change (UNFCCC) parties since the 2015 Paris Agreement. Its success, particularly in binding the world to a set of Nationally Determined Contributions, is crucial to securing international cooperation in limiting global temperature rise to substantially below 2°C and keeping 1.5°C within reach.

1.2 What is this Guide and Who is it for?

This is a comprehensive but easy-to-understand guide to the **technology options** available for a UK Net Zero energy system for anyone who is interested. This guide requires no technical knowledge or scientific background. Information on each technology is supplemented by endnotes and references at the end of each chapter.

1.3 Energy & Power: Units & Scale

Energy is a physical quantity that must be transferred to an object to move or heat it. *The energy system* refers to the supply, flow and conversion of energy via *carriers* – such as electricity and petroleum – to meet our demand for *energy services* – such as heat, transport and the powering of our electrical appliances. Although our focus here is on the technologies, the energy system is a socio-technical one that includes the institutions and people that supply, transfer and use energy.

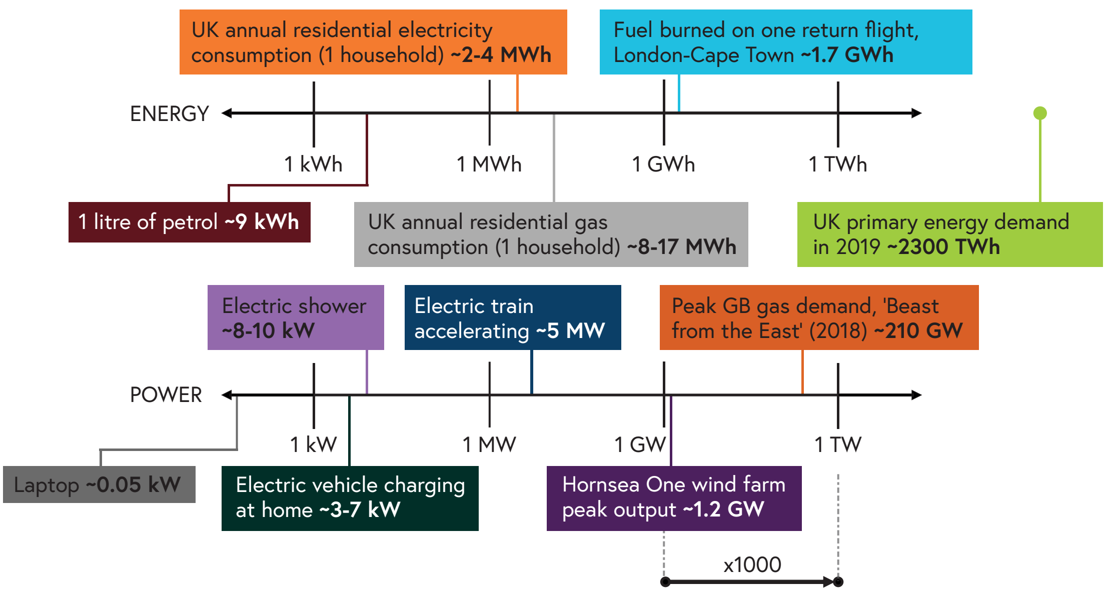
Power is a measure of *how quickly* energy is produced, converted or used (energy per unit time):

$$Power\ (kW) = \frac{Energy\ (kWh)}{Time\ (h)}$$

For example, a 1 kW electric heater uses energy at the rate of 1 kW. If it was on for an hour, it would have used 1 kWh of energy.

In this guide, energy and power units are kilowatt-hours (kWh) and kilowatts (kW) respectively. For convenience, metric prefixes are used. These may be familiar; 'kilo' = 1,000, 'mega' = 1,000,000, 'giga' = 1,000,000,000 and 'tera' =

Figure 1 Scales for energy and power used in this guide, with typical consumption values shown (numbers from [1.3-1.11])



1,000,000,000,000. Figure 1 shows the units used and some quantities of energy and power to give a sense of scale. The difference between the vertical lines represents a change of 3 orders of magnitude (x1,000).

1.4 UK Emissions

1.4.1 Greenhouse Gases and CO_2 Equivalence

There are seven GHGs whose combined emissions must be Net Zero by 2050. In accordance with international reporting protocols as set out in the Kyoto Protocol, all GHGs are reported in terms of million tonnes CO_2 *equivalent* ($MtCO_2e$). This means that emissions of each gas are weighted by their global warming potential (GWP) – a measure of their relative contribution to the greenhouse effect.

When weighted and expressed in terms of $MtCO_2e$, CO_2 made up 80.3% of UK GHG emissions in 2019 [1.13]. The remainder is methane (11.9%), nitrous oxide (4.9%), HFC (2.8%), and the final 0.3% made up by PFC, SF_6 and NF_3.

For the remainder of this Guide, GHG emissions will be expressed in $MtCO_2e$.

Figure 2 UK GHG emissions in 2018 including international aviation & shipping, in $MtCO_2e$. Data from [1.12][1]

1.4.2 Progress, Difficult Sectors and Carbon Budgeting

In 1990, energy supply (electricity generation and fuel supply) was the largest contributor to terrestrial GHG emissions (35%). This has seen significant decline; in 2019, it made up 19% of the total. This is largely due to the closure of coal-fired power stations and the growth in renewables.

Progress in other sectors has been less drastic, particularly in the residential and transport sectors (Figure 3). This is largely due to the contribution of road transport and space heating, and their dependence on burning petroleum in cars and fossil gas in domestic boilers respectively.

As well as the long-term Net Zero target, the UK has carbon budgets which define the required rate of reduction to Net Zero – amounts of net GHG emissions that the UK can emit in each 5-year period to 2050. As of December 2020, the Climate Change Committee (CCC) has recommended the sixth carbon budget, from 2030 to 2035 (Figure 4).

As cumulative GHG emissions largely determine global surface warming, the UK must keep to its carbon budgets, as well as the longer-term Net Zero target.

Figure 3 UK GHG emissions (including international aviation & shipping) by sector, 1990 to 2019. Data from [1.13][2]

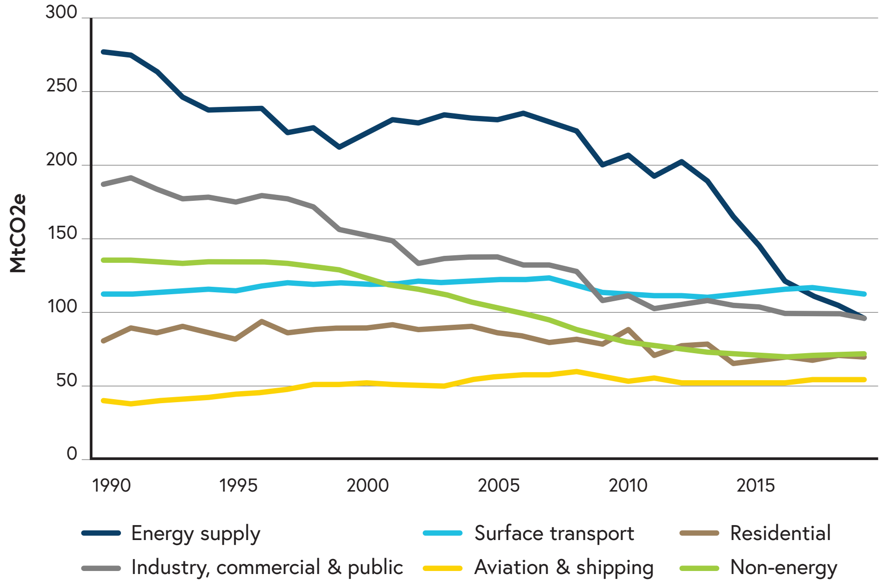
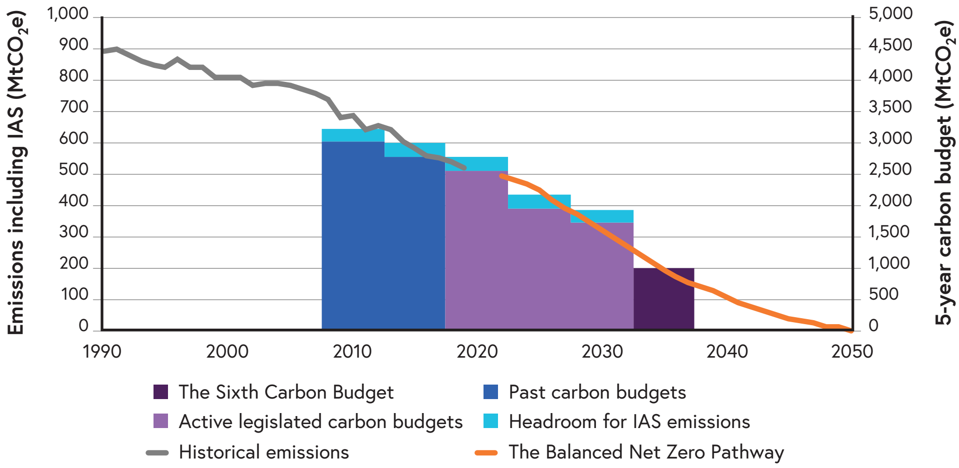


Figure 4 Climate Change Committee (CCC) recommended sixth carbon budget. Chart reproduced from [1.12]



1.5 Chapter 1 Endnotes & References

1.5.1 Endnotes

[1]This chart presents 2018 UK GHG emissions data as per the CCC's recommended 6th carbon budget, released in December 2020. While final 2019 GHG values are available as of early 2021, the way in which emissions are accounted differs between the UK Government's figures [1.13] and the CCC figures [1.14]. CCC numbers are used for this sector-by-sector comparison as they include all recognised sources and are from the Government's statutorily appointed independent advisor on climate change.

[2]These sectors have been altered from those in the original data to simplify the chart and more closely match the sectors shown in Figure 5 – and used by the Department for Business, Energy & Industrial Strategy (BEIS) in [2.1]. In the original data, the sectors were: energy supply, business, transport, public, residential, agriculture, industrial processes, waste management and LULUCF (land use, land use change and forestry).

In Figure 3, industry = business + industrial processes, non-energy = agriculture + waste management + LULUCF. In Figure 3, aviation & shipping includes domestic and international aviation and shipping for both civil and military uses.

1.5.2 References

[1.1] Department for Business Energy and Industrial Strategy, "UK becomes first major economy to pass Net Zero emissions law," 2019. [Online]. Available: https://bit.ly/2Gjy21C.

[1.2] Climate Change Committee, "Net Zero: The UK's contribution to stopping global warming," 2019.

[1.3] D. MacKay, "Planes," in *Sustainable Energy - without the hot air*, UIT Cambridge, 2008.

[1.4] Ofgem, "Typical Domestic Consumption Values," 2020. [Online]. Available: https://bit.ly/3d53jkt.

[1.5] Department for Business, Energy & Industrial Strategy, "Digest of United Kingdom Energy Statistics (DUKES) 2019," 2020. [Online]. Available: https://bit.ly/3ihlLYi.

[1.6] J. Wang and H. A. Rakha, "Electric train energy consumption modeling," *Applied Energy*, vol. 193, pp. 346–355, 2017.

[1.7] UK Energy Research Centre (UKERC), "Gas consumption during the 'Beast from the East,'" 2018. [Online]. Available: https://bit.ly/2Sv1mEz.

[1.8] National Grid ESO, "Transmission Entry Capacity (TEC) Register 01/10/2020," 2020. [Online]. Available: https://bit.ly/3d12QzY.

[1.9] US Department of Energy, "Fuel Properties Comparison," 2014. [Online]. Available: https://stanford.io/3nuj0H5.

[1.10] Energy Saving Trust, "Home appliances." [Online]. Available: https://bit.ly/33zu2mb.

[1.11] Western Power Distribution, "Electric Nation." [Online]. Available: https://bit.ly/33BJRch.

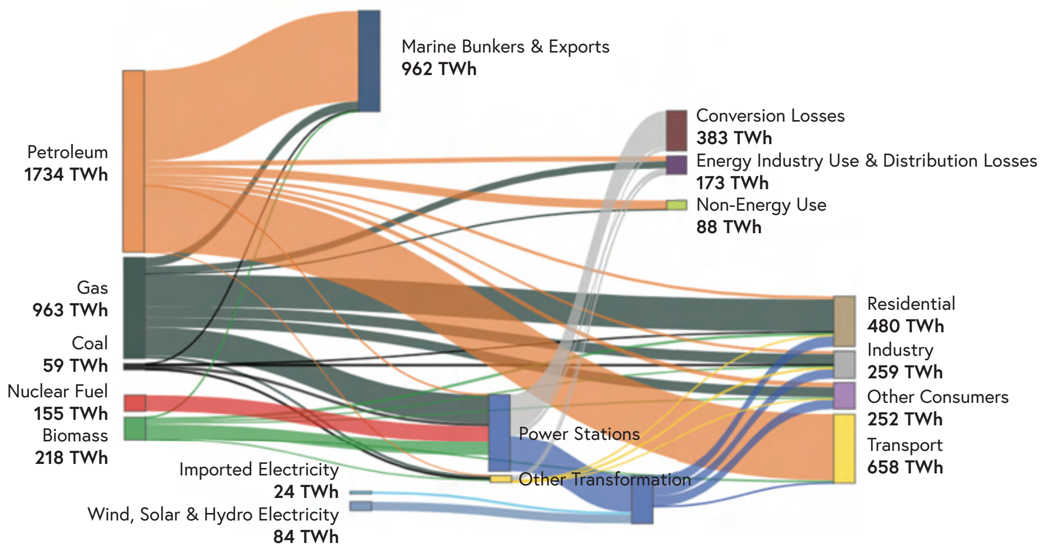
[1.12] Climate Change Committee, "Sixth Carbon Budget," 2020. [Online]. Available: https://bit .ly/3oOIyy6.

[1.13] Department for Business, Energy & Industrial Strategy, "Final UK greenhouse gas emissions national statistics: 1990 to 2019," 2021. [Online]. Available: https://bit.ly/3iWZDmp.

Chapter 2 – The UK Energy Sector

2.1 UK Energy Flows

Figure 5 Sankey diagram (a pictorial representation of flows) showing UK energy flows in 2019. Reproduced from BEIS Energy Flow Charts [2.1] using Plotly [2.2]



Key facts – 2019 UK Energy

- **78.3% of final energy consumption was met by burning fossil fuels** (a record low).
- **37.1% of electricity generation was renewable** – wind, solar, bioenergy and hydro (a record high).
- Overall, **12.3% of energy supply was from renewables.**

UK Energy: A Changing Landscape, 2012-2019

- Since 2012, UK final **energy consumption has grown by 1% to 1,741 TWh/year.**
- **Coal use has fallen dramatically**, whereas use of **fossil gas has only fallen slightly.**
- **Petroleum is the only fossil fuel whose volume has increased**, due to growth in transport demand and limited alternative fuels.
- **Renewables have increased their volumes** more than any other supply sector.

Figure 6 2019 UK energy demand by sector, 2019. Data from [2.3]

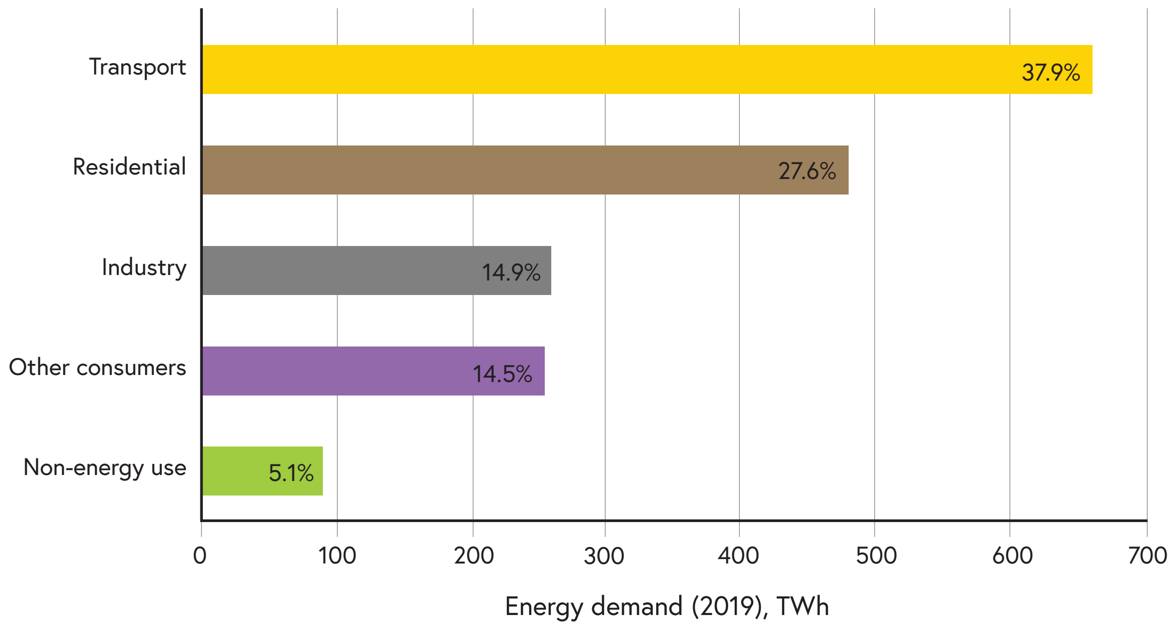


Figure 7 Percentage change in volumes of UK energy supply, 2012-2019. Data from [2.3]

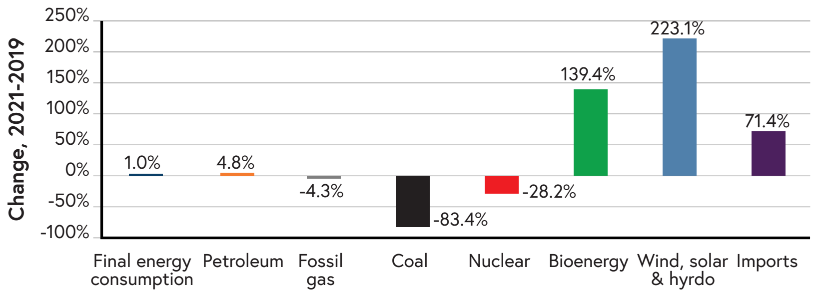
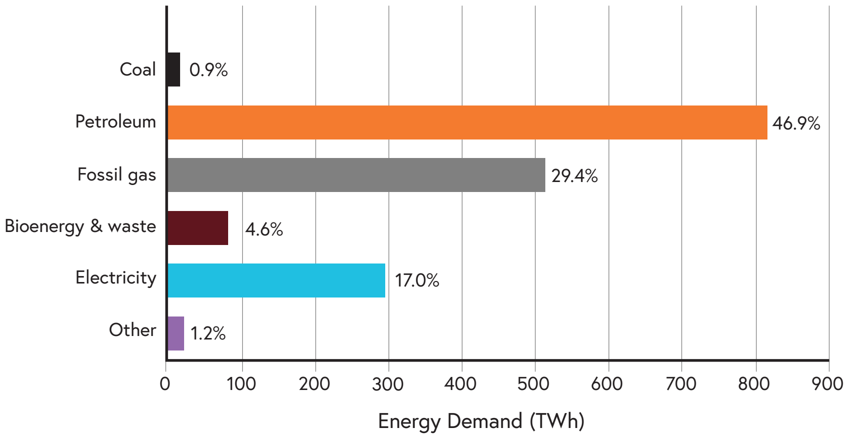
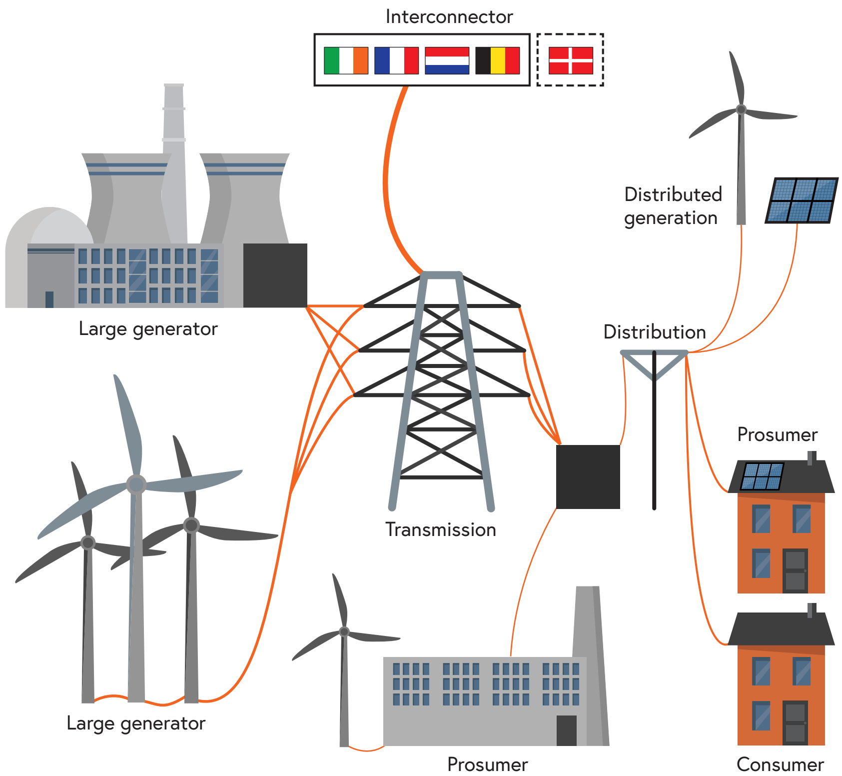


Figure 8 2019 UK final consumption by energy carrier, 2019. Data from [2.3]



2.2 UK Energy Infrastructure

Figure 9 Representation of the UK electricity system



Chapter 2 – The UK Energy Sector

Electricity System

- UK transmission-connected generating capacity was **69 GW** in 2019 [2.3].
- A further **32.9 GW** is embedded in the GB distribution system [2.3] – including **rooftop solar panels** and small **wind farms**.
- **Installed capacity in 2019 was around 180% of peak demand. In 2050, it could be 280-385%** [2.4].

Electrification of Demand

- Many Net Zero trajectories (§5.2) rely on **electrification of heating and transport**, coupled with the **decarbonisation of the electricity system.**
- This is expected to lead to **significant growth in electricity demand (63-160% by 2050)** (§5.2) with **uncertainty** as to when and where this demand growth will occur.

Fuels

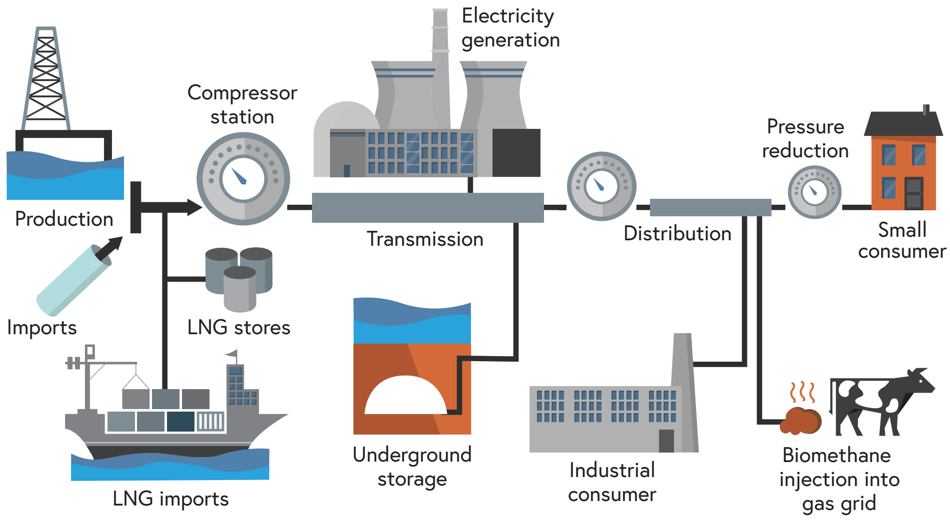
- **Petroleum** and **fossil (a.k.a. natural) gas** make up the majority of final energy demand.
- Both of these are fossil fuels, so **their use in the Net Zero energy system will be very small or non-existent** – with **fossil gas limited to a few industrial processes** and **petroleum limited to – at most – aviation** (§5.2).
- Other fuels used include **bioenergy** and **nuclear fuel**.
- **Nuclear energy** is **not renewable** but has **zero emissions** at the point of use.
- **Bioenergy** is **renewable** if it is **sustainably sourced** (§4.5.2).

The Low-Carbon Electricity System

- Historically, almost all power was generated in **large, thermal power stations** that use heat to make steam at high pressure to drive turbines. Power is **carried over long distances by the transmission system;** the **distribution system delivers power to end users**. Minute-by-minute balancing of generation and demand and respect of network limits are ensured by **control of generation**.
- In a **low-carbon electricity system**, **renewable generators** have replaced many traditional power stations. Large generators (e.g. large wind farms, solar parks) are connected to the transmission system, but **many smaller generators exist within the distribution system** and are known as **distributed generation (DG)**.
- A **low-carbon electricity system** must be more **flexible** than today's electricity system because most renewable energy is **variable**. A **smart grid** makes use of **automation and communications** from **distributed energy resources** – DG, flexible demand and storage – to balance generation and demand while **keeping electricity flows within the network's limits** and **maximising network utilisation.**

Peak electricity demand (2019) = 60.4 GW [3] [2.5]

Figure 10 Representation of the UK gas system



Gas System

- In 2019, **49% of the gas used in the UK was imported**. Imports arrived via gas pipelines and shipments of liquefied natural gas (LNG) [2.3].
- **Residential heating accounts for 32% of UK gas use** (2019) [2.3].
- Unabated use of fossil gas **in 2050 will be very small** or **non-existent**. Parts of (or all of) the gas network may be **converted to run on** low-carbon **hydrogen** (§4.5) to provide heating.

2.3 Chapter 2 Endnotes & References

2.3.1 Endnotes

[3] This is the *forecast* peak total electricity demand in an Average Cold Spell (ACS) as predicted by National Grid ESO. The precise peak electricity demand is not known – National Grid ESO only see the demand on the transmission system, and as distributed generation has come to contribute to supplying a significant portion of demand, National Grid only see this is a negative demand. The transmission system peak in 2019 (which is reliably measured) was 48.8 GW [2.3].

2.3.2 References

[2.1] Department for Business, Energy & Industrial Strategy, "Energy flow chart 2019," 2020. [Online]. Available: https://bit.ly/30mhsVk.

[2.2] "Plotly." [Online]. Available: https://plotly.com/.

[2.3] Department for Business, Energy & Industrial Strategy, "Digest of United Kingdom Energy Statistics (DUKES) 2020," 2020. [Online]. Available: https://bit.ly/3ihlLYi

[2.4] National Grid ESO, "Future Energy Scenarios," 2020. [Online]. Available: https://bit.ly/2HvKY4L.

[2.5] National Grid ESO, "Winter Outlook 2020", 2020. [Online]. Available: http://bit.ly/38ceMwK.

Chapter 3 – Energy Demand Technologies for Net Zero

3.1 Heating & Cooling

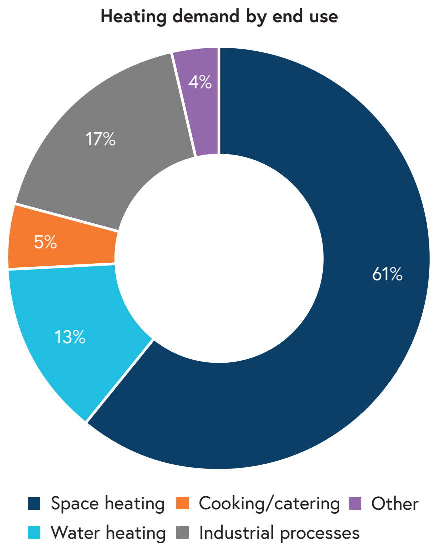
3.1.1 Heating & Cooling Demand

Current UK Heating & Cooling Demand

Heating Energy Consumption

- **UK heating demand (2018) was 735 TWh** [3.1], **45% of final energy demand**.
- **UK cooling demand (2018) was 27 TWh** [3.1], **1.7% of final energy demand**.

Figure 11 UK heating demand by end use – all sectors. Data from: [3.1]



Commercial & Public Sector Heating Demand[4]

- Commercial & public sector heating demand (2018) was **152 TWh** [3.1] (**21% of total heating; 9% of total energy**).
- The end use split (2018) was **73% for space heating**, **10% for water heating** and **10% for cooking**.
- In 2018, **57% was supplied by gas**, **20% by oil**, **13% by electricity** and **7% from bioenergy**.

Figure 13 UK heating demand by sector and end use (bottom). Data from [3.1]

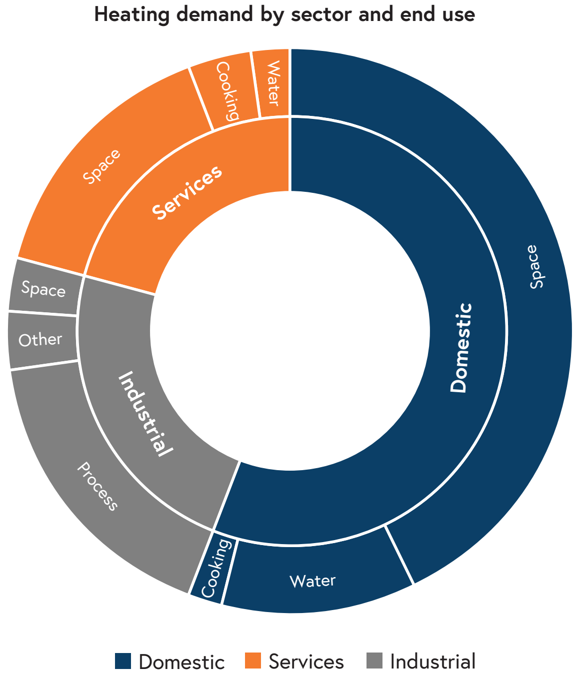
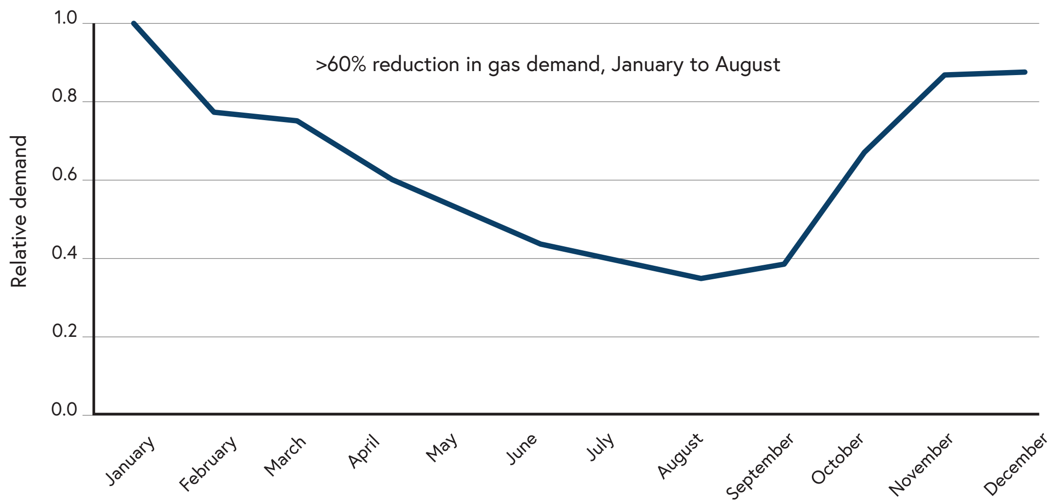


Figure 12 2019 UK monthly gas demand (used as a proxy for heating demand). Data from [3.2]



Industrial Heating Demand[5]

- Industrial heating demand (2018) was **173 TWh** [3.1] (**24% of total heating; 11% of total energy**).
- Industrial heat demand is mostly **process-related**, with **only 13% for space heating** [3.1]. Of the former, **23% is for high temperature processes, 38% is for low temperature processes, 12% is for drying** and the remaining 14% is miscellaneous. [3.1].

Cooling Demand

- **96% of cooling demand is delivered using electricity** [3.1], and includes **air conditioning** (cooling and humidification), **fans, cooling for data centres** and **cooling for warehouse storage**.
- Cooling is predominantly focused on the **service sector**, with **38% for retail, 37% for offices and 13% for hotels** [3.3].
- Cooling demand has **regional, climate-driven variations: 38% of cooled floor area is in London/ South-East**; demand per cooled floor area is **14% above average in London** and **8% below in Belfast and Glasgow** [3.3].
- There is significant **seasonal variation, with demand peaking at 18% of total in July** and **November-April accounting for 31% of total demand**. [3.3].

Residential Heating Demand

- Total residential **heating demand is 410 TWh** [3.1] (**56% of total heating; 25% of total energy**).
- The end use split is **77% for space heating, 20% for water heating** and **3% for cooking** [3.1].
- **77% is supplied by gas** plus **7% each for electricity, oil and bioenergy** [3.1].

Future UK Heating & Cooling Demand

Future UK Heating Demand

- Future demand will be influenced by **climate change, energy efficiency improvements** and the **replacement rate of existing demands/net increase in sources of new demand**.
- Heat demand is expected to **reduce by 2050**. Under current policies, **a fall of around 9%** [3.4] (and potentially **up to 15%** [3.5]) is expected (Figure 15).

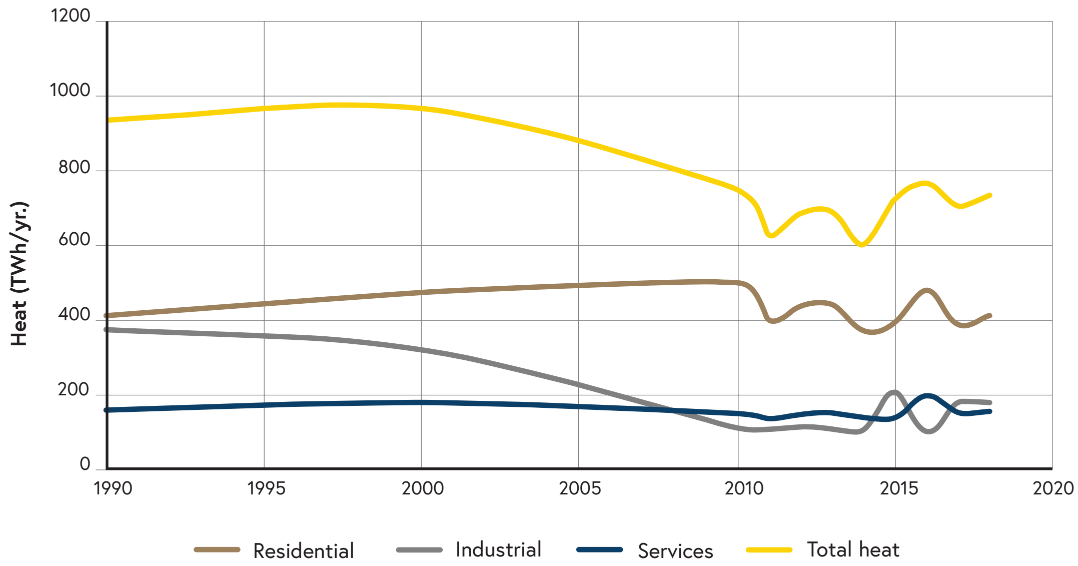
Climate Change Impacts

- **Heating (HDD)**[6] and **Cooling Degree Days (CDD)**[6] give a relative measure of **climate-driven heating and cooling demand**.
- The UK's climate means that demand for heating is **much greater** than demand for cooling: in 2015, the **number of HDD** was **around 100 times** greater than **CDD** [3.18].
- Though **HDD are projected to fall by 15% and CDD to increase by 58% by 2050**[7] [3.15, 3.17], the change in total annual demand for heating and cooling is predicted to be a 15% reduction (Figure 15).
- There will continue to be **regional variations.** In 2050, houses in Northern Scotland will still have greater heating demand and lower cooling demand than those in Southeast England (74% more HDDs and 98% fewer CDDs) [3.15, 3.17].

Recent Trends

- Overall heating demand **peaked in the 1990s** and is rebounding from a low after 2008[8] [3.6].

Figure 14 Annual UK heat demand by sector, 1990-2018. Data from [3.6]



Chapter 3 – Energy Demand Technologies for Net Zero

Energy Efficiency

- For new buildings, reduction in energy demand is determined by the **strength of design standards** and **actual performance** [3.16].
- **The low replacement rate of UK buildings** requires focus on improving existing buildings.
- For existing buildings, energy efficiency changes are driven by **retrofit policies**, mandated **minimum requirements**, **consumer engagement**, plus supply chain and funding availability [3.21].
- State-of-the art design standards that include **performance certification** – such as **Passivhaus** (new-build) and EnerPHit (existing) [3.19] – can reduce heating requirements by up to 80% [3.20].
- Net Zero housing pathways indicate a minimum **9% saving in building energy** is required by 2050 [3.22].

Commercial Heating and Cooling

- There are few projections regarding commercial property floor area and heating/cooling demand.
- Studies range from a **3% decrease** [3.11] to a **43% increase** [3.12] in commercial floor area by 2050.
- **UK cooling demand is predicted to almost double by 2050**, though will still be far less than predicted heating demand (Figure 15).

Industrial Heating and Cooling Projections

- **Complex economic drivers** require **sector-by-sector analysis** [3.13, 3.14].
- **2050 UK predictions range from -4%** to **+5%** [3.4, 3.14, 3.15].

Residential Factors – 2050 Predictions

- Residential floor area is predicted to **increase**, due to **increasing population (+11%)** [3.7], **decreasing household size (-7%)** [3.7-3.9] and **increasing or near-static area per dwelling (+2%)** [3.4].
- Indoor temperature may **increase** (more central heating; **efficiency rebound** effects[9] [3.10]).

Residential Heating & Cooling Demand – 2050 Predictions

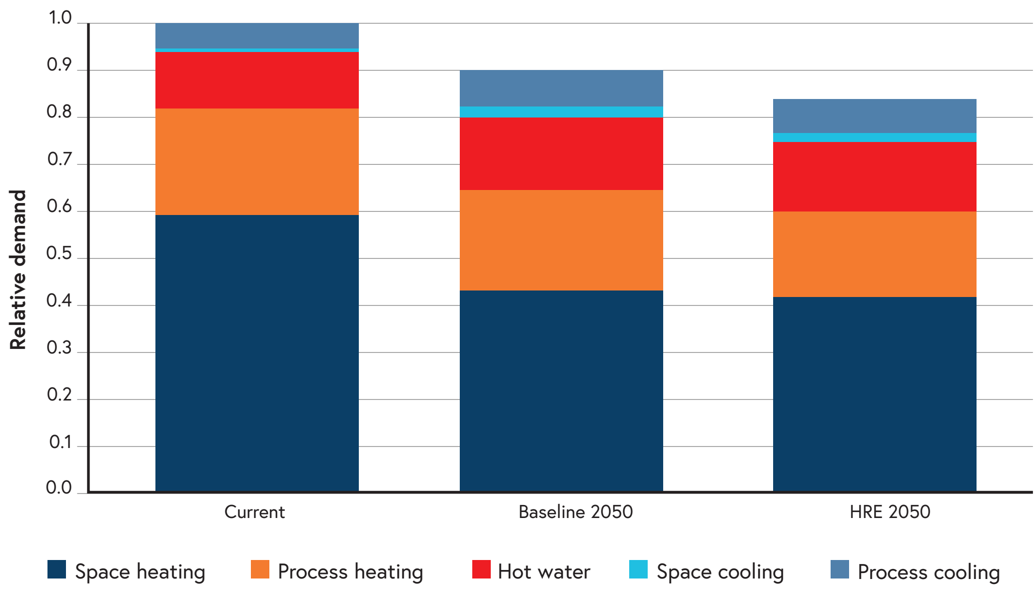
- Predictions range from a 14% increase in demand (no efficiency improvements) to an 11% decrease in demand (current policies) [3.4].

3.1.2 Technologies for Net Zero Heating & Cooling Demand

Heat Pumps

- Heat pumps (HPs) can provide **heating, cooling and hot water** for residential, commercial and industrial applications.
- A heat pump uses a **refrigeration cycle to transfer heat** from low-grade sources (usually air, ground or water) to heat air or water in buildings to a useful temperature.
- Most **heat pumps use electricity** to drive the refrigeration cycle [3.23].

Figure 15 Relative heat demand; current, 2050 baseline under current policies, and Heat Roadmap Europe 2050 strategy. Reproduced from [3.5]

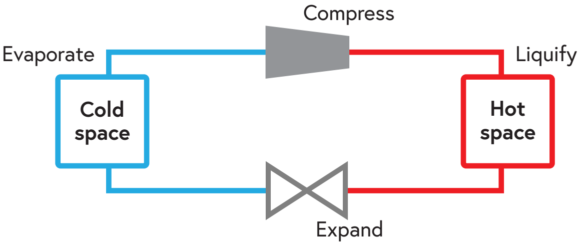


- HPs are very energy efficient since they **transfer heat** rather than generate it – this means they have **an efficiency greater than 100%** (referred to as a Coefficient of Performance (COP)).
- Therefore, widespread HP use would **reduce the input energy to meet heat demand** compared to other options.
- HPs can contribute to Net Zero as the **electricity required can be generated from low-carbon** sources.

Heat Pump/Refrigeration Cycle

- The cycle allows heat to transfer from lower to higher temperature areas. A heat pump cycle is the same as that used in a **refrigerator** – where heat is moved from inside the colder unit to the warmer room.

Figure 16 Heat pump/refrigeration cycle



Heat Pump Performance

- HPs use **between 2 and 4 times**[10] **less energy than direct heating** (via a very efficient gas boiler or direct electrical heating) (Figure 17).
- This is quantified by the **Coefficient of Performance (COP)** (also known as the seasonal performance factor):

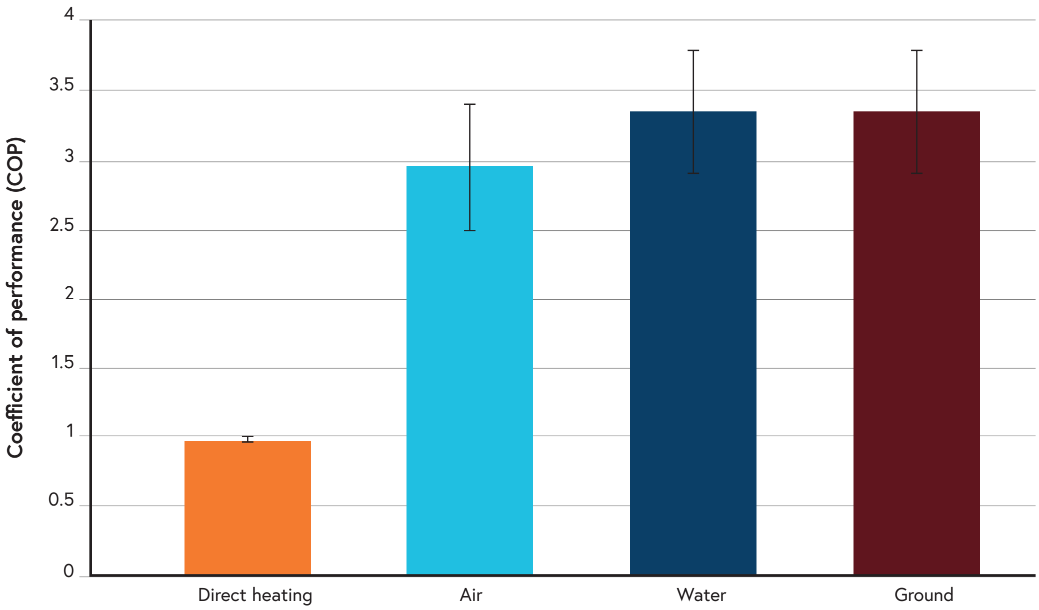
$$COP = \frac{\textit{Heat Out}}{\textit{Electricity In}}$$

- COP increases as **the temperature gap between the source and output reduces**.
- Therefore, a HP's **optimum output temperature is relatively low** (around 55 °C compared to 80 °C for a gas boiler).
- This means that **HPs are most suitable for well-insulated buildings with underfloor heating or larger radiators**.
- Performance is **sensitive to the suitability and quality of the installation and suffers in cold source temperatures**; actual COP can be lower than rated COP[10].

Heat Pump Types

- **Air source heat pumps** (ASHPs) use **outside**, **inside** or **exhaust air** as a heat source.
- **Ground source heat pumps** (GSHPs) use heat from the **ground**, extracted indirectly via water circulating in a closed loop horizontal or vertical collector.
- **Water source heat pumps** (WSHPs) use **water** directly from groundwater, minewater, aquifers, rivers, lakes or the sea.
- Heat pumps can also use excess energy from industrial sources (e.g. waste heat, sewage) and buildings.

Figure 17 Typical rated COP[10] of HPs by source compared to direct heating (either electric or efficient gas boiler) [3.24]



80

Gas boilers sold (1.6m) for every heat pump (20k) in 2017.

1%

UK dwellings currently supplied by heat pumps [3.22].

9%→65%

Increase in non-domestic RHI[11] projects using heat pumps, 2011-18 to 2019-20 [3.24].

55 °C vs 80 °C

Standard temperature limit for a heat pump (55 °C) limits potential as a direct replacement for a gas boiler (80 °C) or for industrial uses.

High Temperature and Hybrid Heat Pumps

- HP operation at a **standard output temperature with existing radiator systems in existing buildings is likely to provide inadequate space heating** on cold days.
- **Higher temperature HPs (up to 80 °C – these could directly replace gas boilers) are available** through upgraded refrigerants and dual-cycle operation. However, these are **more expensive** and **less efficient** [3.25].
- **Hybrid heat pumps** combine a **heat pump with a gas/hydrogen boiler**, either as a retrofit or a new packaged system. The boiler can be used when **high (>55 °C) temperatures are required** (i.e. on cold winter days).
- Several Net Zero pathways (§5.2) predict a **significant roll-out of HPs**, with variations in the balance of electric-only and hybrid heat pumps used.

Market Drivers for Heat Pumps

- **Government incentive schemes** (Renewable Heat Incentive [3.26], Green Homes Grant [3.27]).
- **Building regulations** drive energy efficiency, which makes HP integration beneficial [3.23].
- **Lower HP-specific electricity tariffs** [3.28].
- Social housing environmental targets [3.23].
- 'Low-carbon' as an increasing consumer priority.

Net Zero Applications of Heat Pumps

- Residential buildings: ideal for **new builds** and **deep retrofits**. Replacing fossil fuel boilers with HPs is a bigger challenge – this requires **fabric improvements**, **larger radiators** and/or **hybrid heat pumps**.
- Commercial buildings
- District heating: HPs can provide a low-carbon heat source (Figure 18).
- Industry: **High (80-100 °C)** and **very high temperature (100-160 °C)** industrial heat pumps with large capacities are **emerging solutions in decarbonising industrial heat demand** – and for district heating. **High temperature heat pumps are commercially available**, while **very high temperature heat pumps are limited to experimental solutions and prototypes** [3.30].
- Smart grid services: **heat pumps can provide flexibility to the grid** when used with **thermal and/or battery storage** – this can **provide heating and cooling for several hours** (or even a few days) even if disconnected from the grid [3.30].

Market Barriers to Heat Pumps

- **Low gas price** relative to electricity.
- **High upfront costs** – ASHP >£6,000; GSHP >£10,000.
- Considered a **new/risky technology** by a wide section of the UK public [3.29].
- High uptake when replacing oil or gas boilers will cause a **large increase in electricity system demand** (§4.4.1).
- New **sales and installation networks** needed [3.23].

District Heating

- District heating refers to **heating supplied to multiple consumers by circulating hot water in a pipe network**.
- Supplied from **centralised heating source(s)**, scale can range from supply to a **single, multi-occupant building** ('communal', 'mini-district') to **city scale** (common in Scandinavia) with multiple, dispersed heat sources.
- District heating can contribute to net zero **if the heating source is low-carbon (e.g. HPs fed from renewables).**

Future Contribution to UK Heat Demand

- Provided there is a low-carbon source of heat, district heating can be an efficient way of **providing low-carbon heat supply for dense populations** (towns and cities).
- National Grid's Future Energy Scenarios includes **10-16% of UK homes being fed from district heating** to support Net Zero by 2050 [3.32].

Figure 18 Installation of 2.65 MW WSHP to power the Clydebank district heating network in Glasgow [3.31] Image courtesy of Vital Energi

Combined Heat and Power (CHP)[12]

- **CHP units generate both electricity and heat.**
- Electricity can be supplied to the same consumers as heat or be exported to the national grid.
- **Much higher overall energy efficiency than best grid-scale electricity generation** (CHP 70% [3.35] avg. vs 49% avg. [3.36] for CCGT[13] generation)**, but lower efficiency than heat-only boilers** (90%).
- **Bioenergy, hydrogen, geothermal and carbon capture & storage (CCS)** offer routes for decarbonisation of CHP.

Current Contribution to UK Heat Demand

- **Less than 3%** of UK heat demand [3.33], composed of 5,500 'district' and 11,500 'communal' networks [3.34].
- **1.6% of UK homes supplied** by district heating [3.34], compared to >50% in Sweden.
- **Mostly gas-fuelled**; only 12% of schemes use potentially low-carbon sources [3.34].

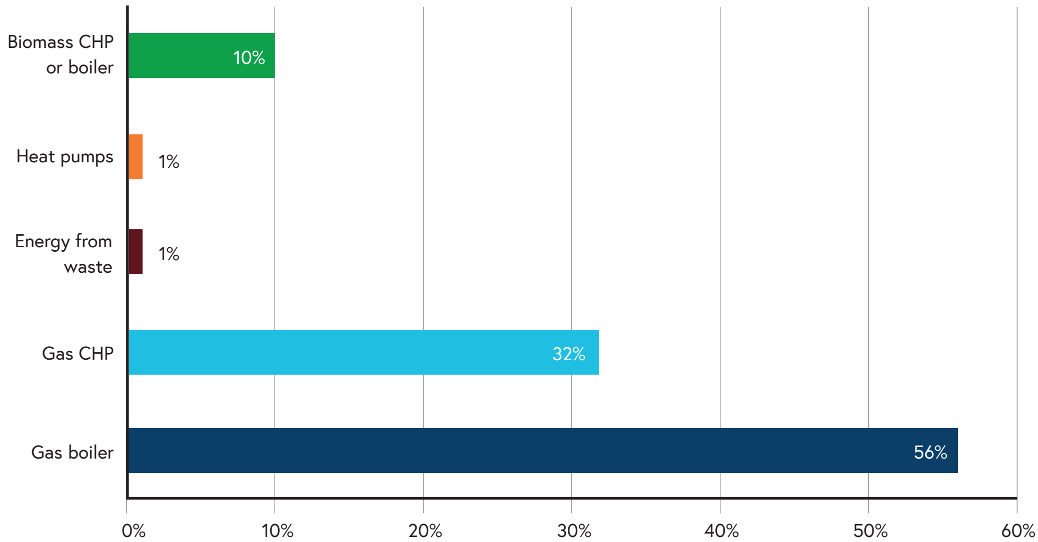
Hydrogen for Heating

- **Hydrogen can be burned in boilers and cookers** in a similar way to fossil gas. Though most gas **appliances would need to be replaced or modified** to work on hydrogen, some hydrogen-ready models are available (Figure 20).
- The UK's **gas network could be converted to run on hydrogen** (see §4.5).

Figure 20 A hydrogen-ready gas boiler available in 2020 [3.37] Image courtesy of Worcester Bosch

- Burning hydrogen gives **zero carbon emissions at point of use**, but **hydrogen is not necessarily low-carbon –** it depends on how it is made.
- Hydrogen can be made from **chemical processing of fuels** (which emits GHGs) or **electrolysis of water** (which does not). See §4.5.1.

Figure 19 UK district heating energy sources (2019). Data from [3.33]



- For **hydrogen from fuels to be compatible with Net Zero, emissions from chemical processing must be captured**.
- For **hydrogen from electrolysis to be compatible with Net Zero**, the **electricity used for electrolysis must be low-carbon**.
- Supplying heating demand with hydrogen – rather than electric heat pumps – would **avoid a large increase in electricity demand** and associated upgrades to electricity system infrastructure (§4.4.1).

Hydrogen vs other technologies

- In all but one of seven Net Zero pathways analysed in §5.2, **hydrogen serves a minority of heating demand**: typically in the form of **hybrid heat pump (HP)/ hydrogen boilers** to provide for **peak winter heating demand where HPs may struggle to meet demand** for **poorly insulated housing**.
- While widespread hydrogen heating is technically feasible, there are **challenges surrounding conversion of the gas network and appliances** (§4.7.2).
- Analysis from the UK Energy Research Centre (UKERC) suggests that if hydrogen is to play a role in Net Zero heating, **significant progress towards rollout will be needed in the next few years** if we are to keep within carbon budgets [3.38].

Hydrogen production

- Hydrogen is **not** naturally available.
- It can be made from **water** using electrolysis (Figure 23) or from **fuels** (currently steam reformation of methane) (Figure 22).
- Each method has **cost**, **efficiency** and **emissions** trade-offs (§4.5.1).

Figure 22 Hydrogen production from steam reformation of methane. CCS = carbon capture & storage

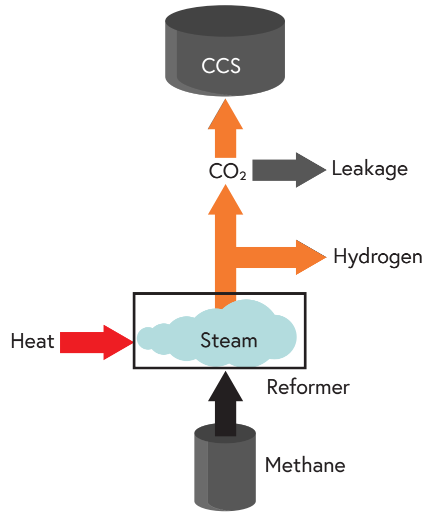


Figure 23 Hydrogen production from water by electrolysis

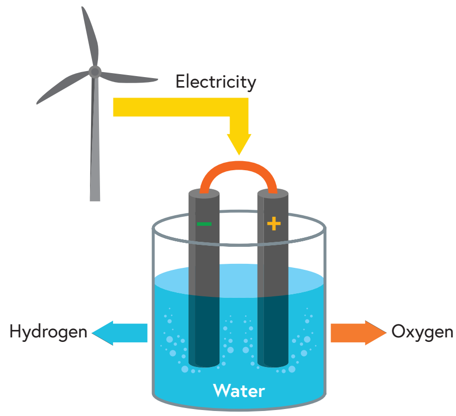
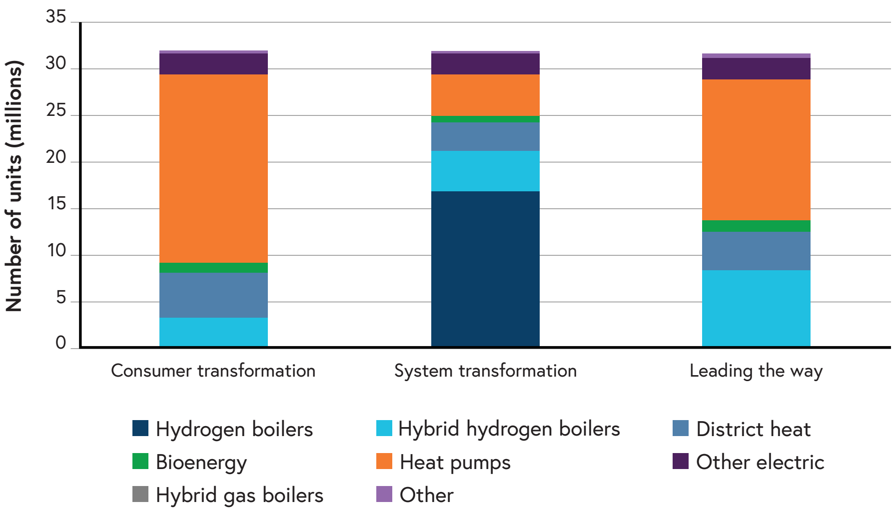


Figure 21 2020 residential heating technology mix, three Net Zero pathways (National Grid ESO). Reproduced from [3.32]



Bioenergy & Waste Heat

- Bioenergy for heating includes **biomass** (e.g. wood-burning stoves) and **biogas/biomethane**. If these are from sustainable sources (i.e. the **land use change that allowed their production did not cause GHG emissions**), they can be considered low-carbon (§4.5.2).
- **15% of UK bioenergy use is for heating buildings** [3.39], and **contributes 8% of total UK heating demand** (2019) [3.1].

Biomass for Heating

- Biomass for heating is typically **woodchips** and **pellets** – wood sources account for **⅓ of heat demand from bioenergy** and **2% of residential heating demand** [3.1].
- Net-zero potential is limited by the **time lag between CO_2 released on burning** and **reabsorption by growth** of replacement woodland [3.1].
- Low-carbon biomass includes the use of **waste materials, avoiding land use conflicts, planting on degraded land** and **suitable species selection** for the chosen planting site [3.1].
- **Burning biomass releases smoke particulates and oxides of nitrogen which impair air quality** – especially in cities [3.41].

Waste Heat

- **Waste heat** from **industrial processes** can be used for **district heating** schemes.
- **1% of UK heating demand** could be provided from waste heat with direct economic potential [3.40].

Biogas/Biomethane

- Biogas is derived from **plant and animal waste** via **anaerobic digestion** (§4.5.2).
- The main product is **biomethane**, which can be used in the same way as fossil gas – or blended into mains gas.
- As biomethane is **derived from waste**, resources are limited. It could provide at most **3-10%** of 2019 UK gas demand [3.42].

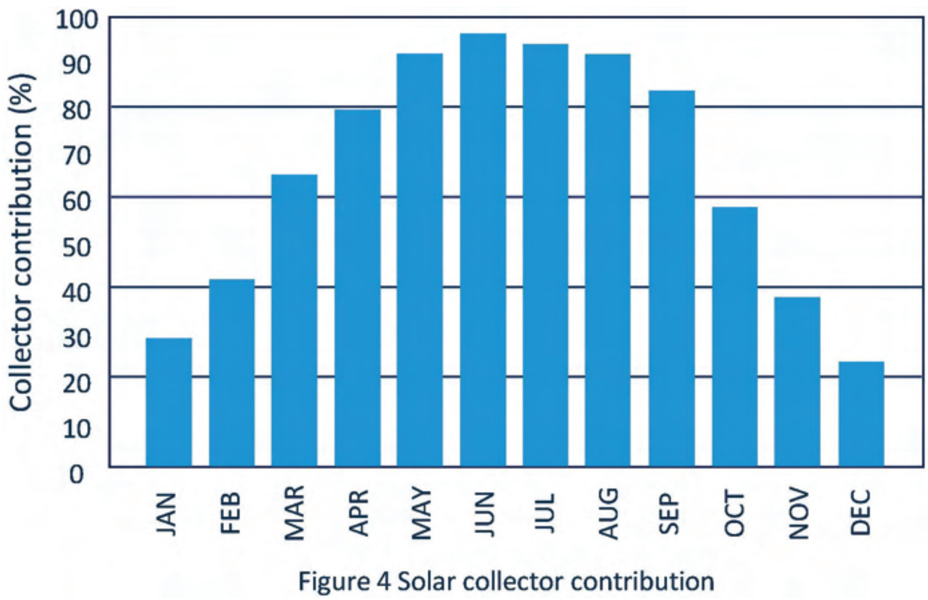
Solar Thermal

- **Solar thermal** systems use solar energy to heat water directly: **water is circulated through a collector** with high surface area (that is **heated by the sun**).
- There are two types of solar thermal system: **flat plate** and **evacuated tube**. The latter has **higher up-front cost** but **higher efficiency**.
- **0.08% of UK heat demand** is currently provided by solar thermal [3.43].

Solar Thermal vs. Solar PV

- Solar thermal and solar PV use the **same installation space** (south-facing roofs).
- Solar thermal has **much higher efficiency** (70% vs. 15-20%) but has a **higher cost per kWh** and is **limited to providing hot water**.
- **Hybrid PV-T** panels combine **solar thermal and PV in a single unit**, though matching the outputs of the two can be difficult.

Figure 24 Seasonal solar thermal contribution to domestic hot water - London. Source: [3.44]



Applications of Solar Thermal

- Solar thermal can provide **hot water** for homes (new builds and retrofits), public buildings and industrial processes.
- Solar thermal can provide **heat for district heating** schemes.
- Typically, solar thermal is installed **alongside another heat source** (gas/biomass boilers; heat pumps). These **hybrid systems are to provide heat when solar energy is unavailable or insufficient** (at night or in the winter).

Integration of Solar Thermal with Heat Storage

- Solar thermal is typically built with **storage** to help match supply to demand.
- Storage for solar thermal can be deployed at different **physical** (e.g. home-based or utility-scale) and **time** (e.g. daily or seasonal) scales. See §4.11.3.

40%

A well designed solar thermal system can provide 40% of domestic hot water for a typical home [3.44]

3.2 Transport

3.2.1 Transport Demand & GHG[14] Emissions

Current UK Transport

UK Transport Emissions

- Road transport made up **68%** of transport **emissions** in 2019.
- Private cars are the biggest single contributor, making up **41%** of UK transport emissions.
- While rail makes up **10% of passenger journeys** (Figure 28), it contributes **1% of UK transport** emissions.
- Aviation makes up **23%** of UK transport emissions – of which **96%** is from international flights.

UK Transport Energy Consumption

- **96%** of UK transport energy was provided by **burning petroleum** in 2019.
- Road transport made up **72%** of final energy use, with **24%** accounted for by aviation. Rail and shipping made up **2%** each (Figure 26).

Figure 25 Annual UK transport emissions by sector and mode (2018)[15]. Data from [3.45]

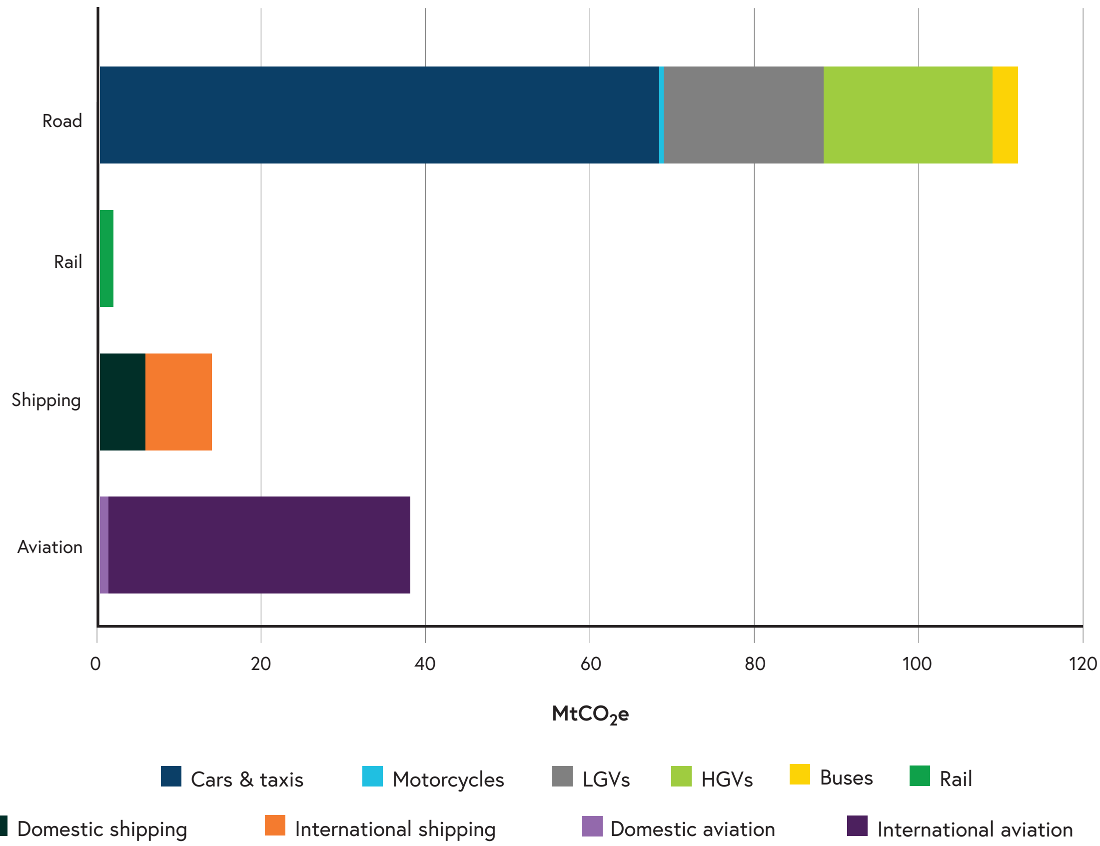
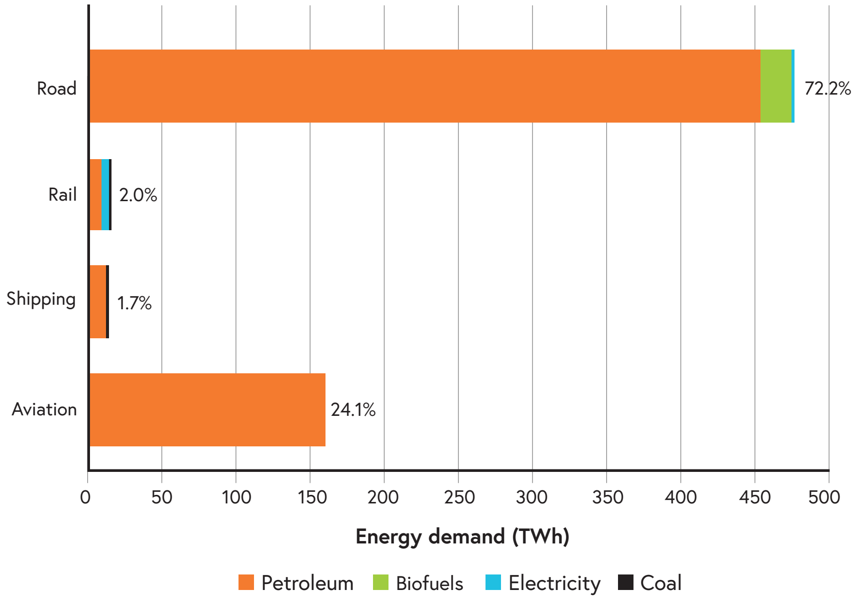
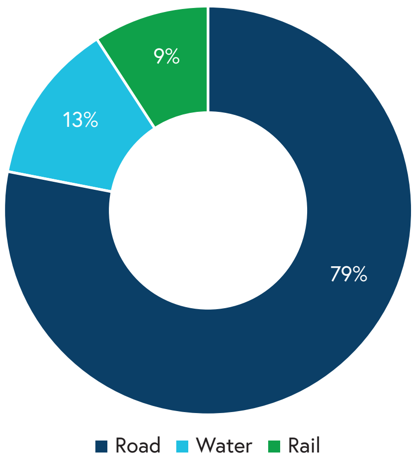


Figure 26 Annual UK transport energy consumption by sector and fuel (2019). Data from [3.45]



Transport made up **38% of UK final energy use** and **31% of GHG emissions** in 2019 (including the UK's share of international aviation and shipping[16])

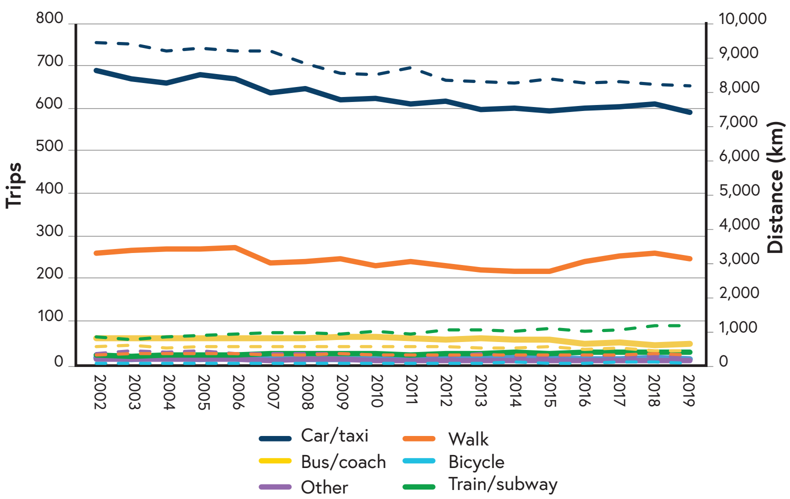
Figure 27 Annual domestic freight (goods moved) by mode, 2018. Data from [3.47]

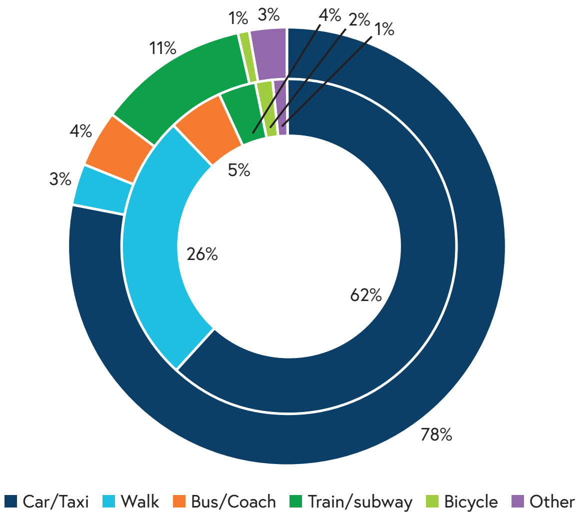


UK Travel Habits

- **Distance and trips have been in steady decline** since 2002, down **10%** and **11%** respectively.
- **Private cars dominate**: **62% of trips** and **78% of distance** in 2019 were made in a car, either as a driver or passenger [3.46].
- **Walking** constituted **26%** of trips in 2019, but only 3% of distance.

Figure 28 Annual average UK modal shares (2002-2019) by trips (solid lines) and distance (dashed lines) (top); UK modal shares by trips (inner circle) and distance (outer circle) (2019) (bottom)





The Scale of Net Zero and the Transport Sector

- Transport is a **problem sector** for emissions (Figure 3) – and **with the notable exceptions of aviation and shipping, must reach zero emission by 2050**.
- The evidence suggests that technology-based solutions ***or*** demand-based solutions alone are **unlikely to be enough to meet Net Zero**. Figure 30 shows projected emissions resulting from different UK policy actions relating to banning internal combustion engine (ICE) cars and large-scale lifestyle shift[17]. **Only a combination of technology- and demand-based solutions are able to produce the necessary reductions.**

Despite DfT projections (Figure 29), aviation growth 2019-2050 is limited to at most **25%** in seven published Net Zero pathways (§5.2).

Future UK Transport

Future UK Transport Demand & Emissions

- The Department for Transport (DfT) forecast that demand across all passenger and freight modes (except buses) is expected to **grow significantly by 2050** (Figure 29).
- While emissions from **shipping, rail and aviation** are expected to **rise,** they are likely to **fall** in other sectors.
- This is based on i) **deployment of more efficient end-use technologies** and **ii) changes in the dominant fuel source** – electrification, hydrogen, biofuels, synthetic fuels and ammonia.

Technology-based Solutions

- A technology-based solution seeks to cater for **transport demand** in a manner compatible with Net Zero: i.e. any residual emissions are low enough that they can be offset.
- Technology solutions include replacing fossil fuelled cars with **electric vehicles (EVs)**, serving aviation with **synthetic fuels** or powering HGVs with **hydrogen**.
- Some technology-based solutions interact with demand-based solutions: e.g. **e-bikes** could help **facilitate modal shift** away from cars by making cycling more attractive.

Figure 29 Forecasted % change in demand (passenger km for passenger modes; vehicle km for freight modes) and GHG emissions, 2018-2050. Data from [3.49]

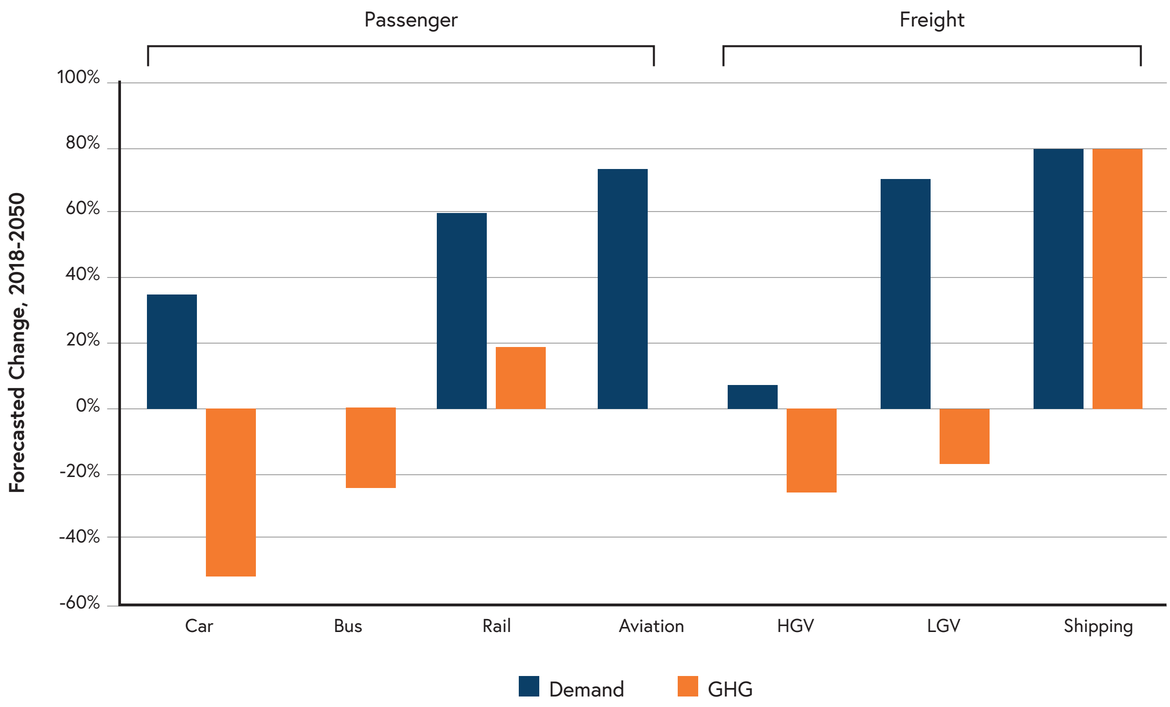
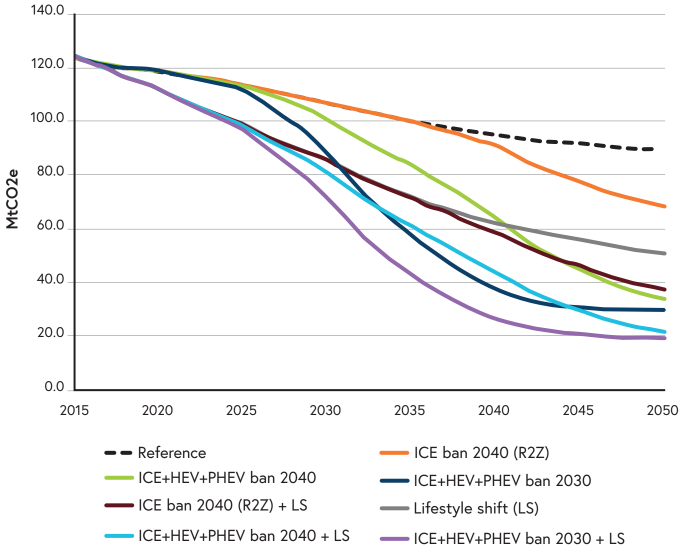


Figure 30 Modelled lifecycle GHG emissions from road transport (2015-2050) in various fossil fuelled car bans and lifestyle shift (LS) options[17]. ICE = internal combustion engine; HEV = hybrid EV; PHEV = plug-in hybrid EV; R2Z = Road to Zero. Reproduced from [3.50]



Demand-based Solutions

- A demand-based solution seeks to **change** the nature of transport **demand**. This could involve **incentivising active travel** or **public transport** over car use ('modal shift'), or simply reducing the demand for travel.
- These incentives could include **road pricing**, **active travel infrastructure** and **frequent flyer levies.**
- This guide focuses on Net Zero *technologies* but also addresses their potential when interacting with demand-based solutions, as **technology alone is unlikely to be able to allow the UK to reach Net Zero.**

COVID-19 Impacts

- The **biggest energy system impacts of COVID-19 have been on transport**, though most of this is expected to be short-term.
- **Long-term behavioural shifts**, such as a greater propensity to work from home, are likely to **reduce** transport energy demand. Other shifts, such as **increased car dependency** caused by fear of using public transport, could lead to an **increase.**

3.2.2 Technologies for Net Zero Transport Demand

Surface Transport – Passenger

Battery Electric Vehicles (EVs)[18]

- When used instead of internal combustion engine (ICE) vehicles, EVs can **reduce primary energy demand** for transport due to their **much higher efficiencies (~80% vs. ~20%)**[19] [3.51].
- An **EV roll-out will increase demand for electricity**. The **electricity system will thus need technological interventions** to supply these additional demands.
- EV emissions **depend on emissions within the electricity sector** and emissions **associated with EV manufacturing** (especially their batteries).
- EV **uptake is quickly growing in Britain** – in one year (2019 to 2020) EV market share has **increased by 184%** [3.52] – but barriers remain surrounding upfront cost and 'range anxiety'.

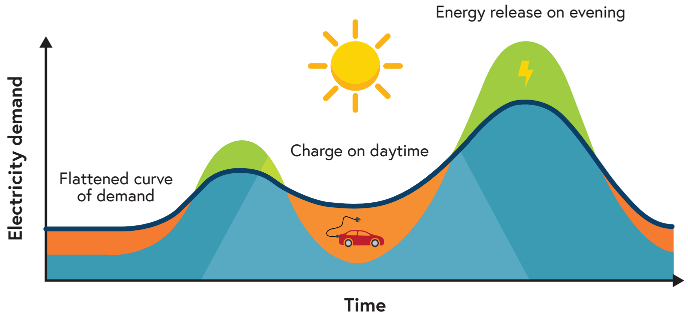
Types of electric vehicles

- **Battery electric vehicles (EVs)** are 'all-electric'; their propulsion is provided by a large rechargeable (typically Lithium-ion) battery.
- **Plug-in hybrid electric vehicles (PHEVs)** have a smaller battery to deliver a lower electric range and a petrol/diesel engine for longer journeys.
- **Hybrid electric vehicles (HEVs)** have an even smaller battery that is recharged from a petrol/diesel engine while driving to offer superior fuel economy compared to an ICE car.
- **Fuel cell vehicles (FCVs)** generate their electricity from a fuel cell (generally using oxygen from the air and compressed hydrogen).

Table 1 EV charging: power and time to add 100 km range[20]

Charging	Home	Workplace	Public	En route
Power	3-7 kW	7-22 kW	7-22 kW	50-150 kW
Time to add 100 km range	190-450 mins	60-190 mins	60-190 mins	9-27 mins

Figure 31 Illustration of V2G concept – adapted from [3.55]



Batteries, Range & Charging

- BEVs on the market have battery capacities of **30-100 kWh**. Given that **BEVs have an 'mpg' of around 15-20 kWh/100km**, this gives these **vehicles a range of around 150-500 km**.
- **PHEVs have smaller batteries (5-10 kWh)** and hence **a shorter electric range (25-50 km)**
- Plug-in EV drivers **rely on charging at home, work, public places** (e.g. on-street parking, supermarkets) and at **en-route charge points** (e.g. motorway services).

Smart Charging and V2G

- 'Smart' (controlled) charging can **reduce peak demand on the electricity grid** [3.53] and **shift demand to times when renewable output is high and other demand is low.**
- **Vehicle-to-Grid (V2G) (Figure 31) is bidirectional charging** – the **two-way exchange of energy between the EV's battery and the grid.**
- V2G can provide extra **flexibility** to **support electricity system operation**. V2G can thus **allow for more renewable generation**, and can **hasten decarbonisation** [3.56].

EV Emissions & Net Zero Potential

- Battery EVs have **zero tailpipe emissions**, whereas PHEVs and HEVs do not.
- There are **emissions associated with battery manufacturing** for EVs – and reported values differ widely by source.
- Most analysis suggests that **BEV lifecycle emissions are 50-70% lower than that of ICE cars** [3.57].
- This will **improve further as electricity decarbonisation targets are met.**

E-bikes

- **E-bikes** (or **pedal-assist**) bikes use a **battery and motor to reduce the effort of cycling**. This can make **cycling easier and more appealing**, especially for **longer journeys**.
- They are being actively encouraged as a **viable option for longer trips (up to 15 km)** in other European countries such as Denmark [3.58].

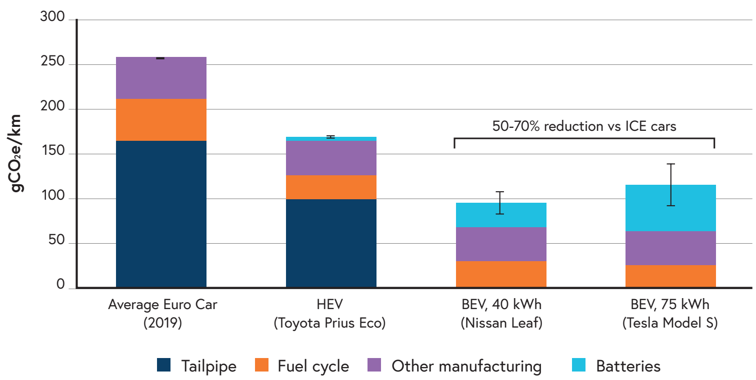
Net Zero Potential of E-bikes

- E-bikes and bikes have **~95% lower lifecycle GHG emissions per km than ICE cars**, and **~85% lower than those from EVs** than those from EVs[19] (Figure 33). [3.59].
- A UK study found that **large-scale switch to E-bikes could save the UK up to 30 million tonnes CO_2 per year** – around half the total emissions from cars [3.60].

E-bikes: Range and Charging

- E-bikes have a **small (~0.5 kWh) battery** that can be removed from the bike by hand and **charged indoors from a standard plug in ~3 hours.**
- E-bikes assist the cyclist when pedalling for ranges of **50+ km.**

Figure 32 Lifecycle emissions, EVs vs. ICE cars, assuming 150,000 km lifetime mileage for all vehicles. Fuel cycle emissions for BEVs based on 2019 GB electricity mix. Chart reproduced from [3.57]



Rail & Bus

- **Zero emission buses and trains are a vital part of reducing transport emissions**, particularly if their **modal share is to be increased.**
- The main candidates for zero emission rail are **electric trains** and **hydrogen trains** – the former is a mature technology in the UK.
- Evidence suggests that **Net Zero can only be met if all diesel trains are replaced by electric and hydrogen** locomotives [3.61].
- Unlike private cars, **buses' journeys and energy usage are very predictable**. Furthermore, as they finish their journeys at large depots, this makes it **easier to site hydrogen refuelling and electric charging infrastructure**.

Low emission buses

- There are **~500,000 electric buses worldwide**, 99% of which are in China [3.62].
- London has introduced **electric buses on 8 of its routes**, and is **testing the potential for hydrogen buses on one of its routes** [3.63]. Aberdeen is also introducing hydrogen buses [3.64].

Low emission rail

- **~40% of UK railways are currently electrified** [3.65]
- Widespread rail electrification has been delivered in Scotland since 2010 [3.66], though electrification projects have been stalled in the rest of the UK [3.65].
- Hydrogen trains can be a solution for non-electrified lines, though **they are unsuitable for busy routes that require high speed and acceleration** [3.66].

Net Zero Potential

- Most evidence suggests that rail and buses are **of significantly lower emissions per passenger-km** compared to private cars, especially when electrified or powered by hydrogen (Figure 34).

Demand Reduction & Modal Shift

- Transport energy demand has **increased by 16% since 1990**, vs. a UK economy-wide decrease of 4% [3.72].
- **Emissions have remained static** and **grown as a share of the UK total** with **no reduction since 1990** (compared to a 45% reduction across all sectors – Figure 3).
- Transport remains **97% dependent on fossil fuels** (Figure 26).
- **Demand for transport is expected to grow significantly** (Figure 29). Strategies for reducing emissions rely on making end use technologies more efficient and shifting the dominant fuel source from fossil fuels to **low emission energy sources** – mostly **electricity** with some **low-carbon fuels** (§4.5).
- The Department for Transport (DfT)'s own forecasts predict that **the uptake of EVs will lead to increased traffic growth** due to a reduction in the cost of motoring; the **exclusive reliance on technical solutions will only reduce emissions sufficiently in the DfT's lower traffic growth scenario** [3.73].

Figure 33 Lifecycle emissions, bikes and e-bikes, compared to ICE cars and EVs[21]. Car data from [3.57], bike and e-bike data from [3.59]

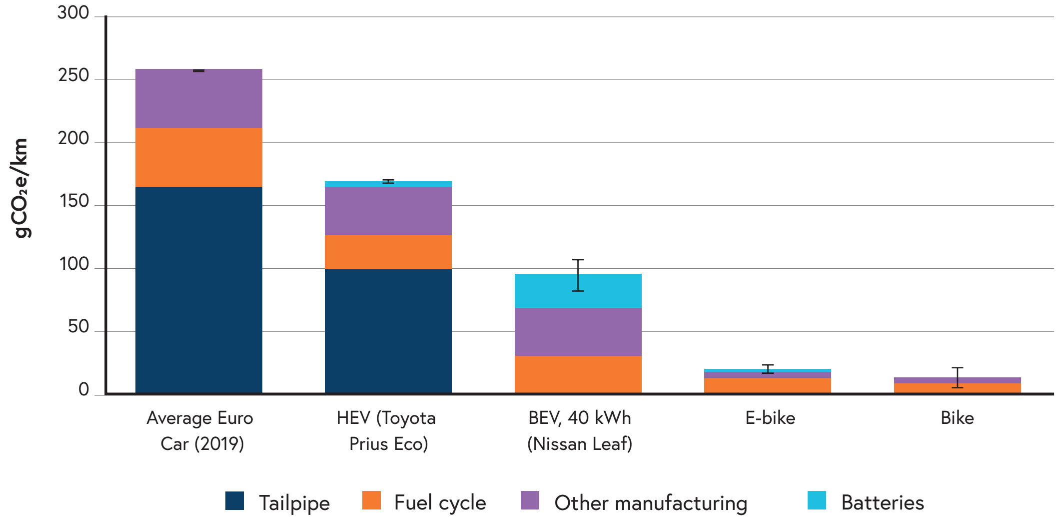
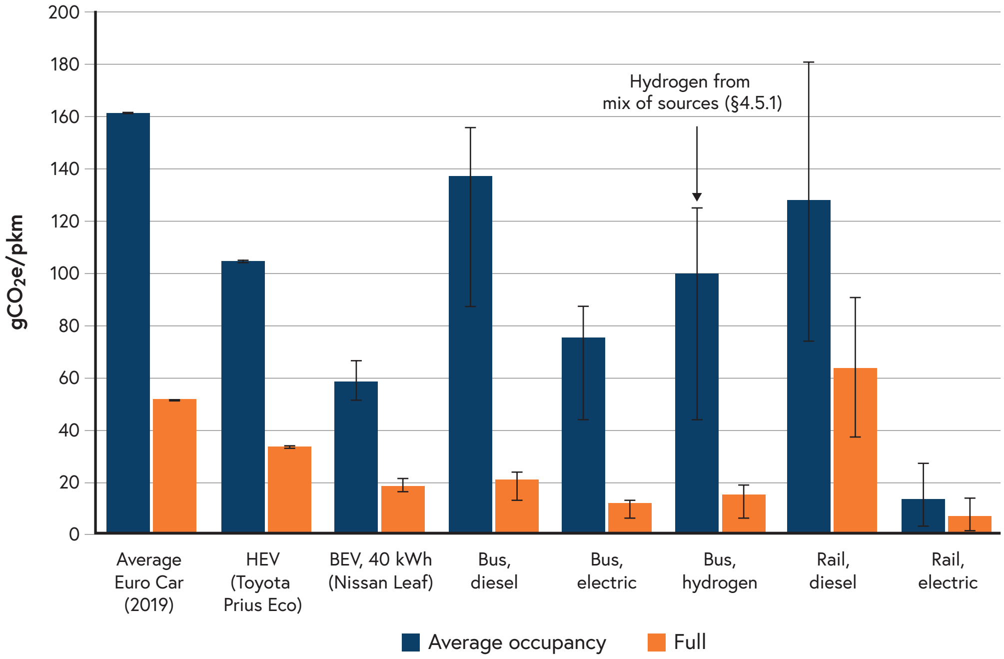


Figure 34 Lifecycle emissions per passenger km (pkm), average occupancy and fully occupied, for cars, buses and rail (different powertrains)[22] Data from [3.67-3.71]



Future Trajectories for Travel Demand

- Since the early 1990s, aside from general population growth, **only an aging cohort of people (now 60+) have contributed to traffic growth** (Figure 35).
- Driving licence-holding, car ownership and use have **declined among successive cohorts of younger people**.
- This **changes the 'business as usual' approach to traffic forecasting in the future**.

Shared Mobility & Autonomous Vehicles

- Shared vehicles lead to **reductions in car ownership and km driven** – and **increased use of other modes** of transport [3.78].

Transport Demand Reduction and Co-Benefits

- Transport **energy demand and emissions can be reduced by better land-use planning, restrictions on car use in central and residential areas**, and **promoting alternatives to private car use** (public transport, walking and cycling – including e-bikes).
- Such measures have been shown to **benefit the vast majority of the population** and **approval of such measures is high** [3.74]. They can also **improve life quality, health, commercial vitality, safety and equity** [3.73].
- Local authorities and urban planners from Lyon [3.75] to Glasgow [3.76] are planning for **a future with drastically reduced car dependency in urban areas**.
- On the other hand, **pro-car use policies disadvantage those in lower income groups**, who are less likely to have access to cars (Figure 36).

Figure 35 Percentage change in car driver km per head by age group, England (2002–05 to 2011–14). Reproduced from [3.73]

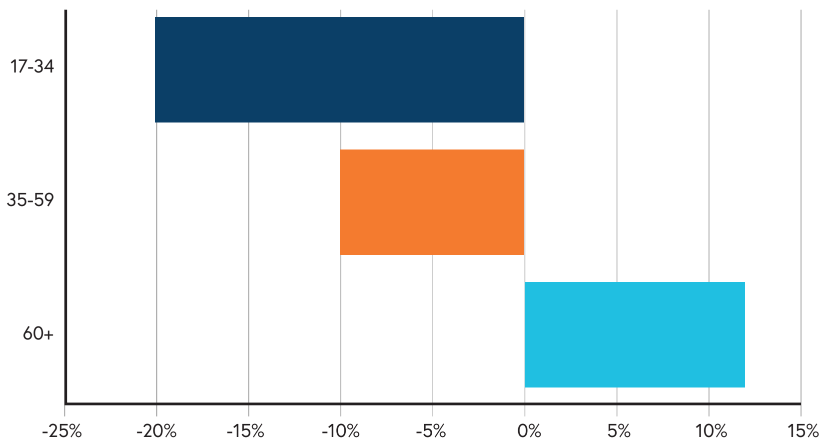
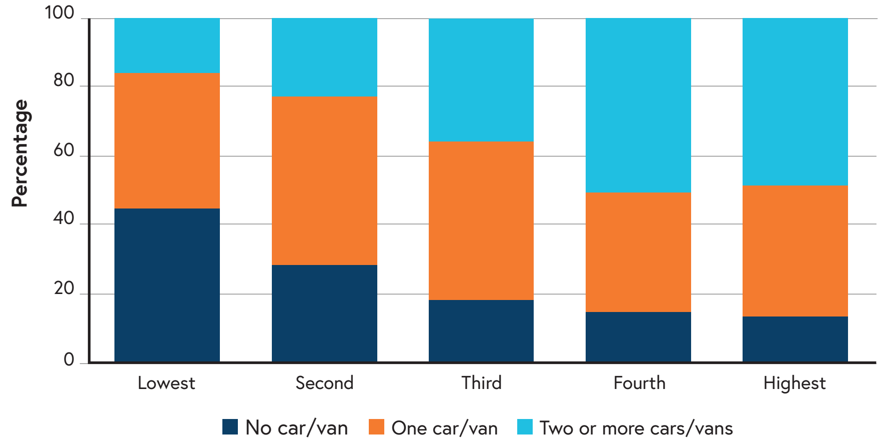


Figure 36 Car ownership by income quintile (England), 2019. Data from [3.77]



Coordination of Transport & Planning

- By aligning the objectives of housing development and the timing of services (e.g. schools, hospitals and workplaces), **the need for transport can be reduced**.
- For example, Paris has set a goal of being a '15-minute city', in which **essential amenities are within a 15-minute journey by walking or cycling** [3.79].

Regulation on High Emissions Vehicles

- **Restricting the sale of high-emissions vehicles** (e.g. SUVs) as soon as possible will **reduce subsequent constraints in car use** necessitated by future carbon budgets.
- This option was **favoured in the UK Climate Assembly** [3.80].

Support for Lowest Energy/Emissions Modes of Transport

- **Expensive public transport can deter modal shift** to low-carbon transport [3.81].
- By ensuring **low-carbon modes are always low-cost**, modal shift can be encouraged [3.82].

Pricing Structures

- **Carbon pricing** (applied to cars as fuel duty) and road pricing can **push consumers towards low emission transport**, **enable subsidy of low-carbon options** and **fund abatement of emissions**.
- A carbon price of **£40-100/tCO_2**[23] to 2050 is recommended in one study for Net Zero road transport [3.83].

Surface Transport – Freight

Low Emission Surface Freight

- UK domestic freight is mostly moved by **road (79%)**; the remainder is **shipping (13%)** and **rail (9%)**.
- While **rail and shipping require much less energy** to move a tonne of goods along a given distance (Figure 34), the **flexibility of road freight** has resulted in its high share of freight transport.
- **Van traffic has doubled since the early 1990s**, and **emissions have increased by 67%.**

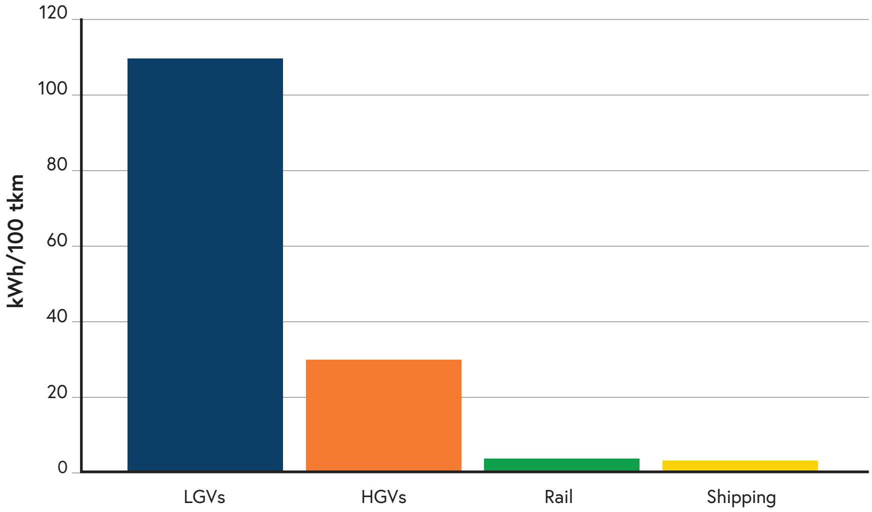
Electric Powertrains for Road Freight

- **Battery electric powertrains form the mainstay of the Government's approach to decarbonising LGVs** – they are included in the ICE car ban [3.49].
- **Battery electric HGVs are being developed** (e.g. Tesla Semi [3.85]) and **initial trials of electric trucks have been positive** [3.86]. The **size and weight** of batteries required for trucks' driving distances – without a fundamental re-design of trucks with electric drivetrains (as alleged by Tesla) – has meant that some Net Zero pathways **limit battery electrification to LGVs** [3.87].
- Some electric HGV concepts are based on an **electrified overhead line** – like on a railway. Demonstrations are underway in Sweden and Germany, and while this gets around the battery problem, the infrastructure is of similar cost to electrifying rail lines (~**£1m per lane-km**) [3.84].

Low-Carbon Fuels for Road Freight

- Most HGVs can be converted to run on **biofuels**, though these can only **have a limited contribution to providing for transport demand** and **have further serious negative environmental consequences** (§4.5.2).
- **Hydrogen fuel cells are regarded as a key technology for the decarbonisation of heavy road freight** [3.87] and are the way in which zero-emission HGVs are being trialled in the Government's ongoing Low Emission Freight and Logistics Trial [3.88].
- Most Net Zero pathways assume that **hydrogen fuel cells will be used as the dominant means of propulsion for HGVs** (§5.2).
- GHG emissions of hydrogen depend on how it is produced (§4.5.1).

Figure 37 Energy intensity of freight by mode, kWh per 100 tonne-kilometres (tkm). Reproduced from [3.84]



Low Emission Rail Freight

- As for passenger rail, **electrification** can allow for zero-emission rail freight.
- Other technologies that do not rely on overhead lines, such as **hydrogen and battery-powered trains, struggle to provide enough power** for long, heavy freight trains [3.69].

E-Cargo Bikes for Last Mile Logistics

- E-cargo bikes can **drastically reduce emission of last-mile logistics**, such as **grocery deliveries** and online shopping deliveries.
- In a UK trial, **97% of grocery shop orders could be fulfilled using e-cargo bikes**, and **delivery times were shorter** than for vans [3.89].

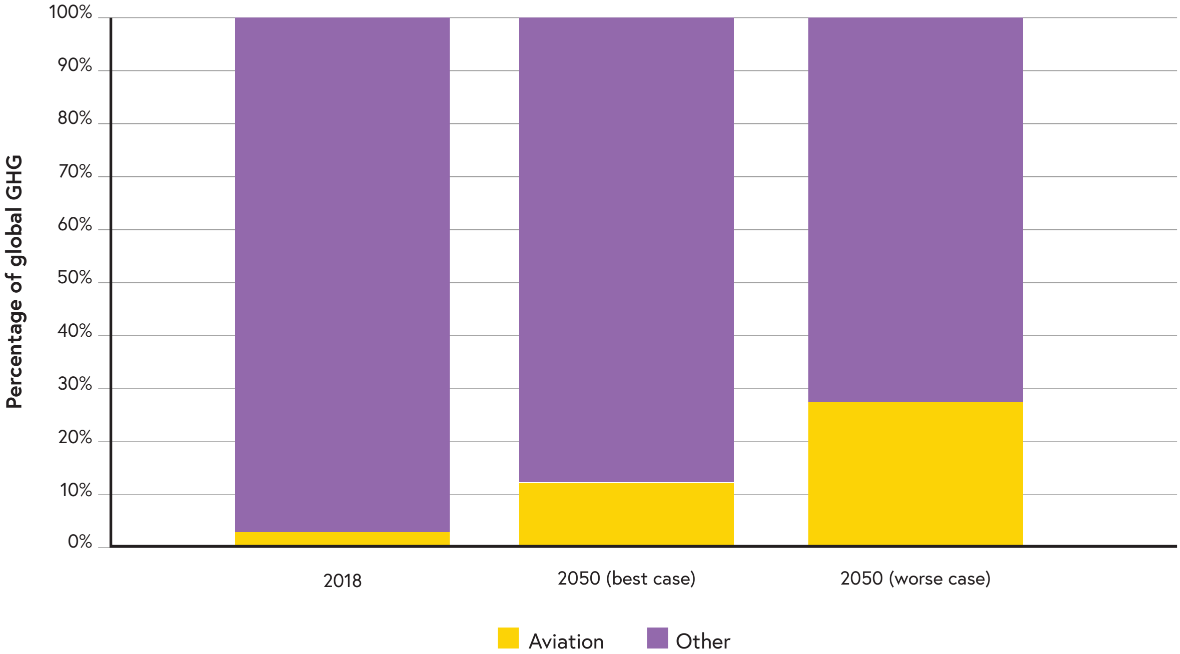
Aviation

- CO_2 from a business-as-usual aviation sector could increase (globally) **up to 4.5x by 2050** [3.90] – this would mean that **aviation would account for 27% of 1.5 °C global carbon budgets 2015-2050** [3.91].
- The CCC places an upper limit of **25% growth** in UK aviation demand (including international flights) to 2050 to meet Net Zero [3.92].
- GHG reduction is likely to come from **low-carbon fuels** (§4.5) and some **electrification**. Limiting demand growth via **taxation** and **airport expansion limits** will also be part of meeting Net Zero.
- Aviation has **non-CO_2 warming effects** from **NO**x, **sulphates**, **aerosols** and **contrail cirrus** – this **multiplies the global warming impacts of aircraft by 3x** [3.93].
- CORSIA[24] is the UN aviation agency's scheme for **offsetting and removing emissions from 2020** – but it **does not include non-CO_2 emissions** or CO_2 **emissions up to 2019 levels each year**. The price of offsets is **also very cheap** relative to actual emissions abatement [3.94]. **Inclusion of aviation and all GHG emissions** in COP26 is **vital** to meeting Net Zero [3.92].

Sustainable Aviation Fuels (SAF)

- SAFs are based on **biofuels** (§4.5.2) or **synthetic fuels** (synfuels) (§4.5.4). Rather than burning jet fuel containing carbon from fossil fuels, **SAFs are jet fuels containing carbon extracted from the air** (by **crops**, **CCS** or **direct air capture**) (§4.10.2).
- **Biofuels** for aviation are subject to the **same problems as biofuels for surface transport**. For context, **the wheat required to meet 2018 aviation energy demand through biofuels is almost as much as the global calorie requirement for feeding all humans on the planet** [3.95]. While there are more efficient crops (e.g. algae [3.96]), the problem remains that **biofuels are very difficult to scale up to aviation demand**.
- Synfuels are manufactured jet fuels using **hydrogen** and **carbon** captured directly from CO_2 in the air. Unlike biofuels, their manufacture does **not require arable land** and could be done **without competing with global food supply.**
- Synfuel manufacturing is **very energy intensive**[25], though synfuels could be produced alongside large-scale renewable resources outside the UK (e.g. desert solar) (§4.5.4).

Figure 38 Global aviation GHG emissions as a proportion of global total, 2018 and 2050 (worst/best case scenarios from ICAO). Reproduced from [3.91]



Hydrogen

- Hydrogen could be used to power aircraft, either by **generating electricity in a fuel cell** (for smaller aircraft) or by **being burned in a modified jet engine** (for larger aircraft)[26] [3.97].
- In a jet engine, **hydrogen combustion creates oxides of nitrogen (NO_X)** [3.98], which contribute to aviation's warming effects [3.93].
- Hydrogen (when liquefied, which itself requires cooling below **–250 °C**, or compressed to 500 atm at –200 °C [3.99]) is **around 4x less energy dense by volume than jet fuel**.
- Therefore, hydrogen fuel tanks must be 4x larger for a given energy storage, resulting in **larger planes** (more drag) or **fewer passengers** (higher seat price and higher energy demand per passenger).

Limiting Aviation Demand

- Due to the difficult nature of aviation emissions reduction, **limiting growth of air traffic** is a key method of reducing emissions in the sector.
- Ways to **effectively limit air traffic growth** include **limiting airport expansion, increasing the price of jet fuel** through **removing tax exemptions and subsidies,** or introducing a **frequent flyer levy**[27].
- Higher prices for jet fuels would also **encourage development of low-carbon propulsion systems** (e.g. electrification, synfuels and hydrogen).

Battery Electric Aircraft

- Electric planes would operate in a similar manner to EVs – **a large battery would be charged when the aircraft is on the ground** to provide enough i) **energy to allow it to reach its destination** and ii) **power to allow it to take off.**
- The main limitation on electric flight is the **size and weight of the battery required**: lithium-ion batteries are **around 44x less energy dense by mass than jet fuel** [3.100].
- There are **no plans for large electric commercial aircraft within the next 30 years**, though **electric hybrid systems are proposed** [3.97].
- Electric planes within the next 10-20 years could serve **regional routes** which **can compete with high efficiency surface transport** such as high-speed rail. However, **80% of aviation emissions are from routes over 1,500 km** [3.101], which for the foreseeable future remain **out of reach**.

Shipping

- Shipping makes up **95% of UK trade** [3.102] and provided for **42.7 million domestic passenger journeys** in 2018 [3.103].
- Shipping constituted **8.3% of UK GHG emissions in 2017** (Figure 25), but that is forecast to rise as other sectors decarbonise.
- Like aviation, **shipping is a difficult sector to decarbonise**.
- Most Net Zero pathways assume that **hydrogen and/or ammonia will dominate** the energy supply of the shipping sector by 2050 (§5.2).

Technologies for Low Emission Shipping

- Technologies for decarbonising shipping are the **same as those for aviation**: **hydrogen/ammonia** (either burning or powering a fuel cell), **biofuels, synfuels** and **battery electric**.
- Smaller passenger vessels are more likely to be electrified, whereas **large ocean-going vessels will likely be unsuitable for electrification** due to the required size and weight of such batteries.
- Some designs include **primary renewable electricity generation onboard** (for example, by wind turbines on deck). This could **reduce but not replace** fuel consumption [3.104].
- **Hybrid systems** (e.g. hydrogen/ammonia and electric) are decarbonisation strategies for large ocean-going vessels [3.105].
- **Ammonia** is a potential zero-emission shipping fuel, as it is **easier to liquefy** and has a **higher energy density by volume** compared to hydrogen[28]. Ammonia can be burned in an engine or used in a **fuel cell** to generate electricity (§4.5.3).

3.3 Electrical Appliances, Machines & Lights

3.3.1 Electricity Demand & Emissions

Current UK Electricity Demand

UK Electricity Demand

- Electrical appliances, machines and lights made up **17% of UK final energy consumption** in 2019 [3.72].
- Annual UK electricity demand has **reduced from a peak in 2005 of 395 TWh** to **323 TWh in 2019** – a **reduction of 18.3%.**
- This is due to **increased efficiency of end-use technologies** (energy saving appliances, switching from old-style TVs to LCD screens etc.)
- **Electricity demand is likely to increase significantly** as other energy uses are electrified (§4.4.1).

Figure 39 UK electricity demand by sector, 1998-2019. Data from [3.72]

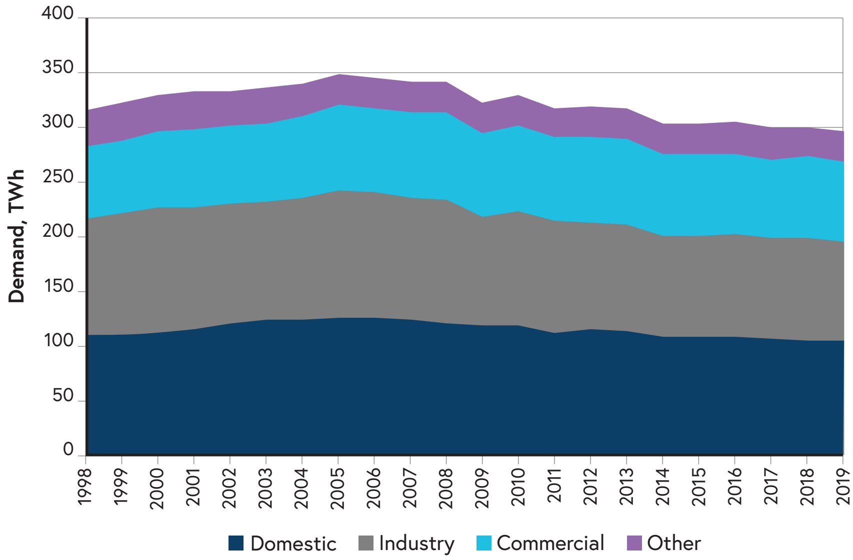
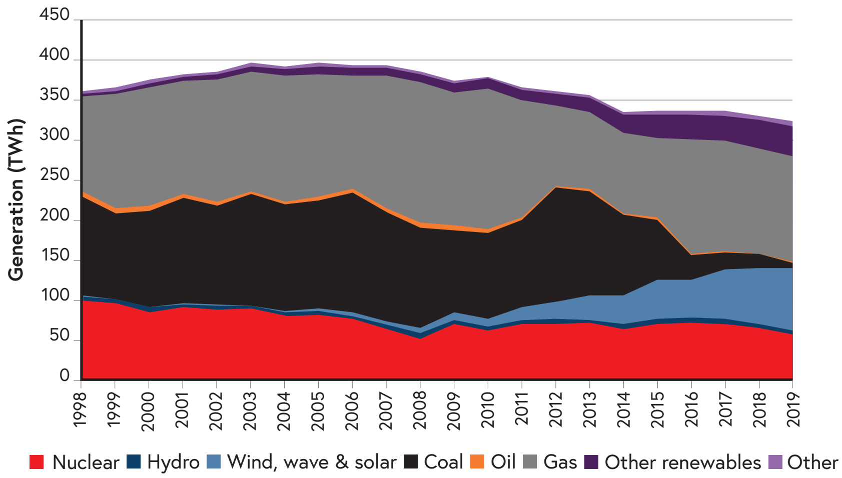


Figure 40 Electricity generation by source in the UK, 1998-2019. Data from [3.72]



UK Electricity Supply

- Renewables' share has increased from **2.6% of total supply in 1998** to **37.3% of total supply in 2019**.
- Coal, the highest-emitting means of electricity generation, has decreased from **34.1% of total supply in 1998** to **2.1% of total supply in 2019**.
- Gas has provided a **significant portion of generation**, increasing from **32.6% of total supply in 1998 to 40.8% of total supply in 2019**.
- Information on generation technologies can be found in §4.1.

Progress in the Power Sector

- **Electricity generation has decarbonised far faster than any other part of the UK energy system.**
- Carbon intensity of UK generation **has fallen 65% from 471 gCO_2/kWh in 1998 to 167 gCO_2/kWh in 2019** [3.72].
- This success has been a result of **policy-driven progress in the power sector** – including a **stable and predictable carbon price**, **investable market instruments** (such as the Renewables Obligation and Contracts for Difference) and a **clear direction** regarding heavy decarbonisation of the power sector to support decarbonisation of other sectors via electrification [3.108].

Future UK Electricity Demand

Future UK Electricity Emissions

- National Grid ESO publishes a yearly set of predictions of future UK energy demand, generation and emissions – **Future Energy Scenarios (FES)** [3.32].
- **All Net Zero scenarios require negative emissions from the power sector by the early/mid 2030s.** This is due to projected growth in Bioenergy with CCS (BECCS) (§4.5.2).

Electricity and Energy Demand

- Heavy electrification of heating and transport will **reduce overall energy demand** because of **significant efficiency** improvements compared to burning fossil fuels (§3.1.2, §3.2.2).

Future UK Electricity Demand

- Future electricity demand depends on **the rate of electrification of other sectors**, namely heating and transport.
- There is uncertainty in this, particularly for **heating, heavy goods transport, buses, aviation and shipping**, whose decarbonisation may depend on a mix of low-carbon fuels (§4.5).

Figure 41 Carbon intensity of UK electricity generation sources at the point of generation. Data from [3.106, 3.107]

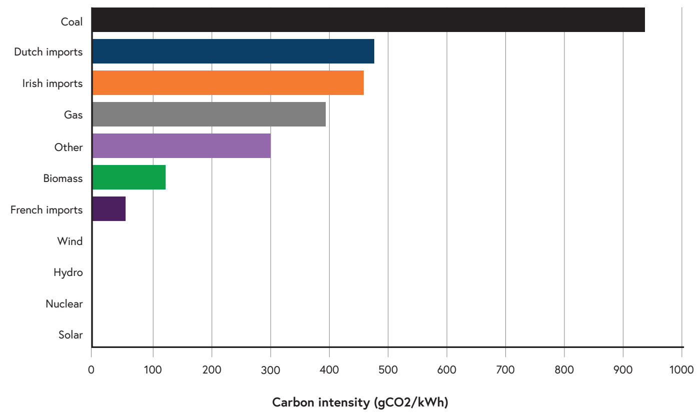


Figure 42 Future electricity generation carbon intensity in four different scenarios: 'Steady progression' does not meet Net Zero. Reproduced from [3.32]

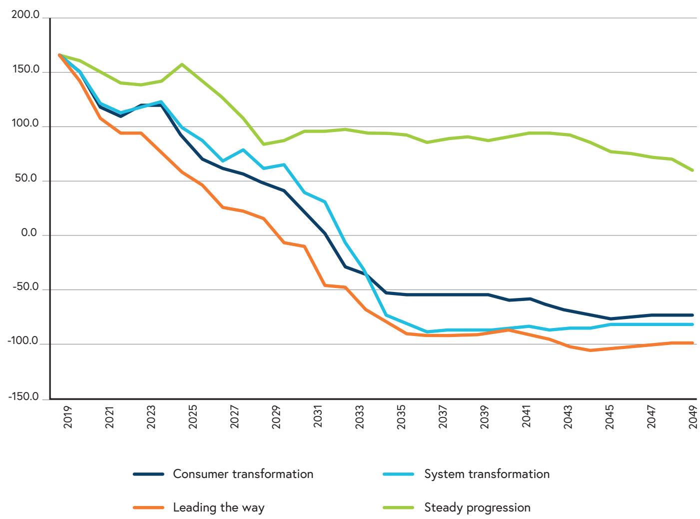
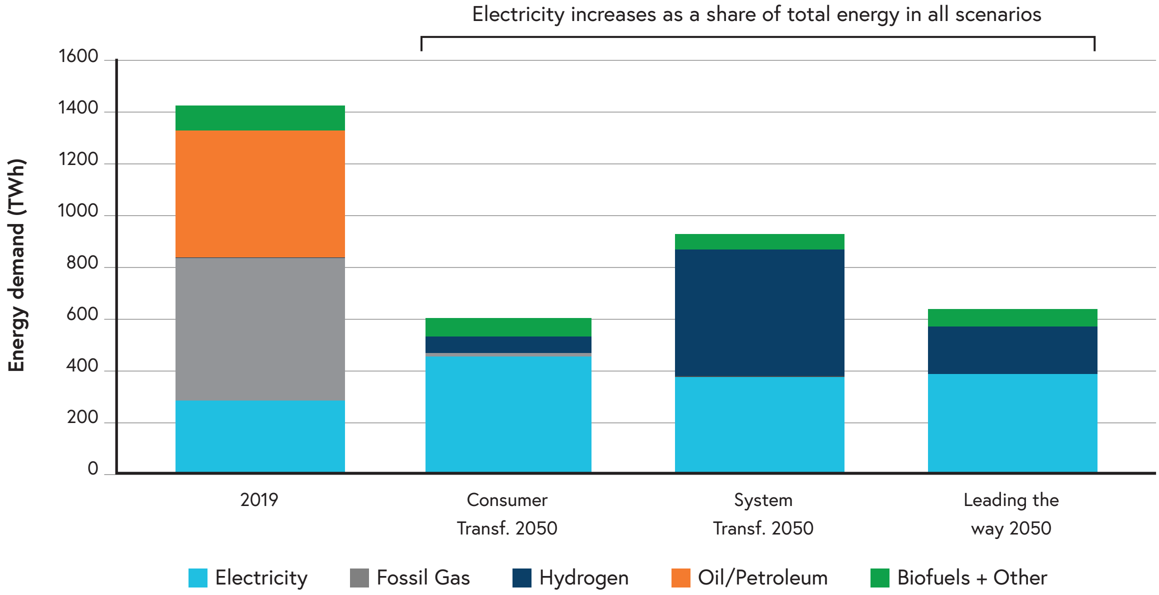


Figure 43 Projected future UK energy demand, including electricity. Reproduced from [3.32]



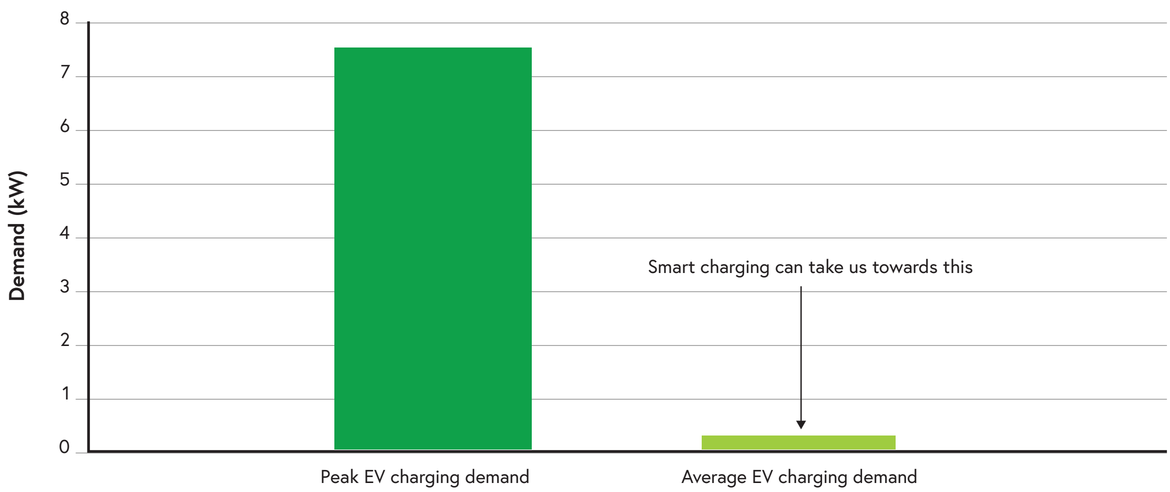
Load Factors and Capacity

- Load factors – or capacity factors – (the average output relative to capacity) are lower for variable renewables than for thermal generation[29]. Therefore, **total installed generation capacity in a high-renewables generation mix will exceed peak demand by a higher margin than it does today. Installed capacity in 2019 was around 190% of peak demand. In 2050, it could be 280-385%** [3.32].

Flexibility

- **Many future demands** such as **EV charging** and **making hydrogen from electrolysis** for heavy transport and heating **are inherently flexible**. That is, the precise timing of electricity consumption can be changed. This will help with the balancing of an electricity system with lots of renewables with varying available power.
- **EV charging** is an example of flexibility (Figure 44). The rated power draw of a 'fast' home EV charger is **7.4 kW**. However, if all its charging were done at home (where **the average UK car spends 76% of its time** [3.46]) then to replenish the energy required for a week of average driving (223 km [3.46], corresponding to around 40 kWh[30]) would result in an **average** demand of 0.3 kW – no more than a **domestic refrigerator**.
- Thus, **smart charging can reduce the power drawn by an EV charger, while still ensuring the car is ready for its next journey.**

Figure 44 Peak vs theoretical average EV charging demand based on average weekly UK driving



3.4 Chapter 3 Endnotes & References

3.4.1 Endnotes

[4]The commercial & public sector, here, includes community, arts and leisure; education; emergency services; health; hospitality; military; offices; retail; and storage. Agriculture is excluded.

[5]Primary energy sources for industrial heating demand are not captured in the ECUK data. All industrial energy has an average conversion efficiency of 61.3% [3.1] between primary energy input and demand.

[6]Heating Degree Days (HDDs) is a measure of the potential heating demand based on by how much the average temperature of a day is below a set value (typically 15.5 °C in the UK). HDD is zero for days where the average temperature exceeds the set value. Cooling Degree Days (CDDs) are a similar concept for cooling demand based on by how much the average temperature of a day is above a set value (22 °C is used for consistency with [3.15]). Degree days are typically summed per month or year [3.18].

[7]This is based on the IPCC RCP4.520 (Representative Concentration Pathway) emissions scenario – an intermediate emissions scenario where i) radiative forcing stabilises at 4.5 W/m^2 and ii) CO_2 increases to c. 650ppm until 2050 then stabilises.

[8]Detailed sector values only annually from 2010 plus 1990 and 2000 values [3.6].

[9]The rebound effect for space heating is where a consumer uses the benefit of an improved heating system or increased energy efficiency to increase comfort rather than reduce consumption. This is particularly relevant to consumers in fuel poverty. The effect can range from 10-30% reduction in energy savings [3.10].

[10]Stated COP values are based on rated performance of the supplied heat pump. Real-world performance can differ, notably in very cold outdoor temperatures. In 2017, UCL Energy Institute published empirical performance data of a sample of 297 ASHPs and 94 GSHPs operating in the UK throughout the year [3.109]. In the winter months (January and February, where the COP is at its lowest due to cold outdoor temperatures), the median COP for is around 2.7 for ASHPs and around 3 for GSHPs. The COP was found to drop below 2 on very cold days: this happened 10% of the time for the ASHPs and 5% of the time for the GSHPs.

[11]Renewable Heat Incentive, a UK government financial incentive to promote the use of renewable heat [3.110].

[12]CHP plants are based on typical electricity generation systems, such as engines and turbines, with the waste heat from the exhaust gases and coolant recovered using heat exchangers to heat water.

[13]Combined Cycle Gas Turbines (CCGT) are gas turbines whose waste exhaust heat is used to power a steam turbine. They are the most efficient type of thermal power station in terms of primary energy converted.

[14]This guide concerns GHG emissions (primarily CO_2) and the technological solutions to meeting Net Zero. Burning of fossil fuels and biomass also causes other emissions, including oxides of nitrogen (NO_x), fine particulate matter (e.g. PM10, PM5 and PM2.5) and volatile organic compounds, which

cause poor air quality and are harmful to people's health and the environment. This is highlighted as a particular issue for the transport sector due to the proximity of the combustion to major population centres. To combat poor air quality, several local authorities have introduced Low Emission Zones, or Clean Air Zones.

[15]This includes the emissions associated with power generation for electrified rail.

[16]This includes international aviation and shipping. As defined in [3.111], the calculation of emissions from international aviation & shipping is based on the total deliveries of aviation and shipping fuel in the UK. It is worth noting that while these have been included (as they are significant contributors to total emissions), they have not (up to this point) been reported with the UK's total emissions to the UNFCC in line with territorial emissions accounting as per the 2008 Kyoto Protocol. There have since been developments. Firstly, the UN aviation agency's CORSIA scheme covers emissions after 2020 – though non-CO_2 emissions are not covered by CORSIA, and it does not cover emissions up to 2020. Secondly, as of April 2021, the UK government will include its share of international aviation & shipping in its sixth carbon budget (2033-2037) following CCC advice, which has consistently been to include such emissions in UK carbon budgets.

[17]The lifestyle shift scenario in this study represents a radical shift in mobility relating to personal mobility, including changing social acceptance on mobility actions – such as 'binge flying' and driving children to school – and increased working from home. The resulting scenario is that trips and distance per person will fall in line with historical trends (a 13% reduction in average km per person travelled in 2050 compared to 2020), but mode splits will be significantly different. This scenario predicts that by 2050, 41% of distance will be covered by car, 28% by bus/rail and 17% by walking and cycling. That compares to 2020, in which the scenario corresponds to 71% of distance covered by car, 14% bus/rail and 3% walking/cycling.

[18]The focus of this section is on battery electric vehicles (BEVs), with some attention paid to plug-in hybrid electric vehicles (PHEVs) and hybrid electric vehicles (HEVs). Although a definition is provided for fuel cell vehicles (FCVs), which also count as electric vehicles, they are not covered in detail in this guide due to their scarcity in the UK market and the timescales involved in meeting Net Zero. FCVs remain very rare in the UK, with only two mainstream models available (Toyota Mirai and Hyundai Nexo, retailing at the time of writing at £65,000 and £68,000 respectively before £3,000 government grants). There are only 17 hydrogen fuelling pumps in the UK [3.112], compared to over 34,000 public BEV charging points spread across over 12,000 locations [3.113] and over 8,000 petrol stations [3.114].

[19]Efficiencies of any heat engine – a device that converts heat to motion – are very low. In petrol cars, efficiencies tend to be around 20% - meaning that 80% of the energy in the fuel is lost, mostly as waste heat. Thermal power stations are more efficient, due to their larger scale and higher temperatures – around 30-55%, depending on the type of power station. Once renewables are included in the generation mix, whose 'efficiencies' cannot be properly compared as the wind, sun and rivers are not fuels bought as commodities, the efficiency of electricity generation increases. Even when accounting for ~10% losses through the electricity system [3.115], this means a switch from ICE cars to EVs would reduce the primary energy demand of the transport sector.

[20]These power ratings are on the side of the charger. EVs (like any battery) are charged in Direct Current (DC) but the grid runs on Alternating Current (AC). Therefore, a converter is required, either at the charger or onboard the vehicle. EVs on the market today usually have two charging ports: one for AC charging and one for DC charging. Power into the AC port passes through an onboard AC/DC converter;

power into the DC port bypasses this. DC charging is generally restricted to high-power en route charging (50+ kW), whereas AC charging is used at locations where the vehicle would be parked for a longer duration. This AC charge rate is limited by the onboard converter: in practice, while an AC charger may be rated at 22 kW, many EVs are limited to ~7 kW of AC charging power.

[21]Emissions of cycling are derived based on the additional energy (food) required by the cyclist versus a car driver, based on an average diet. For e-bikes, the additional energy consumed is less, though the embodied energy of the e-bike's manufacturing (including the battery) is greater. The result is that they are almost the same as calculated in [3.59] – 22 gCO_2e/kWh for e-bikes and 21 gCO_2e /kWh for bikes. However, if the cyclist was going to exercise anyway (perhaps a cycling journey was replacing a trip to the gym), or if the propensity to cycle does not affect their calorific intake, this energy requirement can be discounted. Therefore, the lower limit on the error bars corresponds to a 0 g/CO_2 intensity associated with their 'fuel cycle'.

[22]Lifecycle emissions data for cars is the same as for Figure 32, but converted from gCO_2e/km to gCO_2e/pkm by dividing by the average car occupancy in the UK of 1.6 [3.67] (for the average occupancy values) and by an occupancy of 5 people (for the 'full' values). For buses, gCO_2e km values are taken from [3.71] and divided by 16 and 105 respectively for average and full occupancy passenger counts for a study of bus occupancy per km in [3.71]. Rail values for gCO_2e/pkm are taken from [3.68] and [3.69], and converted to 'full' values based on data in [3.68] detailing that average UK train occupancy is around 50% of capacity. As elsewhere in this report, lifecycle analyses are sensitive to the input data and assumptions used and direct comparison is difficult, though care has been taken in preparation of this report to compile a range of values. Where clear differences are present, key messages can be stated. In this case, buses and rail are significantly less carbon intensive per passenger-km than private cars if their mode of propulsion is zero-emission at the point of use (hydrogen or electricity). As hydrogen trains are a relatively new technology, lifecycle analysis results are not included.

[23]A carbon price of £40-100/tonne added to fuel duty is aligned to the Climate Change Committee's projected cost of abatement per tonne of CO_2 in 2050. In practice, this would relate to an increase of 9-23 p/litre added to the price of fuel (1 litre of petrol burns to create 2.31 kg of CO_2; 433 litres of petrol burns to create 1,000 kg – 1 tonne – of CO_2).

[24]CORSIA - Carbon Offsetting and Reduction Scheme for International Aviation – is the means by which the UN aviation body (the International Civil Aviation Organization (ICAO)) will monitor, offset and reduce CO_2 emissions from 2020. Whereas domestic flights were included in the 2015 Paris Agreement, international aviation will now (from 2020) be covered under CORSIA. However, there are two major flaws with CORSIA. Firstly, it does not include emissions levels up to 2020. If an airline emits 900 MtCO_2/year up to and including 2019, and 1,000 MtCO_2/year from 2020 onwards, the airline must only offset the difference – 100 MtCO_2/year. Secondly, it does not include non-CO_2 emissions, which have been estimated to triple the global warming impacts of aviation [3.93].

[25]Net Zero-compatible synfuel would combine hydrogen made from electrolysis, or chemical processing of fuels with CCS, and carbon from CO_2 captured from the air, in a chemical process called the Fischer-Tropsch process. If an optimistic power-to-fuel conversion efficiency of 50% is assumed, production of synfuel for current UK aviation fuel demand (16.18 million tonnes of oil equivalent, or 188 TWh, per year) [3.111] would require 376 TWh of electrical energy per year. This is 27% greater than total final electrical energy consumption in 2019 (295 TWh) [3.72]. Of course, the fuels need not be made using electricity produced in densely populated countries like the UK. Recent feasibility studies include studies for countries with low populations and lots of land and renewable

resources. For example, Morocco has a total potential for offshore wind of around 250 GW, which is approximately 25 times the current generating capacity in the country. This would provide 770 TWh of electricity annually, which is sufficient to produce synfuel for more than twice UK aviation demand [3.116].

[26]Flying energy demand is very skewed among the population. In 2018, 1% of English residents took almost a fifth of overseas flights and 10% took over half [3.117]. By introducing a frequent flyer levy, flying would be taxed at a higher rate for a higher rate of flying.

[27]Hydrogen fuel cells generate electricity to power the aircraft using an electric motor to drive propellers, which is a more efficient process (approx. 60% for the fuel cell and 90% for the motor, giving ~50-55% overall [3.116]) than combustion in a jet engine (~35-40% efficiency). This higher efficiency, in addition to the avoidance of combustion and NO_x emissions, would seemingly make fuel cells a better candidate than burning hydrogen in a modified jet engine. However, as made clear in Airbus' hydrogen aircraft concepts [3.97], only small aircraft use fuel cells and larger planes use hydrogen combustion. This is due to the scalability of electric motors: electric motors are typically around 90% efficient, and the 10% losses (expelled as heat) become problematic when large values of thrust are required. Of the order a few hundred MW are required at take-off for a large aircraft (such as a Boeing 747) [3.118] and so 10% of this (tens of MW) would require a significant (and heavy) heat exchanger to be able to carry the heat away. As a result, the hydrogen proposals for larger planes use jet engines to provide the necessary power requirements, sometimes as a hybrid system with fuel cells which can increase the thrust at take-off, allowing the jet engines to be optimised for cruise.

[28]Ammonia has received attention as a potential route to decarbonising fuels used in shipping. It can be made from hydrogen relatively easily, and could be used as a 'hydrogen carrier', as it is far easier to transport and store in bulk. The ammonia can then be 'cracked' into its constituent nitrogen and hydrogen, for use in a hydrogen fuel cell. As with hydrogen, there are several options for manufacturing ammonia. At present, most ammonia is produced for fertiliser from reformation of fossil fuels, which is carbon intensive. There is potential for producing ammonia from electrolysis, which along with other potentially zero-emission production methods is referred to as 'green ammonia' [3.116].

Regarding storage and transport, ammonia has higher energy density on a volume basis than hydrogen under ambient conditions and, unlike hydrogen, is easy to liquefy to achieve far high energy densities. Hydrogen can be compressed, to achieve broadly comparable energy densities, but this entails expense and energy losses.

Ammonia is already transported internationally for use in chemicals, fertiliser manufacture, and as a refrigerant; there is already infrastructure in place for its carriage by ship, road tanker and in pipes. Furthermore, tankers currently used to ship liquefied natural gas (LNG) could be converted to ship ammonia.

Table 2 shows a comparison of energy densities of hydrogen, ammonia and methane at different temperatures and pressures.

[29]The load factor (or capacity factor) of an electricity generator is a measure of how intensively the generator is used. It is the ratio of the generator's *total energy output* (MWh) in a year divided by *the energy the plant would have produced* (MWh) if it had operated at maximum capacity all year with no interruptions.

Table 2 Energy density of hydrogen, ammonia and methane at different pressures and temperatures.
1 MJ ~0.28 kWh. Sources: [3.119-3.122]

Property		Hydrogen (H_2)	Ammonia (NH_3)	Methane (CH_4)
Calorific value per kg		142 MJ/kg or 39.4 kWh/kg	22.5 MJ/kg or 6.2 kWh/kg	55.5 MJ/kg or 15.4 kWh/kg
Calorific value per cubic metre, in gaseous state	**25 °C, atmospheric pressure (1.01 Bar)**	11.7 MJ/m^3 or 3.2 kWh/m^3	15.7 MJ/m^3 or 4.4 kWh/m^3	36.5 MJ/m^3 or 10.1 kWh/m^3
	25 °C, compressed to 200 Bar	2,300 MJ/m^3 or 650 kWh/m^3	Not done. Much easier to liquefy.	
	25 °C, compressed to 800 Bar	9,400 MJ/m^3 or 2,600 kWh/m^3		
	Cryo-compressed to 500 Bar, at -200 °C.	11,000 MJ/m^3 or 3,000 kWh/m^3		
Calorific value per cubic metre, when liquefied		10,200 MJ/m^3 or 2,800 kWh/m^3	13,900 to 15,700 MJ/m^3 or 3,900 to 4,400 kWh/m^3 (depending on temp & pressure)	23,500 MJ/m^3 or 6,500 kWh/m^3
Conditions required to turn to a liquid	**at atmospheric pressure**	-253 °C or below	-33 °C or below	-162 °C or below
	at higher pressures	-240 °C, 13 bar pressure	Ambient temperature, 10-15 bar pressure	Not done.

$$Load\ \ factor = \frac{Electricity\ \ actually\ \ generated\ \ in\ \ a\ \ year\ (MWh)}{Electricity\ \ generated\ \ if\ \ operating\ \ continuously\ \ at\ \ full\ \ power\ (MWh)}$$

The UK Government's *Digest of UK Energy Statistics (DUKES)* [3.72] lists collective load factors for various types of generators.

In 2019 in the UK, gas (*combined* cycle gas turbine, CCGT) and bioenergy-fuelled power stations had load factors of around 50% (43% and 55% respectively). These plants *could* operate most of the time, but the cost of fuel (gas, wood etc.) is significant. Thus, they normally operate at full output only when the wholesale market price for electricity is high (at times of high demand for electricity, or when there is little output from wind or solar generators). Gas and bioenergy plants do not normally run at times when the market price for electricity is low (at times of low electricity demand, or high output from wind or solar PV). Coal plants had a load factor of only 8% in 2019: a small carbon tax (via the EU Emissions Trading Scheme) makes their operation viable only at times of particularly high market price for electricity. The UK Government also publish load factors *net of availability*, which tells us what proportion of the time the generator *could* be used (discounting down-time for maintenance and outages). CCGT plants in the UK have an average load factor of 89% net of availability [3.123].

In contrast, wind and solar plants would normally operate whenever there is wind or sun, regardless of market price for electricity, because there is no fuel cost. In 2019 in the UK, the load factors for offshore wind, onshore wind and solar PV were 40%, 27% and 11% respectively. The load factor for onshore wind would have been slightly higher, by around 1 or 2 percentage points, if windfarms had not been *curtailed* – switched off or turned down, on instruction from National Grid or the local electricity network, because of constraints in the electricity grid [3.124]. The UK Government expects load factors of offshore windfarms to increase over coming decades, possibly to over 60%, as technology developments allow larger turbines, further offshore, in areas with greater wind resource [3.125].

Nuclear power stations would normally run most of the time (with load factors over 80% or even 90%), because the cost of fuel is very small, compared to the major fixed costs of power station construction and decommissioning. Furthermore, the types of nuclear power station built in the UK are not designed to be turned up or down except for maintenance. In 2019, UK nuclear power plants had an overall load factor of 63%, which is very low for this type of plant, and reflects significant downtime for maintenance, of the UK's fleet of now ageing nuclear power stations.

[30] Assuming a 'fuel economy' of 18 kWh/100km.

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Chapter 4 – Energy Infrastructure for Net Zero

4.1 Electricity Generation

4.1.1 Wind

- Wind is now the UK's **second largest** source of electricity, providing **64 TWh (approximately 20%) of final consumption in 2019** [4.1].
- Both **onshore and offshore wind capacity is rising in the UK**, but **offshore installations are being built at a faster rate** (Figure 45)**.**
- **Turbines are growing in size and capacity, and wind farms are getting larger** – particularly for offshore installations (Figure 47).
- Their costs continue to fall: wind generation is now **cheaper** (by Levelized Cost of Energy) **than gas-fired power generation** [4.2].

Figure 45 UK Onshore and offshore wind installed capacity and generation by year, 2009-2019. Data from [4.1]

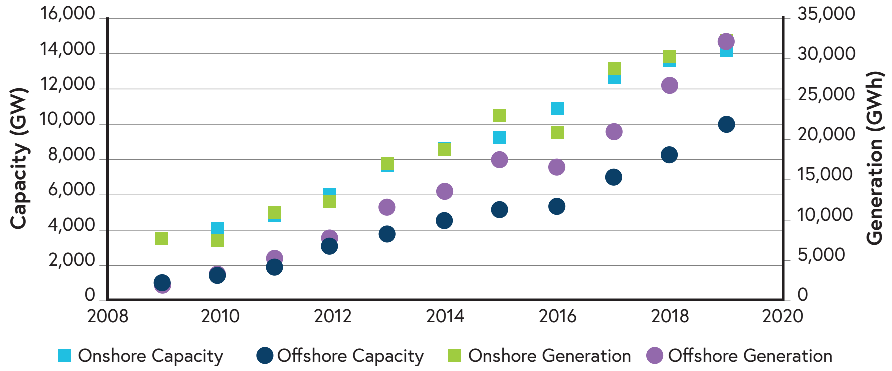


Figure 46 Levelised Cost of Energy (LCOE) for gas plants, onshore and offshore wind for commissioning years of 2025-2040. Data from [4.2]

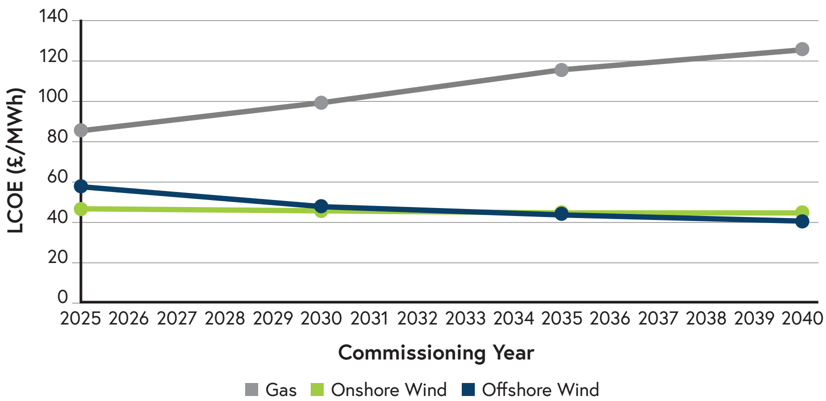
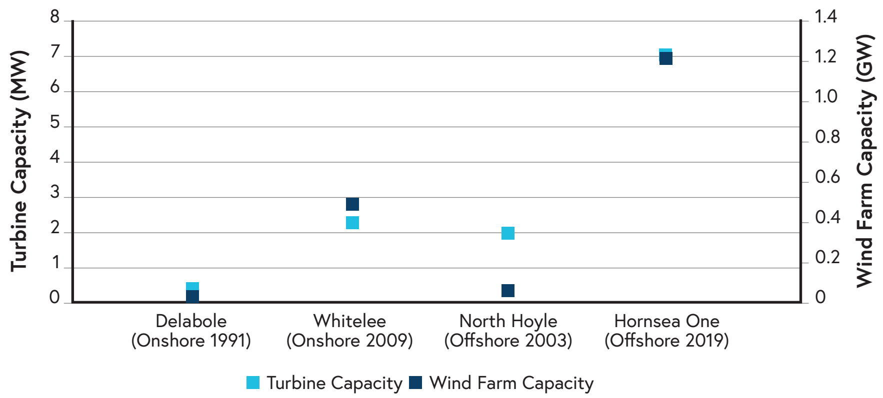


Figure 47 Comparison of turbine capacity and wind farm capacity for the UK's first and largest onshore and offshore wind farms. Data from [4.3]



Cost of Wind Generation

- In the 2019 Contracts for Difference (CfD) auctions[31], twelve offshore wind farms agreed to supply **9% of the UK's electricity** for **£44/MWh**, coming online from 2023. This is around **17% lower than the government's reference price for electricity.**

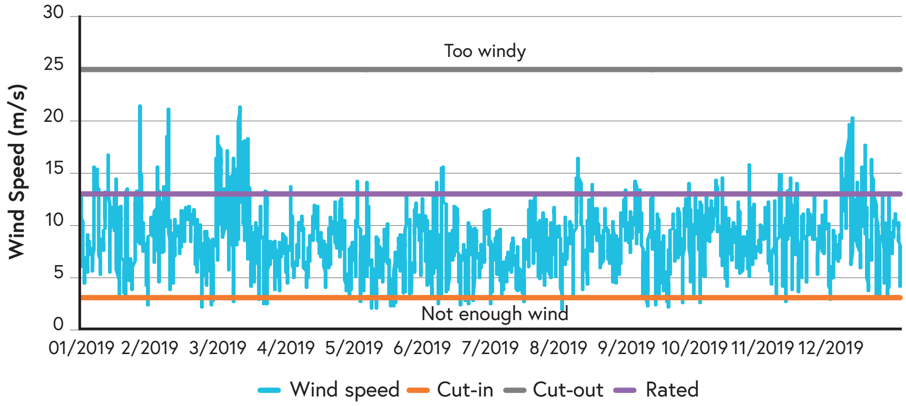
Technology Trends in Wind Generation

- Wind farms and wind turbines are getting larger. The capacity per turbine at Hornsea One (2019) is **17.5 times greater** than that at Delabole (1991), the UK's first wind farm.
- **Floating offshore wind** allows generation in deep water and has the potential to unlock **123 GW of capacity in Scottish water alone** [4.4].
- **Floating offshore wind** is a small but **rapidly growing industry**; with **global capacity expected to boom by 7500%** from 2019 to 2030 [4.5].

Intermittency – how much does wind vary?

- Below a wind turbine's cut-in speed, **the wind is too slow** to make the blades turn. This happened for **1.2% of the time** in 2019 at Hornsea One; the longest spell was 10 hours.
- Above the cut-out speed, turbines shut down to protect themselves. This didn't happen in 2019 at Hornsea One.
- The **load factor** tells us what proportion of the wind turbine's rated power it generated. In 2019, this was **40.4%** for offshore wind and **26.6%** for onshore wind [4.7].

Figure 48 Wind speeds by month (1-12) in 2019 at 1 hour intervals at location of Hornsea One wind farm. Data from [4.6]



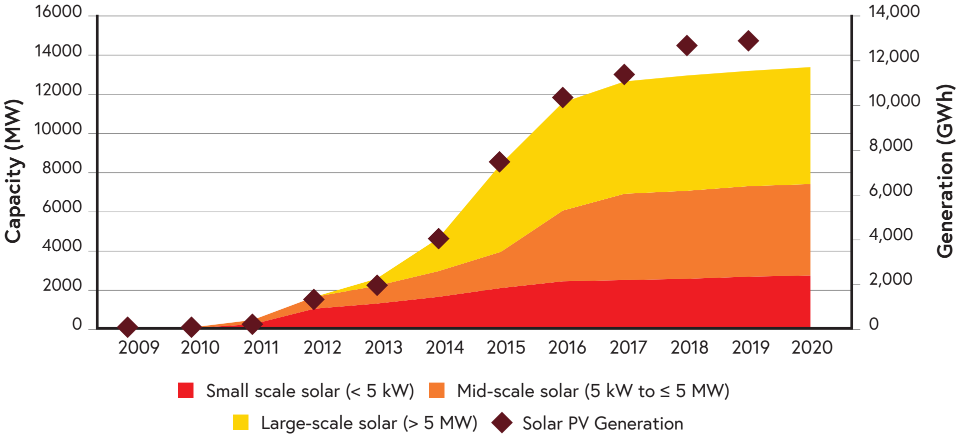
4.1.2 Solar PV

- Solar photovoltaic (PV) **boomed in the UK in the 2010s**, due to the feed-in tariff (FiT) scheme – by which **homeowners were paid to generate electricity via rooftop solar panels.**
- **Growth has slowed recently** as the FiT scheme closed to new entrants in 2019.
- Solar PV **represents the vast majority of small-scale renewables** in the UK – 99% by installations; 81% by capacity [4.7].
- As **costs continue to fall**, future large-scale solar developments are planned.

Energy from the Sun

- At the UK's latitude, daily peak solar irradiance in the summer is around **twice** that in the winter (Figure 50).
- Although **solar is limited in its contribution in meeting peak demand** (on winter evenings), **solar PV is a cost-effective means of producing zero-carbon electricity**.
- Incident **solar energy on the Earth's land area outstrips global energy demand by a factor of seven thousand**. Globally, solar generation could have an enormous role in producing **low-emission fuels** (e.g. hydrogen; synfuels for aviation and shipping)[32] (§4.5).

Figure 49 UK Solar PV installed capacity by size (2009-2020) and generation by year, 2009-2019. Data from [4.1, 4.8]



Costs of Solar

- Given its exclusion from recent CfD allocations, **new solar PV is 'subsidy free'** and will have lower costs per unit generation than gas and offshore wind (Figure 51).
- These low costs are driving growth in large-scale solar: **3.8 GW of projects are currently in the pipeline** [4.3]

Figure 50 Solar irradiance by month (1-12) in 2019 at 1 hour intervals at Whitstable, Kent. Data from [4.6]

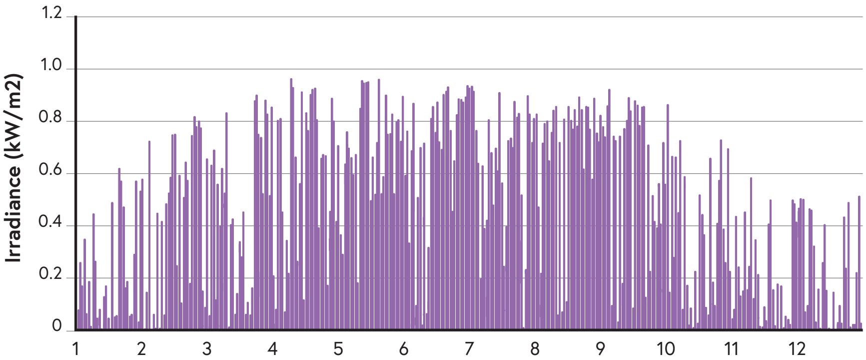
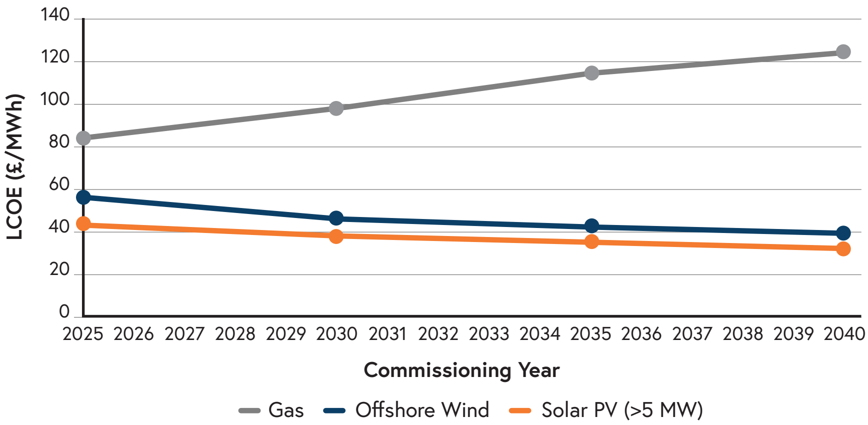


Figure 51 Levelised Cost of Energy (LCOE) for gas plants, offshore wind and large-scale solar for commissioning years of 2025-2040. Data from [4.2]



4.1.3 Wave & Tidal

- Electricity can be generated from **tidal currents** using **underwater turbines**, or by **tidal barrages and lagoons** that work more like hydroelectric dams.
- Compared to other renewable options for the UK, although tidal power is variable, it is **predictable**.
- **Wave Energy Converters (WECs)** can generate electricity from waves on open water, usually by **resisting the waves' motion** and **absorbing their energy to power electrical generators**.
- **Wave and tidal power are not widespread in the UK**, though both have potential to **contribute to low-carbon electricity.**

Waves

- Waves in open water are created by the **wind moving across oceans**.
- The UK is well situated to utilise **significant wave resources** from its Atlantic-facing coastline.
- **Waves are slower and much easier to forecast than the wind**, but **not as easy as tidal** (for which their schedule is known).

Figure 52 Mocean Energy Blue X wave energy converter [4.9]; La Rance tidal barrage [4.10]; tidal stream generator being installed at Nigg, Scotland [4.11]

Tides

- Unlike most other renewable sources available in the UK, **tides are not affected by weather**. Tide times and ranges are known in advance[33].
- This **high level of predictability** has driven interest in tidal generation as a renewable power source for a long time, with interest in the UK for building a **Severn Estuary tidal barrage** first formally arising in 1981. Barrage proposals have since been scrapped due to their high upfront costs and environmental concerns[34].
- In recent years, interest has surrounded **tidal stream generators**, which resemble **underwater wind farms** in areas where ocean currents resulting from tides are high, and **tidal lagoons**, which create an **artificial 'pond' of high water** from an incoming tide, which can be used to generate power as it flows out through turbines[35].

Growth in Wave & Tidal

- There is currently 22 MW of wave and tidal installations in the UK (around **0.05% of renewable capacity**). Most of this is sited at the **European Marine Energy Centre (EMEC)**, operating test sites around Orkney.
- There are **three tidal stream projects** (totalling 427 MW) and **two tidal lagoon projects** (totalling 530 MW) in the pipeline for operation dates between 2021 and 2030 [4.3].
- There are **no commercial-scale wave generation projects** in the pipeline.

Costs of Wave & Tidal

- Wave and tidal stream are eligible for 'pot 2' Contracts for Difference (CfD), signifying that they are not technologically mature[36]. This leads to **high costs per unit generation** (Figure 54).
- While costs are forecast to reduce [4.2], these costs reflect the **engineering challenges** of harnessing the energy while being sufficiently robust against hostile conditions.

Figure 53 Wave & tidal installed capacity and generation by year, 2009-2019. Data from [4.7]

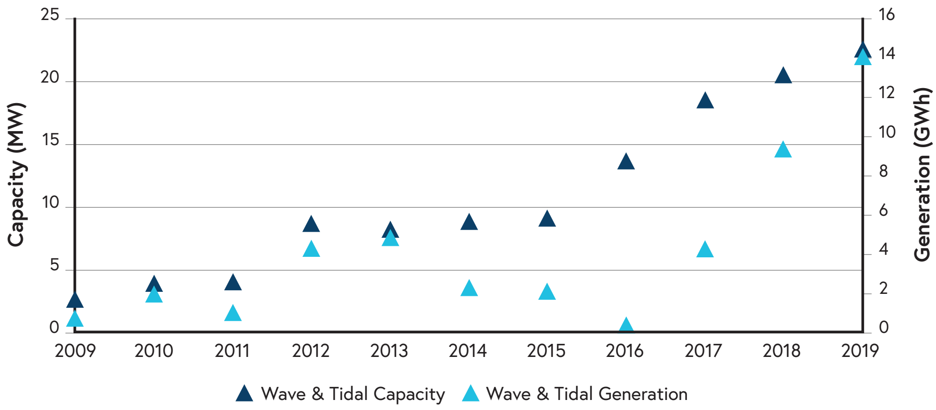
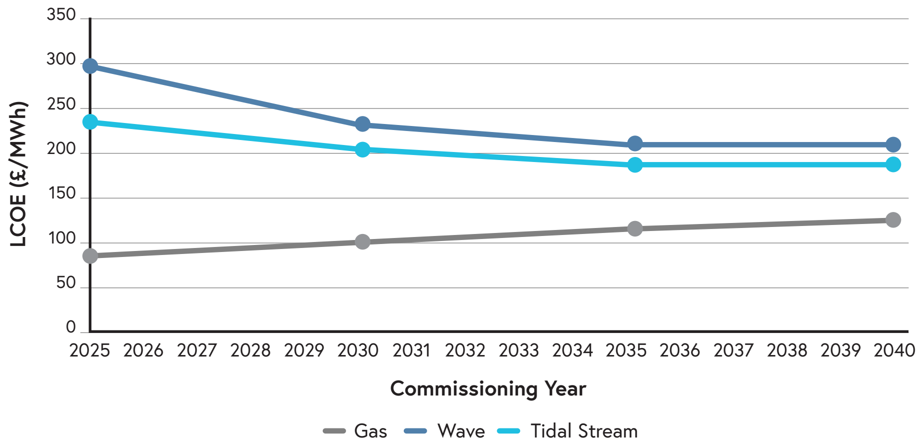


Figure 54 Levelised Cost of Energy (LCOE) for gas plants, wave and tidal stream for commissioning years of 2025-2040. Data from [4.2]



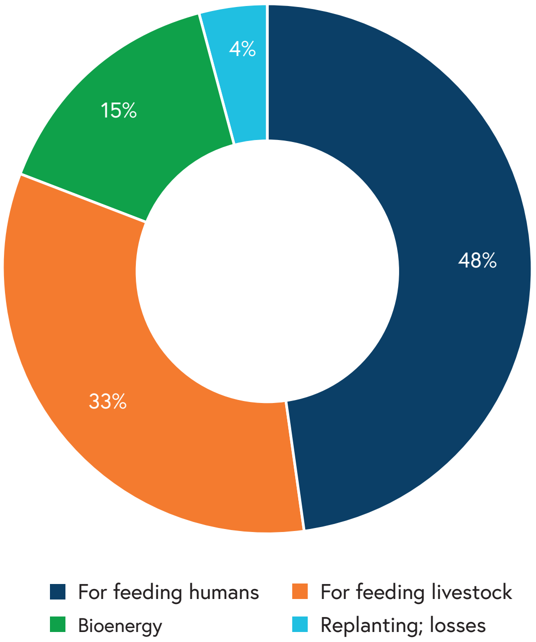
4.1.4 Bioenergy for Electricity Generation

- Bioenergy is a collection of **thermal** fuels that can be burnt in power stations in the same way as coal or gas.
- Bioenergy is **renewable if sustainably sourced**.
- Rather than burning carbon that has been locked away for millions of years as fossil fuels, bioenergy generation is **burning biological matter** that has itself sequestered carbon from other sources within the carbon cycle (including the air).
- These fuels include: **energy crops**, **animal biomass** (e.g. chicken manure), **biogas** (made from anaerobic digestion of biomaterial or sewage), **landfill gas**, and **residual household waste** used as a fuel.

Bioenergy Sustainability

- Already, bioenergy **makes up 15% of global crops by energy content** (Figure 55). In 2019 it provided 12% of UK electricity.
- **Land for growing plant biomass is in direct competition with land for food supply** [4.13]. **Bioenergy will put pressure on global food supply** if the steep increase in plant biomass (Figure 56) continues.
- Bioenergy generators of ≥ 1 MW must meet Ofgem's **biomass sustainability criteria**[37] [4.14].
- Bioenergy from waste can contribute, though quantities will be **limited by how much waste we produce** (§4.5.2).

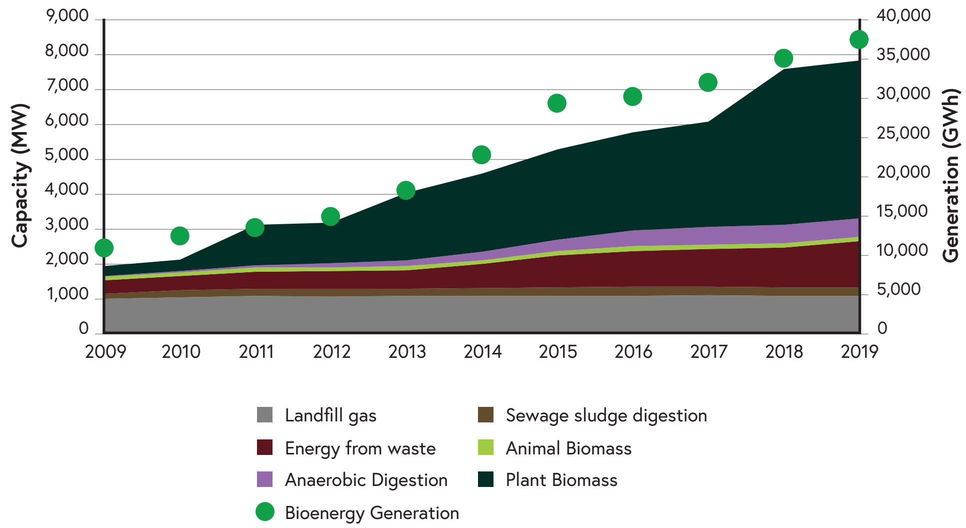
Figure 55 Global End use of crops by energy content. Reproduced from [4.12]



Bioenergy with Carbon Capture and Storage (BECCS)

- BECCS is bioenergy with Carbon Capture & Storage (CCS) (§4.10.2). With the important caveat that the bioenergy sources are **sustainable** and do not cause emissions elsewhere due to changes in land use, BECCS will be an **important source of negative emissions**. The **plants remove CO_2 from the atmosphere** by growing, and **CO_2 is removed** (usually after combustion) and stored.
- This is a **major part of the UK's Net Zero strategy**: the CCC's Net Zero scenarios from 2019 project that BECCS can remove around **50 $MtCO_2$** from the atmosphere every year by 2050 [4.15].
- The CCC's 2018 report on biomass [4.16] advocates **expanding the land used for growing energy crops to over 10,000 km^2 by 2050 (around 7% of current agricultural land)**, coupled with mass afforestation.
- Growth of BECCS to effectively remove CO_2 from the air will make achieving Net Zero much easier. However, **effective governance and regulation** of bioenergy must **ensure that energy crops do not put pressure on global food supply.**

Figure 56 Bioenergy capacity by fuel source and total bioenergy generation by year, 2009-2019. Data from [4.1]



4.1.5 Nuclear

- Nuclear power **generates heat** by releasing the energy that **holds atoms' nuclei together**.
- They use that heat to **drive a steam turbine** in the same way a coal, gas or biomass-fired power station does.
- Nuclear power has **declined** in the UK since 2000, though **new plants have been proposed** – of which only Hinkley Point C is being built.

Figure 57 Sizewell B nuclear (fission) power station; Joint European Torus (JET) fusion experiment, CCFE, Oxfordshire. Image courtesy of EUROfusion Sources: [4.17, 4.18]

Figure 58 Nuclear capacity and generation in the UK, 1998-2019. Data from [4.7]

Nuclear Fission

- All commercial-scale nuclear generation in the world is done by **fission** – splitting apart large atoms (such as **uranium**) to release energy and smaller atoms.
- This energy is huge – 'burning' **1 gram of uranium fuel** in a reactor releases as much energy as burning **8 kg of fossil fuels**[38] [4.19].
- The products of fission – **nuclear waste** – are **dangerous** and **long-lasting** (>1,000 years).
- There are **potential alternative fuels for fission**, which could **reduce** the problem of waste.

Nuclear Fusion

- Experimental devices in operation are aimed at **fusion** – the process that powers the **sun**.
- This is done by fusing **small atoms** (hydrogen) into helium, releasing energy in the process.
- This energy is enormous – 'burning' **1 gram of fusion fuel** in a reactor releases as much energy as burning **nearly 8 tonnes of fossil fuels**[39] [4.19].
- Waste from fusion exists, but is **smaller in quantity**, **less dangerous** and **less long lasting**.
- Fusion research is active, but **fusion is unlikely to be a viable power source in time for Net Zero.**

Flexibility and Inertia

- Nuclear is much **less flexible than gas**[40] and stations are not designed to be shut down and re-started on a regular basis.
- Nuclear power stations provide **inertia**, helping to maintain **system stability**. However, new nuclear generating units are so large that measures to limit the system impact of a sudden outage will be costly.

Sustainability of Nuclear

- Nuclear is not renewable: fission relies on a supply of **uranium**, which is **mined as an ore** and **enriched**. Fusion fuel could come from **deuterium** (occurring in **seawater**)[41], and while abundant, is also not renewable.
- Alternative fuels, such as **thorium**, and reactor technologies, such as **fast breeders**, could increase the abundancy and efficiency of fission fuel, such that reserves could last **60,000 years** at the current level of electricity demand [4.19].

Cost of Nuclear

- The highest costs of nuclear power stations are **building** and **decommissioning**.
- The agreed CfD strike price of **£104.48/MWh** for Hinkley Point C is **2.4 times greater than the strike price for offshore wind**, though unlike offshore wind this is **not variable**.

4.1.6 Hydro & Geothermal

- Electricity can be generated from turbines powered by the **flow of rivers** – this can be done with **run of river hydro**, or by building **hydroelectric dams**.
- **Pumped storage** is a form of hydroelectricity that **pumps water uphill** in times of **low demand**, and generates power as the water **flows back downhill** in times of **high demand**. This helps **balance total generation with total demand** minute-by-minute**.**

- **Geothermal** generation takes heat from below the Earth's surface. While there are no active geothermal generators in the UK, some regions have potential for **deep geothermal** – SW England has the potential for 100 MW of geothermal generation capacity [4.20].

Hydroelectricity

- Hydro power provided 2% of the UK's electricity in 2019, **79% of which was 'large scale'** [4.1].
- Large-scale hydro requires large dams, which can have **adverse environmental impacts**.
- There is **limited scope for hydro in the UK**, bounded by lack of altitude and rainfall. Analysis suggests that even if 20% of the UK's high-altitude rivers were dammed, this would amount to 0.8% of energy demand[42] [4.21].

Geothermal

- In the UK, **deep geothermal** would come from natural heating from radioactive rocks[43].
- The same plants could be used to generate heat for **district heating** – increasing the potential energy production from geothermal.

4.1.7 Fossil Fuels with CCS

- Some **flexible generation** is very likely to be required in a Net Zero electricity system to help balance the system, e.g. from **fossil gas or hydrogen-fired power stations** (§5.2).
- Carbon Capture and Storage (CCS) can be applied to **fossil fuel power stations** as well as other CO_2-intensive industries.
- CCS may not be **zero emission**, but emissions will be **greatly reduced** (§4.9). These residual emissions could be offset.
- **Net Zero targets will be very difficult to meet without CCS** [4.15].

CCS Methods

- In **post-combustion CCS**, CO_2 can be removed from the gases exiting a power station chimney.
- This is the **most mature method** of CCS with more industrial experience than pre-combustion CCS – and it can be **retrofitted** to existing power stations
- In **pre-combustion CCS**, carbon can be **removed from fossil fuels** before combustion, to give **hydrogen** (which can be burned to generate electricity).
- **Oxyfuel CCS** burns the fuel in **pure oxygen**, which allows for easier capture post-combustion (as the CO_2 stream is much more concentrated).
- More detail on CCS is given in §4.10.2.

4.2 Life Cycle Emissions of Electricity Generation

- **All electricity generation (and demand) technologies cause some GHG emissions** at some point over their lifecycle.
- Life Cycle Assessment (LCA) attempts to **quantify GHG emissions per unit of energy generated (kWh)** over the **entire lifecycle of a technology** from raw materials extraction to disposal/recycling (Figure 59).
- While individual **LCA approaches often differ** in what they take into account, **meta-analyses** of LCA studies have been performed – for example, by the National Renewable Energy Laboratory (NREL) (Figure 60).

Figure 59 Life Cycle Assessment (LCA) approach. Image from [4.22]

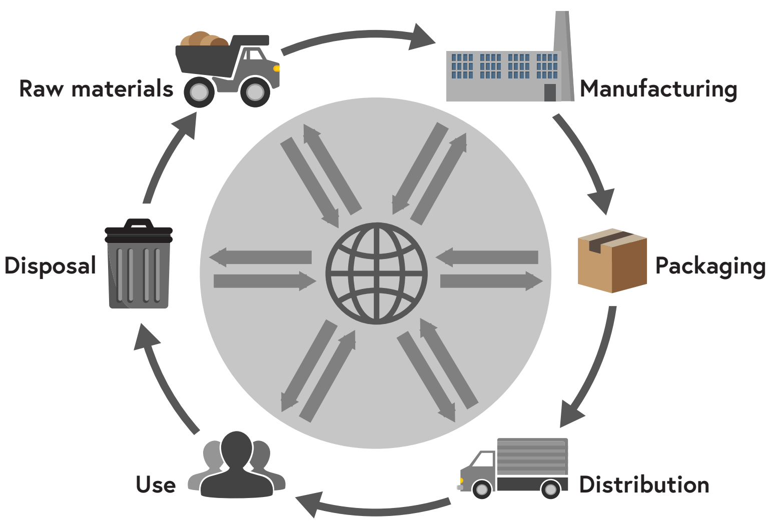


Figure 60 NREL estimates of current LCA GHG emissions from electricity generation by technology; median values and full data ranges shown. Source: [4.23]

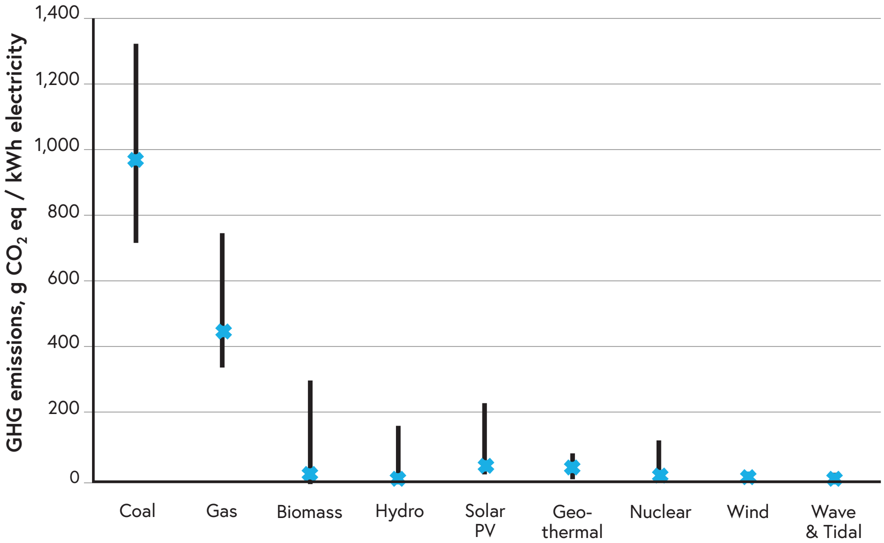
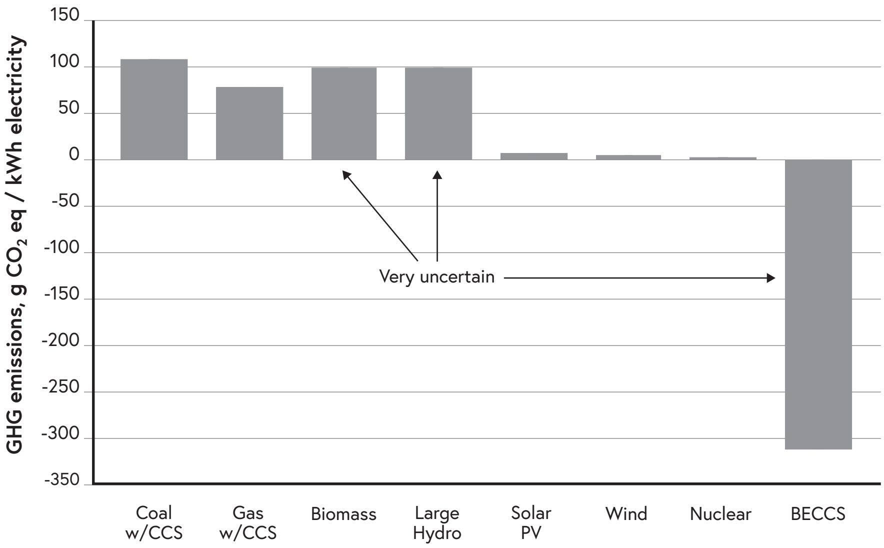


Figure 61 Estimates of 2050 LCA GHGs from electricity generation by technology. Reproduced from [4.24]



Meta-analyses of electricity LCA GHG emissions[44]

- Figure 61 shows a meta-analysis of LCA GHG emissions of electricity technologies, 1970-2012.
- Estimates vary in LCA results because of i) **differences between sites, locations and technologies**, ii) **gaps in information** and varying assumptions and iii) **different accounting methods** – better studies **harmonise methods** or follow LCA industry standards.

Estimates of LCA GHG of electricity (2050)

- The study in [4.24] (Figure 60) assumes a global move towards Net Zero.
- Solar PV, wind and nuclear GHG emissions are expected to be **very low**; below ~10 gCO_2e/kWh.
- BECCS has negative emissions by 2050; around -300 gCO_2e/kWh.
- GHG **emissions of biomass, hydro and BECCS vary** enormously according to site details and region.

LCA GHG Emissions – Summary

- All electricity generation – other than BECCS – produces positive GHG emissions. However, some technologies (wind and nuclear) produce **very few GHGs: under 10-20 gCO_2e/ kWh.**
- **Existing coal and gas stations are major GHG emitters** of the order **several hundred** gCO_2e/kWh.
- **Even with CCS**, coal and gas stations are likely to have moderate lifecycle GHG emissions. This is due to **incomplete carbon capture** and **emissions of methane from its extraction and transport**.
- **Biomass energy and large hydro plants may cause moderate or even major land-based emissions, especially if poorly sited or managed.**
- **Good siting** is also needed for **onshore windfarms**, to avoid causing GHG emissions from disturbing **deep peat. These considerations are routine** in the Scottish Planning process [4.25, 4.26].

Land Use Implications

- **Land can absorb or emit GHGs** – including methane and nitrous oxide.
- Increasing the supply of bioenergy can cause **more land cultivation and fertiliser use**, which could end up **increasing emissions**[45] [4.24].
- Methane can be emitted from **decomposing vegetation**, including in large hydro reservoirs [4.24].

4.3 Renewable Electricity Resources

- Figure 62 shows the **potential electricity generation** from all the renewable technologies covered in §4.1, compared to generation from those technologies in 2019. The numbers are based on analysis presented by David MacKay in [4.27] with some assumptions updated using information from the CCC [4.16] and the International Renewable Energy Agency (IRENA) [4.28].
- **UK renewable resource is much greater than what we currently use**. Available generation capacity from **solar and wind** (especially if floating offshore is included) is **much greater than all other sources combined**.
- Figure 63 shows a comparison of total UK renewable resource, electricity demand in 2019

Figure 62 Potential UK renewable electricity generation resources by technology. Analysis based on [4.27] and [4.16]. Detailed assumptions in endnote[47]

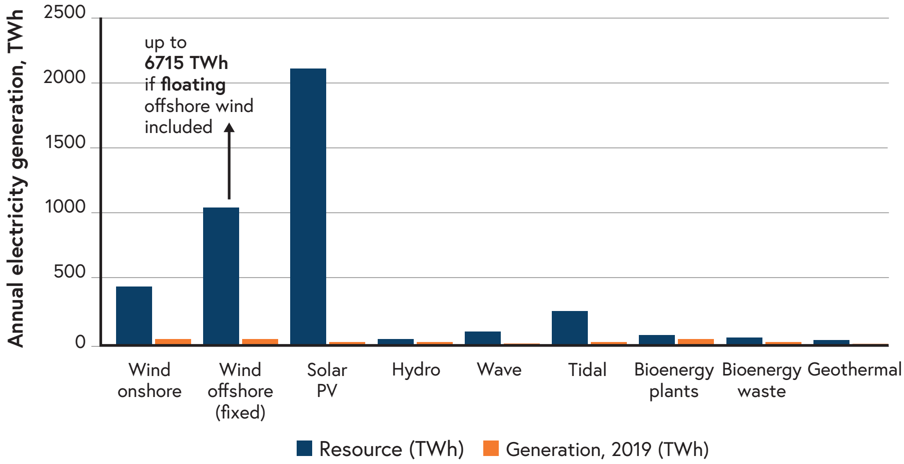
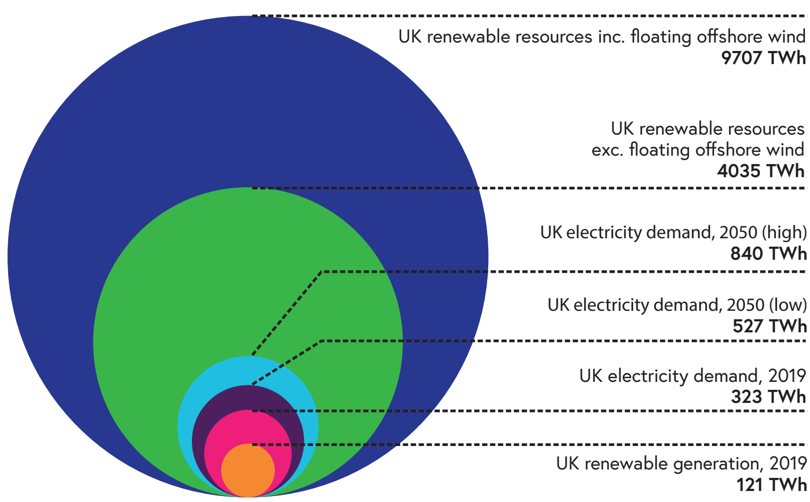


Figure 63 Comparison of UK renewable resources with 2019 electricity demand & renewable generation and two scenarios of 2050 UK electricity demand: the low scenario is from National Grid ESO's System Transformation Net Zero pathway; the high scenario is from Centre for Alternative Technology's Zero Carbon Britain Net Zero pathway. For more information, see §5.2



and two scenarios representing the range of projected 2050 electricity demand in seven Net Zero pathways (§5.2).
- 2019 generation as a proportion of resource is greatest for **bioenergy from plants** (42% of total available UK resource) although, currently, UK electricity generation from bioenergy largely uses imported biomass[46].

Maximum Potential Resources

- The numbers shown in Figure 62 are based on the same levels of resource extraction as in [4.27] and intended to be an illustration of the **maximum possible resource** from these technologies.
- While the area that would be devoted to power generation is significant[47], the analysis indicates that **UK renewable electricity resource is significantly greater than current electricity demand and all projected levels of 2050 demand needed to meet Net Zero** (Figure 63).

UK wind, solar, other

- UK Wind and solar PV resource is 7.7 times greater than everything else combined (if floating offshore wind is not included).
- Potential electricity production from plant-based bioenergy is **55 TWh,** assuming a power station efficiency of 40%. This would result in **138 TWh of primary energy,** which is around the 141 TWh given in the CCC's biomass report[48] [4.16].

Supplying UK electricity demand now and in 2050 from renewables is feasible. Doing so requires an appropriate electricity network (§4.4).

4.4 Electricity Network

4.4.1 Implications of Net Zero

- The GB[49] electricity network consists of a **transmission network** to transport bulk electricity over long distances and a **distribution network** to transport electricity from the transmission network to consumers.
- To minimise losses[50], transmission is done at **high voltage** (up to 400 kV). Transformers on the distribution network **step the voltage down** from the transmission system to the domestic voltage used in homes across Europe – **230 V**. Some customers – generally in industry – take electricity at higher voltages (e.g. 11 kV).

Decarbonisation of Electricity Supply

- To meet Net Zero, electricity supply will have to be carbon **negative as soon as 2030** [4.29].
- Increasing the share of renewables is changing **power system dynamics – new ancillary services and technologies** can help ensure that **security of supply is not affected** from decarbonisation.

Alternative Fuels Manufacturing

- Decarbonising **freight transport**, **shipping and aviation**, in addition to demand for **hydrogen for heating**, is likely to involve manufacturing of a range of alternative fuels – e.g. **hydrogen**, **ammonia** and/or **synthetic hydrocarbons** (§4.5).
- This has **significant demand for electricity** - Figure 65 is indicative of a scenario where those energy demands are **met by synthetic hydrocarbons** (with an optimistic 50% power to fuel efficiency)[51].
- Such fuel manufacturing could be done overseas, and it may make more sense to be **done alongside large renewable energy resources** (e.g. desert solar).

Figure 64 2019 final UK energy demand (electricity, road transport, heating) and illustrative electrical demand if transport & heating were 100% electrified by electric vehicles (EVs) and heat pumps (HPs)

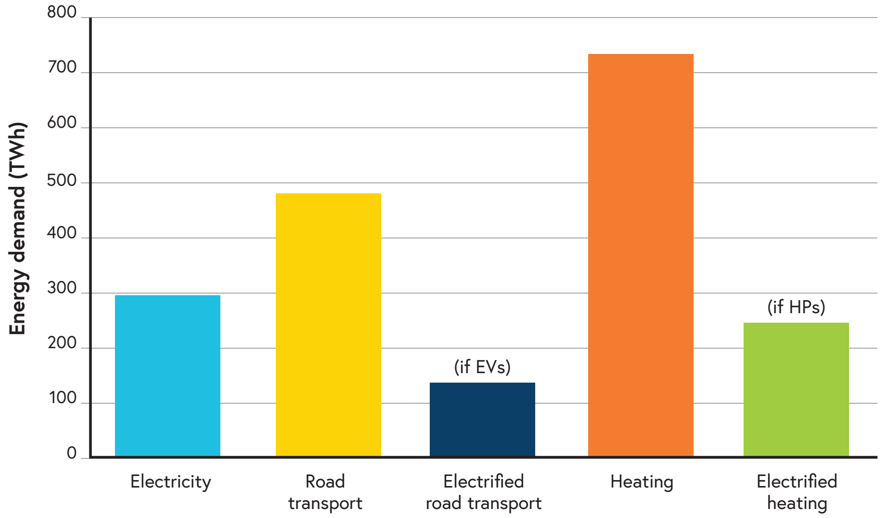
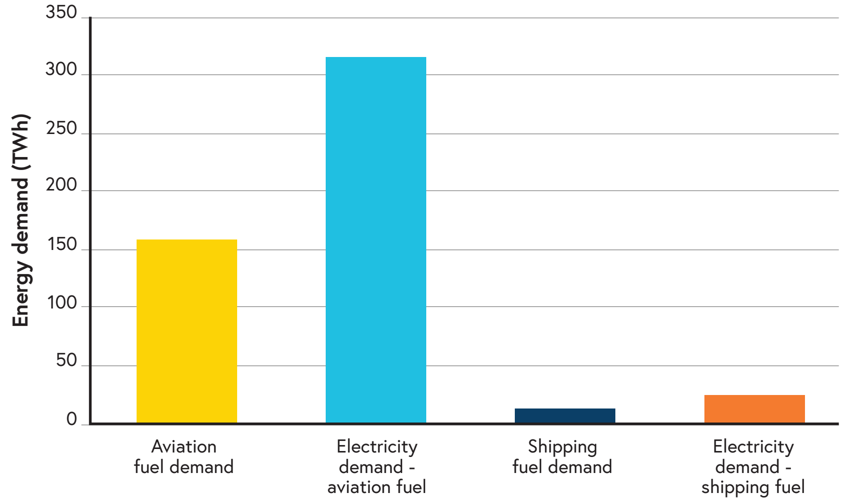


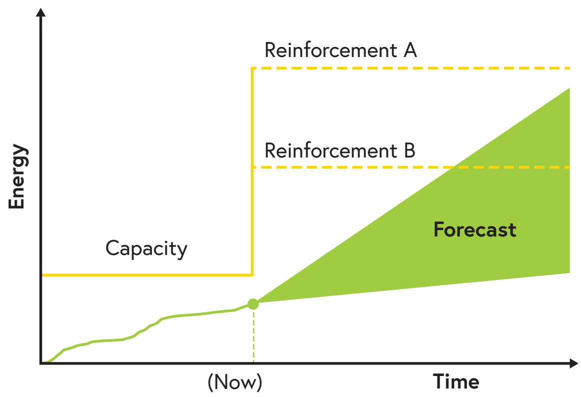
Figure 65 Aviation and shipping fuel demand; illustrative electricity demand if those demands were met with synthetic fuels[51]



Electrification of Heat & Transport

- Heating and transport are both likely to see significant electrification.
- If significant portions of these energy demands were transferred to the electricity system, electrical demand would **increase significantly**.
- However, the increase to electricity demand would be **less than transferring the entire energy demand of road transport and heating to the electricity stack**. Battery electric vehicles (EVs) (§3.2.2) and heat pumps (HPs) (§3.1.2) use electrical energy around **2-3 times more efficiently than equivalent technologies burning fossil fuels**.

Figure 66 Reinforcement options, given demand/generation forecast



4.4.2 Peak Demands and Reinforcements

- The electricity system – generation and the network – is designed to have enough capacity to meet the **peak demand**. Network reinforcements are triggered when peak power flows increase.
- Reinforcements result in **step changes** in capacity. It can be **difficult to forecast demand (or generation) increase**; this **affects the need for reinforcement** (Figure 66).
- **Networks** are paid for by consumers as **use of system charges**. If system peak demand can be reduced, **reinforcements can be deferred** and **the cost reduced**[52].

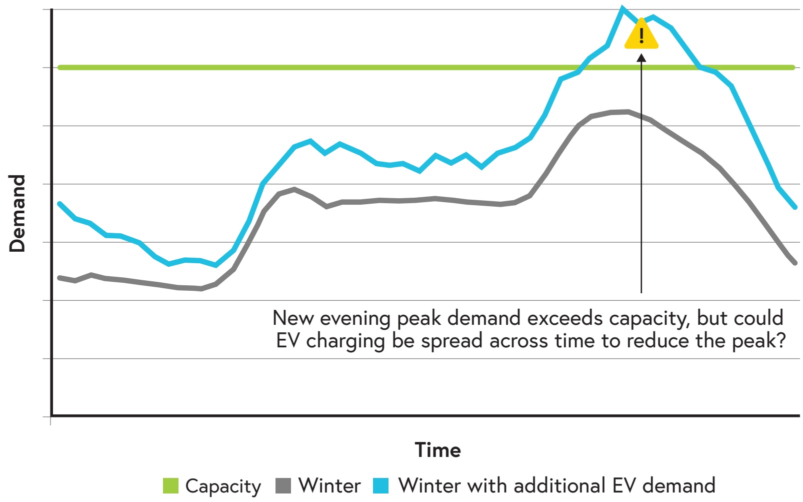
4.4.3 Smart Grid Technologies

- **Smart grid technologies** aim to **maximise the utilisation** of the electricity network by generators and demand, and facilitate larger **growth in demand** and generation[53] within a given level of network capacity.
- Historically, large scale **generation has been controlled to match demand** in real time.
- In a smarter grid, a significant part of **demand can be flexible** and be timed to match generation, and **smaller scale generators can be actively controlled**.

Electricity Storage

- Electricity can be **converted to other forms of energy for storage** (§4.11.1), and then converted back when needed.
- Storage of electricity is **very expensive** (§4.11.1).
- Pumped hydro power is the most established form of electricity storage, though battery costs are coming down. EVs can also act as widespread battery storage[54].

Figure 67 Typical domestic electricity network daily demand profile, showing existing winter demand, network capacity and increased demand from (uncontrolled) EV charging. Chart from [4.30]



Demand Side Response (DSR)

- Sudden losses of sources of electricity need to be very quickly compensated by increases from other sources or reduction in demand.
- DSR is a **very fast reduction in demand**, e.g. by switching off air conditioning, heating or EV charging[55] for a time. To date, it has been enabled **aggregators** that can group energy users together to provide services (such as frequency response) to the system operator.

Time of Use & Dynamic Tariffs

- Time of Use (ToU) tariffs set **different prices for electricity depending on how expensive the generators are** that are needed to meet demand at that time. Long-established Economy 7 tariffs have different prices at fixed times of the day based on the typical historic pattern of demand being low overnight and so needing only the cheapest generation.
- Dynamic tariffs set **different prices at different times depending on the wholesale cost of electricity**. As use of variable renewables grows, these tariffs will generally **align low prices with high renewable output**.
- Electricity users that can be **flexible** in exactly when they want electricity can **benefit from dynamic tariffs**.
- There is growing interest in ToU tariffs for EV smart chargers [4.31].

Smart Meters

- Smart meters allow **more accurate billing including time of use,** and easier switching of supplier.
- With appropriate displays, they can encourage **more efficient use of energy**.
- They can also allow **network operators to see where and when demand is,** enabling smarter use of the network.

Communications and Cyber Security

- Enabling the smart grid requires embedded **communications** in lots of equipment that was previously **passive**.
- **Vulnerabilities** in power system communications and controls could have **disastrous consequences**[56].

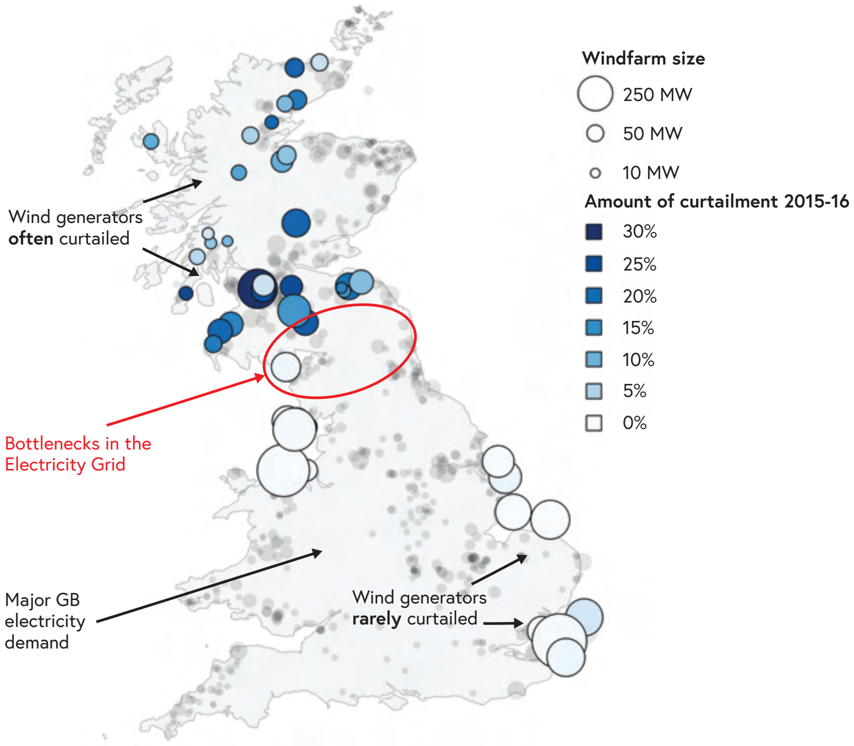
Distribution System Operation (DSO)

- Historically, Distribution Networks Operators (DNOs) have not actively controlled generation or demand.
- **Smarter use of network capacity** requires the **use of flexibility of generation or demand** as system conditions change and for DNOs to act more like transmission system operators, i.e. to become **Distribution System Operators** (DSOs).
- **Active Network Management** (ANM) can automatically adjust generation output so that network limits are respected. In spite of lost revenue to a generator due to its output sometimes being curtailed, this can be **lower cost than network reinforcement** [4.32].
- The Orkney ANM project spent **£500k** on an ANM solution that avoided **£30m** of reinforcement costs (in this case, laying cables to the mainland) [4.33].

4.4.4 Renewable Generation and the Grid

- The transmission network was developed largely to serve large demand centres and transfer power from where fossil fuel and nuclear power stations were best located.
- The distribution network was first developed to serve historic patterns of demand.
- Many locations with **plentiful renewable resources do not have much existing network capacity**[57]. Failure to develop the network can result in excessive curtailment of renewable generation output (Figure 68).

Figure 68 Curtailment of large wind generators, 2015-2016. Adapted from [4.36]. This figure illustrates the issue of curtailment of renewable power in constrained networks. The curtailment of wind in Scotland will have reduced due to the installation of the Western Link in 2018[58]



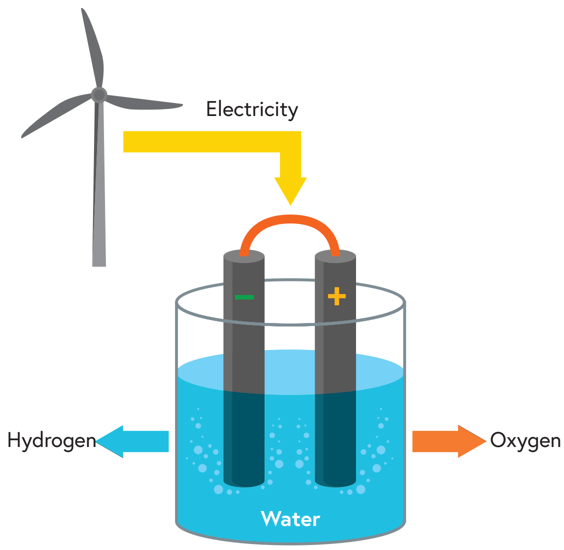
Interconnection

- Different countries' electricity systems can be **connected together** to provide **access to cheaper resources** or **extra reserves** for security of supply.
- Britain has interconnections **to France, Ireland, the Netherlands and Belgium** with new ones under construction to **Norway and Denmark**.
- Interconnectors can help to **balance total generation and demand across a larger area**, making use of **diversity of generation and demand**, reducing curtailment.
- Proposals include **'hub and spoke' wind farms** [4.34], and **long-distance cables supplying European demand** with **solar electricity generated in the Sahara Desert** [4.35].

Network Capacity and Curtailment

- Network capacity enables **demand to use generation located far from it**. It also allows a **choice in which generation to use**, usually through a wholesale market, and **pooling of reserves.**
- Ideally, **new generation and demand would locate where there is spare network capacity**. This might be encouraged by **locational price signals**. Otherwise, **network capacity must be enhanced** to accommodate the increased power flows.
- **Flexibility** in generation and/or demand can reduce the amount of network needed. **The optimal amount of network capacity is a trade-off** between the respective costs of reinforcement, compensation to curtailed generators and demand, and the cost of power replacing what is curtailed.

Figure 69 Hydrogen production from electrolysis of water



4.5 Fuels for Net Zero

4.5.1 Hydrogen

- Hydrogen is likely to provide energy for parts of the **transport, industry, heating** and **back-up power** sectors in a Net Zero energy system.
- Although hydrogen emits no CO_2 at the point of use, it is **not necessarily zero-carbon – the carbon intensity of hydrogen** depends on how it is produced.

2050 UK hydrogen demand is projected to be in the region **100-600 TWh/year** according to seven published Net Zero pathways (§5.2).

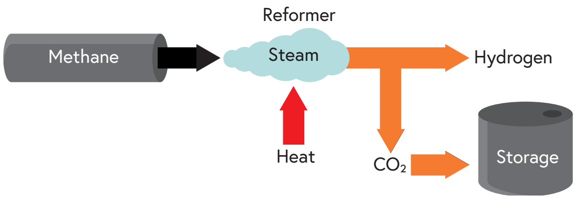
Hydrogen Production Methods

- Hydrogen has been manufactured for decades for use in **chemicals** and **fertiliser** – 70 million tonnes/year globally [4.37].
- Hydrogen can be made in several ways. At present, the predominant methods are: **from fuels** (most commonly **steam reformation of methane**), and **from water** via **electrolysis.**
- Making hydrogen requires **energy**, likely to be in the range of an additional **20% to 80% of fuel or electricity** compared with using the fuel or electricity directly (Figure 72).

Hydrogen from Fuels

- **Hydrogen is currently manufactured by reacting fuels with water or steam.** ~75% of global production is from gas & oil; ~25% is from coal [4.37, 4.38].
- Such hydrogen is known as **'grey hydrogen'** because its production is very **CO_2-intensive** (§4.6) [4.39].
- If carbon capture and storage facilities (CCS – §4.10) are added, the hydrogen is called **'blue hydrogen'**.
- **Some emissions will continue** at the hydrogen production site, as some CO_2 evades capture (currently 10-40% of **process emissions**). There will also be **upstream emissions** from sourcing the fuel (§4.6).
- Aside from fossil fuels, hydrogen can be **synthesised from biomass** via **gasification** [4.40].
- Hydrogen from fuels is **suitable for combustion**, but is of **lower purity** than that required for use in **fuel cells** and would need **further purification** [4.41].
- The CCC believes that hydrogen from fuels with **CCS will be important in establishing a mass market for hydrogen** (providing 60% of supply by 2035). However, because of residual GHG emissions, this method will play only **a supporting role for hydrogen production by 2050 (providing 32%)** [4.42].

Figure 70 Hydrogen production from steam reformation of methane with CCS



Hydrogen from Electrolysis

- Water can be split into **hydrogen and oxygen** by passing electricity through it (electrolysis[59]).
- If this electricity is made from renewables, this hydrogen is known as **'green hydrogen'.**
- Hydrogen made by electrolysis is **very high purity**, and can be used in fuel cells [4.41].
- **Hydrogen made by electrolysis of seawater**, using **surplus energy from renewables,** could be a key form of **seasonal electricity storage** (§4.11.1) [4.39]
- GHG **emissions could be near zero**, depending on the method of electricity generation (§4.2).
- Hydrogen from electrolysis currently makes up **2% of global production** [4.37]. **Enormous upscaling** of electrolysers is required to meet likely future demands for low-carbon hydrogen [4.40].
- Rollout is currently constrained by cost and the installation of renewables, but the CCC believes **electrolysis will form the largest share of production (44%) by 2050** [4.42].

Hydrogen in the Future UK Energy System

- **Hydrogen is likely to be used in smaller quantities** than our current fossil gas consumption (877 TWh in 2019 [4.7]). Analysis of seven published Net Zero pathways (§5.2) predicts **hydrogen demand will be in the range 100-600 TWh/year by 2050**, though **six out of seven predict that 2050 demand will be in the range 100-250 TWh/year**. This significant uncertainty arises from the rates of electrification of demand in other sectors (particularly heating).
- All these pathways suggest hydrogen is most likely to be used for **peak winter heating** (often via hybrid heating systems comprising a heat pump and hydrogen boiler), **heavy transport** and **long-term renewable electricity storage**.
- Hydrogen can also be used to manufacture **fuels**: namely **ammonia** (§4.5.3) and **synthetic fuels** (§4.5.4) – including **jet fuel**. As with hydrogen production itself, **additional energy is required** to manufacture these fuels to power the necessary conversion processes. This means that primary energy demand (renewable electricity, if these fuels are to be considered Net Zero) will **increase** relative to using fossil fuels.

Producing 2050 Hydrogen Demand from Gas

- Chemical processing (e.g. steam reformation) of fossil gas could provide our 2050 demand for hydrogen – though **carbon capture & storage (CCS)** is needed to allow reductions in emissions versus burning gas unabated.
- Because of the **energy demand of the conversion process and the associated CCS**, gas demand for hydrogen production could outstrip 2019 gas demand in a high H_2 scenario (600 TWh/year by 2050) (Figure 71).

Producing 2050 Hydrogen Demand by Electrolysis

- Electrolysis from **renewable** electricity or **nuclear** could provide our 2050 demand for hydrogen.
- For a hydrogen demand of 100 TWh/yr, **15,000 km^2 of windfarm or 6 nuclear power stations** equivalent to Hinkley Point C would be required (Figure 72).
- For a hydrogen demand of 600 TWh/yr, **89,000 km^2 of windfarm or 37 nuclear power stations** equivalent to Hinkley Point C would be required.

Figure 71 2050 hydrogen and fossil gas requirement, if making hydrogen entirely from gas: high and low hydrogen scenarios. Low hydrogen scenario is taken from the Centre for Alternative Technology (CAT)'s Zero Carbon Britain Net Zero pathway; high hydrogen scenario is taken from National Grid ESO's System Transformation Net Zero pathway. For more details on Net Zero pathways, see §5.2; for more details on assumptions used to make this figure see endnote[60]

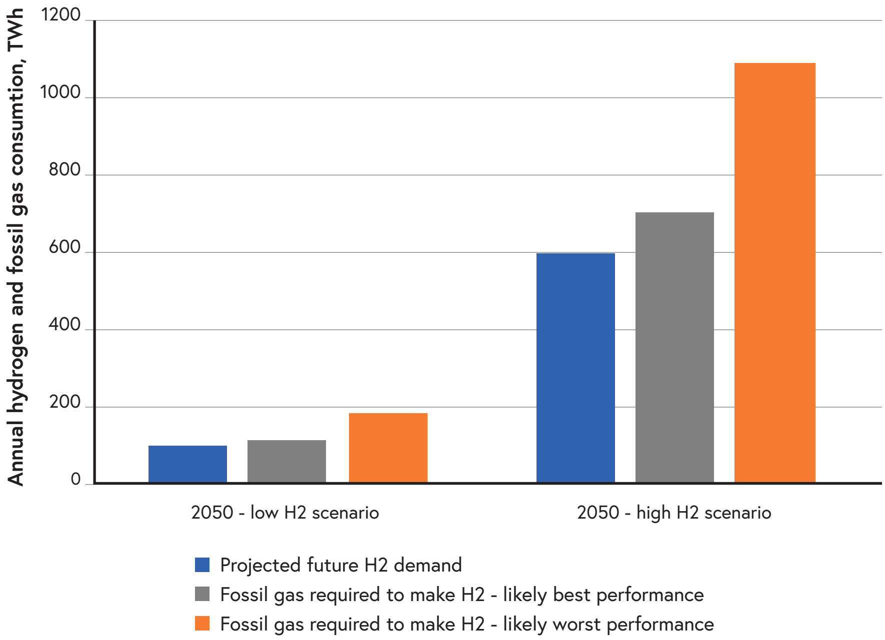
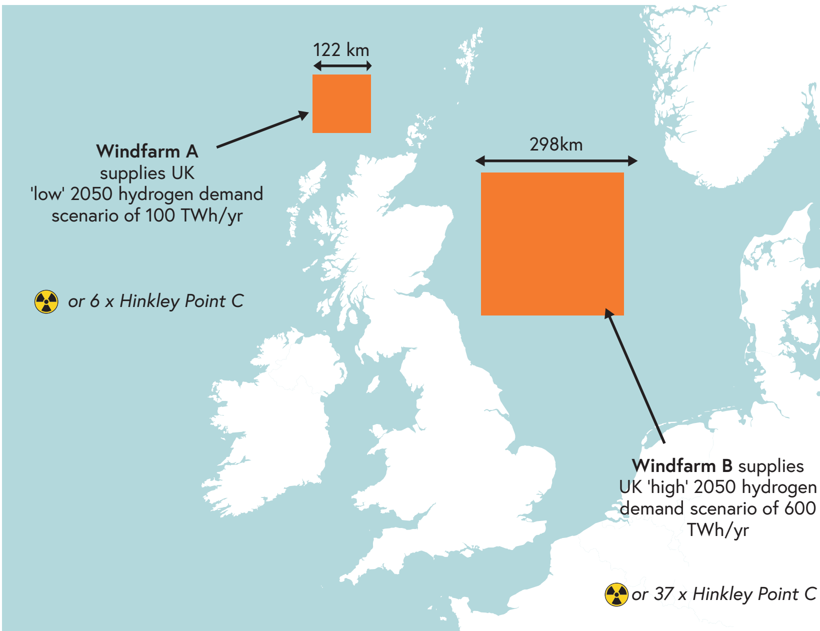


Figure 72 2050 offshore wind farm area or nuclear capacity in multiples of Hinkley Point C required if making hydrogen entirely from electrolysis. Windfarm A (or 6 x Hinkley C) provides for the low hydrogen scenario (from the Centre for Alternative Technology (CAT)'s Zero Carbon Britain Net Zero pathway). Windfarm B (or 37 x Hinkley C) provides for the high hydrogen scenario (National Grid ESO's System Transformation Net Zero pathway). For more details on Net Zero pathways, see §5.2; for more details on assumptions used to make this figure see endnote[61]



4.5.2 Bioenergy

- Bioenergy refers to **organic material** that can be burned as it is or converted into other fuels. This organic material can be derived from **plants** (energy crops) or **waste**.
- Bioenergy is used across all sectors – from **wood-burning stoves** to **biodiesel in cars** and **biomass in power stations** to generate electricity. Many countries in sub-Saharan Africa are reliant on bioenergy for cooking.
- **Plants capture carbon from the air** as they grow – so burning them is **Net Zero emissions**, **providing changes in land use to enable its growth did not result in emissions elsewhere**.
- Food and agricultural **wastes and residues** are another bioenergy resource. Utilising these can **displace emissions that would otherwise result from waste disposal**, though **some residues have existing uses** – displacing this demand **may cause emissions to rise in other sectors** [4.16].
- BECCS is bioenergy paired with CCS (§4.9). This is a significant part of most Net Zero pathways (§5.2), as it allows for **significant removal of CO_2 from the atmosphere** (plants grow, capturing carbon, which is then prevented from re-entering the atmosphere by CCS before or at the point of combustion). See §4.1.
- Bioenergy should be approached with **caution** – plants also have to provide **food and habitats for humans and animals**. Any bioenergy used must be from **sustainable sources**, and its finite contribution to energy supply must be recognised.

Sustainable UK bioenergy resource

- **Potential future demand** for bioenergy is likely to **outstrip sustainable supply** [4.16].
- Sustainable bioenergy **must not compete with food supply or biodiversity**, both of which are as important to humanity as avoiding climate change.
- The CCC's 2050 limit on UK land for energy crops is **14,000 km^2** (around 7% of agricultural land) [4.16].
- This is a **44% increase on 2019 domestic UK bioenergy** demand. This **limits** bioenergy's contribution to 10-15% of energy demand.

Figure 73 Domestic and imported bioenergy demand in 2019; domestic biomass resource in CCC's 2050 high biomass scenario [4.31]

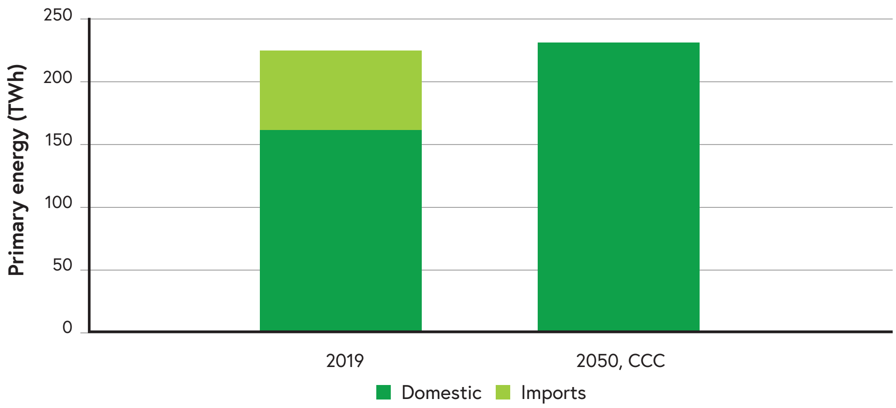
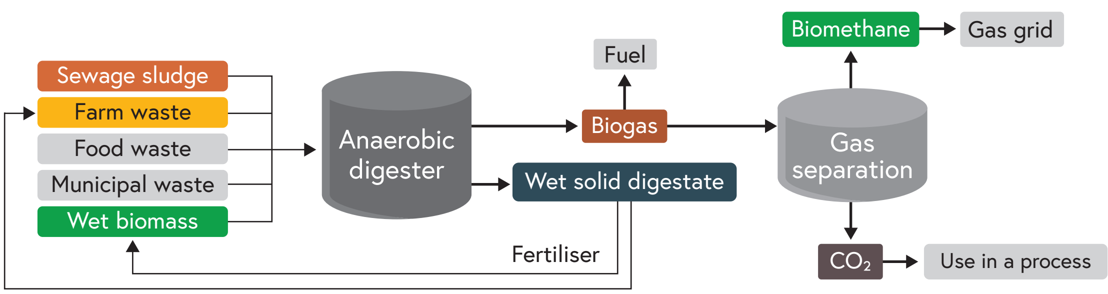


Figure 74 Production of biogas and biomethane from anaerobic digestion



Biogas & Biomethane for Heating

- **Biogas & biomethane** (its main product) are gaseous fuels made from biomass by **anaerobic digestion (AD)** from waste products including **farm waste** and **sewage**.
- **Biomethane** can be added to mains gas to **reduce emissions** of gas for heating (§4.5). At present this is done in tiny amounts (**0.5%** of gas supply in 2019) [4.7].

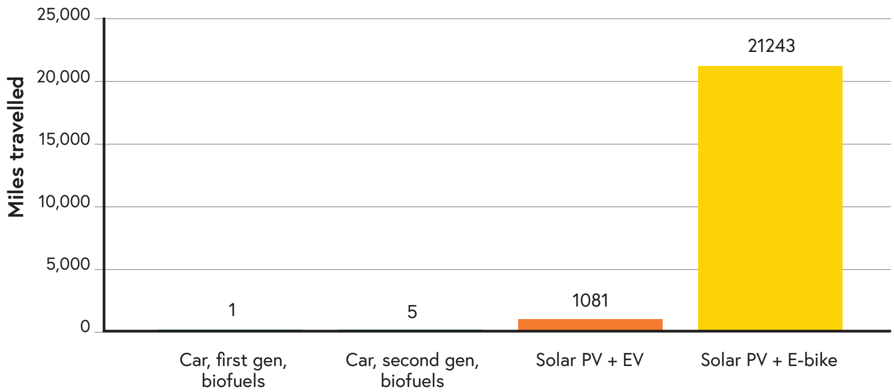
A Square Metre of Land for a Year

- Biodiesel from a year's harvest of 1 m² of wheat could be used to power a car around **1 mile**. Second generation biofuels (e.g. willow grass) could increase this to **5 miles**. If the same square metre were used for solar PV, an EV could use that electricity to drive **1,081 miles**.
- Whereas edible crop biofuels **compete with the food supply**, solar PV can be planted on **non-productive land** (e.g. desert).

Biofuels for Transport

- Replacing transport fuels with **combustible biofuels** – hydrocarbons derived from plants or waste – has been proposed (particularly by fossil fuel companies [4.43]) as a way of decarbonising the transport sector.
- Biofuels are classified into **generations** [4.44] – based on whether they are derived from edible or non-edible biomass, or whether (at the advanced end) they can be derived from **algae**, which grows faster and is more energy dense than edible energy crops. Advanced algal biofuels are still under development and **significant challenges** remain [4.45].
- Biofuels are currently **blended** with petrol and diesel for use in road transport (mostly freight) – these constitute **5% of road transport fuels** used in the UK (2019) [4.46]. The main fuels are i) **bioethanol**, which is made from crops such as corn and sugar beet and can replace petrol, and ii) **biodiesel**, which is primarily made from **waste cooking oil** and other waste materials.
- **Almost 90%** of biofuels used in the UK in 2019 were imported [4.46].
- Even if they are not based on edible crops, **biofuels require a lot of land to provide enough energy** compared to the demand from transport (Figure 75).

Figure 75 Distance driven from energy provided by 1 m² of solar PV or energy crops. Reproduced from [4.12]



4.5.3 Ammonia

- Ammonia (NH_3) can be made by combining **hydrogen** (made by one of the production modes in §4.5.1) and **nitrogen** (which constitutes around 78% of air).
- This is already common practice – ammonia is made in great quantities as **fertiliser** and consumes **43% of global hydrogen production** [4.47].
- Using ammonia as a fuel has attracted interest because it is around **50% more energy-dense per unit volume than hydrogen** and is **easier to liquefy**, making it more suitable for transport applications.
- Ammonia can be **burned** in a modified gas turbine or used in a **fuel cell to generate electricity**.
- Converting hydrogen to ammonia entails **energy loss**, which may be compensated by its higher energy density.

Figure 76 Ammonia production: the Haber-Bosch process

Ammonia for Net Zero

- Ammonia production is already the world's **third-largest industrial GHG emitter** after cement and steel (around 2% of global emissions) [4.48].
- Most of these emissions come from **hydrogen production** – from methane, without CCS.
- If the hydrogen is zero-carbon (§4.5.1), then low-carbon ammonia could be an important fuel for Net Zero **transport** (especially shipping).

4.5.4 Synthetic Fuels (Synfuels)

- Synthetic hydrocarbons (including methane and kerosene) can be manufactured from hydrogen (made by one of the production modes in §4.5.1) and carbon – either **captured directly from the air** or from **organic material**.
- **Other synfuels** include **ethanol** and **methanol** (liquid fuels that can substitute for **petrol**).
- Synthetic fuels burn in the same way as the fuels they are made to replicate, so **very few or zero modifications** to engines are required.
- The main drawbacks of synthetic hydrocarbon fuels are **technology immaturity** and the large **energy requirement** – producing enough synfuel to power the UK's aviation industry from hydrogen made by electrolysis and carbon captured from the air would require **127% of 2019 UK electricity consumption**[62].
- Due to their high cost, **effective emissions pricing** is required to make them preferable to fossil fuels.

Figure 77 An example of synthetic fuel production (synfuel for aviation): the Fischer-Tropsch process

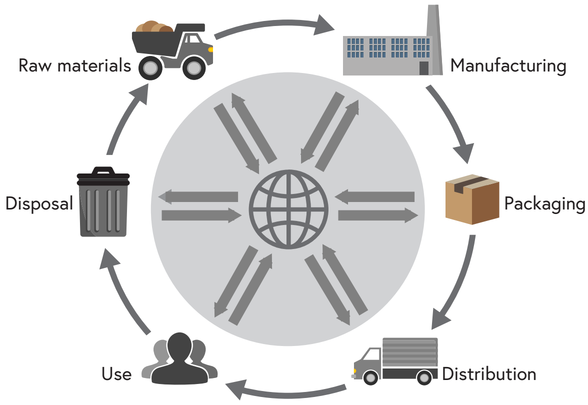
A Future for Synfuels

- Synfuel manufacturing's high energy intensity requires **plentiful low-carbon electricity**.
- Synfuels could be made at **large scale dedicated solar facilities** in places with high resource[62]. This could provide **revenue streams** to oil-exporting countries in West Asia and North Africa.
- Synfuels could be used for **seasonal electricity storage** then burning it in a power station to provide flexible power. If emissions were captured, this could be **CO_2-negative**.

4.6 Life Cycle Emissions of Gaseous Fuels

- Life Cycle Assessment (LCA) attempts to **quantify GHG emissions per unit energy (kWh)** over the **entire lifecycle of a technology** from raw materials extraction to disposal or recycling (Figure 78).
- As was the case for electricity generation (§4.2), the **extraction**, **processing**, **transportation** and **use** of gaseous fuels (including fossil gas, biomethane and hydrogen – with knock-on effects for fuels produced from hydrogen) has associated GHG emissions.

Figure 78 Life Cycle Assessment (LCA) approach. Image from [4.22]



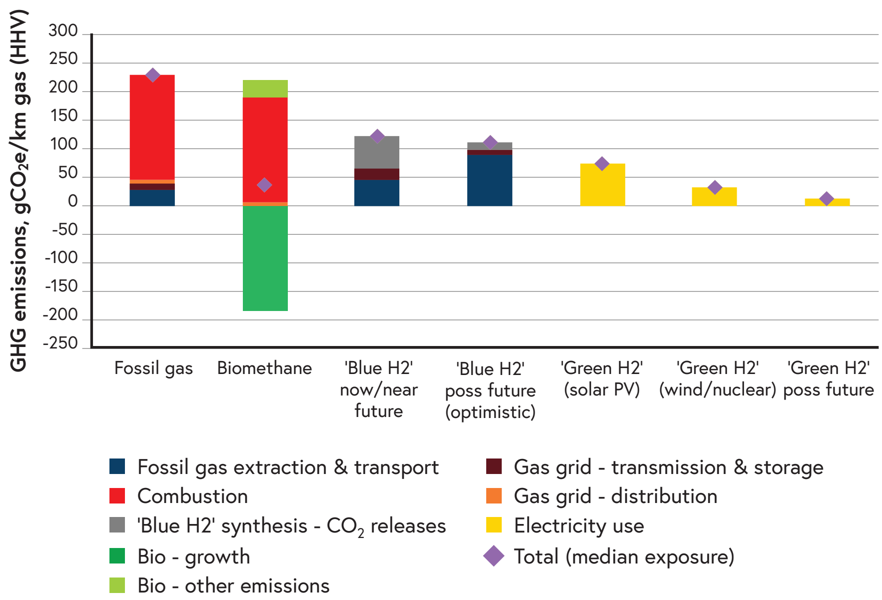
Emissions at the Point of Burning – Gaseous Fuels

- **Fossil gas** causes fewer GHG emissions at the point of burning than other fossil fuels – coal and oil. However, emissions are still high and so **unabated burning of fossil gas is not compatible with Net Zero**.
- **Biomethane** is the same substance as methane, the main constituent of fossil gas (§7).
- **Hydrogen** causes no GHG emissions at point of burning.

Supply Chain Emissions – Gaseous Fuels

- Estimates of emissions vary widely, and there are gaps in information. Estimates in Figure 79 assume good practice in all stages of production.
- **Poor practice in any stage of the supply chain will cause much higher emissions** from that step - perhaps tenfold or more – **especially true for unconventional ('fracked') gas imports.**
- The UK will increasingly rely on **imported liquefied fossil gas (LNG)** (20% of 2019 consumption) which has a **higher GHG footprint**, mainly because of the energy used for its liquefaction and shipping.
- 'Blue' hydrogen (from fuels with carbon capture & storage (CCS)) will **continue to have significant supply chain emissions even with high carbon capture rates**, unless global gas supply chains are also decarbonised.
- 'Green' hydrogen (electrolysis from renewables) **emissions depend on the lifecycle emissions of the generation technology used** (§4.2).
- If hydrogen is **compressed** to higher pressures or **liquefied**, this will cause additional GHG emissions from the additional energy required.

Figure 79 Estimated whole life cycle GHG emissions from gas: fossil gas and alternatives. Median values of estimates only shown. Ranges of estimates are wide. Based on [4.41] and [4.49]. All values relative to higher heating value (HHV) of methane or hydrogen

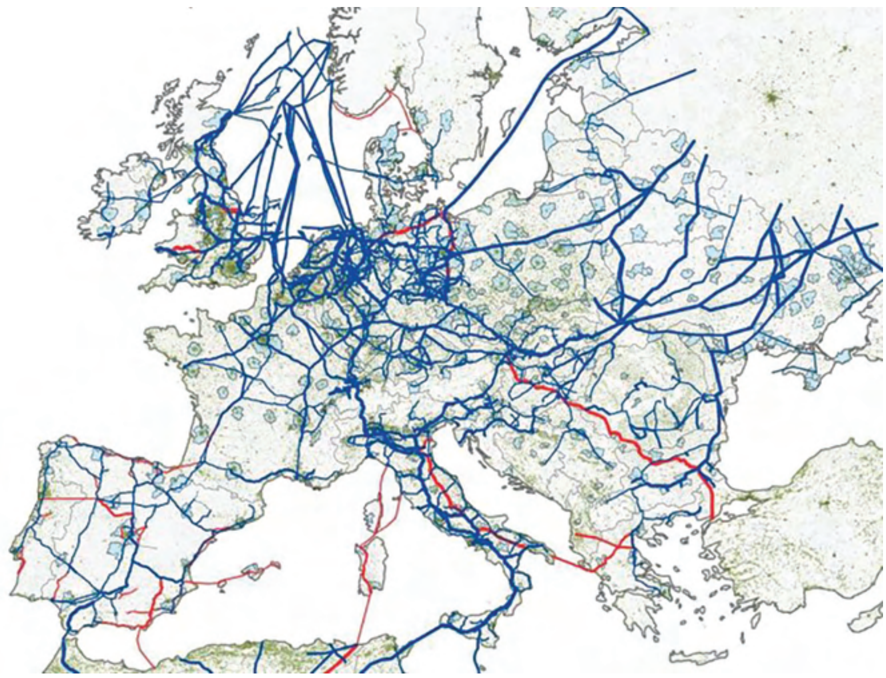


4.7 Gas/Hydrogen Network

4.7.1 Implications of Net Zero

- The UK gas system is **highly developed** – it supplies **80% of UK homes and businesses**.
- **270,000 km of pipes**, international pipeline **connections** and **shipping terminals** (Figure 80) deliver for peak demands of up to **210 GW** (as seen in the Beast from the East, 2018) **– 3-4 times larger than the electricity system peak**.

Figure 80 UK gas network in Europe. Image from [4.50]. Image courtesy of ETH Zurich



- The gas network has inherent **energy storage** (§4.11.2) of **300 GWh per day in the pipes themselves**, and **1,500 GWh per day** at **storage sites** [4.41].

Will the UK gas grid support a Net Zero energy system?

- The gas grid **can support Net Zero** if it is converted to carry a **low-carbon gas**. This could be **biomethane** and/or low-carbon **hydrogen**.

Option 1) Hydrogen/biomethane/fossil gas mix

- This mix would be **mostly fossil gas**, with up to **20-30% low-carbon gas** by volume.
- This could **reduce GHG emission** of the gas system but **significant residual emissions would need bigger reductions** in other sectors.
- **Biomethane could be used**, but **supply would be limited to 3-10% of demand** [4.51, 4.52].
- Unlike blends containing more hydrogen, **current gas appliances would work**[63], and little change would be required to the gas grid.

Option 2) 100% Hydrogen

- The gas system could be switched to 100% hydrogen.
- This would require a step change in the gas system: **all appliances would need to be adapted or replaced. Significant investment would be needed in the gas transmission network** if it was to be used to carry hydrogen.
- To be compatible with Net Zero, hydrogen production must be from either **electrolysis of water using low-carbon electricity**, or **from gas with CCS** (with a very high capture rate).

4.7.2 Conversion to a Hydrogen Gas Grid and Hydrogen Readiness

- Converting the gas grid to run on **up to 100% hydrogen** is likely to be a key to meeting Net Zero – even if **just for peak winter heating supply** (§3.1.2).
- Pursuing a **hydrogen gas grid would not prevent** (and may be **complementary to**) deployment of other heating technologies such as **heat pumps** and **district heating**.
- Hydrogen **behaves differently** from fossil gas: it has wider flammability limits and a higher flame speed. Therefore, **safety must be demonstrated at every scale** – a **new set of standards** is currently being established [4.53].
- This also means that **most boilers, cookers and other appliances** will need a new burner to work on hydrogen[64].
- The **UK underwent a gas switch in the 1960s-70s** from **town gas** (coal-derived gas containing methane, hydrogen, carbon monoxide and other flammable hydrocarbons) to fossil gas (methane)[64]. A **gas switch to hydrogen would be a larger task**, because i) there are many more gas consumers now than in the 1970s and ii) the chemical differences between fossil gas and hydrogen are greater than those between town gas and fossil gas [4.51].

Hydrogen Readiness – The Gas Grid

- Local **distribution grids** will be largely **hydrogen-ready** by the early 2030s due to the Iron Mains Replacement Programme which started in 1991[65].
- If it is to be used for hydrogen, the national **transmission grid** is likely to need **upgrading** – **replacing** or **lining with plastic pipes**.
- Some **changes to other equipment** (e.g. compressors) might be needed [4.56].

Hydrogen Readiness – Gas Appliances

- Most domestic appliances **cannot run on pure hydrogen** and are **not designed for easy adaptation**[66].
- The British Standards Institute has developed standards for the development of new hydrogen appliances[67], and **manufacturers are developing new products**. Some early **hydrogen-ready boilers** are now available.
- Government could mandate new appliances to be **hydrogen-ready** well in advance (e.g. by mid 2020s) **to avoid large-scale premature scrappage**.

Demonstration Project – HyDeploy [4.54]

- HyDeploy seeks to demonstrate the feasibility of mixing **up to 20% hydrogen** into gas networks.
- Mixing hydrogen into a private gas network (Keele University) was approved for the first time.
- Initial results from the project have found that i) **existing gas appliances can be used without modification** up to and over 20% hydrogen, ii) **leakage detection is possible** with current technology, iii) **no materials related issues were identified** and iv) **consumers don't notice a difference** when using the hydrogen blend.

Demonstration Project – Hy4Heat [4.55]

- Hy4Heat is exploring the possibility of using **100% hydrogen** in existing buildings and homes.
- Whereas HyDeploy found that appliances can be used up to (and over) 20% hydrogen, **for 100% hydrogen new burners must be fitted** to existing appliances.
- **Hy4Heat** surrounds the development of **quality standards, appliance certification, design & development** of new appliances and **hydrogen smart meters**.
- Hy4Heat has already demonstrated that hydrogen can be made as safe as fossil gas for use in some homes; trials are ongoing.

A UK Gas Switch

- A large-scale switch from fossil gas to hydrogen could be done **nationally**, or **region by region**.
- It would need **major advanced planning, preparation** and **resourcing**, years ahead [4.51].
- There could be varying levels of **consumer disruption**.

- Their **scale** allows for high **demand diversity**[68] – this enables maximum system loading and **cost-effectiveness**.
- Large thermal storage of DH networks can be used to store surplus **renewable energy** (§4.11.3).

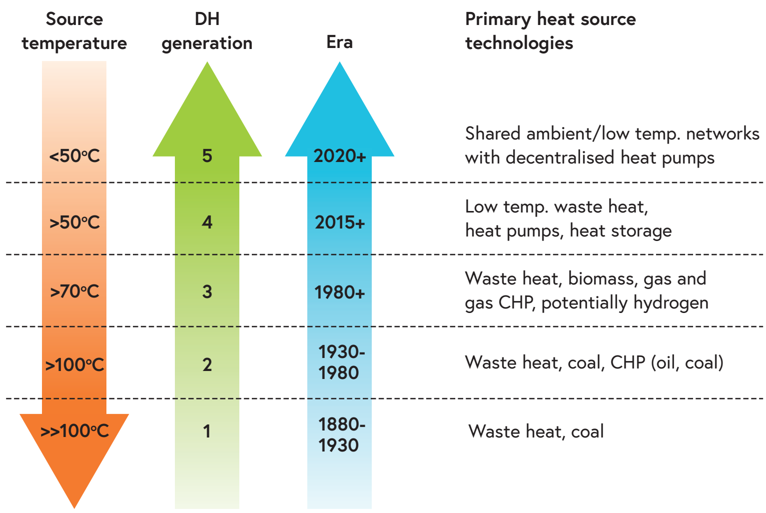
4.8 District Heating

- District heating (DH) can **accelerate development of zero-carbon heating** by serving large-scale demand with single projects.
- DH is **future proof**: its **heat source can be replaced easily** (compared to individual heating systems).
- DH is **flexible**, with range of potential heat sources (heat pumps, hydrogen, industrial waste heat).

District Heating for Net Zero – Technology Options

- **The majority of UK DH builds are '3rd Gen'**[69] (70-80 °C output, predominantly gas-based and from limited low carbon sources).
- '4th Gen'[69] systems (<60 °C) can extend viability into high and medium heat density areas.
- '5th Gen'[69] ambient temperature systems supplying individual heat sources **reduce piping costs and losses** but **increase heat generation costs**.
- A relatively **low supply temperature** is desirable because it **minimises heat losses** and enables a higher contribution from **low-carbon sources** (heat pumps; waste heat) [4.57].

Figure 81 District heating generations by source temperature, era and primary heat source



Cost & Installation Works

- DH has a **high initial investment cost** and requires **stable, long-term demand**.
- Increasing building energy efficiency can **reduce** the attractiveness of DH relative to other options.
- DH installation works (underground heat pipes) are **disruptive**, especially when **retrofitting to existing housing**. [4.58].
- DH requires a suitable, competitive supplier business model (or public sector ownership) to **increase consumer confidence** and **prevent abuse by supply monopolies**.

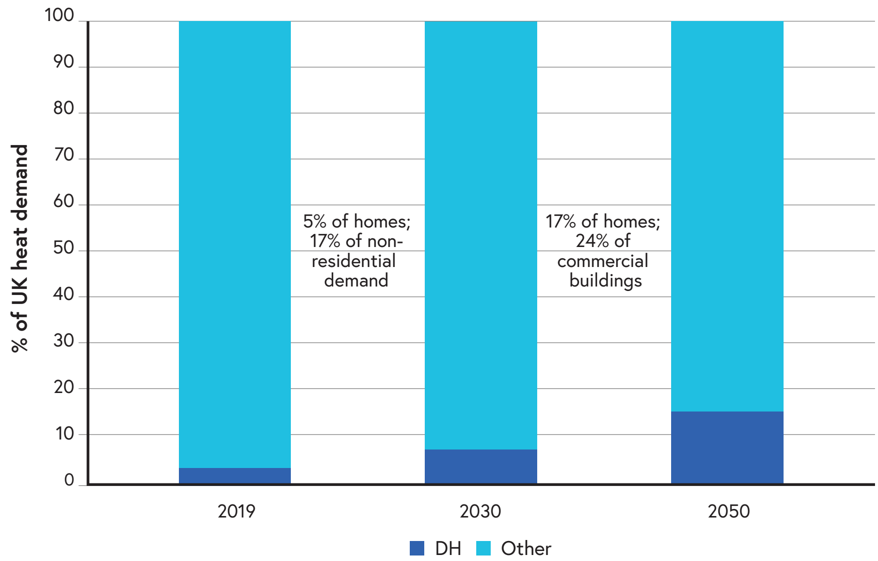
Area Potential - Heat Density[70]

- **Heat density is a key parameter for assessing DH potential** due to high fixed costs of transporting heat [4.59] .
- **69% of UK heating demand** has high/very high DH potential[71].

District Cooling (DC)

- **Cold water for cooling** can also be supplied via piping networks
- Low-carbon sources include direct **groundwater supply**, **renewables-powered electric chillers** and **waste-heat absorption chillers** [4.60, 4.61].
- Potential locations (>300 TJ/km^2) assessed to be 27% of UK cooling demand [4.59].

Figure 82 Potential share of UK heat demand met by district heating: 2030 and 2050 [4.58-4.60]



4.9 Buildings

4.9.1 UK Building Stock

- There are currently **29 million** dwellings in the UK.
- The number of households is projected to **increase by 37% by 2050**, due to **smaller households and increasing population** [4.61].
- The UK has the **oldest housing stock in Europe** (38% built pre-1946, 76% pre-1980) [4.62].
- There has been only **gradual improvement in energy efficiency** since 1996 [4.63].

Annual Demolition Rates

- **0.04% for housing** in England (very low) [4.64]
- **1-1.5% for commercial buildings** [4.64].

Energy Efficiency

- Average Standard Assessment Procedure (**SAP**) energy rating has increased **modestly from 45 to 63** from 1996 to 2018 (Figure 83).
- Average Energy Performance Certificate (EPC) rating for UK homes is **D** (Figure 84).

UK Commercial Buildings [4.64]

- 679 million m^2 total floor area.
- 22% retail, 16% offices, 56% industrial[74], 7% other

The UK is the **2nd most gas dependent country** in the OECD for heating [4.73].

Figure 83 Mean housing SAP rating, England. Data from [4.63]

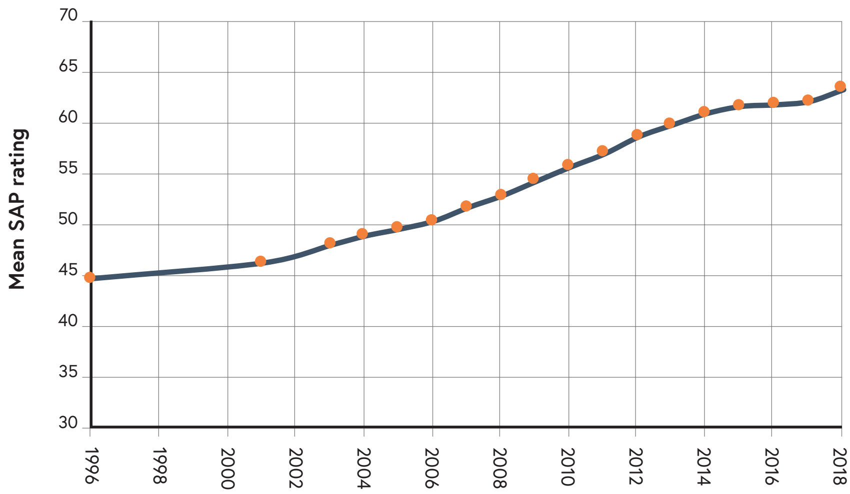
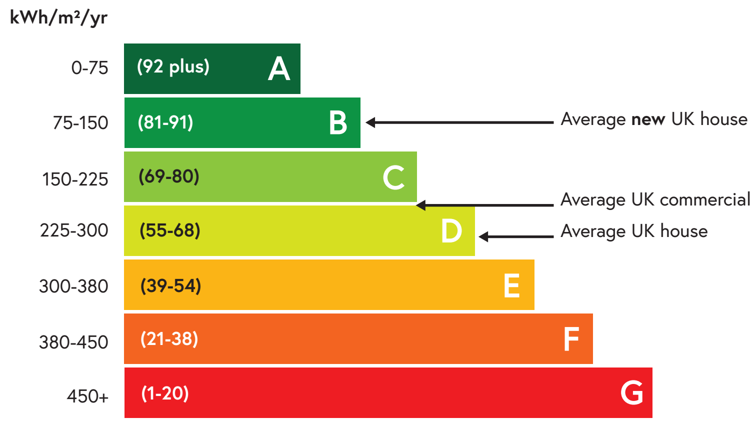


Figure 84 Regulated energy[72], SAP[73] and EPC[73] energy bands, UK houses and commercial buildings. Data: [4.65-4.68]



4.9.2 Low Carbon Heating

- Net Zero requires **complete elimination of unabated fossil gas heating** [4.69].
- There are **multiple pathways to Net Zero for heating** (§3.1.2), generally split between heat pumps, hydrogen boilers and district heating. All of these options require **significant infrastructure changes** [4.70-4.73] and a mix of **situation-dependent solutions** [4.69, 4.74].
- A **heat pump-focused strategy would require 19 million heat pumps to be installed by 2050 – this is 25x the current installation rate** [4.69]. Furthermore, **heat pumps require buildings to have significant energy efficiency improvements** due to their lower output temperature (§3.1.2) and would **significantly increase electricity system demand** (§3.3.1).
- A **hydrogen-focused strategy** would require **modification or replacement of virtually all the UK's gas appliances**, and **widescale modifications to the gas network** (§4.7.2).
- A hybrid approach, including **heat networks in dense urban areas and suitable off-grid locations** [4.71, 4.75], **heat pumps for buildings that can feasibly be made energy-efficient** and hybrid heat pump/hydrogen boilers to **supply winter peak heating in less energy efficient buildings** [4.70] is a low-cost option.
- Such an approach – with varying proportions – is used in **several published Net Zero pathways** (§5.2).

Figure 85 Fuel share by % of heating demand, selected OECD nations. Reproduced from [4.73]

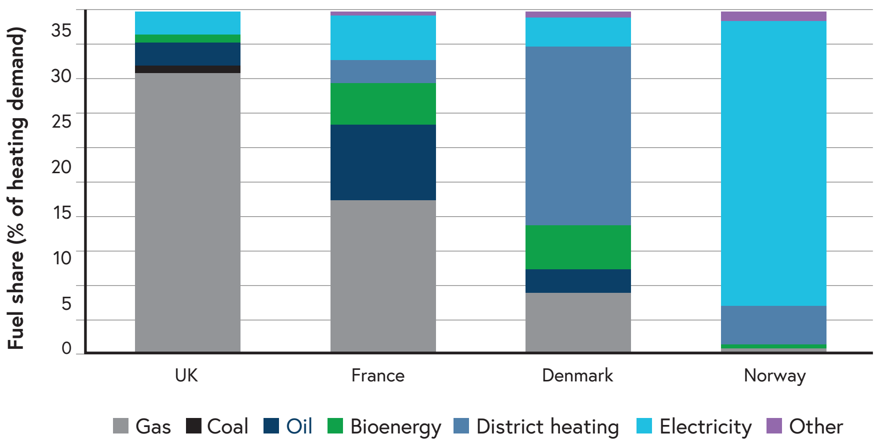


Figure 86 Required vs. actual retrofit annual rate (houses per year) to achieve Net Zero [4.68]

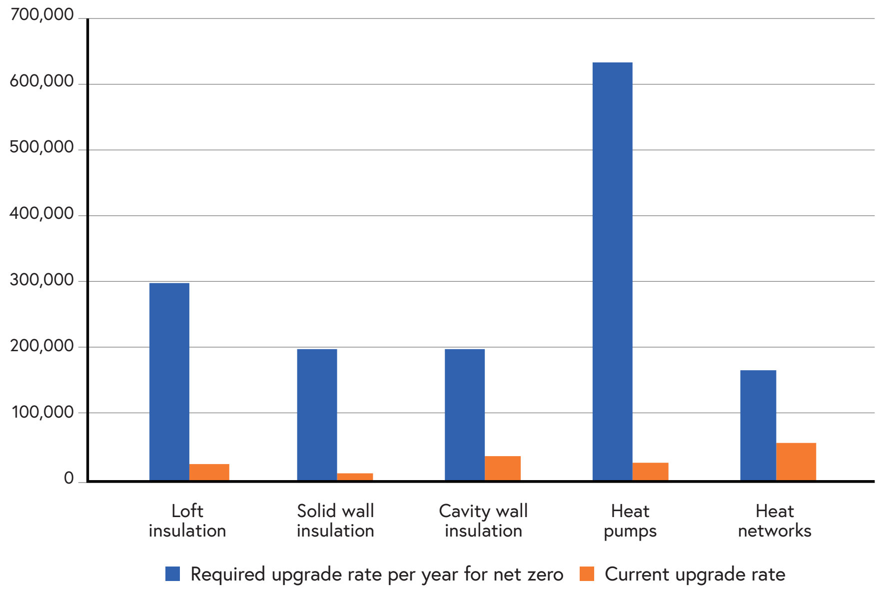
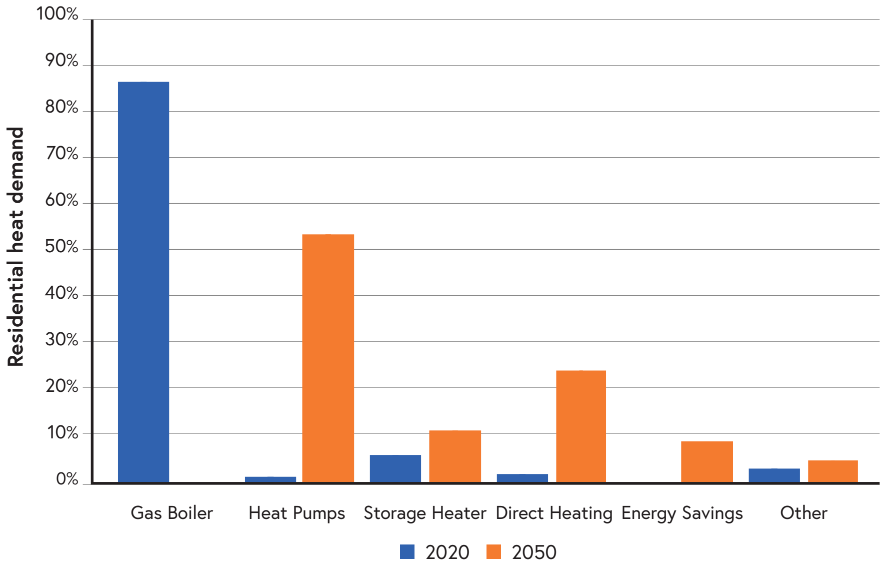


Figure 87 2050 Net Zero housing heating scenario vs 2020 [4.68]



Integrated Generation Offsetting

- Typically **rooftop solar PV**.
- Solar PV output **does not match** with heating demand; this leads to grid imbalances [4.76, 4.77].

Occupant Behaviour

- **Consumer education** in heating controls best practice can improve energy efficiency.
- A **1°C reduction in average thermostat settings could save 5% of housing heating energy** [4.76].

4.9.3 Existing Building Stock for Net Zero

- **Housing energy accounts for 30% of total UK energy demand** and **20% of emissions** [4.77].
- UK **demolition rate for housing is very low −0.04% per year** [4.78].
- The CCC "Balanced" Net Zero pathway (§5.2) requires **all homes to be EPC C rated by 2035**, up from 29% in 2019 [4.79].

75%

Housing energy for heat and hot water [4.77]

80%

2050 housing that already exists [4.66].

Low-Carbon Retrofit Options

- **Energy efficiency upgrades** [4.60]: **insulation** (cavity, solid wall, loft); **glazing**; **air tightness/heat recovery**; **low-flow water devices**; **occupancy controls** (lighting, ventilation) (Figure 88).
- **Low-carbon heating** and cooling (§3.1.2)
- **Integrated generation**: typically a combination of solar thermal (for heat) and solar PV (for electricity)[75].

Building Standards for Deep Retrofits

- **Enerphit** [4.80] is a stepwise retrofit to near-**Passivhaus**[76] standards, in which **flexible solutions** are applied to achieve significant energy savings (**75-90%**) for housing and commercial properties.
- **PAS2035 is the UK standards framework for retrofitting** [4.81].

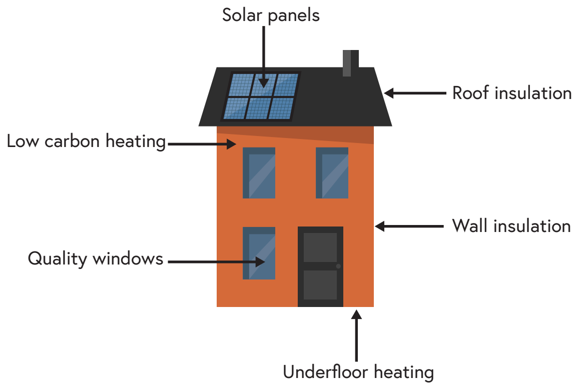
75-90%

Potential energy savings from Enerphit retrofits [4.64].

16-29%

Energy efficiency improvements required in the heating sector for Net Zero (§5.2).

Figure 88 Whole house/deep retrofit visualisation



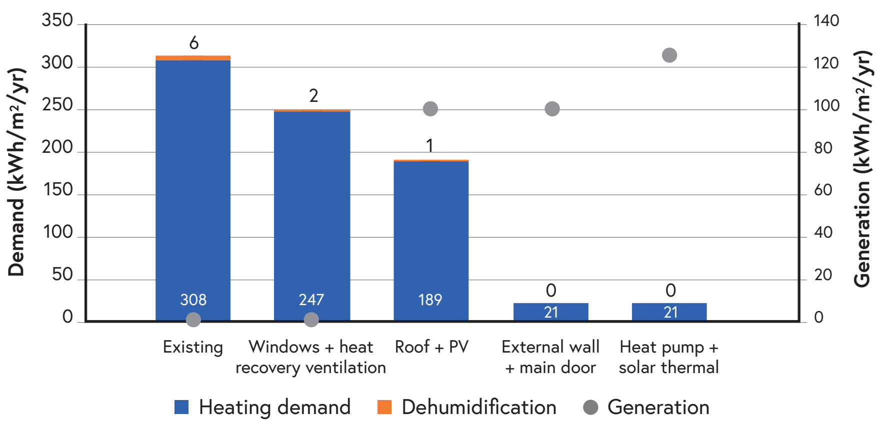
Energy Efficiency Upgrades for Housing

- Energy efficiency upgrades are necessary to (i) **allow direct replacement of a boiler with a heat pump** [4.72, 4.77], (ii) **reduce the impact on the electricity grid** of many houses switching on heat pumps at the same time [4.72] and (iii) **minimise overall costs**.
- Current penetration levels in homes are **70% for cavity insulation, 9% for solid insulation, 66% for loft insulation (35% >200 mm) and 85% for double glazing** [4.80].
- Effective energy efficiency upgrades have potential for a **cost-effective 15% reduction in housing heating energy by 2030** [4.60]. Energy efficiency savings of up to **29%** by 2050 are required by published Net Zero pathways (§5.2).
- Slowing uptake and the **relatively low overall impact** of piecemeal fabric improvements indicates a need to **move beyond individual upgrades** to **high impact whole house low-carbon ('deep') retrofits** [4.77].

Packaged Deep Retrofits

- Packaged deep retrofits are **modularised full-house upgrades**.
- **Energiesprong** is one such scheme, which includes **insulated cladding**, a **heat pump**, rooftop **solar PV** and a **30-year performance guarantee** [4.77].
- Packaged deep retrofits have **high capital costs** and **long payback times** – suitable for **social housing** [4.83].

Figure 89 Stepwise Enerphit retrofit process. Data from [4.82]



4.9.4 New Buildings for Net Zero

- Net Zero compatible new buildings must have a **reduced construction footprint** and **reduced operational energy use**.
- This can be done by **fabric thermal efficiency**, **building form, glazing, passive heat** and **thermal controls**.
- **Low-carbon heating** must be accompanied by **increased renewable energy supply**.
- **Residual emissions** in this sector must be offset elsewhere.

Building Fabric Thermal Efficiency

- Construction elements' **thermal properties are rated by a U-value**[77].
- Building Standards have mandated **increasing fabric thermal standards since 1965** in the UK.
- Since 2006, the focus has been on **overall energy efficiency** with mandatory limits, and **recommended** targets for fabric thermal properties[78].

Construction Emissions

- **Lifecycle emissions** of construction come from **material extraction, manufacturing, transportation, assembly, maintenance, replacement, demolition** and **disposal** [4.84].
- Construction is responsible for **65-70%** of lifecycle emissions for **new-build high energy efficiency offices, warehouses** and **houses** [4.85] – with **materials** (mostly **steel and concrete**) dominating [4.84].
- Construction's overall **impact must be considered for retrofit vs. rebuild** decision making [4.86].
- Current building standards **do not** account for embodied carbon, and assessment is difficult [4.87].

Ventilation & Heat Recovery

- **Building Standards** and **Passivhaus** target **higher air tightness** to minimise heat loss.
- **Forced ventilation** may be required for comfort in buildings with low natural ventilation.
- Heat in the vented air can be **recovered** using a **heat exchanger to heat incoming air** [4.88].

Building Standards

- Current basis of UK building standards only includes **regulated** energy[72].
- **Minimum fabric standards have not improved since 2010** and only **marginally from 2002**.
- Passivhaus standards [4.88] enforce a **stringent heating demand target (<15 kWh/m^2/year)** and includes **unregulated** energy requirements.

Passivhaus

- **Passivhaus** is a voluntary **design and certification process** for new buildings from the Passivhaus Trust to achieve **very low energy buildings** [4.88].
- The process focuses on **minimising heat losses** and the use of **natural solar heating**, with **performance certified** on completion.
- **40%** of potential CO_2 savings are lost if **high energy efficiency standards** (e.g. Passivhaus) are not used in place of current buildings standards (Figure 91) [4.91].

The 'Performance Gap' of New Builds

- **Most new-build buildings have been found to not comply with standards** and design specification for energy and carbon emissions [4.91].
- Energy use for **housing** has been on average **60% higher than design** – but up to 147% in Passivhaus and 241% in non-Passivhaus [4.90].
- Emissions from **commercial buildings** have been on average **3.8x higher than in design targets** [4.89].
- Low compliance can **challenge the performance of low temperature heating** systems [4.66, 4.91].

Low-Carbon Heating for New Buildings

- The **new-build heat strategy** should be **consistent** with the **overall** heat strategy.
- New buildings have a **greater flexibility** than existing buildings **to have individual heat pumps** or **be integrated with heat networks, if designed for** [4.60].
- **Heat Pumps** will provide a **90% CO_2 saving** compared to a gas boiler over 50 years as a result of **increasing grid decarbonisation** [4.91]. **50%** of the **potential CO_2 savings** are lost if heat pumps are only retrofitted in 2030 (Figure 91).
- The implementation of **low-carbon heating** for new buildings is the **most effective option** to support the **overall Net Zero strategy** [4.91].

Offset Residual Emissions ('Allowable Solutions')

- Where **carbon reduction targets** for new buildings cannot be **cost effectively** achieved by installed solutions, this can be mitigated through **mandated indirect funding** of **remote, grid-scale decarbonisation projects**. This is known as **'Allowable Solutions'** [4.92, 4.93].
- The UK Government decided to scrap the zero carbon buildings standard in 2016, removing the requirement to offset residual emissions from new-build homes. [4.93].

Figure 90 Domestic Building Standards U-value requirements [4.87, 4.89]

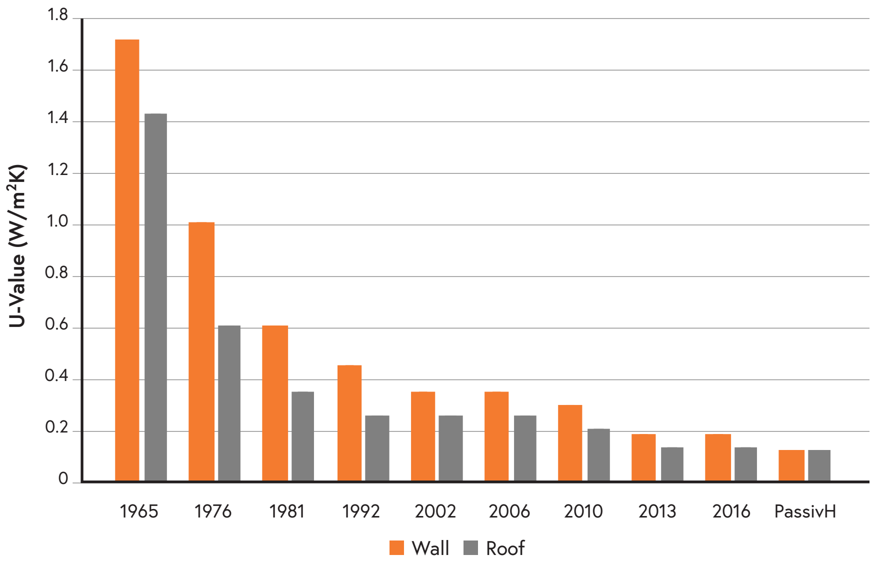
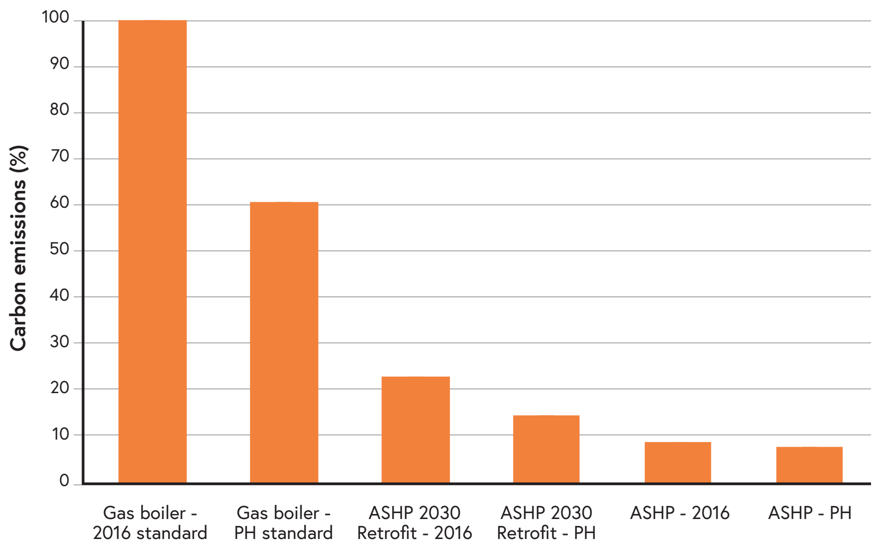


Figure 91 CO_2 emissions for 2016 Building Standard and Passivhaus for Gas Boiler, ASHP and Boiler replaced by ASHP in 2030 [4.91]



4.10 Carbon Capture, Utilisation and Storage (CCUS)

4.10.1 Carbon Capture & Utilisation (CCU)

- Carbon Capture & Utilisation (CCU) involves **capturing carbon dioxide** and **using it in a process**.
- Unlike Carbon Capture & Storage (CCS), the purpose of CCU is **not to remove CO_2** from the atmosphere permanently.
- While development of CCU may **help facilitate CCS technologies**, CCU itself is expected to remain niche in its applications [4.94].
- CCU is already practised on a small scale, as it offers **commercial advantages** to some industries.
- As the demand for CO_2 is much smaller than our rate of production, **quantities of CCU are likely to remain far smaller than those contemplated for CCS.**

Some Potential Uses of CO_2

- **Chemical** and **polymer** manufacturing.
- **Synthetic fuel manufacturing**: carbon can be combined with hydrogen to **manufacture energy-dense fuels such as kerosene and methane**. These could be used in **aviation** and **shipping (§4.5.4).**
- **Construction materials manufacturing:** CO_2 can be used to produce limestone aggregate for construction [4.94]. This **stores CO_2** and **displaces emissions** in the sector.

Figure 92 Clockwise from top: polymers; agriculture; cargo shipping. All are potential end uses of CO_2. Sources: [4.95-4.97]

Case Study - Maersk

- **Shipping giant Maersk** proposes to investigate the use of **synthetic methanol** – using **CCU and low-carbon hydrogen** – as a potential low-carbon fuel for shipping and aviation [4.98].

4.10.2 Carbon Capture & Storage (CCS)

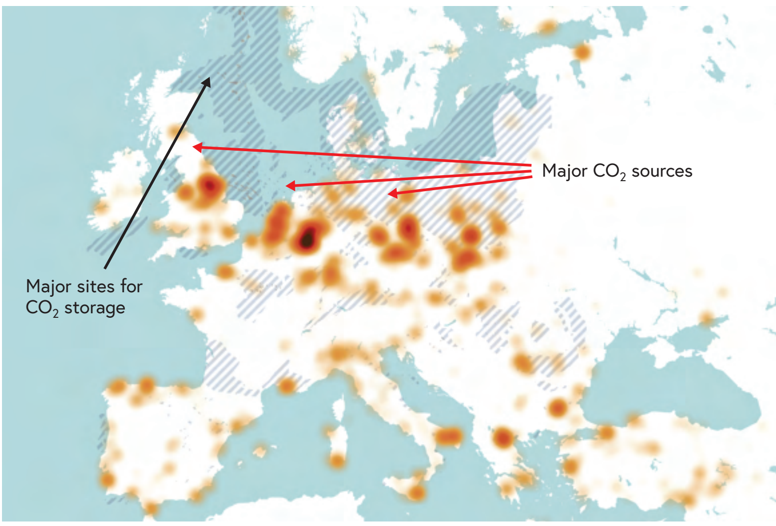
- Carbon Capture & Storage (CCS) involves **capturing carbon dioxide** and **depositing it at sites where it is to be stored indefinitely**.
- There are **5 large-scale CCS projects** worldwide. The first was built **in 1996 off the coast of Norway** [4.99].
- Similar operations have been used in the oil industry – injecting CO_2 into oil wells for **enhanced oil extraction** (EOR) – since the 1970s and 1980s. There are **13 large EOR projects**[79]; most are in the USA [4.100, 4.101].
- **All CCS** and **most EOR projects** received **financial and/or policy support** from their **governments** [4.99].
- **2 storage sites** are under the **North Sea**, both off **Norway**: Sleipner and Snøhvit [4.98, 4.99].

CO_2 Storage Locations

- In Europe, the main potential carbon storage sites are under the North Sea [4.98, 4.99].
- Estimated **UK storage capacity is up to 20 GtCO_2** in old oil fields and **~78 GtCO_2 in total** [4.102] – around **200 years' worth of CO_2 emissions at 2019 levels.**
- All UK CCS storage sites would be **offshore and under the North Sea** or **Irish Sea** [4.101-4.103].

Figure 93 Norway's Sleipner oil field and CCS site. Source: [4.101] courtesy of Statoil/Equinor

Figure 94 Map of CO_2 sources and potential geological sources in Europe. Source: [4.104]



Chapter 4 – Energy Infrastructure for Net Zero

UK Proposed CCS Projects

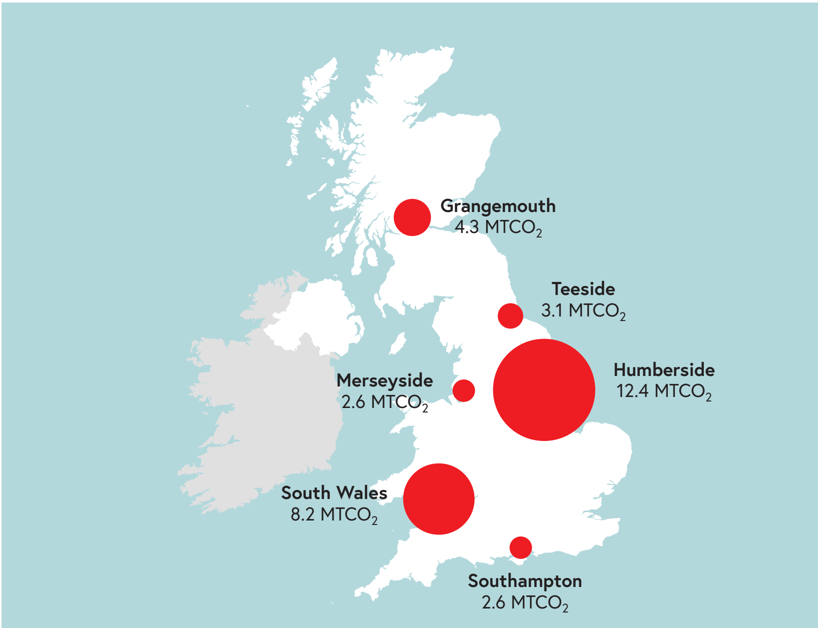
- CO_2 will be collected from **industrial hubs** (Figure 95) – **heavy industry** and **power stations.**
- CO_2 will be **transported** by **pipeline** or **ship** to North Sea storage sites.
- **Existing oil & gas pipelines will be used** to transport CO_2 where possible [4.105, 4.106]

There are **three methods to capture CO_2 from industrial processes and power generation (Figure 96).**

Post-Combustion Carbon Capture

- CO_2 is **captured from exhaust** gases, usually by a **solvent**.
- This is the **main technology used for CCS** today [4.100].
- It can be applied to existing combustors as a **retrofit**.
- **Approx. 10-15% of the energy generated** from combustion is needed for the CCS process.
- CO_2 capture rates of **85-90%** are aimed for [4.100, 4.104].

Figure 95 Proposed UK industrial hubs for CCS. Source: [4.101] (note that this is missing the proposed CCS scheme at Peterhead)[80]



Pre-Combustion Carbon Capture

- Fossil fuels are **broken down** into carbon and hydrogen; the **carbon is removed** before combustion (§4.5.1)
- Hydrogen is burned in air, which **does not produce CO_2**. This requires **a hydrogen-ready combustor**.
- CO_2 capture rates are **60-90%** [4.104]. Alternative plant designs could **achieve 95%** [4.15].

Oxy-fuel Carbon Capture

- The fuel is burned in **pure oxygen**. **Requires a combustor designed for oxy-fuel combustion**.
- The resulting exhaust gases have a much **higher CO_2 concentration**.
- **CO_2 capture rates can be very high** due to **near-pure stream of CO_2** (removal of sulphur and water is required).

Bioenergy with CCS (BECCS)

- BECCS is based on **burning biomass** (derived from plants or waste) as a fuel and **capturing the CO_2 at the source**.
- Compared to DACCS, **CO_2 concentration is much higher**, which makes **capture easier** and less energy intensive.
- BECCS relies on a source of **sustainable biomass** (§4.5.2).

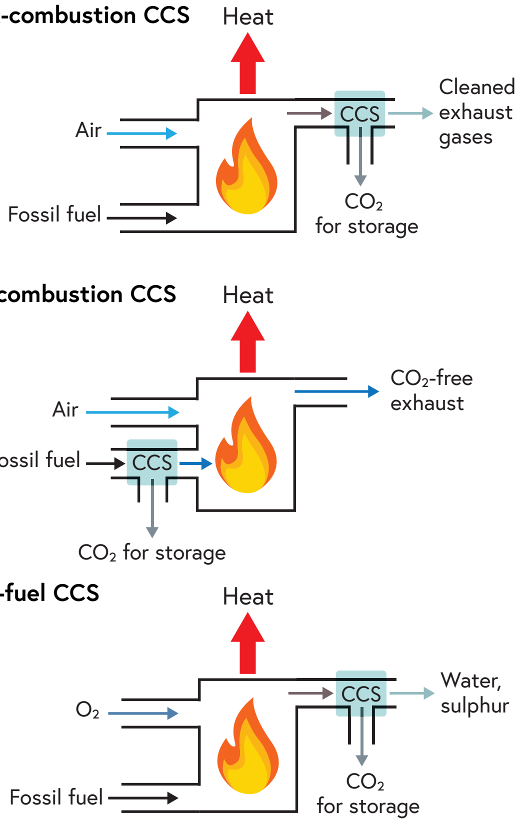
CCS for Residual Emissions

- CCS facilities could **reduce CO_2 emissions** from some industrial clusters.
- Emissions would **continue** as i) CCS is **not complete** (60-90% of CO_2 is removed at present); ii) CCS requires energy input, which would require **additional fuel use**; iii) there are emissions from fuel supply chains [4.100, 4.101] (§4.2).
- The CCC and the IEA **believe CCS is needed** to meet Net Zero [4.104, 4.107]
- UK Government is providing **funding for CCS demonstration projects** [4.108].

Direct Air CCS (DACCS)

- CO_2 is captured directly from the air by chemical reaction.
- This is a **negative emissions** technology which **does not rely on sustainable biomass or significant land use**.
- DACCS is a **major part of the UK's Net Zero pathways** [4.107].
- Because the CO_2 concentration in air is low, the **energy demand of DACCS is significant**[81].

Figure 96 Post-combustion CCS (top); pre-combustion CCS (middle); oxy-fuel CCS (bottom)



4.11 Energy Storage

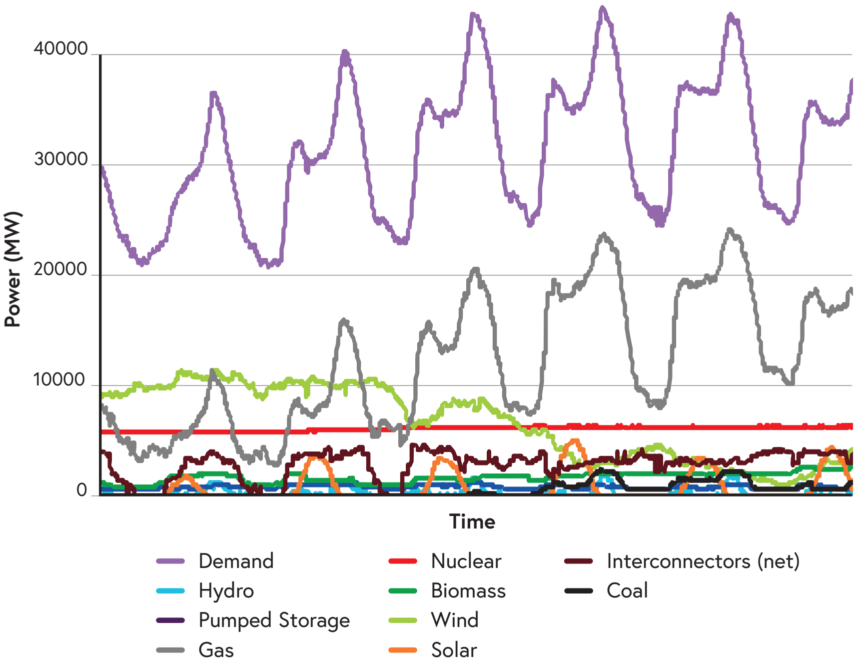
4.11.1 Electricity Storage

- As the output of most UK renewable resource is **variable**, the ability to **store electrical energy to use later** is a key technology to moving towards a Net Zero electricity system.
- Electricity storage is required **at different timescales**, from **fractions of seconds** to the **changing of seasons**.
- Storage must have enough **energy capacity** to meet our requirements at times of low renewable resource, and enough **power capacity** to be able to deliver that energy quickly enough.
- There are **different technologies** available for electricity storage, each of which are well suited to operating at particular **physical** and **time scales**.

The Need for Storage

- National Grid ESO operates the GB electricity system to **ensure demand and generation are matched continuously**.
- When renewable resources drop (the right-hand side of Figure 97) **gas plants pick up the slack**.
- **Some energy is stored** as **inertia** in **spinning generators** that can be released very quickly and is useful in helping to stabilise the power system after disturbances.
- On longer timescales, **storage can enable renewable generators to meet demand**.
- **Demand side management (DSM)** can be used to shift flexible demand (§4.4.3) – **effectively 'storing' demand** for electricity for another time.

Figure 97 GB transmission-connected electricity demand and generation mix, 31 October-6 November 2020. Data from [4.109]



Battery Storage

- **Different battery types are used at different scales** due to trade-offs in their cost, energy and power density.
- **Grid-scale batteries** (~10 MW) are being trialled in the UK for **intra-day storage** and **grid services**. [4.110].
- EVs have the potential to provide **widespread domestic storage** in the UK. An EV's battery **has enough capacity to meet a typical UK household's electricity demand for 5 days**[54], and when amassed together, EVs could provide **frequency support** to help **stabilise** the grid.

Supercapacitors

- Supercapacitors are **high-capacity capacitors** (a fundamental building block of electronic circuits).
- They can deliver power **rapidly** but have **limited energy capacity.**

Compressed Air Storage

- Compressed air storage systems pump air into **underground cavities** like disused mines.
- **The air can drive turbines on its exit** to generate electricity when needed[82].
- They are used for **short-term** energy storage.

Flywheels

- Flywheels are spinning discs that are **sped up** using excess electricity.
- They are coupled to a generator to produce **electricity when needed**.
- They face **few geographical constraints**.
- They offer very **short-term** storage.

Pumped Hydro and Other Gravitational Storage

- Pumped hydro storage (Figure 98) pumps water **uphill** when demand is low and **generates** when demand is high.
- Pumped hydro represents **99% of electricity storage in** Europe [4.111]. There are **four** pumped hydro schemes in Britain, all 40-50 years old and built into **natural mountainsides**.
- They are designed for **short-term** storage (seconds to hours) of electricity and are called upon to balance supply and demand.
- There are other gravity-based electricity storage techniques under development[83].

Chemical Storage: Hydrogen & Ammonia

- With large-scale renewables deployment, there are times where **available generation far outstrips demand**.
- **Currently, generation is curtailed** during these times (generators are required to turn down their output).
- Alternatively, excess renewable generation could be used to produce **hydrogen by electrolysis of seawater, ammonia from hydrogen and air** or **synthetic hydrocarbons from hydrogen and carbon** (§4.5).
- These fuels could be used as **long-term fuel stores** for **electricity generation** (either gas turbine or fuel cell) for use when electricity demand is high, or as **zero-carbon fuels** in the difficult-to-decarbonise **shipping** and **aviation** sectors.

Thermal Storage

- Thermal storage systems use excess electricity to **heat a material** – this can be **volcanic stones** or **molten salts** [4.112].
- By keeping the material in a **well-insulated container**, the **heat can be largely retained**. When it is needed, **the heat can be used to drive a steam turbine** attached to a generator.
- Thermal storage can also be used for the storage of **heat** (§4.11.3).

Costs of Electricity Storage

- Costs of storage technologies are **not easily compared** as they **operate at different timescales**, providing different services to the energy system: for example, **supercapacitors provide the grid with millisecond-by-millisecond stability; power to hydrogen provides seasonal bulk energy storage**.
- Costs of these technologies, with the exception of pumped hydro being the only mature storage technology, are also expected to **fall significantly** [4.115].
- There is **no 'one' storage technology**: all the technologies covered in this chapter have an important role to play in **maintaining security of supply** in a Net Zero electricity system.

Figure 98 Pumped hydro storage

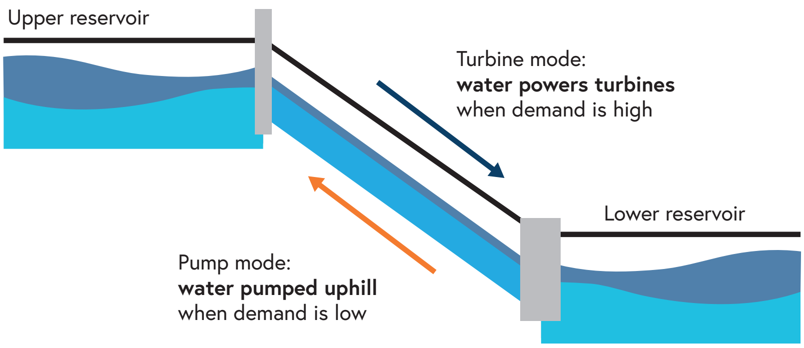


Figure 99 Potential long-term storage of electricity as hydrogen/ammonia/synfuel for transformation back into electricity or as transport fuels

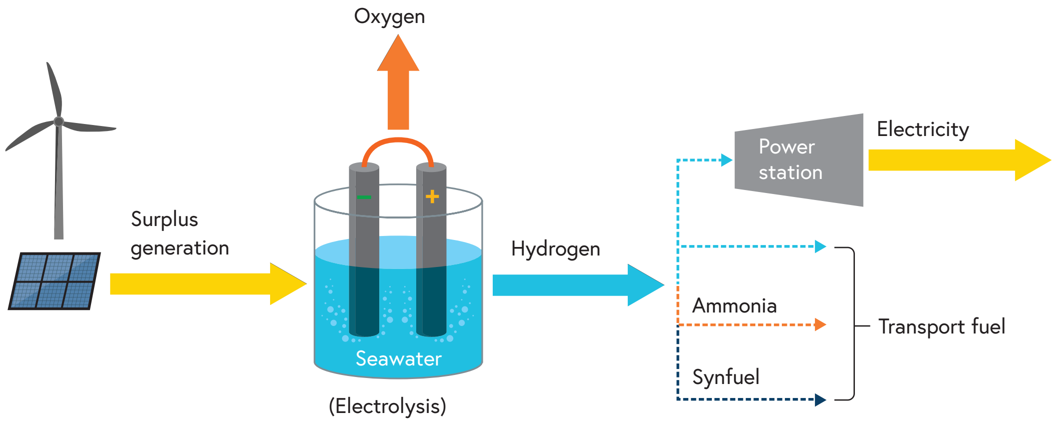


Table 3 Comparison of selected grid-scale electricity storage technologies by roundtrip efficiency (electricity to electricity), timescale of storage provision, cost and constraints/limitations[82]. Data from [4.113-4.115]

Technology	Roundtrip efficiency (electricity → electricity)	Timescale suitability	Constraints/Limitations
Lithium ion batteries	85-95%	Milliseconds → hours	Batteries requires resources (such as cobalt and lithium) whose supply chains tend to be GHG-intensive with negative impacts for biodiversity and human toxicity[84].
Flow batteries	60-85%	Milliseconds → hours	Requires more space than solid batteries; for some types, scarcity/cost of resources and toxicity of components (e.g. vanadium, bromine).
Supercapacitors	95-98%	Milliseconds → seconds	Few space limitations; limited energy capacity, used for rapid delivery of relatively small amounts of energy.
Compressed Air	55-70%	Seconds → days	Requires large underground air-tight caverns (e.g. salt caverns). The UK does have significant salt deposits that could be used to create ~1 TWh of compressed air energy storage.
Flywheels	70-95%	Milliseconds → seconds	Few space limitations.
Pumped Hydro	75-85%	Seconds → hours	Geographically constrained to mountains with lakes at the top and the bottom, or bodies of water separated by hundreds of vertical metres have to be made.
Hydrogen/ derived fuel (e.g. ammonia)	25-45%	Seasonal	Hydrogen could be made from any water source; to ease pressure on water resources, electrolysis of seawater is the most suitable.
Thermal	60-70%	Hours	Few space limitations; high temperature (>300 °C) or cryogenic (<-100 °C) operation.

4.11.2 Gas/Hydrogen Storage

- There are **sizeable gas stores within the gas grid infrastructure** in Britain.
- These stores complement the supplies the gas grid receives from North Sea gas fields and shipments of liquefied fossil gas (LNG).

Seasonal Storage

- GB **gas consumption** is ~**3-4 times higher in winter than in summer** (Figure 104).
- **Seasonal storage** helps to meet the **higher demand for** gas **in winter.**
- Seasonal gas stores are in **geological sites** (salt caverns and spent oil & gas wells) and also at **LNG storage sites** [4.120, 4.121].
- Total storage capacity of seasonal stores is **~30,000 GWh** of fossil gas.
- During 2018-2020, the quantity of **stored gas has fluctuated, between** around **5,000 GWh and 28,000 GWh.** Larger quantities were stored at times during previous years, using a storage site since decommissioned [4.119, 4.121].
- During the **'Beast from the East'** cold weather event in March 2018, **gas stores plummeted to 5,000 GWh,** around **one day's gas demand at the time** [4.119].

Within-Day Storage

- National Grid varies the ***linepack* – quantity of gas in the pipework – by increasing the pressure in** the gas transmission **pipes overnight**, ready for a steep rise in demand in the morning [4.116, 4.117].
- The gas transmission **pipework contains** around **300 GWh of useable storage capacity** [4.117, 4.118].

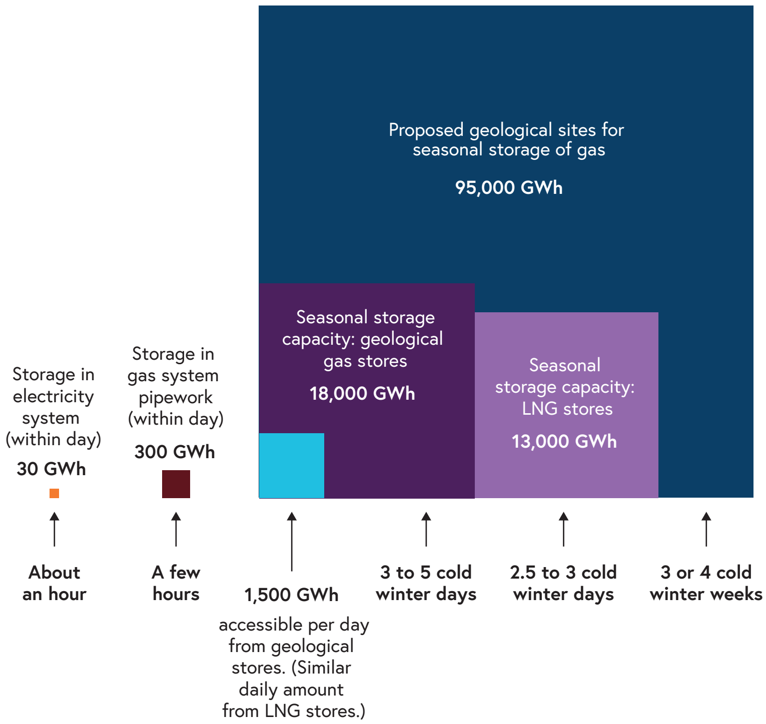
Energy Storage in GB Gas vs Electricity Systems

- Total GB gas storage is **around 1000 times** greater – in terms of energy – than GB electricity storage (Figure 100).
- The **within-day storage** in the gas system (linepack) holds **around 10 times more energy** than electricity system stores (pumped hydro).
- These gas stores support **far greater** daily and seasonal **peaks in demand for gas**, compared to electricity (Figure 104).
- National Grid **proposals for expansion** in seasonal storage sites could **more than triple** GB **seasonal gas storage** [4.120].

Future Hydrogen Storage in the Gas Grid

- **Substantial quantities of hydrogen could be stored** in a similar manner to existing storage of fossil gas.
- Exact **quantities of hydrogen** stored **would depend on what kind of future gas grid** we choose to build (§4.7.2) – to what extent the **transmission grid is retained/upgraded**, and what **pressure** it would operate at.
- **Hydrogen is less energy-dense** than fossil gas by volume. Therefore, if the existing mains gas storage spaces held hydrogen instead of fossil gas at the same pressure, the **energy stored would be lower, by a factor of 3-4.** Additional short-term storage facilities may be required**.** [4.41, 4.123].
- **Additional storage could be built if needed** using geological sites and/or tanks.
- Other options include storing hydrogen i) at much **higher pressure**, ii) as **a liquid** or iii) converting the hydrogen to **ammonia.** (These options involve **additional energy demand**.)

Figure 100 Current energy storage in GB mains gas & electricity systems. Data from [4.118-4.122][85]



4.11.3 Heat Storage

- Heat storage can be **sensible** (no change of state), **latent** (change of state – typically solid/liquid) or **thermochemical** (which uses a chemical reaction to store energy).
- **Sensible** options include hot water tanks, pit/aquifer/borehole storage, electric storage heaters, seasonal ground injection and fabric integrated storage.
- **Latent** options include phase change material (PCM) and fabric integrated storage.

Electric Storage Heaters

- Electric storage heaters **combine heat supply and storage**.
- They are typically **charged off-peak** (at night) and can **hold their heat for more than 24 hours**.
- They have potential as **flexible storage** using **surplus renewables** [4.124].
- Their **efficiencies are much lower than HPs** (COP≈1 vs 2.5+), so **running costs are higher**.

Latent Heat Storage

- Latent heat storage uses **reversible phase changes** to store heat energy.
- They have a **much higher (3-5x) energy density** than that of sensible heat storage [4.126].
- A range of suitable **organic and inorganic materials can be used** (e.g. paraffins, salt hydrates, fatty acids) [4.126].

Thermochemical heat storage

- Thermochemical heat storage uses a **reversible exothermic**[86] **and endothermic**[86] **chemical reaction** to store energy.
- Examples include **steam methane reforming** and **ammonia dissociation**.

Fabric Integrated Storage & Building Thermal Mass

- Thermal storage can be part of a **building structure**, either integral or via integrated storage [4.127].
- This can be **passively heated by a variable source** (e.g. solar heat) or **actively heated using a standard heat source** (e.g. heat pump) and can **provide a slow release of stored heat to match demand**.
- Fabric Integrated Storage can also form a natural part of the building structure using **high thermal mass structural materials** (examples include stone, rammed earth, water and concrete).

Heat Storage for Net Zero

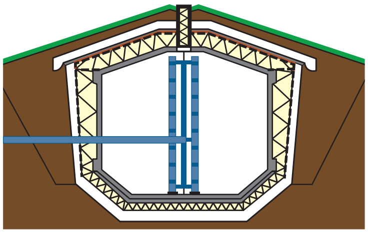
- Heat storage can store **surplus renewable energy** for future heat demand.
- **Seasonal** storage of heat from the summer for use in the winter is possible.
- Lowest-cost Net Zero modelling recommends **prioritising thermal storage** (>650 GWh compared to <50 GWh of electricity storage) (Figure 102).

Table 4 Summary of heat storage technologies. Data from [4.128-4.130]

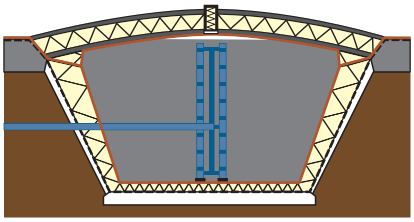
Technology		Advantages	Barriers	Efficiency	Compatibility	Application	Duration[87]	Market
Sensible	Hot Water Tank	Mature, scalable, cost-effective, thermal capacity	Capital cost, space, heat loss	50-90%	All sources	District heat, residential, commercial	Short-medium	Mature
	Pit	Large capacity, cost-effective	Land availability	<80%	Solar thermal, district heating	Commercial	All	Limited
	Aquifer	Large capacity, cost-effective	Location-specific	70-90%	GSHP, waste heat, CHP	District heat, commercial	Long	Limited
	Borehole	Scalable, expandable	Low capacity, duration to operability	40%	Solar thermal, GSHP, CHP, waste heat	District heat	Very long	Limited
Latent	Phase change material (organic)	High heat-to-volume ratio, easier to package	Cost, flammability	75-90%	All sources	District heat, residential	Daily	Proto-types
	Phase change material (inorganic)	High heat-to-volume ratio, low cost	Harder to package	75-90%	All sources	District heat, residential	Daily	Proto-types
	Thermo-chemical	Compact	Unproven	>90% (in theory)	Industrial waste heat	District heat, commercial	Daily	None

Figure 101 Large-scale sensible heat storage options with heat densities. Source: [4.125]

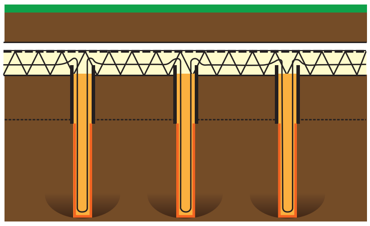
Tank thermal energy storage (TTES)
(60 to 80 kWh/m³)



Pit thermal energy storage (PTES)
(60 to 80 kWh/m³)



Borehole thermal energy storage (BTES)
(15 to 30 kWh/m³)



Aquifer thermal energy storage (ATES)
(30 to 40 kWh/m³)

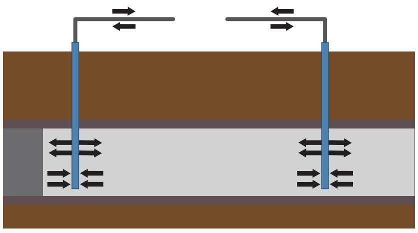
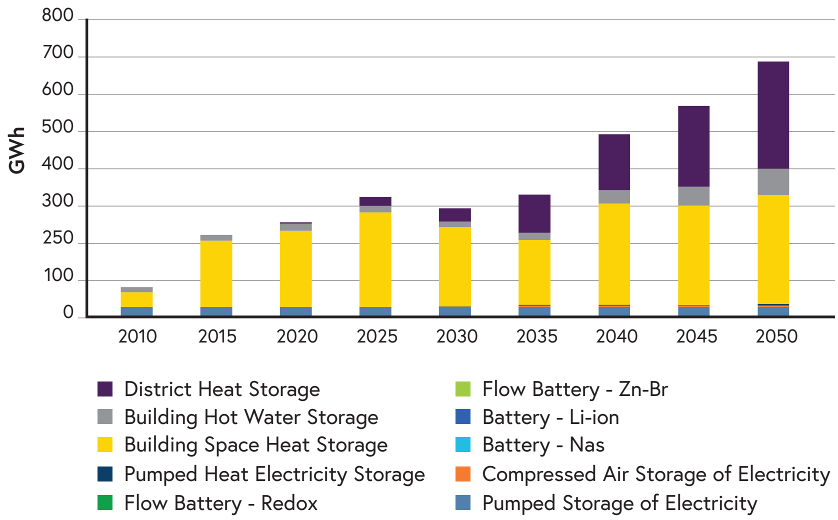


Figure 102 Path to Net Zero by 2050 with key thermal storage contributions. Source: [4.130]



650 GWh

Equivalent to ~8 hours average UK heat demand and 9.3 million m^3 of hot water storage at 80 °C.

Seasonal Storage

- **Summer solar energy can be stored** to provide winter heating demand when solar output is low (Figure 103).
- **GSHPs can reinject heat into the ground** during summer to increase output efficiency in winter.
- Seasonal heat storage requires **very large storage volumes** and **effective insulation**.
- Alternatively, energy can be stored **chemically (e.g. as hydrogen)** and used to **generate heat when needed**.

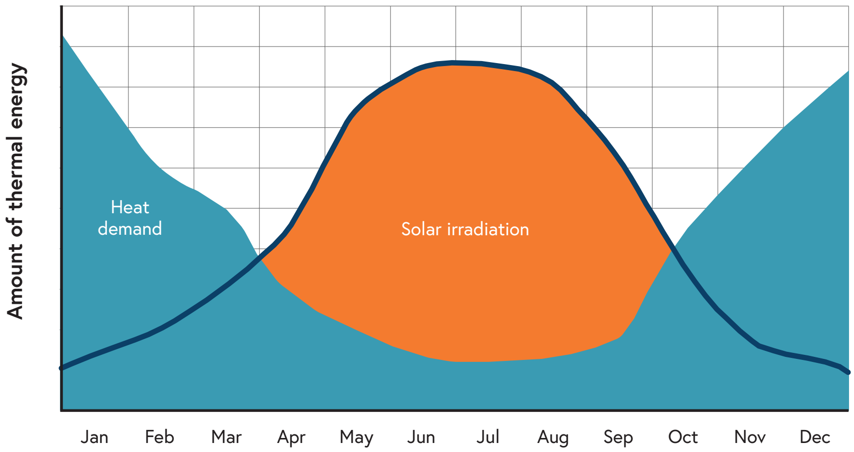
Technological Maturity

- Many heat storage technologies **have been around longer** and have more **mature markets** than electricity storage technologies [4.133].
- **Heat storage** can complement electricity storage and gas/hydrogen/fuel storage in a Net Zero energy system [4.133] (§5).

Sizing/Storage Cycle Duration[87]

- Determined by **source/surplus availability, time to charge** and **time to discharge**.
- Heat storage economics improve significantly with **scale** [4.131].

Figure 103 Indicative relative solar output vs. heat demand. Source: [4.133]



4.12 Chapter 4 Endnotes & References

4.12.1 Endnotes

[31]Contracts for Difference (CfD) is a UK Government policy instrument (part of the Electricity Market Reform) introduced in 2014. CfDs are intended to encourage the provision of low-carbon electrical generation, by guaranteeing low-carbon generators a sale price for the electricity they generate. CfDs set a fixed price at which eligible generators (such as offshore wind and nuclear) will be paid at a fixed price per unit of energy over the 15-year course of the contract, the aim being to minimise risk of investment. If the open market price of electricity dips below the CfD 'strike price', then the generator is paid extra to make it up to the strike price. If the market price rises above the strike price, then the generator pays out to make up the difference. CfD auctions are run approximately every two years (there have been three to date – 2015, 2017 and 2019, with the next due for 2021) and during the auctions, generators will bid to provide energy at the lowest price. Once all the energy in the auction is acquired, the 'strike price' (the price all generators in the scheme will receive) is the price of the last unit of energy acquired. While 'mature' renewable generation technologies (notably onshore wind and solar) have been excluded from CfD auctions so far, they are to be included in the next CfD auction in December 2021.

[32]Solar energy incident on the Earth's land area is approximately 1,068,720,000 TWh over the course of a year – around 7,000 times greater than global energy (i.e. not just electricity) demand. Given that solar PV cells can convert around 20% of this energy into electricity, global energy demand in 2019 could be met by covering 0.07% of the world's surface in solar panels: an area 228 × 228 miles [4.12]. These numbers mean that on a global scale, solar generation (both PV and concentrating solar power (CSP)) could have an enormous contribution to energy system decarbonisation. While the UK lacks in sunshine and has a high population density, there are countries with large swathes of empty, unproductive land (desert). Furthermore, many of these countries are oil-exporting nations, and the potential to use solar generation as a means to produce zero-emission fuels (e.g. hydrogen and synfuels) enabling the Net Zero transition could offer sources of income as the world halts fossil fuel extraction.

[33]Tides are in a constant cycle with the moon and its position relative to the Earth and the sun. The incoming (flood) and the outgoing (ebb) tides switch over every 12 hours 25 minutes – as it takes around 24 hours 50 minutes for the moon to orbit the Earth. Spring tides – where the difference between high and low tides (and hence the energy available) is greatest – happen at new and full moon. Neap tides – where this difference is at a minimum – happen at quarter moon. There are two spring and two neap tides each month.

[34]A large barrage across an estuary such as the Severn would alter the difference in height attained by the tides, the level of silt that builds up and the movements of many species that live in these areas. On the other hand, a tidal lagoon is designed to alleviate these concerns by not damming off the estuary, but creating a separate 'pond' along the coast of an estuary.

[35]Some lagoon concepts have two ponds; one 'high' and the other 'low'. This enables the operator to pump water from the low to high during times of low demand, and generate as the water is allowed to flow from high to low when demand has increased. This enables 'scheduling' of tidal power generation, and also allows it to act as a form of pumped storage.

[36]CfDs in Britain to date have had different categories (and different pots of funding) for different types of generator, with the least mature technologies (wave and tidal) receiving greater support than more established types of generation.

[37]These criteria include i) land use criteria, which focuses on the land from which the biomass/biogas/bioliquid is sourced and ii) greenhouse gas criteria, which account for the life cycle emissions of the bioenergy source. The development of the land and GHG criteria has come from the requirements imposed by the European Commission via the Renewable Energy Directive (RED).

[38]This is based on analysis in [4.19], based on a 'standard fission reactor'. Improvements of roughly 60x can be made to the 'burn rate' of nuclear fuels if used in a breeder reactor. These reactors 'breed' more fissile fuel as the reactions progress, which results in smaller amounts of waste and higher amounts of energy per kg of fuel. Fast breeder reactors have not become widespread mainly due to fears of nuclear proliferation; they require fuel with higher enrichment, and their 'bred' products include plutonium, which can be used to make nuclear weapons.

[39]This is based on deuterium fusion, from analysis in [4.19].

[40]The output power of a nuclear reactor can be adjusted by changing the volume of steam that enters the turbines, or by altering the position of control rods, which change the reactivity of the fission reactions in a similar way to how adjusting the flow of gas into a gas-fired power station will reduce its thermal power output. However, if the reactor's output is reduced past around 80% of its rated output, fission products build up in the core as they are not burned off (this is known as reactor poisoning). When this happens, the operator must wait some time (typically days) for these fission products to decay before ramping power up again in a safe manner. While there are many possibilities regarding advanced reactor architectures and fuel types that can enhance the flexibility of nuclear [4.134], flexible nuclear operation is not as simple as flexible gas plant operation: operators can't flex power output as much toward the end of the fuel cycle and it takes a lot of planning, forecasting and time to decrease the power output [4.135]. In countries where nuclear constitutes a majority of the generation mix (like France), nuclear power stations are operated with a degree of flexibility as the larger fleet size places less of an onus on individual plants to sharply reduce their output – though even in the case of France, where nuclear comprises the vast majority of electricity, some flexible gas-fired plant is generally also required to cater for sudden rises and falls in demand. In the UK, where nuclear has historically constituted a more modest portion of the generation mix, they are generally allowed to run at full output all of the time. This is more a question of economics than of engineering; the most significant cost of nuclear is building (and decomissioning) a nuclear power plant – by running it at full output, the plant developer knows that they can recover these costs. To increase the flexibility potential of nuclear power in the future, a large fleet of small modular reactors could be built (so each reactor could be operated 'flexibly' within 80-100% of its rated output, thus avoiding reactor poisoning) or nuclear power could be used for co-generation: when the electricity from the power station is not required for consumption, it could be used to provide other energy-intensive services including the production of hydrogen from electrolysis, direct air capture of CO_2 and seawater desalination [4.136].

[41]Deuterium (a.k.a. 'heavy water') is an isotope of hydrogen (i.e. it is hydrogen, but with a neutron included in its nucleus), and constitutes 0.015% of natural hydrogen. Furthermore, it can be extracted inexpensively from seawater. Though deuterium-deuterium (D-D) fusion is possible, positive-energy fusion has only ever been achieved using deuterium-tritium (D-T) reactions (tritium is an isotope of hydrogen with two neutrons). Tritium can be 'bred' within a fusion reactor from lithium. For more information on fusion energy, see [4.137].

[42]Hydroelectricity extracts energy from the flow of water as it runs from hills down to the sea. Therefore, it requires rainfall and altitude – hydroelectricity output varies year to year as a result in changes in rainfall. In [4.21], analysis suggests that even if 20% of the UK's 'high land' in Scotland, North Wales and Northern England were dammed for generating hydroelectricity, its output would amount to less than 0.8% of UK energy demand.

[43]There are large deposits of radiothermal granite in the UK, particularly in South West England (Cornwall and Devon). While residents of these areas may be familiar with warnings regarding radon gas seeping into cellars, the heat produced by radioactive decay within the rocks is significant, with large patches of rock over 100 °C less than 5 km deep. Tapping this reserve and using the heat to power steam turbines could produce the 100 MW of generating capacity stated in [4.20]. While this is still small and geothermal generation does not have the potential to be a significant part of the UK energy mix, it does have enormous potential in other parts of the world (Iceland, New Zealand, Italy, Turkey, Japan and parts of the USA, for instance).

[44]Two related studies of whole life cycle emissions from onshore and offshore windfarms in Scotland are available for further reading [4.138, 4.139]. They include a brief comparison of whole life cycle emissions from other types of generation, though offer a less expansive set of technologies than in the NREL study [4.23].

[45]In some cases, there might be little or no GHG benefit of growing biomass. If the newly cultivated land sequesters less GHG than it did before cultivation, then biomass production would actually increase GHG emissions. Woodland owners in the UK can sign up to the UK Woodland Carbon Code, which arranges independent verification of a woodland's carbon sequestration [4.140].

[46]Imported biomass accounts for 33% of the bioenergy burned in UK power stations, significantly more than home-produced biomass, which makes up 23% of the bioenergy used for this purpose. (The remainder of bioenergy used in power stations is from waste materials and landfill and sewage gases (all 2019 figures) [4.7]). In 2019, the UK imported almost 9 million tonnes of wood pellets, principally from North America, with smaller quantities from Eastern Europe and elsewhere. This compares with 2019 UK wood fuel production of 2.6 million green tonnes and total timber production of 11 million green tonnes [4.141]. In 2019, the UK was the world's second largest importer of forestry products, after China [4.141]. The UK Government has previously considered environmental impacts of wood imports from North America [4.142, 4.143].

[47]Assumptions relating to renewable resources in the UK are detailed below:

- *Wind (onshore):* average power intensity of wind farms = 2 W/m^2, as derived in [4.27] from average onshore wind speeds of 6 m/s. Covering 10% of UK land surface in wind farms is taken as the upper limit (as in [4.27]) which gives 2 W/m^2 × 0.1 × 2.42×10^{11} m^2 [UK land area] × 8766 [hours in a year, including leap years] = 425 TWh/yr.
- *Wind (offshore):* average power intensity of offshore wind farms = 3 W/m^2, as assumed in [4.27]. UK territorial waters are 7.74×10^{11} m^2, of which 1.2×10^{11} m^2 are less than 50 m deep (taken as the limit of fixed offshore wind installations in [4.27]). If ⅓ of these waters are covered in offshore wind farms, leaving ⅔ to allow shipping channels and fishing areas, the available resource is 3 W/m^2 × 0.33 × 1.2x10^{11} m^2 × 8766 = 1040 TWh/yr if constrained to fixed offshore wind. If floating wind installations

are to be included, and ⅓ of the UK's territorial waters were covered in offshore wind farms, the resource would be 3 W/m^2 × 0.33 × 7.74x10^{11} m^2 × 8766 = 6710 TWh/yr.

- *Solar PV:* average insolation (over a year, including night-time and cloud cover) in the UK is 110 W/m^2 [4.27]. In 2019, average efficiency of crystalline silicon (representing 95% of global installations) solar PV cells was 18% [4.28]; therefore, the average power density of solar PV is taken as 0.18 × 110 W/m^2 = 19.6 W/m^2. If 5% of the UK's land area (including rooftop space) were covered in solar cells (as per the assumption in [4.27]) the total resource would be 19.6 W/m^2 × 0.05 × 2.42x10^{11} × 8766 = 2100 TWh/yr.
- *Hydro:* average power density of hydro in the UK 'highlands' (land of at least 200 m elevation) with average rainfalls of around 2000 mm/year is 0.24 W/m^2; the area of the highlands is 6.07x10^{10} m^2. If 20% of the highlands' valleys and rivers were dammed to harness the power of the rainfall as it makes its way back to the sea (the same assumption for maximum possible resource as used in [4.27]), this would correspond to a total resource of 0.24 W/m^2 × 0.2 × 6.07x10^{10} × 8766 = 26 TWh/yr.
- *Wave*: average power density of Atlantic waves has been measured to be around 40,000 W/m of exposed Atlantic coastline [4.27]. If the efficiency of wave energy generators is taken to be 50%, and 50% of the UK's Atlantic coastline (10,000 km) is covered in wave generation, the total resource would be 40,000 W/m × 0.5 × 0.5 × 10,000x10^3 m × 8766 = 88 TWh/yr. This can be compared to the 2012 estimate of maximum wave resource of 69 TWh/yr from the Crown Estate [4.145].
- *Tidal:* it is derived in [4.27] that, through a combination of tidal barrages, lagoons and stream generators placed in Britain's largest tidal resources, that 11 kWh per person per day could be generated from tidal. Based on a UK population (2008) of 60 million, this corresponds to a maximum resource of 241 TWh/yr. This can be compared to the maximum tidal resource (also from barrages, lagoons and stream generators) of 216 TWh/yr from the Crown Estate [4.145].
- *Bioenergy (plants):* It is stated in [4.27] that high-performance energy crops capable of being grown in Northern European climates carry an energy density of around 0.7 W/m^2. The Climate Change Committee recommends an upper bound of 7% of UK agricultural land (around 1.27 million hectares – 12,700 km^2) to be covered in energy crops for plant biomass in their 2018 biomass report [4.16]. The maximum energy resource for bioenergy from domestically grown energy plants on this basis would be 0.7 × 12,700x10^6 m^2 × 8766 = 78 TWh/yr (this is close to the value of 80 TWh given in [4.16]). Assuming a 40% efficient power plant for electricity generation, the resulting resource would be 0.4 × 78 = 31 TWh.
- *Bioenergy (waste)*: the power resource from waste depends, obviously, on how much waste is produced (something in itself that should be minimised). The 2018 Climate Change Committee report on biomass [4.16] implies that the energy resource from waste is roughly equal to half of that from energy crops: therefore, the maximum resource of bioenergy from waste is 39 TWh/yr; in a 40% efficient power plant this translates to a resource of 16 TWh/yr.
- *Geothermal*: it is derived in [4.27] that sustainable geothermal power extraction (by which the rate of heat extraction is less than or equal to the rate of heat transfer from the Earth's core to the hot rocks reachable by a geothermal power station) could provide 2 kWh per person per day. Based on a UK population (2008) of 60 million, this corresponds to a maximum resource of 22 TWh/yr.

[48]Compared to UK final energy demand and other renewable means of electricity generation, bioenergy resource is fairly small. As described in §4.1 and §5.2, bioenergy with carbon capture & storage (BECCS) is being pursued as a significant contributor to offsetting the UK's residual emissions. While its contribution to the power sector will remain a relatively small proportion of the total, its negative CO_2 intensity of around -300 gCO_2/kWh means that a resource of 141 TWh primary energy would deliver 141x10^9 kWh × 300x10^{-6} t/kWh = 42 MtCO_2 of emissions *abatement* per year.

[49]The electricity system in Northern Ireland is part of a single electricity market (SEM) with the Republic of Ireland. The Northern Irish electricity networks (both transmission and distribution) are owned by Northern Ireland Electricity (NIE), which is a subsidiary of the Irish state-owned Electricity Supply Board (ESB), the transmission and distribution owner in the Republic. The regulations pertaining to the operation

and ownership of the electricity system are broadly similar to those in GB. There are two separate companies in charge of operating the electricity systems: System Operator Northern Ireland (SONI) Ltd. for Northern Ireland, and EirGrid for the Republic of Ireland. Through a partnership between EirGrid and SONI, Eirgrid plc is the single electricity market operator (SEMO) for the whole of the island of Ireland.

[50]Ohm's law states that the rate of energy lost along a conductor is equal to the square of current times the resistance. Therefore, for a doubling of the current, the losses go up by a factor of four. If the current (by analogy, the flow) is reduced, then for a constant resistance (by analogy, the pipe diameter) the voltage (by analogy, the pressure) will be increased. Voltage levels are a trade-off between the money saved minimising losses and the money spent on the necessary safety and electrical protection measures for high voltage electrical equipment.

[51]Net Zero-compatible synfuel would combine hydrogen made from electrolysis, or chemical processing of fuels with CCS, and carbon from CO_2 captured from the air, in a chemical process called the Fischer-Tropsch process. If an optimistic power-to-fuel conversion efficiency of 50% is assumed, production of synfuel for current UK aviation fuel demand (16.18 million tonnes of oil equivalent, or 188 TWh, per year) would require 376 TWh of electrical energy per year. UK pathways for DACCS of 25 $MtCO_2$/year (around 7% of the UK's 2019 emissions) would require 50 TWh energy input (around 17% of final UK electricity demand in 2019) [4.146].

[52]Electricity transmission and distribution network charges make up 22% of the average UK electricity bill [4.147]. If large-scale network upgrades are to be undertaken as electricity demand is due to increase, network charges on consumers will increase. Although a low voltage (e.g. residential) consumer's use of system charge is calculated based on their predicted energy consumption over the year, their contribution to a requirement to reinforce is linked to their contribution to peak demand. This system is due to change as part of Ofgem's Targeted Charging Review (TCR) – in which flat rate charges for the "residual" (cost collection element of bills) are collected according to category of customer – this change is expected to come into force in 2022.

Conventional wisdom is that avoiding or deferring work to reinforce electrical networks is ***always*** good and will ***always*** save money. However, some researchers argue otherwise: reinforcement will replace thinner electrical wires with thicker ones, which have lower electrical resistance and so reduce the electrical losses. Over time, the avoided electrical losses will offset some or even all of the reinforcement costs.

Other researchers [4.148] find that such reinforcements will indeed increase costs to consumers via higher electricity bills, but at the same time will deliver wider economic benefits, including GDP growth and greater employment levels. There is also the question of whether reinforcements are, in some places, *necessary* to enable more low-carbon generation, or low-carbon heating and transport (even with support from "smart" technological systems): if so, whether they should be performed sooner rather than later.

[53]Conventionally, increases in demand would exceed the capability of the existing network, and trigger network reinforcements. However, with increasing penetration of distributed generation (particularly wind farms and solar PV), it has been the increase in generation that has been the limiting factor in some (particularly rural) networks.

[54]Based on an annual household residential electricity consumption of 3 MWh (Figure 1), daily consumption is taken as 8 kWh. Assuming an EV battery capacity of 40 kWh, present in 'budget' EV models available on the market such as the Nissan Leaf, this would cater for household energy demand for 5 days (if the EV was not used to go anywhere).

[55]Smart EV charging – spreading the demand from EVs out across the night – was found to reduce the evening peak demand by 50% in the Electric Nation project [4.30], though it resulted in a new peak demand

in the early hours of the morning. In future, EV chargers could be used as distributed energy storage assets. By charging when electrical energy is cheap and – generally speaking – renewable power is plentiful, EVs could increase the utilisation of renewable energy sources – thus offering further incentive for renewable plant developers. Their ability to be quickly turned up or down en masse (via a communication signal) offers potential for EV chargers to offer vital grid services (including frequency response) to National Grid, helping to support increasing proportions of renewable generators on the GB power system. This potential increases when chargers allow V2G: sending power to the grid as well as receiving it (Figure 31).

[56]In a 2015 cyber-attack in Ukraine, three distribution networks were effectively shut off leaving more than 230,000 residents in the dark for six hours. The cause was hackers, who carried out a Denial of Service attack in which they took control of the network operator's control systems to deliberately shut down the power system [4.149].

[57]The UK Government authorised a scheme 'Connect and Manage' in 2009 to encourage the construction of more renewable generation, in advance of necessary reinforcements on the transmission network. Some windfarms were granted a 'firm connection' and are thus compensated for lost revenue when grid constraints require the windfarm to reduce or cease output. The compensation costs are socialised over all users of the electricity system [4.150].

[58]Since the study in [4.36], a major new electrical connection (the Western HVDC Link) has been installed between Southwest Scotland and Northeast Wales to reduce the amount of wind curtailment in Scotland. The Western Link is a sub-sea cable that carries high voltage direct current (HVDC). The cable has a capacity of 2.2 GW and has reduced curtailment of Scottish windfarms. A second Eastern HVDC Link from Peterhead, Scotland to Humberside, England is planned to further enable Scottish renewable generation to be used to power English and Welsh demand as more renewables are scheduled to be built North of the border.

[59]There are three types of electrolyser used for hydrogen production: alkaline, Proton Electrolyser Membrane (PEM) and Solid Oxide Fuel Cell (SOFC). Conversion efficiencies vary. This report cites reported values for alkaline and PEM electrolysers only, as SOFC electrolysers are not yet commercially available. This report assumes performance is likely to be a little lower under actual operating conditions than manufacturers' datasheets suggest [4.151], especially when powered with a variable electricity source such as a wind generator. All values are Higher Heating Value (HHV) efficiencies. Reported electrical efficiencies for SOFC (not included in this guide) are often very high, some approaching or exceeding 100% (not inclusive of heat input), and these electrolysers may become a key technology in the future. However, one must note that reported efficiencies are often *electrical efficiencies* only, and omit the additional heat input requirements, which are substantial, as SOFCs operate at temperatures up to 1,000 °C.

[60]The likely worst-case efficiency for conversion from fuels to hydrogen is 55%, assuming a conversion efficiency around 60% and an extra 5% energy penalty required to fuel the CCS process. The likely best-case efficiency is 85%, based on best possible performance being cited as up to 90% and a 5% energy penalty for the CCS process. These numbers are based on a set of reports in [4.37], [4.39] and [4.41].

[61]The map in Figure 71 was made with the assumption that the efficiency of the electrolyser is 65%; windfarms have a capacity of 2.9 MW per square kilometre (calculated on the basis of Hornsea 1 offshore windfarm, which has a capacity of 1.2 GW and an area of 407 km^2 [4.152]); and the annual load factor is 40% [4.7]. The nuclear power stations needed to provide the same quantity of electricity are assumed to have a rated capacity of 3.2 GW (i.e. the same as Hinkley Point C) and a load factor of 90%.

Offshore wind turbines vary in size, some 200 m tall or taller; turbines are usually spaced a kilometre or more apart. Looking at recent large offshore windfarms (built, under construction or in planning as listed in the BEIS Renewable Energy Planning Database [4.153]), the maximum output per square km ranges considerably. The lowest are from around 2-2.5 MW/km^2 (Dogger Bank, East Anglia Array - Norfolk Boreas); several are around 3 MW/km^2 (including Hornsea 1 & 2, East Anglia Array - Norfolk Vanguard) with some around 4 MW/km^2 or over (Moray Firth, Beatrice, Neart na Gaoithe and East Anglia 3). London Array has an exceptional rated output of 6.3 MW/km^2. Reasons for differences include site-specific environmental considerations and different turbine arrangements, with larger more powerful turbines needing much greater spacing. If the windfarms were built with a higher capacity per square km (e.g. 4 MW/km^2) the windfarm areas needed would be proportionately smaller.

Some wind turbine manufacturers claim higher annual load factors (some over 60%) for the very largest wind turbines (over 10 MW each). If turbines can achieve this load factor in the field, in future, the output would be greater and required windfarm size lower. The load factor depends very much on wind conditions, as well as turbine design.

The windfarm area is not necessarily 'closed' to all other activity. Regarding wildlife, many species may be unaffected by the development, though other species may be more sensitive to large windfarms. Effects should be assessed in the projects' Environmental Impact Assessment and reflected in the development consent documentation.

[62]Net Zero-compatible synfuel would combine hydrogen made from electrolysis, or chemical processing of fuels with CCS, and carbon from CO_2 captured from the air, in a chemical process called the Fischer-Tropsch process. If an optimistic power-to-fuel conversion efficiency of 50% is assumed, production of synfuel for current UK aviation fuel demand (16.18 million tonnes of oil equivalent, or 188 TWh, per year) [4.154] would require 376 TWh of electrical energy per year. This is 27% greater than total final electrical energy consumption in 2019 (295 TWh) [4.7]. Of course, the fuels need not be made using electricity produced in densely populated countries like the UK. Recent feasibility studies include studies for countries with low populations and lots of land and renewable resources. For example, Morocco has a total potential for offshore wind of around 250 GW, which is approximately 25 times the current generating capacity in the country. This would provide 770 TWh of electricity annually, which is sufficient to produce synfuel for more than twice UK aviation demand [4.48].

[63]Under EU regulation (EN 437), domestic gas boilers sold since 1996 must be able to operate with up to 23% hydrogen by volume. This is due to gas compositions still in use in parts of Southeast Europe. However, 0.1% hydrogen by volume is the limit set for the GB gas grid as per UK legislation. For hydrogen demonstration projects such as HyDeploy, in which up to 28% hydrogen by volume was injected into the gas grid, exemptions were granted from the Health & Safety Executive.

[64] During the previous gas switch, from town gas to North Sea gas in the 1960s and 70s, most gas appliances were modified, such as having a new jet or burner fitted. Around 40 million appliances were adapted during this switch [4.155]. Further information about the gas switch is available here [4.156]

[65]Much of the gas distribution grid – low and medium-pressure gas pipes near homes and business – is in the process of upgrade for safety reasons, which started in 1991 and was due to take 30 years. The programme planned to replace just over 90,000 km of pipework – iron pipes which lie within 30 m of a building [4.157] – with polyethylene pipes. Pipes considered at risk of degrading and developing leaks are prioritised. Fortuitously, the polyethylene pipes used in upgraded sections are hydrogen ready and such sections will comprise a significant part of the distribution grid by the early 2030s. Some other pipework is decommissioned [4.157], and new pipework is generally made of polyethylene. However, as the total length of distribution networks was estimated at over 200,000 km, further investment will still be needed. The gas transmission grid – large, high-pressure pipes, which transport gas hundreds of miles – is made of steel pipes. To carry hydrogen, these pipes – 7,630 km in total [4.158] – are likely to need upgrading – replacing, or lining with polyethylene [4.50]. European gas transmission owners and operators propose several alternative options, including operating at lower pressures [4.159].

[66]Hydrogen-ready appliances either i) can run on either fossil gas, or hydrogen, without modification, or ii) have the *burner* located in an easily accessible place. In the latter case, each appliance could have its burner changed by a gas technician within a short time (e.g. half an hour) during a future gas switch.

[67]BSI has developed PAS 4444: Hydrogen-fired gas appliances in engagement with industry [4.53].

[68]Diversity is the reduction in peak loading of a heat network compared to the sum of individual peak loads. This happens when different households use heating (or appliances) at different times, rather than all at the same time.

[69]1st and 2nd Generation are typical of pre-1980's systems operating at >80 °C. 3rd Generation is the most common current type, operating typically at 70-80 °C but incorporating packaged generation and pre-insulated pipework with limited renewables integration. 4th Generation covers recently developed lower temperature systems (45-60 °C) to allow heat pump use and minimise piping heat losses. 5th Generation systems are a different concept involving circulation of a lower temperature source fluid for the heat pump to supply individual heat pumps per consumer or direct supply to consumers from deep geothermal systems.

[70]Heat density is the annual heat demand per unit area for a location.

[71]'Very High' = highly feasible, 'High' = currently possible, 'Medium' = requires 4th Gen+, 'Low' = not feasible.

[72]'Regulated' energy includes heating, hot water, cooling, lighting but not appliances ('unregulated'), minus onsite generation contribution.

[73]Energy Performance Certificates (EPC): An EU regulation to define the energy efficiency of a building. A building is rated A-G, and is a UK requirement for new buildings and the sale or rental of existing buildings. Standard Assessment Procedure (SAP) is the methodology used by the UK Government to assess and compare the energy and environmental performance of dwellings.

[74]'Industrial' is warehouses, distribution centres, factories etc., 'Other' includes hospitals, student accommodation etc.

[75]Solar PV output (highest in the summer/in the middle of the day) does not match with heating demand (highest in the winter/in the evening), which leads to grid imbalances. Integrated generation is the least effective means to achieve Net Zero for heating and overall building energy.

[76]Passivhaus is an international low energy design standard with 65,000 installed buildings. The basic principle of the Passivhaus design is to use passive solar heating combined with very high thermal efficiency requirements and, if required, forced ventilation for comfort [4.87, 4.88].

[77]The U-value of a construction material is the thermal transmittance of the material typically expressed in W/m^2K. It specifies the rate of heat transfer through a material per °C (or Kelvin, K) of temperature difference.

[78]1965 to 2002 – Maximum values, 2006 – Area Weighted, 2010 – 'Limiting Fabric', 2013/16 – 'Notional Dwelling' – change in basis reflects increasing flexibility to combine fabric and non-fabric related solutions to overall energy rating.

[79]There were 14 Enhanced Oil Recovery CCS plants world-wide in 2019 [4.101]. One – Petra Nova, in the USA – was mothballed in 2020, apparently being uneconomic to operate at times of low oil prices [4.161]. Petra Nova was a new CCS plant, one of two world-wide which provided post-combustion CCS to coal power stations [4.101].

[80]A further CCS hub has been proposed for Northeast Scotland [4.105, 4.106, 4.162].

[81]UK pathways for DACCS of 25 $MtCO_2$/year (around 7% of the UK's 2019 emissions) would require 50 TWh energy input (around 17% of final UK electricity demand in 2019) [4.146].

[82]Compressed air energy storage systems are of two types: diabatic and adiabatic. In the former, the heat generated as the air is compressed is lost and, upon release, the air must be heated again to power a turbine – this is normally achieved by burning gas. In the latter, the heat from compression is retained and released with the air upon generation – therefore, no additional heat is required. Adiabatic compressed air energy storage is therefore also a form of thermal energy storage. Different battery chemistries have trade-offs with respect to efficiency, cost, energy & power density and longevity. In grid-level storage applications, the main two in use are lithium-ion (larger versions of the kind in phones, laptops and EVs) and flow batteries. Li-ion batteries have high power and energy densities and high efficiencies (95% roundtrip); flow batteries are physically larger for a given amount of storage and have lower efficiencies (80% roundtrip), but have lower self-discharge (charge leakage) rates and their energy storage capacity can be scaled up cheaply and easily. Flywheels and capacitors are considered alternative technologies for providing energy storage on very short timescales. These technologies are useful for smoothing out fluctuations in power quality, voltage and frequency, all of which are crucial to a resilient power system. Cost was left out of Table 3 for two reasons. Firstly, the costs of the technologies are volatile and, with the exception of pumped hydro as the only mature technology listed, are all expected to fall dramatically. Battery costs per kWh have fallen 87% from 2010 to 2019 [4.163], and these reductions are showing no sign of slowing. Secondly, there is no easily comparable price for storage technologies, as they generate revenue for doing different things: while hydrogen/ammonia storage is providing seasonal bulk energy storage, supercapacitors provide the grid with millisecond-by-millisecond stability.

[83]Two storage start-ups intend to use the principal of the potential/kinetic energy of weights suspended on ropes, which can move vertically, up and down, when required to use or deliver energy. One intends to use repurposed mineshafts or purpose-built shafts [4.164]; another uses weights suspended from cranes [4.165]. A different approach, much closer to pumped hydro, is one intending to pump a dense liquid instead of water. If commercialised, this approach could provide sizeable energy storage with a much smaller altitude difference between the upper and lower reservoirs, compared to a conventional pumped hydro scheme (i.e. it could be built in hills, rather than mountains) [4.166].

[84]Metal ore mining from the ocean, rather than on land, could have the potential to significantly reduce the carbon footprint, human toxicity and biodiversity impact of resource extraction for battery production [4.167].

[85]The electricity and gas stores would not, in practice, supply all GB electricity demand for an hour, nor all winter gas demand for the days stipulated. The stores can deliver at slower rates, and could supply a small fraction of GB electricity demand for several hours, and over half peak daily winter gas demand for around 10 days, if all stores were full to begin with.

[86]Exothermic: a chemical reaction that releases heat energy. Endothermic: a chemical reaction that requires heat energy.

[87]Durations: 'short' = daily cycles, 'medium' = weekly-monthly cycles, 'long' = seasonal cycles.

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Chapter 5 – Energy Systems for Net Zero

5.1 Energy Carriers

5.1.1 Today's Energy Carriers

78% of final energy consumption in the UK was met by burning fossil fuels in 2019. While this is a very long way off Net Zero, it represents a record low since the beginning of the Industrial Revolution (§2.1). For the most part, petroleum is burned in heat engines for transport and gas is burned in boilers and furnaces to provide heat – from residential space heating to high-temperature industrial processes. Gas is also burned to provide a significant portion (41% in 2019) of electricity generation, which powers our machines and appliances.

Aside from the volumes of energy they provide, the rate at which these carriers are demanded varies significantly in time (Figure 104).

Transport fuels use is relatively consistent year-round (though was clearly the most impacted out of the three by COVID-19). On the other hand, electricity use varies, both seasonally and within each day. Gas use displays similar characteristics, though the seasonal variation is much larger. Whereas winter electricity peaks are around 25% greater than summer electricity peaks, winter gas peaks are (without accounting for exceptional peaks like that seen in the 'Beast from the East', visible in Figure 104 in March 2018) around 420% greater than summer gas peaks.

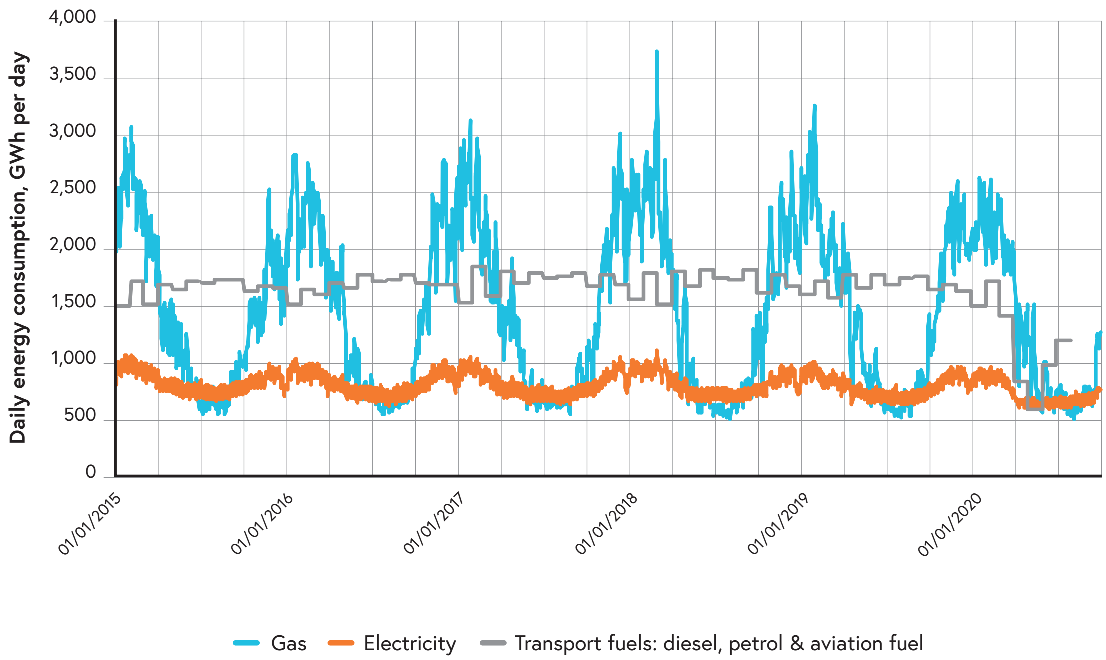
The way in which these fossil fuel-based energy carriers flow to supply our energy-based services (heating, transport and electricity demand) will form the basis of how Net Zero energy carriers can supply our energy demand.

5.1.2 Net Zero Energy Carriers

There are several possible routes to a Net Zero energy system by 2050 (§5.2) and, while it is not yet clear which one will be taken, there are several themes that emerge amongst all pathways that have been published:

1. Heavy electrification of heating and transport will **increase electricity system demand** but **reduce final energy demand**.
2. **Storage (short and long-term) and flexibility** will be required to match demand to an

Figure 104 Great Britain energy carriers by volume: gas, electricity and transport fuels. Figure courtesy of Dr Grant Wilson, University of Birmingham. Data from National Grid, Elexon, and Department for Business, Energy & Industrial Strategy. [5.1]



electricity supply that has a large share of variable renewable generators (mostly wind and solar).

3. **Some amount of fuels (hydrogen, ammonia, biofuels and synthetic hydrocarbons)** will be required to provide energy for heavy transport (including aviation and shipping), some industrial demand and peak winter heating.
4. A **small amount of fossil fuels** may still be in use by 2050, so long as the emissions produced from burning them are either captured at the point of combustion or offset elsewhere in the system. This may include burning fossil gas with CCS for backup electricity generation, the production of hydrogen from fossil gas with CCS, or the use of petroleum-derived jet fuels for aviation.
5. Any **residual emissions will need to be offset** by negative emissions elsewhere in the system.

Our future energy carriers for a Net Zero system could involve a range of technologies, as demonstrated throughout this guide and across the spread of published pathways (§5.2). How these carriers will interact with other parts of the energy system – namely land use & agriculture, lifestyle & behaviour and the extent to which greenhouse gases will have to be removed from the atmosphere – is also uncertain.

Figure 105 and Figure 106 illustrate two key overarching impressions of energy flows in the 2050 Net Zero energy system.

Figure 105 shows an energy system in which a mix of electricity generation technologies (including renewables, nuclear and gas with CCS) are used to supply a large electrical demand resulting from widespread electrification of heating and surface transport. Hydrogen and synthetic fuels also play an important role in supplying heating and transport demand, which are produced from a mix of renewable sources (electrolysis from renewables and biomass gasification) and from fossil gas with CCS. A small portion of transport demand (likely to be aviation) is still met by petroleum. In this scenario, behavioural change happens at a comparatively slow rate, including continuation of car use and limited shift away from animal-based diets. As a result, engineered removals of greenhouse gases must be applied at several points in the energy system.

Figure 106 shows an energy system in which a 100% renewable generation mix supplies a large electrical demand resulting from widespread electrification of heating and surface transport. Hydrogen and synthetic fuels also play an important role in supplying heating and transport demand, which are produced entirely from renewable means (electrolysis from renewables and biomass

Figure 105 Illustrative Net Zero energy flows: technology mix (renewables, nuclear & fossil fuels); low behavioural change; higher engineered GHG removals (i.e. CCS)

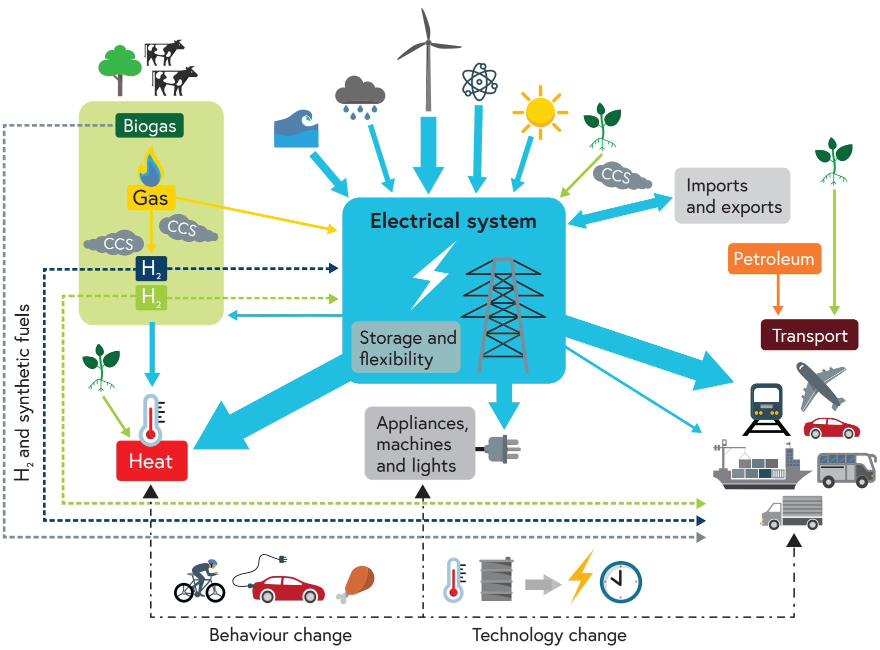
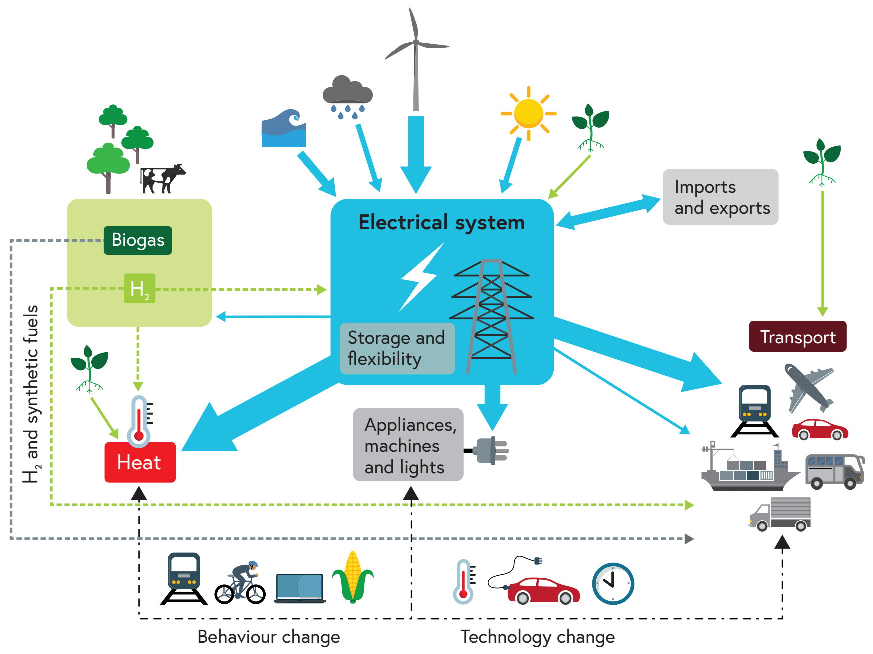


Figure 106 Illustrative Net Zero energy flows: renewables only; high behavioural change; fewer engineered removals



gasification). In this scenario, there is no petroleum use in transport – heavy transport is met entirely by electricity, hydrogen, synthetic fuels and biofuels. In this scenario, behavioural change happens at a comparatively fast rate, including modal shift away from car use and a hastened shift away from animal-based diets, which enables more land to be used for afforestation rather than rearing livestock. As a result, there is a reduced need for engineered removals of greenhouse gases.

These two scenarios represent the two extremes of the Net Zero energy system – what we end up with may be something in between (as highlighted in §5.2).

In both scenarios, the electricity system is an important supplier of low-carbon energy: both directly for electrified heating, transport and appliances, machines & lights, and for the production of fuels including hydrogen, ammonia and synthetic fuels. A key difference between Figure 105 and Figure 106 is how the energy system is operated in order to ensure that supply meets demand. The key challenges regarding the operation of a Net Zero energy system are illustrated in Figure 107.

These illustrative examples highlight how the Net Zero energy carriers will supply our way of life in 2050. In the next sub-section (§5.2), seven published Net Zero pathways are reviewed for how they have analysed and calculated a path to a UK Net Zero energy system.

5.2 Pathways to Net Zero

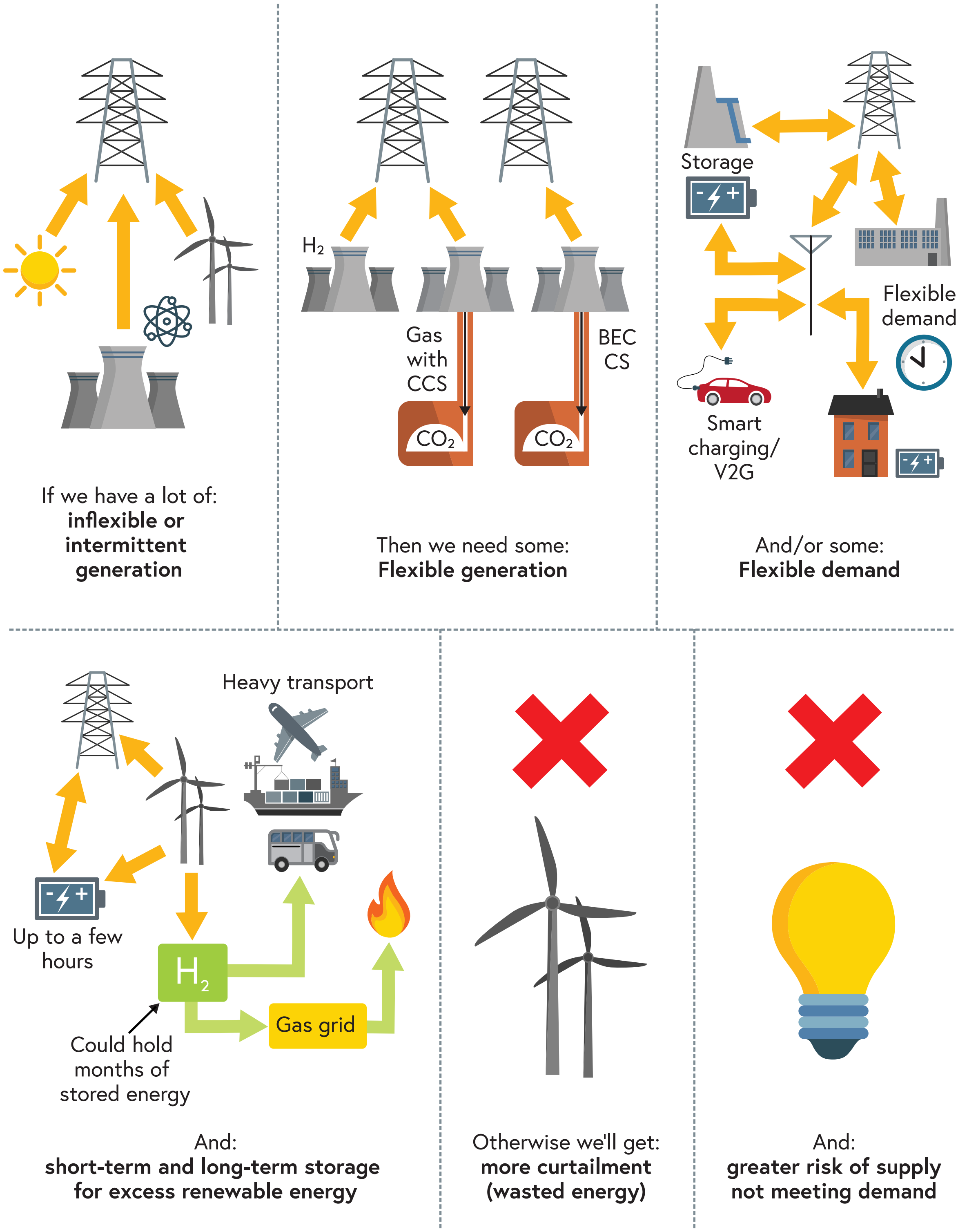
5.2.1 Seven Published Net Zero Pathways

Seven published pathways to Net Zero have been analysed to explore what the energy systems modelling community thinks should be supplying a Net Zero energy system by 2050. Each pathway makes different assumptions as to how energy demand will change to 2050, based on a mix of technology changes and lifestyle shifts (full details are given in Table 5).

Two of these are from the **Energy Systems Catapult** [5.2], both published in 2019 – i) a **Clockwork (ESC-C)** scenario to represent minimal behavioural shift and large-scale, centralised changes to energy supply; ii) a **Patchwork (ESC-P)** scenario, in which a higher level of behavioural change is offset by a weaker central policy framework.

A further three come from National Grid ESO's 2020 **Future Energy Scenarios** (FES) [5.3]– i)

Figure 107 Options for ensuring that supply meets demand in a Net Zero energy system



Leading the Way (FES-LTW), in which significant demand reductions accompany a mix of electric and hydrogen-powered heating; ii) **System Transformation (FES-ST)**, in which minimal behavioural change accompanies large-scale hydrogen deployment and moderate electrification with high supply-side flexibility; iii) **Consumer Transformation (FES-CT)**, whereby near-total electrification accompanies high energy efficiency and moderate behaviour change.

The sixth scenario is the **Centre for Alternative Technology**'s 2019 **Zero Carbon Britain (CAT-ZCB)** pathway [5.4], in which a 100% renewable electricity system accompanies seasonal storage of synthetic fuels produced from hydrogen and biomass to smooth out supply & demand and provide energy for shipping & aviation. This scenario involves significant changes to energy demand behaviour by 2050.

The seventh scenario is the **Climate Change Committee**'s **Balanced (CCC-B)** pathway which, as the name suggests, is the most 'balanced' of 5 pathways presented in their sixth Carbon Budget report published in December 2020 [5.5]. This pathway relies on a mid-level (compared to the other pathways) amount of behaviour change, extensive electrification and development of a low-carbon hydrogen supply.

5.2.2 Level of Change to 2050

Figure 108 shows that credible pathways to Net Zero exist for a wide variety of changes in energy demand behaviour, energy supply and the removal of residual emissions. The horizontal axis is not to scale but attempts to give an approximate sense of the position of each scenario relative to the others in respect of different emissions sectors and of broad lifestyle changes.

Although the scenarios are difficult to directly compare due to differences in their methodologies, the clear pattern that emerges is:

- **Pathways that rely on little behavioural change to 2050 rely on significant changes in technology.**
- **Pathways that rely on significant behavioural change to 2050 rely on less significant changes in technology.**

For example, ESC-C relies on little or no change in car ownership or use habits and is the only pathway in which heating demand does not decrease relative to today. To counter for this, CCS is applied extensively to heavy industry and capture rates must reach 99%. Furthermore, DACCS and BECCS are both scaled up to their maximal permissible rates as per the Energy Systems Catapult modelling scenarios. Despite the general low-level behavioural change in the ESC-C pathway, meat & dairy consumption does reduce by 20% to 2050. As a pathway on the opposite side of this spectrum, CAT-ZCB relies on significant behavioural change: car miles driven drop by 13%, aviation demand falls by 66% and demand for meat & dairy falls by 58%. As a result, the removal of residual emissions can be less drastic; this is achieved through mass afforestation and peatland restoration (achievable through the reduction in land requirement for livestock).

Most scenarios involve various trade-offs between technology change – including switching from fossil fuels to zero-emission energy carriers and improvements in energy efficiency – and energy demand changes resulting from lifestyle shifts. A full comparative analysis is provided in Table 5.

It must be noted that the ESC and FES pathways do not include emissions from the UK's share of international aviation & shipping. Therefore, while the ESC-C pathway includes an expansion in aviation demand by 60% to 2050 relative to today, only a small proportion of the increase in emissions from this demand increase (i.e. from domestic flights only) are included in scope for decarbonisation in that pathway. (In 2019, the UK's share of international aviation – aircraft leaving UK airports and landing overseas – made up 96% of total UK aviation emissions [5.6].) Both the ESC and FES documents in which their pathways are published cite CCC advice for the decarbonisation of the aviation sector; as of the CCC's 6th carbon budget recommendation, this means UK aviation demand can grow by no more than 25% to 2050 relative to current demand.

5.2.3 Net Zero Energy Carriers in 2050

Electricity and hydrogen are key energy carriers for decarbonisation in all pathways. Figure 109 shows how these carriers are used to decarbonise key demands for all seven pathways and where fossil fuels are still present (whose emissions must be captured and/or offset).

Figure 110 shows the means of electricity generation and hydrogen production in all seven pathways to ensure the supply of these carriers is compatible with Net Zero.

Figure 108 Level of change to 2050 for seven published Net Zero pathways

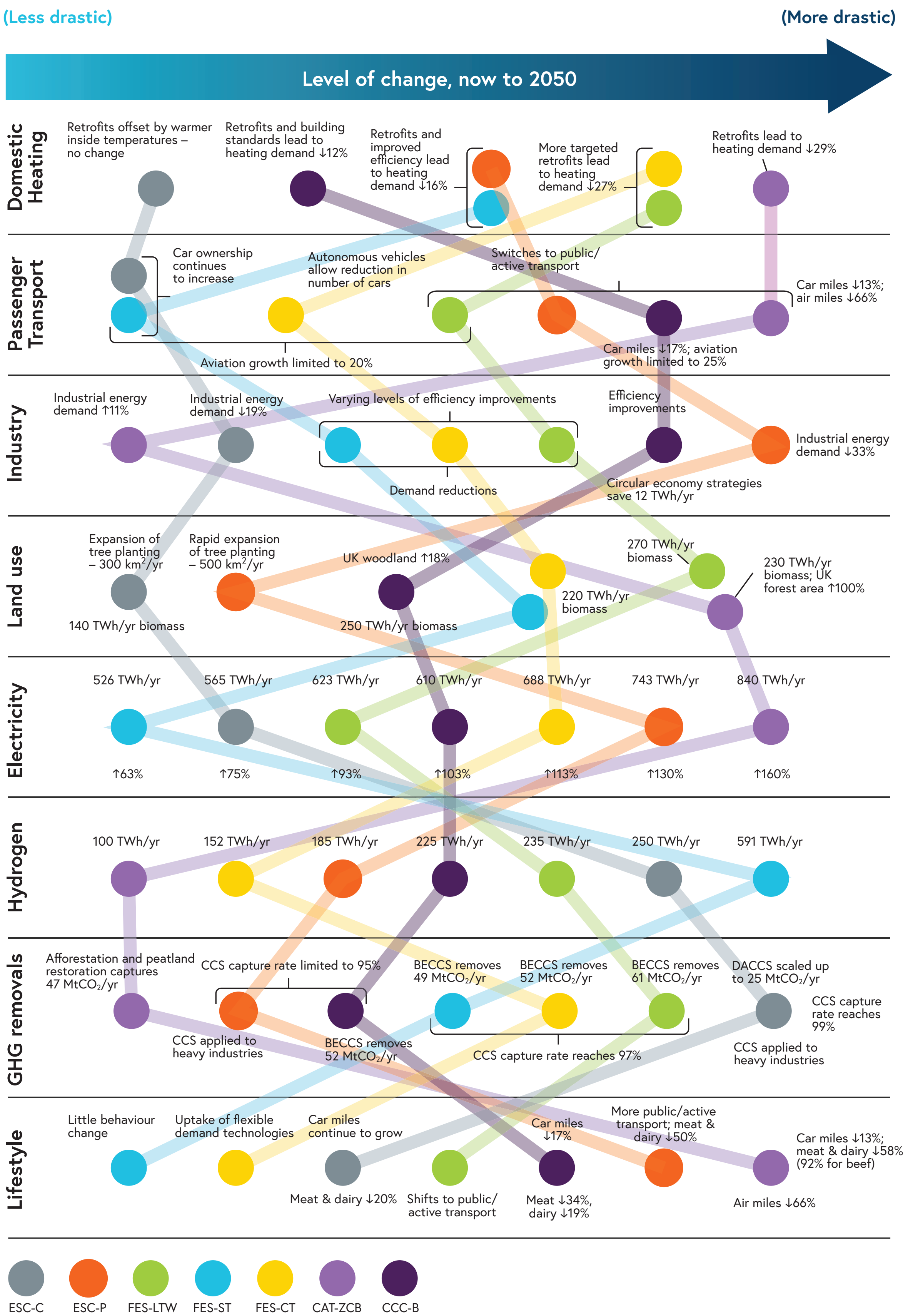
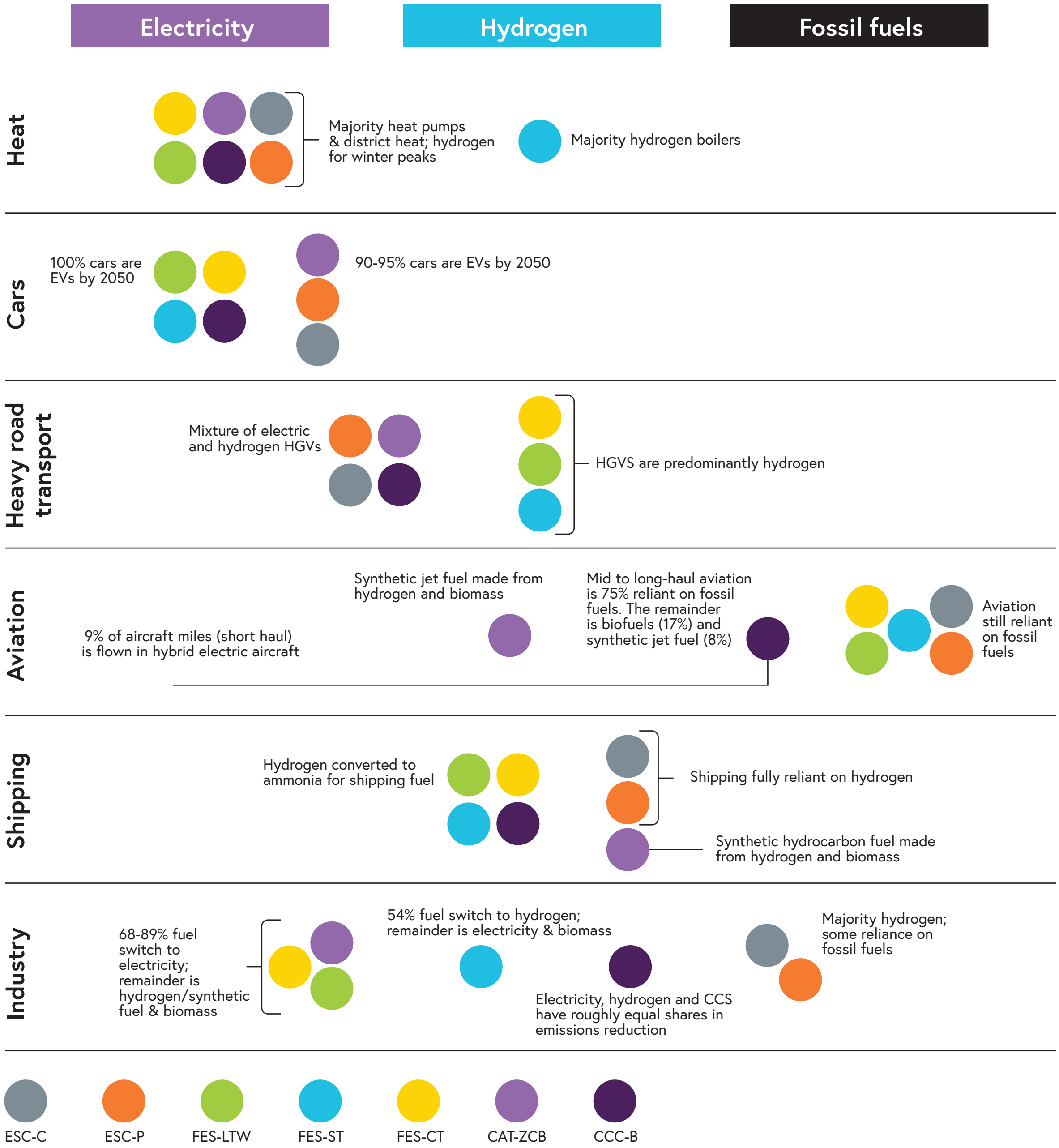


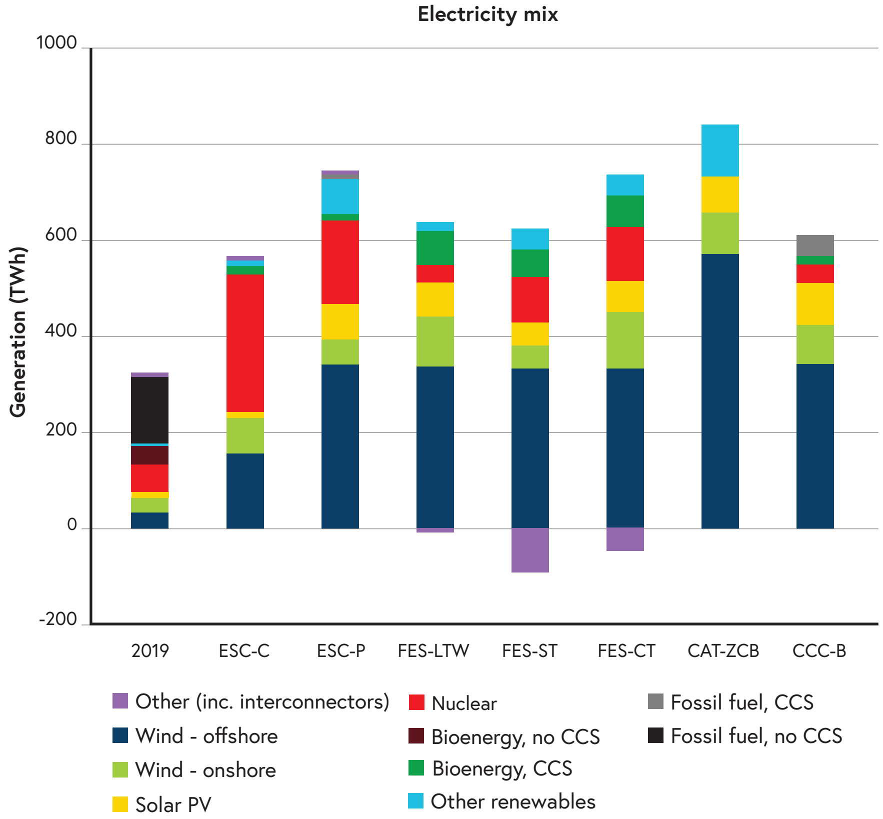
Figure 109 Reliance on electricity, hydrogen and fossil fuels in 2050 for key areas of energy supply according to seven Net Zero pathways



5.2.4 Comparative Analysis of Net Zero Pathways

A full comparison of the seven Net Zero pathways is given in Table 5. In some cases, pathways are difficult to directly compare: for instance – ESC-C, ESC-P, CAT-ZCB and CCC-B all detail the proportion of demand that would be supplied by heat pumps and other Net Zero technologies; on the other hand, FES-LTW, FES-ST and FES-CT state what proportion of homes would be connected to each heating technology. Where possible, comparative values have been drawn out from the publications.

Figure 110 Electricity generation (top) and hydrogen production (bottom) for 2050 in seven Net Zero pathways[88]



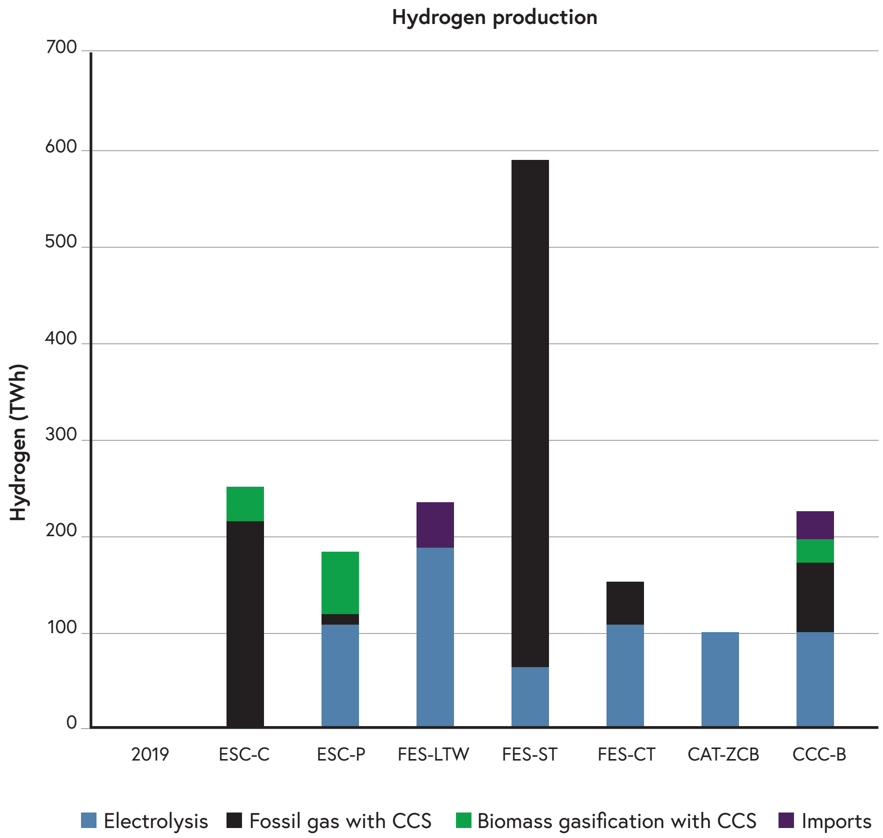


Table 5 Comparative analysis of selected Net Zero pathways

Pathway	ESC-C	ESC-P	FES-LTW	FES-ST	FES-CT	CAT-ZCB	CCC-B
Heating demand	Residential heating demand in 2050 remains similar to today (~370 TWh). Efficiency improvements from retrofitting 10 million homes are countered by increased indoor temperatures.	Residential heating demand reduces by 16% to ~310 TWh by 2050, driven by efficiency improvements from retrofits in 11.5 million homes and lifestyle shifts (wearing more layers).	60% of UK homes are EPC C or higher by 2035, leading to reduction in heating demand by 27% to ~270 TWh by 2050[89].	Less drastic program of retrofits due to lower reliance on heat pumps and higher reliance on hydrogen. Heating demand falls by 16% to ~310 TWh by 2050[89].	60% of UK homes are EPC C or higher by 2035, leading to reduction in heating demand by 27% to ~270 TWh by 2050[89].	Residential heating demand reduces by 29% to 264 TWh by 2050, as a result of targeted retrofits and efficiency improvements without people seeking increased indoor temperatures relative to today.	Residential heating demand reduces by 12% by 2050, as a result of energy efficiency and behavioural measures. All rented UK homes are EPC C by 2028, all homes with mortgages achieve EPC C by 2033 and no home can be sold below EPC C past 2028. All new builds are zero-carbon (i.e. high levels of energy efficiency and low-carbon heating) as of 2025.
Heating supply	58% of UK's 2050 residential heat demand is supplied by heat pumps; large district heating networks are rolled out across large population centres to provide 18% of heating demand. While parts of the gas network are decommissioned, some areas with poorly insulated housing stock retain gas networks for conversion to hydrogen to provide winter peak heating demand. This results in around 17% of heating demand being provided by hydrogen.	61% of UK's 2050 residential heating is provided by heat pumps. District heating is rolled out in major cities – powered by large heat pumps, geothermal resource or nuclear small modular reactors, this provides 19% of heating demand by 2050. Hydrogen boilers are used more sparingly than in the Clockwork scenario, providing around 6% of heating demand.	By 2050 74% of UK homes are fitted with heat pumps, 56% of which are hybrid HP/hydrogen boilers to supply winter peak heating. District heating rollout in urban centres leads to 13% of UK homes being connected to district heating. Hydrogen boilers (without heat pumps) are not used in this scenario. The remainder is met by biomass boilers and electric storage heaters.	By 2050 27% of UK homes are fitted with heat pumps, 96% of which are hybrid HP/hydrogen boilers to supply winter peak heating. District heating rollout in urban centres leads to 10% of UK homes being connected to district heating. Hydrogen boilers (without heat pumps) are used extensively due to a mains gas network switchover to hydrogen: 53% of homes are fitted with one by 2050. The remainder is met by biomass boilers and electric storage heaters.	By 2050 74% of UK homes are fitted with heat pumps, 16% of which are hybrid HP/hydrogen boilers to supply winter peak heating. District heating rollout in urban centres leads to 16% of UK homes being connected to district heating. Hydrogen boilers (without heat pumps) are not used in this scenario. The remainder is met by biomass boilers and electric storage heaters.	63% of UK's 2050 heating demand is provided by heat pumps, some of which are large-scale heat pumps attached to district heating networks. 12% of heating demand is provided by solar thermal, 7% is provided by geothermal heating and 18% is provided by biomass.	By 2050 all UK heat demand is met by 52% heat pumps, 42% district heat, 5% hydrogen boilers and 1% direct electric heating. The heat pumps include hydrogen hybrid designs for provision of the winter peak, enabled by rapid gas grid conversion to hydrogen from 2030 onwards. District heating sources are dominated by water- and sewage-source heat pumps and waste heat from industry.

Table 5 Comparative analysis of selected Net Zero pathways (*continued*)

Pathway	ESC-C	ESC-P	FES-LTW	FES-ST	FES-CT	CAT-ZCB	CCC-B
Transport demand	Car travel and private car ownership continues to rise to 45 million private cars by 2050. Aviation demand continues to increase to 7,500 km/year on average by 2050.	Car ownership becomes less important due to a combination of urbanisation, different working habits and a perceived need for climate action. As a result, the number of private cars rises less than in Clockwork, to 38 million by 2050. Demand for international aviation falls away from 2035 due to the 'flight shame' movement; average distance flown is 5,000 km per year by 2050 (2 trips to Europe each year).	Car ownership reduces due to improved public transport, changing travel habits and rapid development in autonomous vehicles (AVs): by 2050, 1.8 million electric shared AVs are driving an average of 90,500 miles each per year. There are 20 million cars in total in the UK by 2050, a 35% reduction from today. Aviation demand increase is limited to 20% higher in 2050 than it is today.	Development of shared electric AVs is able to displace some private car ownership, but most AVs are privately owned. By 2050, 5.9 million electric AVs are driving an average of 14,800 miles each per year. There are 31 million cars on the road by 2050, roughly equal to today. Aviation demand increase is limited to 20% higher in 2050 than it is today.	Car ownership reduces due to AV development, but personal travel habits do not change much. A higher proportion of AVs are privately owned than in the LTS scenario. By 2050, 6.3 million electric shared AVs are driving an average of 17,000 miles each per year. There are 28 million cars in total in the UK by 2050, a 10% reduction from today. Aviation demand increase is limited to 20% higher in 2050 than it is today.	Car distance driven per person decreases by around 13% by 2050, as better communication tools replace the need for some journeys and urbanisation reduces many other journey times. People cycle and walk more often, and public transport increases from a share of 14% to 28% of domestic travel. Average car occupancy increases from 1.6 to 2. International aviation demand falls by two thirds.	Car distance driven per person decreases by 17% from 2019 to 2050, as modal shares of cycling, walking and public transport increase. Aviation travel demand increases by 25% from 2018 to 2050, but this is offset by 1.4% efficiency improvements year-on-year (resulting in a net 18% reduction in aviation energy demand to 2050). By 2035, there are 28 million EVs (3 million of which are plug-in hybrids) whose charging is supported by 390,000 public charge points. Total HGV miles decrease by 10% by 2035 as a result of improved logistics such as expanded use of consolidation centres, extended delivery windows and higher loading.
Transport supply	Less than 10% of 2050 transport demand is met by fossil fuels (compared to 97% today). 93% of cars on the road by 2050 are EVs, with the remainder being hybrids. As a result of mass electrification, road transport energy demand in 2050 is a third of what it is today. Hydrogen serves a niche role for heavy-duty transport including shipping. Aviation is still reliant on fossil fuels in 2050.	Improvements in access to public transport and cycling & walking infrastructure allow a slower uptake in car ownership. 95% of cars in 2050 are EVs. Shipping is completely decarbonised by a switch to hydrogen; aviation is still reliant on fossil fuels.	All passenger cars are battery electric by 2050 at the latest. HGVs predominantly run on hydrogen. Shipping is decarbonised via hydrogen (converted to ammonia). Aviation is still reliant on fossil fuels; Net Zero is achieved by limiting demand and offsetting in other sectors.	All passenger cars are battery electric by 2050 at the latest. HGVs predominantly run on hydrogen. Shipping is decarbonised via hydrogen (converted to ammonia). Aviation is still reliant on fossil fuels; Net Zero is achieved by limiting demand and offsetting in other sectors.	All passenger cars are battery electric by 2050 at the latest. HGVs predominantly run on hydrogen. Shipping is decarbonised via hydrogen (converted to ammonia). Aviation is still reliant on fossil fuels; Net Zero is achieved by limiting demand and offsetting in other sectors.	90% of road passenger vehicles in 2050 are electric. There is zero demand for fossil fuels across the transport sector by 2050. Shipping and aviation are decarbonised using synthetic fuels made from hydrogen from electrolysis and biomass.	100% of cars in 2050 are electric; 100% of buses in 2050 are zero-emission (either battery electric or hydrogen). 100% of HGVs are zero-emission (either battery electric or hydrogen) by 2050. 9% of aircraft distance is flown by hybrid electric aircraft in 2050; the remainder is still reliant on liquid jet fuels. Of this, 75% is fossil fuels. The remainder is 'sustainable aviation fuels', split two-thirds biofuels and one-third synthetic kerosene produced from low-carbon

Table 5 Comparative analysis of selected Net Zero pathways (*continued*)

Pathway	ESC-C	ESC-P	FES-LTW	FES-ST	FES-CT	CAT-ZCB	CCC-B
							hydrogen and carbon captured from the air. Shipping is decarbonised primarily by burning ammonia in combustion engines (meaning that the vast majority of existing ship types and sizes can be retrofitted to burn it), made from low-carbon hydrogen. 75% of the ammonia for shipping propulsion is made in the UK, the remainder is made abroad from low-carbon hydrogen. A small minority of shipping energy demand is electrified.
Industrial demand	Growth in industrial output to 2050 is offset by energy efficiency improvements and a shift away from energy-intensive industries: industrial demand in 2050 is overall a 19% reduction versus today.	A shift towards less energy-intensive industries leads to a fall in industrial energy demand by ⅓ compared to today.	Rising energy (electricity and gas) prices in the early 2020s trigger energy efficiency drives across industry earlier than in the other two NG ESO scenarios. Industrial demand follows positive trajectory based on growing GDP.	Energy efficiency improvements are encouraged with strong carbon pricing. Industrial demand follows positive trajectory based on growing GDP.	Energy efficiency improvements are pursued due to effective carbon pricing. Industrial demand follows positive trajectory based on growing GDP.	Growth in industry leads to a 11% growth in industrial energy demand by 2050.	Industry is decarbonised by policies that ensure manufacturing is not moved offshore. Energy efficiency improvements lead to savings of 12 TWh/year by 2050 (compared to an industrial final energy demand of 259 TWh in 2019). Additional energy reductions are acquired through circular economy strategies.
Industrial supply	Industries switch fuels from fossil fuels to biomass, hydrogen and electricity. Industrial emissions are 12 $MtCO_2e$ in 2050, down from 100 $MtCO_2e$ today.	Industry goes part way to decarbonising its supply; 68% of demand is met by hydrogen, electricity and biomass. Gas continues to play a significant role, with CCS. Industrial emissions fall to 10 $MtCO_2e$ in 2050.	Industries switch fuels to electricity (68%), hydrogen (31%) and biomass (1%). Gas demand is completely phased out, and residual industrial emissions are 4 $MtCO_2e$ in 2050.	Industries switch fuels to electricity (45%), hydrogen (54%) and biomass (1%). Gas demand is very small (0.1% of demand) and CCS is applied to remove emissions. Industrial emissions are 4 $MtCO_2e$ in 2050.	Industries switch fuels to electricity (89%), hydrogen (5%) and biomass (1%). Gas demand lingers for 5% of demand and CCS is applied to remove emissions. Industrial emissions are 4 $MtCO_2e$ in 2050.	Total industrial fuel switch to 68% electricity, 18% synthetic gas, 5% synthetic fuels and 9% biomass. Industrial emissions are Net Zero.	Large-scale fuel switches to electricity and hydrogen which, expressed in terms of GHG abatement, provide 14 $MtCO_2e$/year of abatement each in 2050. Significant industrial emissions remain from processes by which no decarbonisation routes have been found: around 15 $MtCO_2e$/year is residual before CCS and BECCS are applied to industrial processes to reduce residual emissions to around 3 $MtCo_2e$/year by 2050.

Table 5 Comparative analysis of selected Net Zero pathways (*continued*)

Pathway	ESC-C	ESC-P	FES-LTW	FES-ST	FES-CT	CAT-ZCB	CCC-B
Land use/ biomass	1.4 million hectares of UK-grown biomass and 30,000 hectares of forest provides 140 TWh of domestic biomass by 2050.	UK biomass supply is constrained to 80 TWh by 2050 due to a disjointed policy framework. Tree planting enjoys public support, and 50,000 hectares of new forest are planted per year by 2050 – much of this is on land previously used for animals.	The UK imports biomass from overseas and makes full use of its domestic resource to give a resource of around 270 TWh/year by 2050.	Strategically managed land use and waste products leads to a UK domestic biomass resource of around 220 TWh/year by 2050.	Strategically managed land use and waste products leads to a UK domestic biomass resource of around 220 TWh/year by 2050.	75% of current livestock land is repurposed, freeing up space for other purposes including afforestation and growing energy crops for biomass. As such, UK biomass resource is increased to 230 TWh/year. Forest area is doubled to 24% of the UK's land area, and 50% of UK peatland is restored.	UK woodland area increases by 18%; peat areas restored increases from 25% in 2019 to 89% in 2050. 720,000 hectares of dedicated energy crops provide 200 TWh of bioenergy resource.
Carbon capture and removal	Early innovation in CCS pushes capture rates to 99%. CCS is applied to heavy industries, and 28 $MtCO_2e$/year r is captured directly from industry by 2050. DACCS scaled up to remove 25 $MtCO_2e$/year by 2050; BECCS provides around 15 TWh/year of electricity and 34 TWh/year of hydrogen production by 2050.	A failure to innovate CCS limits capture rates to 95%. CCS is applied to industry to capture 13 $MtCO_2e$ of industrial emissions. Emissions are captured by rapid increases in tree planting. BECCS provides around 15 TWh/year electricity and 65 TWh/year of hydrogen production by 2050.	CCS capture rates reach 97% by 2050. CCS is used to capture residual emissions in industry (4 $MtCO_2e$/year by 2050). BECCS provides around 64 TWh/year electricity by 2050, but is not used for hydrogen production. Removals from BECCS are 61 Mt-CO_2e/year by 2050.	CCS capture rates reach 97% by 2050. CCS is used to capture residual emissions in industry (4 $MtCO_2e$/year by 2050). BECCS provides around 52 TWh/year electricity by 2050 and 8 TWh/year of hydrogen production by 2050. Removals from BECCS are 49 $MtCO_2e$/year by 2050.	CCS capture rates reach 97% by 2050. CCS is used to capture residual emissions in industry (4 $MtCO_2e$/year by 2050). BECCS provides around 55 TWh/year electricity by 2050, but is not used for hydrogen production. Removals from BECCS are 52 $MtCO_2e$/year by 2050.	Afforestation and peatland restoration leads to capture of 47 $MtCO_2e$/year by 2050.	CCS capture rates reach 95% by 2050. Carbon capture and storage from industry reaches 8 $MtCO_2$/year by 2050. Engineered emissions removals reach 58 $MtCO_2$/year by 2050 (BECCS provides 52 $MtCO_2$/year of removals across power, energy-from waste, industry and hydrogen production by 2050; DACCS provides 5 $MtCO_2$/year; LULUCF provides 1 $MtCO_2$/year) in addition to nature-based sinks of 39 $MtCO_2$/year.

Table 5 Comparative analysis of selected Net Zero pathways (*continued*)

Pathway	ESC-C	ESC-P	FES-LTW	FES-ST	FES-CT	CAT-ZCB	CCC-B
Hydrogen/ low-carbon fuels	~250 TWh/year hydrogen needed by 2050 to supply industry, peak heating, electricity storage and heavy-duty transport (including shipping). 86% of this is to be made from steam reformation of methane with CCS (99% capture rate). The remaining 14% is produced by biomass gasification with CCS.	~185 TWh/year hydrogen needed by 2050 to supply industry, peak heating, electricity storage and heavy-duty transport (including shipping). 59% of this is produced from electrolysis provided by renewables; 35% is produced from biomass gasification with CCS; the remaining 6% is produced from steam reformation of methane, which is limited by the 95% CO_2 capture rate.	235 TWh/year hydrogen needed by 2050 to supply industry, peak winter heating, electricity storage and heavy-duty transport (including shipping). 80% of this is produced from electrolysis powered by renewables, the remaining 20% is supplied by imports.	591 TWh/year hydrogen needed by 2050 to supply widespread domestic heating, industry, electricity storage and heavy-duty transport (including shipping). 89% of this is produced from methane reformation with CCS (97% capture rate), the remaining 11% is from electrolysis powered by renewables.	152 TWh/year hydrogen needed by 2050 to supply industry, peak winter heating, electricity storage and heavy-duty transport (including shipping). 72% of this is produced from electrolysis powered by renewables, the remaining 28% is produced from methane reformation with CCS (97% capture rate).	~100 TWh/year hydrogen needed by 2050. Only ~10% of this hydrogen is used as hydrogen (in hydrogen vehicles); the remainder is used to produce synthetic fuels for shipping, aviation and industry. Hydrogen is 100% produced by electrolysis using excess renewable electricity.	225 TWh/year hydrogen needed by 2050 to supply demands for which electrification remains difficult – mostly shipping, industry, some heating and seasonal storage of surplus renewable electricity. 45% of hydrogen supply comes from electrolysis using surplus renewable energy by 2050, 32% is from fossil gas with CCS, 11% is from biomass gasification and 13% is from imports produced from excess renewable electricity abroad. Around 31% (70 TWh/year) of the hydrogen supply in 2050 is used for ammonia production for shipping; around 13% is used for synthetic jet fuel production.
Electricity demand	Electrification of road transport, heating and industry leads to a 75% increase in electricity system demand from today to 2050.	Heavy electrification of road transport, heating and industry leads to a 130% increase in electricity system demand from today to 2050.	Heavy electrification of road transport, heating and industry leads to a 93% increase in electricity system demand from today to 2050.	Heavy electrification of road transport, heating and industry leads to a 63% increase in electricity system demand from today to 2050.	Heavy electrification of road transport, heating and industry leads to a 113% increase in electricity system demand from today to 2050.	Heavy electrification of road transport, heating and industry leads to a 160% increase in electricity system demand from today to 2050.	Heavy electrification of road transport, heating and industry leads to a 103% increase in electricity system demand from today to 2050.

Table 5 Comparative analysis of selected Net Zero pathways (*continued*)

Pathway	ESC-C	ESC-P	FES-LTW	FES-ST	FES-CT	CAT-ZCB	CCC-B
Electricity mix	40% of generation is wind (27% offshore, 13% onshore), 50% is nuclear. The remainder is solar PV, biomass and flexible generation: 6 GW of gas with CCS and 22 GW of hydrogen turbines are required to smooth out gaps in supply and demand.	53% of generation is wind (46% offshore, 7% onshore), 21% is from other renewables – solar PV, tidal stream and geothermal. While a programme for large-scale nuclear fails to materialise, nuclear still supplies 23% of electricity by 2050. 20 GW of gas with CCS and 30 GW of hydrogen turbines are required to smooth out gaps in supply and demand.	71% of generation is wind (54% offshore, 17% onshore), 11% is solar, 11% is BECCS and 3% is other renewables including wave & tidal and hydro. 6% of generation is met by nuclear. Britain becomes a net exporter of electricity, which amounts to -4% of demand per year by 2050. Hydrogen-powered generators offer flexible generation, providing 1% of annual energy demand. There are no fossil fuel plants by 2050.	72% of generation is wind (63% offshore, 9% onshore), 9% is solar, 11% is BECCS and 8% is other renewables including wave & tidal and hydro. 18% of generation is met by nuclear. Britain becomes a net exporter of electricity, which amounts to -20% of demand per year by 2050. Hydrogen-powered generators offer flexible generation, providing 3% of annual energy demand. Gas with CCS provides some peaking plant, contributing 0.01% of electricity generation by 2050.	65% of generation is wind (48% offshore, 17% onshore), 10% is solar, 9% is BECCS and 7% is other renewables including wave & tidal and hydro. 16% of generation is met by nuclear. Britain becomes a net exporter of electricity, which amounts to -8% of demand per year by 2050. Hydrogen-powered generators offer flexible generation, providing 1% of annual energy demand. There are no fossil fuel plants by 2050.	78% of generation is wind (68% offshore, 10% onshore), 9% is wave & tidal, 9% is solar PV, 3% is geothermal electricity and 1% is hydro. Large-scale renewable power generators use their excess electricity to manufacture synthetic fuels (gaseous and liquid) by electrolysing water (for hydrogen) and combining with biomass. These synthetic fuels enable decarbonisation of shipping & aviation, and provide fuel for gas plants for when demand outstrips supply.	70% of generation is from wind (of which, by installed capacity, is 75% offshore and the remainder onshore) and 14% is from solar PV. Gas with CCS and BECCS contribute around 10% of generation, and the remainder is met with nuclear. Uncertainty exists for the future of i) carbon prices and ii) carbon capture rates. If the price of carbon and/or capture rates are not significantly high, the role of hydrogen will increase as fuel for flexible electricity generation.
Storage and Flexibility	Geological storage of 660 GWh of hydrogen is needed by 2050 to provide peak winter heating demand and electricity generation for flexibility. 8 GW of grid-level electricity storage with a capacity of 35 GWh smooths out peaks and troughs in supply.	Geological storage of 600 GWh of hydrogen is needed by 2050 to provide long-term electricity storage and winter peak heating demand. 4 GW of grid-level electricity storage with a capacity of 29 GWh smooths out peaks and troughs in supply.	16 TWh of hydrogen storage (including geological and pipeline) is needed by 2050 to provide long term electricity storage and winter peak heating demand. Widespread adoption of time of use tariffs (83% of households by 2050) and vehicle 2 grid (45% of households by 2050) results in considerable domestic demand flexibility.	18 TWh of hydrogen storage (including geological and pipeline) is needed by 2050 to provide long term electricity storage and winter peak heating demand. Widespread adoption of time of use tariffs (60% of households by 2050) and vehicle 2 grid (11% of households by 2050) results in considerable domestic demand flexibility.	18 TWh of hydrogen storage (including geological and pipeline) is needed by 2050 to provide long term electricity storage and winter peak heating demand. Widespread adoption of time of use tariffs (73% of households by 2050) and vehicle 2 grid (26% of households by 2050) results in considerable domestic demand flexibility.	Geological storage of 80 TWh of synthetic methane is needed by 2050. The synthetic methane is made from hydrogen (from electrolysis, using surplus renewable energy) and biomass. 200 GWh of pumped hydro and battery storage provide day-to-day flexibility between supply of renewable power and demand.	Additional flexibility is met with 18 GW of battery storage capacity by 2035 and expansion of interconnector capacity 4.5x from current levels to 18 GW by 2050. Around 13% of electricity demand is for hydrogen production to allow for seasonal energy storage.

Table 5 Comparative analysis of selected Net Zero pathways (*continued*)

Pathway	ESC-C	ESC-P	FES-LTW	FES-ST	FES-CT	CAT-ZCB	CCC-B
			203 GWh of pumped hydro, battery and compressed air electricity storage systems provide day-to-day flexibility.	146 GWh of pumped hydro, battery and compressed air electricity storage systems provide day-to-day flexibility.	194 GWh of pumped hydro, battery and compressed air electricity storage systems provide day-to-day flexibility.		
Lifestyle/ behaviour	High levels of technology change allow Net Zero with little impact on peoples' lives. Car travel and aviation demand continues to rise, and indoor temperatures rise to an average of 21 °C compared to 18 °C today. However, a shift towards plant-based diets leads to a 20% reduction in meat and dairy demand by 2050.	A fairly active society seeks low-carbon ways of living, including reducing car use in favour of public & active transport and constraining flight. Warm layers are sought instead of turning up thermostats (average room temperatures reach 19.5 °C). Meat and dairy demand falls by 50% by 2050.	Fairly significant lifestyle changes, including reduced car ownership in favour of public/active transport and car sharing. Highest uptake of flexible demand schemes such as time of use tariffs and V2G.	Consumers are less willing to change their behaviours, and uptake of flexible demand-enabling technologies remain fairly low outside of an engaged few. Private car ownership remains high.	Consumers are somewhat willing to change their behaviours, and uptake of flexible demand-enabling technologies is moderate. Some two car households become one car households because of the advent of autonomous vehicles, but their travel habits do not change much.	People seek no rise in indoor temperature relative to today. Transport behaviour changes significantly: average car mileage per person reduces to ~4,400 miles in 2050 relative to ~6,500 miles today, offset by a four-fold increase in cycling and two-fold increase in bus usage. Demand for beef and lamb falls by 92%; other meat demand falls by 58%; dairy demand falls by 59%.	Transport patterns change, in that growth in aviation demand is limited and car mileage per person reduces to ~7,300 miles in 2050. Waste per person, after prevention and recycling, reduces by 39% by 2050 compared to 2019 levels. Demands for meat and dairy reduce by 34% and 19% respectively.

5.3 Chapter 5 Endnotes & References

5.3.1 Endnotes

[88]The CCC's Balanced pathway is less prescriptive than the other six in terms of share of generation as it acknowledges that there is significant uncertainty as to the development of technologies and economic systems between 2020 and 2050. It is prescribed that wind provides 70% of generation in the 2050 electricity system, which is split (by capacity) to 75% offshore and 25% onshore. Using 2019 capacity factors for offshore and onshore wind of 36% and 28% respectively, their shares of generation as part of the 70% are estimated as 79% for offshore and 21% for onshore. A 14% share for solar is prescribed, and it is stated that gas with CCS and BECCS make up 10%. By capacity, gas with CCS and BECCS are in a ratio of 3:1 (15 GW to 5 GW). Assuming the same capacity factor for each, this means that gas with CCS will comprise 7.5% of generation and BECCS will comprise 2.5% of generation. The remainder is said to be met by nuclear – this is 6%.

[89]In their Future Energy Scenarios report, National Grid ESO provide only the electrical demand required for space heating. To derive the heating primary energy demand, their assumptions as detailed in [5.7] and [5.8] were used: 2050 heat pump coefficients of performance (COPs) were assumed as 3.5 for Consumer Transformation and Leading the Way, and 3.2 for System Transformation. Hydrogen boiler efficiencies were assumed as 96% by 2050 [5.8]. The primary heat demand was found by finding a weighted COP for all technologies in a given scenario and multiplying this by the stated electricity demand.

5.3.2 References

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[5.2] Energy Systems Catapult, "Innovating to Net Zero," 2019. [Online]. Available: https://bit.ly/36vByi7.

[5.3] National Grid ESO, "Future Energy Scenarios," 2020. [Online]. Available: https://bit.ly/2HvKY4L.

[5.4] Centre for Alternative Technology, "Zero Carbon Britain: Rising to the Climate Emergency," 2019. [Online]. Available: https://bit.ly/35wAETj.

[5.5] Climate Change Committee, "Sixth Carbon Budget," 2020. [Online]. Available: https://bit.ly/3oOlyy6.

[5.6] Department for Transport, "Greenhouse gas emissions by transport mode: United Kingdom," 2020. [Online]. Available: https://bit.ly/3xu0Z06.

[5.7] National Grid ESO, "FES 2020 FAQ document," 2020. [Online]. Available: https://bit.ly/2IxtSE3.

[5.8] National Grid ESO, "FES 2019 Questions and Answers," 2019. [Online]. Available: https://bit.ly/35qZ6pk.

Chapter 6 – Conclusion: A Vision of the 2050 Energy System

There are a great many technology options available for the delivery of a UK Net Zero energy system. As identified in §5.2, a clear pattern emerges to how pathways to Net Zero are envisaged. This provides a clear concluding message from this guide:

- **Pathways that rely on little behavioural change to 2050 rely on significant changes in technology.**
- **Pathways that rely on significant behavioural change to 2050 rely on less significant changes in technology.**

A third concluding message is that, even for the most drastic assumed changes in lifestyle:

- **Significant changes in technology are required to meet Net Zero.**

While all of these technologies described in this guide may have a part to play in contributing towards Net Zero, it is clear that there are some that are more suitable to the UK , both in terms of our existing infrastructure and renewable resources and our present day energy demand 'culture'.

Together, these can be combined with visions of changing energy demand summarised in §5.2 to produce an outline of the *most likely* incarnation of the UK's Net Zero energy system in 2050. These are detailed in points 1-12 below.

1. **Electricity demand will have doubled or tripled** compared to 2020.
2. Demand for **petroleum and fossil gas for energy will be much smaller than today or eliminated**. Residual demand for petroleum – if any – will be for aviation. Residual demand for gas – if any – will be for industrial processes, electricity generation for times of peak demand and/or hydrogen production. Emissions resulting from these residual demands will be captured at source and/or offset elsewhere.
3. **The majority of residential heating is most likely to be met by heat pumps** installed directly at UK homes. **Densely populated areas (urban centres) will be connected to district heating networks** powered by a wide variety of low-carbon heat sources including large-scale heat pumps, hydrogen, bioenergy, solar thermal and geothermal. **Some housing stock that is not suitable for direct heat pump replacement will remain connected to the gas grid, which will have switched to run on 100% hydrogen**. In these homes, hydrogen boilers or heat pump/hydrogen boiler hybrids will ensure peak winter heating demand is met.
4. To ensure the success of residential heating decarbonisation, **energy efficiency improvements will be made to existing UK homes** (the most likely path is that all UK homes will be EPC C-rated by 2030) via a programme of 'deep' retrofits. New builds will be built to standards that are compatible with Net Zero (e.g. Passivhaus).
5. **Industrial and commercial heating will be met by a mixture of direct electrical heating, heat pumps, hydrogen** and, for a time at least, **fossil gas with carbon capture, utilisation and storage (CCUS)**. Some industrial and commercial sites will be on **district heating networks, supplying/consuming heat (or cooling) to/from these networks.** Cross-border carbon adjustments may have a role in keeping UK manufacturing cost-competitive with imports from countries which are due to decarbonise later than the UK.
6. **Surface transport will be completely decarbonised by 2050**. **Battery electric vehicles will replace private internal combustion engine cars**, whereas a **mixture of electric, hydrogen and electric/hydrogen hybrid powertrains will supply demand for road freight**. Decarbonisation will be made easier via significant changes in transport energy demand, including **significant modal shift to lower energy demand modes of transport** (electrified/low-carbon public transport and active transport), and **increased use of shared transport** to reduce – or slow the increase – in the total number of cars in the UK. **Major upgrades in cycling and walking infrastructure**, with targeted support for e-bikes, will **encourage people away from private car use and multiple car ownership**. These shifts will be achieved by

measures which will **improve the quality of life, commercial vitality, safety and equity of their communities**.

7. **Shipping will be completely or near-completely decarbonised** by 2050, with the vast majority of demand being met by **hydrogen, ammonia or synthetic fuel** produced using **surplus renewable electricity**, **water**, and either **biomass**, a **carbon capture and utilisation** (CCU) source, or **direct air capture** (DAC).
8. **Aviation demand will be limited to, at most, a 25% increase on today**, with some scenarios seeing a **stagnation or reduction in demand**. This slowing of the rate of aviation demand increase will be achieved by **effective emissions pricing, targeting the few people that cause the majority of emissions via mechanisms such as a frequent flyer levy**. **Energy supply for large aircraft may be the last remaining demand for petroleum in the energy sector**; alternatively, **aviation energy demand could be met from synthetic hydrocarbons made from hydrogen and carbon resulting from direct air capture using surplus energy from large-scale renewables**. Electricity and hydrogen may provide some demand if many aircraft are fundamentally redesigned (e.g. to allow for large, cylindrical liquefied hydrogen tanks as opposed to storing kerosene in the wings as is currently done).
9. **The majority of electricity generation will be from wind and solar PV with some nuclear**. Demand flexibility – particularly from the emerging demand resulting from electric vehicle charging – will play a large role in matching a largely inflexible supply to demand, as will an array of electrical, heat and hydrogen/synthetic fuel-based storage technologies. **Short-term electricity storage will be provided by batteries, pumped hydro and compressed air storage systems**; **seasonal electricity storage will be provided by the conversion of surplus renewable energy into hydrogen** via electrolysis of seawater and/or **synthesis of hydrogen from fossil fuels**, with CCS.
10. Afforestation will be pursued to remove and store CO_2 from the atmosphere in plant matter. **Engineered removals will be achieved via carbon capture & storage (CCS) at industrial hubs** to reduce emissions in difficult sectors. **CCS will be deployed with sustainable bioenergy (BECCS) for electricity generation** to offset residual emissions. **Direct air CCS (DACCS) will contribute to additional removal of emissions**.
11. **Land use will change to allow an increase in domestic plant biomass** via energy crops and sustainably managed woodlands. Stringent regulations on bioenergy will set an upper limit on around 7% of current UK agricultural land area being used to grow plant biomass, so that supply chains for heating, transport and electricity generation do not compete with the supply of food or the provision of biodiversity. **UK forest area will have increased by at least 50% from 2020 and may have doubled**.
12. A **just transition** will ensure that the path to Net Zero is taken in concert with positive impacts on the economy, jobs and peoples' quality of life. As such, **people will continue to regard the need for the Net Zero transition as very important**. **Adoption of new technologies** (heat pumps, EVs and energy efficiency improvements) **will happen at the required rate** with targeted government support for all sectors (costing, as per the Climate Change Committee's Sixth Carbon Budget report, less than 1% of GDP every year over the next thirty years). **Effective emissions pricing will mean that low-emission transportation options are always cheaper than high-emission options**. **Public transport, cycling and walking will have substantially increased their modal share of total travel in towns and cities**, and **car use in dense urban areas will be discouraged via road pricing**. **Diets will continue to shift towards more plant-based foods**, which will lead to **a reduction in meat & dairy demand of 20-50%**. This will free up agricultural land for afforestation and production of sustainable biomass.
13. A Net Zero energy system will have been reached because of **sustained action from Government, business and civil society.**

Annex: The Chemistry of Energy Systems

This annex is optional reading for the enthusiast who would like more information about reactions of fuels, food soils, and human activity. This annex is designed to be read together with carbon and nitrogen cycle diagrams (Figure 111 and 112 respectively). This annex is linked to those diagrams by the numbered circles in the text.

7.1 The Carbon Cycle

7.1.1 Living Matter

All living matter is composed primarily of compounds of carbon, hydrogen and oxygen.

C – is the symbol for carbon	**carbon dioxide is CO_2**	
H – is the symbol for hydrogen	**hydrogen gas is H_2**	**water is H_2O**
O – is the symbol for oxygen	**oxygen gas is O_2**	

Photosynthesis

When plants grow, they remove carbon dioxide from the air by *photosynthesis* to make plant biomass.

The chemical equation of photosynthesis is:

$$6\ CO_2 + 6\ H_2O + \text{light} \rightarrow C_6H_{12}O_6 + 6\ O_2 \quad (1)$$

This builds plant material, for example **glucose** ($C_6H_{12}O_6$, a simple *carbohydrate*).

Other plant materials such as cellulose (in grass) and lignin (in wood), and starches and fats in our diets, are also composed of these elements.

Photosynthesis also produces oxygen gas, O_2.

When we eat plant material (or other food), we break it down in our bodies to release energy (called *respiration*) – the same overall reaction in reverse. For example, glucose ($C_6H_{12}O_6$) breaks down as follows:

Respiration

The chemical equation for respiration is:

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O + \text{heat} \quad (2)$$

This kind of reaction happens in all living things which use oxygen, including plants at night, and microbes in soil. It also happens when biomass decays, in conditions where there is air available.

When biomass *breaks down, without* having oxygen available, a different reaction happens, called *anaerobic breakdown*.

Anaerobic Breakdown

The chemical equation for anaerobic breakdown is:

$$C_6H_{12}O_6 \rightarrow 3\ CO_2 + 3\ CH_4 \quad (3)$$

Reaction products: mainly carbon dioxide and methane, CH_4.

This reaction can occur naturally, for example when biomass breaks down in waterlogged areas.

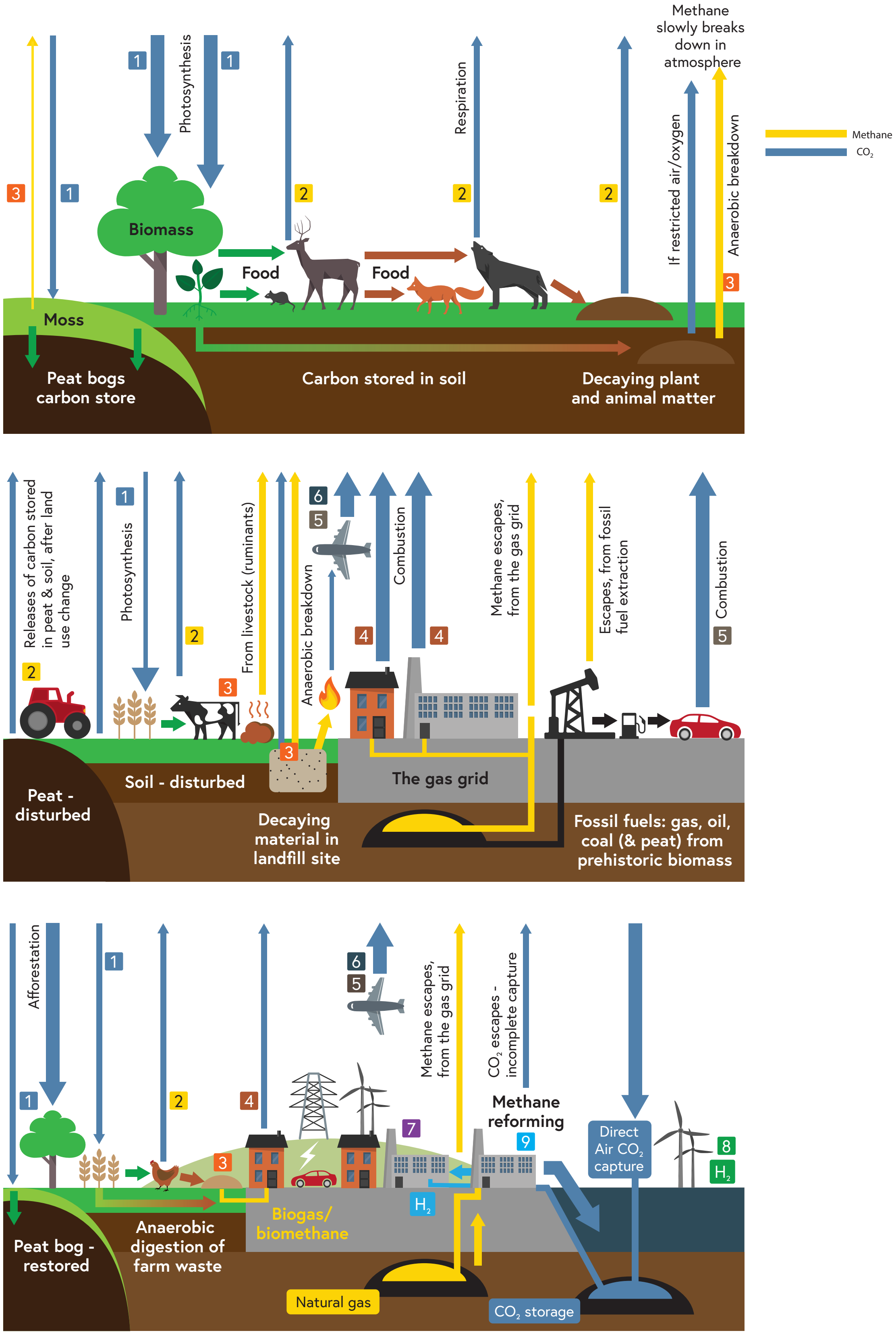
It also occurs in landfill sites containing any biomass (producing *landfill gas*), and may occur in poorly sited (or poorly maintained) large hydroelectric schemes which involve creating a reservoir. (However, it would not normally happen in a well-aerated compost heap). If the methane is not captured, and is vented to air, it contributes to global warming, as methane is a significant GHG. Uncontrolled production of methane can also create an explosion hazard.

This type of reaction happens, by design, in *anaerobic digesters:* organic waste materials are broken down by microbes. The *biogas*, which contains methane, is captured and used as a fuel.

A similar process (called *enteric fermentation*) happens in the digestive tract of some animals – *ruminants* (such as cattle and sheep). These animals have bacteria in their gut, which help them digest grass. The methane produced is the main source of GHG emissions from agriculture.

Annex: The Chemistry of Energy Systems

Figure 111 The carbon cycle – (top) the natural environment, (middle) human activity – current state and (bottom) human activity – possible future



7.1.2 Reactions of Fuels

Combustion of Coal (and Charcoal)

Coal is primarily carbon. Oxygen normally exists as oxygen gas, O_2. The chemical equation for combustion of coal or charcoal is:

$$C + O_2 \rightarrow CO_2 + \text{heat}$$

Combustion of Methane

Methane, the main component of fossil gas, has formula CH_4.

$$CH_4 + 2\ O_2 \rightarrow CO_2 + 2\ H_2O + \text{heat}$$ 4

If there is a *restricted supply of oxygen*, sometimes the following reaction happens. (Similar reactions can also occur with other fuels.)

$$CH_4 + 1\tfrac{1}{2}\ O_2 \rightarrow CO + 2\ H_2O + \text{heat}$$

CO, carbon monoxide, is not a greenhouse gas but it is very poisonous.

Combustion of Transport Fuels

Petrol, kerosene and diesel consist of a mixture of *hydrocarbons* (compounds of carbon and hydrogen), for example $C_{10}H_{22}$, present in all three of those fuels. The chemical equation of combustion of $C_{10}H_{22}$ is:

$$C_{10}H_{22} + 15\tfrac{1}{2}\ O_2 \rightarrow 10\ CO_2 + 11\ H_2O + \text{heat}$$ 5

Other fuels such as methanol (CH_3OH) and ethanol (C_2H_5OH), react in a similar manner:

$$C_2H_5OH + 3\ O_2 \rightarrow 2\ CO_2 + 3\ H_2O + \text{heat}$$

Exhaust emissions from aircraft cause a greater global warming effect than burning the same fuel at ground level, because of reactions between the aircraft exhaust air and the atmosphere. The largest warming effect is from aircraft condensation trails (*contrails*) of ice crystals. 6

Combustion of Biomass

Wood and other biomass can be burnt as fuel, as follows:

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O + \text{heat}$$

Combustion of Hydrogen

Hydrogen (H) exists as hydrogen gas (H_2) at ambient temperatures and pressures. At the point of burning, it emits no CO_2. The chemical equation for combustion of hydrogen gas is:

$$H_2 + \tfrac{1}{2}\ O_2 \rightarrow H_2O$$ 7

Note that the only combustion product is water. This reaction can also occur at ambient temperature in a *fuel*.

All combustion reactions can also produce oxides of nitrogen, NO_x emissions, described in §7.2.

7.1.3 Production of Hydrogen [7.1]

By Electrolysis

Water molecules can be split by electricity, to yield hydrogen and oxygen:

$$H_2O + \text{electricity} + \text{heat} \rightarrow H_2 + \tfrac{1}{2}\ O_2$$ 8

If the electricity is from a renewable source, hydrogen made in this way is sometimes called 'green hydrogen'.

Reformation of Fuels to make Hydrogen

Hydrogen is currently made from fossil fuels, for example from methane:

$$CH_4 + H_2O + \text{heat} \rightarrow 3\ H_2 + CO$$
(methane reformation) 9

$$CO + H_2O \rightarrow H_2 + CO_2 + \text{a little heat}$$
(water-gas shift) 9

Overall reaction:

$$CH_4 + 2\ H_2O + \text{heat} \rightarrow 4\ H_2 + CO_2$$

This reaction produces carbon dioxide, which, at present, is simply vented to air. Hydrogen produced in this way is sometimes called 'grey hydrogen'.

In future, carbon capture and storage (CCS) facilities could be added, which would expect to capture most of the CO_2 evolved from this reaction. Hydrogen produced in this way is sometimes called 'blue hydrogen'.

7.2 The Nitrogen Cycle

7.2.1 Natural Environment [7.2, 7.3]

N is the symbol for nitrogen	**Nitrogen gas is N_2**
	Nitric oxide is NO
	Nitrogen dioxide is NO_2
	Nitrous oxide is N_2O

Approximately 80% of our atmosphere is made up of nitrogen gas. Nitrogen gas is very stable and normally does not take part in chemical reactions.

All living things require *some* nitrogen: it is necessary for growth and cell functioning. The food group *protein* includes food molecules which all contain some nitrogen, in addition to carbon, hydrogen and oxygen.

Formation of NO and NO_2 Gases

A little NO and NO_2 are formed during **lightning strikes**, from nitrogen and oxygen in the air reacting.

$$N_2 + O_2 \rightarrow 2\,NO$$
$$N_2 + 2O_2 \rightarrow 2\,NO_2 \quad (1)$$

In air, some of this nitric oxide reacts with oxygen to give more nitrogen dioxide:

$$NO + ½\,O_2 \rightarrow NO_2$$

These gases both dissolve in rainwater to make an acidic solution containing nitrates (NO_3) and other compounds of nitrogen, which can be taken up by plants.

Nitrogen Fixation

Some microbes in the soil or plant roots can capture or '**fix**' nitrogen gas from the air, and turn it into compounds of nitrogen that are available to plants. This is the major source of nitrogen in soils in a natural environment where no chemical fertiliser is used. In the below chemical equation, microbes turn nitrogen gas (N_2) into ammonia (NH_3), which forms (with water) ammonium compounds (NH_4^+) ('plant foods').

$$N_2 \rightarrow \textit{(microbes)} \rightarrow NH_3 \leftarrow \textit{(in water)} \rightarrow NH_4^+ \quad (2)$$

Nitrogen Uptake by Plants and Animals

Plants take up **nitrates and ammonium compounds** (dissolved in water) from the soil via their roots. From these simple compounds, plants synthesise complex nitrogen-containing foods:

Nitrates & ammonium compounds → amino acids → proteins (3)

People and animals get the protein they need in their diets from eating plant and/or animal protein. (4)

Nitrogen Cycling in Ecosystems

If animals or people eat more protein than they need, they break down the excess amino acids. The nitrogen-containing 'amino' part of amino acid molecules is excreted, usually via urine, which contains *uric acid* and *urea*. In soils, these substances are readily broken down into *ammonium compounds* (NH_4^+) and/or *ammonia gas*, (NH_3).

Manure and decaying biomass contain proteins. *Decomposers* and microbes break these down to simple compounds which plants can take up:

Proteins → amino acids → ammonium compounds ↔ nitrates (5)

Nitrogen Losses from Soils and Greenhouse Gas Emissions

Nitrates and ammonium compounds are easily washed out of soils (*leaching*). Soil microbes can perform *denitrification*: nitrates are converted to **nitrous oxide** and/or **nitrogen gas**, which escape into the air:

$NO_3^- \rightarrow NO_2^- \rightarrow N_2O$ (escapes to air) $\rightarrow N_2$ (escapes to air) (6)

7.2.2 Human Activity [7.3, 7.4]

Emissions of NO_X from High Temperature Combustion

Nitric oxide (NO), nitrogen dioxide (NO_2) and nitrous oxide (N_2O) are collectively known as NO_X.

Any combustion (or very high temperature conditions) causes some nitrogen in the air to react with oxygen and form NO and/or NO_2, and sometimes also N_2O gases (collectively known as 'NO_x'). NO_x is normally predominantly NO and/or NO_2.

$$N_2 + O_2 \rightarrow 2\,NO$$
$$N_2 + 2\,O_2 \rightarrow 2\,NO_2$$
$$N_2 + ½\,O_2 \rightarrow N_2O$$
$$\text{In air: } NO + ½\,O_2 \leftrightarrow NO_2$$

7

Significant NO_x sources include fossil fuel or biomass-burning power stations and vehicles with internal combustion engines. Pollution control legislation in the UK limits allowable NO_x emissions from major (and more recently, medium-sized) combustion plants. Many industrial plants have NO_x-reduction measures in place.

Traffic is the major source of NO_x in most UK urban areas. Some NO_x can be produced from domestic gas cookers.

Impacts of NO_X Emissions

NO_2 is an acidic gas. It is a major air pollutant with serious negative impacts on human health, including increased chances of lung and heart diseases. 8

NO_x (NO and NO_2 components) can also cause ecological damage, affecting some sensitive ecosystems, such as peat bogs in upland Britain, which are important carbon stores.

NO_x from aircraft interacts with other substances in the upper atmosphere, which contributes to non-CO_2 warming effects from aviation [7.5]. 9

Formation of Nitrous Oxide in Combustion

Small amounts of **nitrous oxide, N_2O** can also be produced, under some conditions e.g. *during ignition*, and under *lean-burn conditions*. Engines are sometimes run under such conditions to reduce overall NO_x emissions [7.6]. 10

Catalytic converters on car exhausts aim to change the NO_x in car exhaust fumes to nitrogen gas, N_2. However, the catalytic converters also change some of the NO and NO_2 to N_2O, which is good for air quality, but increases emissions of the greenhouse gas N_2O. Catalyst manufacturers are working on producing catalysts which do not do this [7.7, 7.8].

Nitrous oxide in atmospheric concentrations does not appear to harm human health or the local environment, but it is a **powerful greenhouse gas.**

Agriculture

Intensive farming can lead to **nitrous oxide formation** by *denitrification*. Agricultural soils – which are normally fertilised - are the largest source of nitrous oxide emissions in the UK [7.9]. 6

Chemical fertilisers such as *ammonium and nitrate compounds* are made from reacting nitrogen (from the air) with hydrogen:

$N_2 + 3\,H_2 \rightarrow 3\,NH_3$	ammonia production, Haber-Bosch process	
$NH_3 + 2\,O_2 \rightarrow H_2O + HNO_3$	nitric acid production, the Ostwald process	11
$HNO_3 + NH_3 \rightarrow NH_4NO_3$	ammonium nitrate, acid-base neutralisation	

Intensive farming practices often require chemical fertilisers, and/or other measures, to replenish bioavailable nitrogen in soils, to maintain good crop yields. 11 2 5

Chemical fertilisers are often applied in larger amounts than crops need.

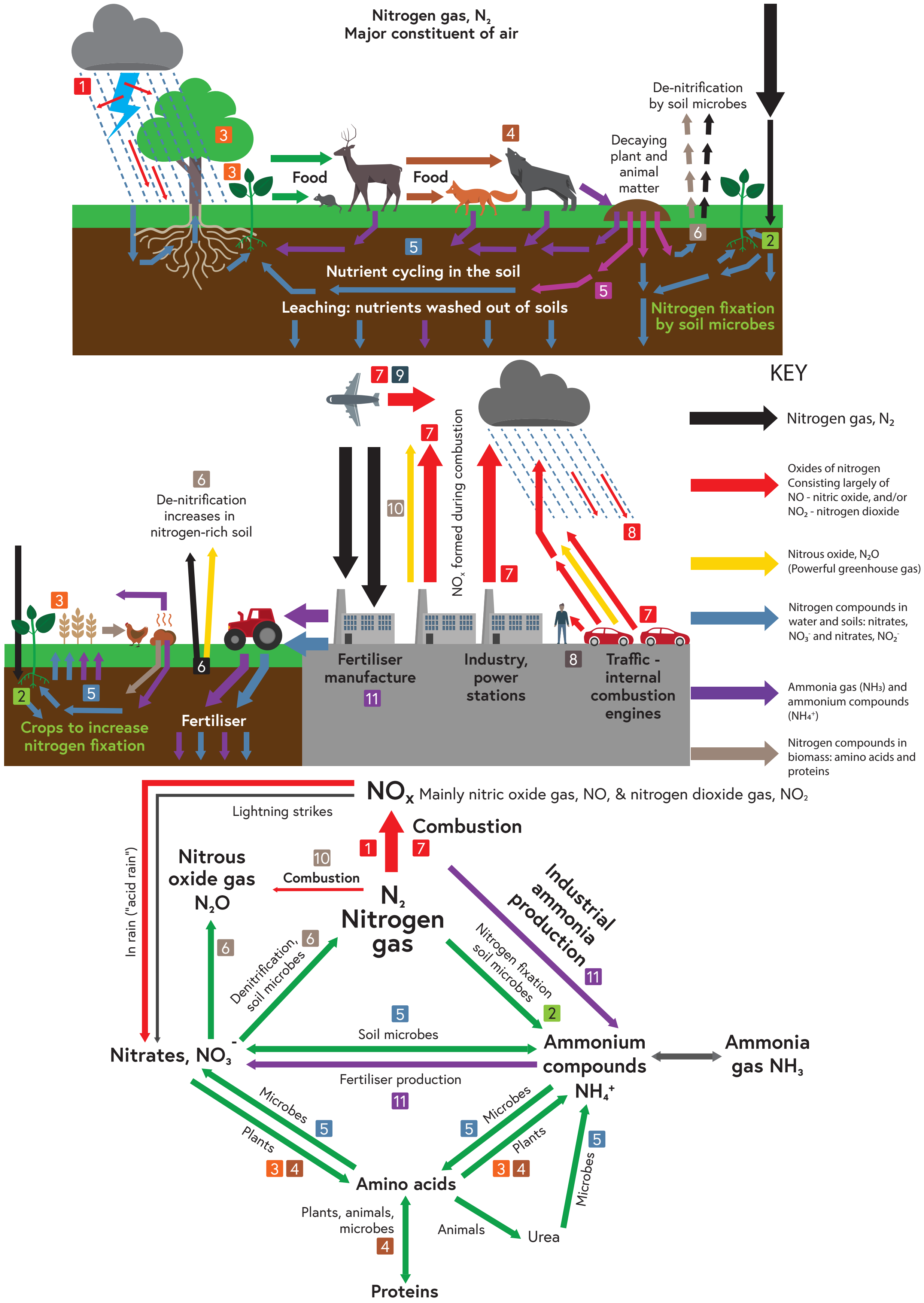
Some of the excess nitrogen ends up **converted to N_2O** by soil microbes.

Nitrous oxide emissions also occur from soils enriched with **crop residues and manure**, and animal urine and dung, as these materials break down.

Ammonia emissions from intensive animal husbandry units can cause other adverse environmental impacts.

An increased demand for energy crops may increase the pressure to farm intensively, which may increase nitrous oxide emissions. It can also cause further land-clearance to create additional arable land, which can release carbon stores from soils.

Figure 112 The nitrogen cycle – (top) the natural environment, (middle) human activity – current state and (bottom) schematic summary



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Glossary

General terms		
Acronym/Abbreviation	**Name**	**Description**
FES	Future Energy Scenarios	National Grid has developed a portfolio of Future Energy Scenarios for Great Britain, which are referenced several times throughout this guide.
GHG	Greenhouse gas	A gas which absorbs and emits solar radiation reflected by the Earth. These gases reduce the rate of heat loss from the planet, and hence if their concentrations increase, the rate of heat loss decreases and the planet warms as a result.
LULUCF	Land use, land use change and forestry	A sector that covers emissions and removals of GHGs from direct human-induced land-use. LULUCF emissions can be net positive (net emissions) or net negative (net sequestration).
-	Net Zero	A policy goal of achieving no net Greenhouse gas emissions. Some sectors may continue to cause GHG emissions, but if offset by enough actions causing negative emissions, overall emissions can still be net zero.
-	Net zero technology	A technology with *low enough GHG emissions* to enable net zero overall emissions.
-	Order(s) of magnitude	A factor(s) of ten. "*One order of magnitude higher*" means "roughly ten times bigger"; "*Four orders of magnitude bigger*" means "roughly 10,000 times bigger".
R&D	Research and Development	The process by which new knowledge is acquired in the hope of developing new technologies, products, systems or services.
Policy Instruments		
Acronym/Abbreviation	**Name**	**Description**
CfD	Contract for Difference	A contract defined in terms of a strike price and its comparison with another price. If the latter is lower than the strike price, an additional payment to the contract holder is made to make up the difference; if it is higher, the contract holder pays back the difference. The net result is that the contract holder always receives exactly the strike price. The UK Government has awarded such contracts for energy to encourage the provision of low-carbon electricity. The prices and participants are determined at auctions, with similar types of technology bidding together. Very new technologies, such as tidal and wave generation, can access higher prices.
FiT	Feed-in-Tariff	A policy instrument designed to encourage small-scale renewable generation. Successful applicants can receive a guaranteed preferential price for electricity they export onto the grid.
RHI	Renewable Heat Incentive	A UK Government policy instrument designed to encourage the provision of heat from renewable sources.

Glossary

Acronym/Abbreviation	Name	Description
RO	Renewables Obligation	A UK Government policy instrument designed to encourage the provision of electricity from renewable generators.
ROCs	Renewable Obligation Certificates	Certificates used as evidence that generation has been sourced by renewables. Under the Renewables Obligation, suppliers are obliged to obtain a minimum number of these certificates. ROCs can also be traded, and have a current market price of around £50/MWh.
Organisations		
Acronym/Abbreviation	**Name**	**Description**
-	Aggregator	Third party intermediary specialising in aggregating and coordinating flexibility in electricity demand. Generally, they send signals to their customers to alter their demand (e.g. modulate – turn up or turn down – or delay the running of an electric vehicle charger or a warehouse freezer) in times when such an action would benefit the operation of the system. Price incentives from the system operator benefit the customer, and the aggregator takes a proportion of the saved cost or revenue.
BEIS	Department for Business, Energy & Industrial Strategy	UK Government department responsible for national policies regarding business, energy and industrial strategy.
CCC	Climate Change Committee	Independent statutory body for advising the UK Government on climate change.
DfT	Department for Transport	UK Government department responsible for national transport policy.
DNO	Distribution Network Operator	The owner of the electricity network infrastructure in a local area, which delivers electricity to end-users. DNOs operate and look after the lower voltage electricity wires and cables.
ENA	Energy Networks Association	A trade body of owners and operators of electricity and gas network infrastructure in the UK.
GDN	Gas Distribution Network	The gas network infrastructure in a local area which delivers gas to end-users through smaller, lower-pressure gas pipes
National Grid ESO	National Grid Electricity System Operator	The part of National Grid responsible for operation of the electricity system in Great Britain. It ensures that the right amount of electrical power is being produced to exactly match the country's consumption of electricity and that power flows and voltages on the transmission network and the power system's electrical frequency are within acceptable limits.
National Grid ET	National Grid Electricity Transmission	The part of National Grid which owns and maintains the high voltage electricity network in England and Wales. In Scotland, the electricity transmission network infrastructure is owned by SP Energy Networks (Southern Scotland) and Scottish and Southern Energy Networks (Northern Scotland).

Glossary

Acronym/Abbreviation	Name	Description
National Grid GT	National Grid Gas transmission	The part of National Grid which owns and maintains the gas transmission infrastructure (large, high pressure pipes) in Great Britain, and ensures correct quantities of gas are delivered daily to meet the needs of the country.
Ofgem	Office for gas and electricity markets	The regulator of gas and electricity markets. It sets the rules governing the revenues that electricity and gas transmission and distribution companies can access, and aims to ensure that there is adequate competition in energy wholesale and retail markets.
	Fuels and chemistry	
Acronym/Abbreviation	**Name**	**Description**
AD	Anaerobic Digestion	The breakdown of organic material by micro-organisms, in the absence of oxygen. AD produces biogas, a methane-rich gas that can be used as a fuel, and digestate, a source of nutrients that can be used as a fertiliser.
-	Bioenergy	Energy made from material of recent biological origin derived from plant or animal matter. It covers solid biomass, biogas, and liquid biofuels. Bioenergy is considered to be renewable if it is sustainable.
-	Biofuel	Liquid or gaseous fuels, made from recently living biological material such as crops, residues or waste products. The main biofuels used in Britain are biodiesel (made largely from used cooking oil and other food waste) and bioethanol (made from fermentation of crops, such as cereals or sugar beet). Future applications for biofuels include fuels for aviation.
-	Biogas	Calorific gas derived from anaerobic digestion or gasification of organic feedstocks such as biomass, sewage sludge, food wastes or farm slurry. Contains methane and carbon dioxide. It is normally considered to be renewable.
-	Biomass	Materials originating from (recently living) plant or animal material, such as wood, agricultural crops or wastes, and municipal wastes. Biomass can be burned directly or processed into biofuels such as ethanol and methane. It is normally considered to be renewable.
Bio-SNG	Bio-synthetic natural gas	Methane formed synthetically, using biomass as the source of carbon.
-	Fossil fuel	A fuel formed from the remains of plant and animal matter from millions of years ago. Coal, petroleum and natural gas are the most common fossil fuels.
	Fugitive emissions	Unintended release of a substance, usually a gas or liquid, e.g. from leaks in equipment.
-	Gasworks	Facilities for the production of town gas, normally from coal.

Glossary

Acronym/Abbreviation	Name	Description
-	Gasification	A process: heat treatment of a solid fuel, to make *syngas*, a carbon-rich gas which can be used as a fuel or for chemical processing.
GCV	Gross calorific value	See HHV.
HHV	Higher heating value	The theoretical calorific value of a fuel, assuming the water produced in the reaction is liquid (or is vapour, but later condenses, and its *latent heat of vaporisation* is fully recovered). For example, the HHV of hydrogen is 39.4 kWh/kg of hydrogen. See also LHV.
-	Landfill gas	Gas derived from landfill sites. Landfill gas contains methane and can be used as a fuel.
-	Latent heat of fusion	The energy required to melt a solid, or released when a liquid solidifies/freezes.
-	Latent heat of vaporisation	The energy required to turn a substance from liquid to gaseous state, or released when a gas condenses into a liquid.
LNG	Liquefied natural gas	Natural gas that has been converted to liquid form (by refrigeration) for ease of storage or transport.
LHV	Lower heating value	The theoretical calorific value of a fuel, assuming the water from the reaction is gaseous (steam/water vapour). For example, the LHV of hydrogen is 33.3 kWh/kg of hydrogen. See also HHV.
-	Fossil gas	Fossil (a.k.a. natural) gas is a mixture of naturally occurring gases found in underground reservoirs, sometimes in association with crude oil. Fossil gas consists largely of methane, sometimes some other hydrocarbons and other substances. It is a fossil fuel, mostly formed from the decay of biomass from millions of years ago.
-	Organic	In this guide, this means material that originated from living beings (plants or animals). Organic materials include all types of biomass (including animal wastes e.g. manure). Organic chemicals are substances with a carbon chain, and so include substances found in petroleum.
-	Renewable	A fuel or source of energy whose use does not deplete any natural resources. Examples include: electricity made from solar, wind, marine or geothermal sources, or biomass or biofuels which are produced in a sustainable manner.
-	Synfuel	Synthetic fuel, made from chemical processing of a feedstock e.g. hydrogen and CO_2. Examples include synthetic methane, ethanol or kerosene.
-	Syngas	A gas made from heat-treatment of a fuel, which can be used as a fuel or for chemical processing. Town gas was a syngas, made in the UK from coal, at gas works, up until the 1970s. It consisted of a mixture of gases, predominantly methane, carbon monoxide, and hydrogen.

Glossary

Acronym/Abbreviation	Name	Description
SNG	Synthetic natural gas	Methane, formed from a chemical process, e.g. combining hydrogen with CO_2
-	Town gas	A calorific gas, historically manufactured from coal in UK towns and cities, at gas-works, to provide gas for lighting and other appliances. Was a mixture consisting mainly of hydrogen, methane, and carbon monoxide. Town gas production was discontinued in the 1970s, with the switch to natural gas.
CH_4	Methane	A gaseous hydrocarbon commonly used as a fuel; the main constituent of natural gas. Methane is also a potent GHG (in the first two decades after its release, it is 84 times more potent than CO_2). The largest UK sources are agriculture (cattle and sheep), and landfill sites. Fugitive emissions also occur from extraction of natural gas (and previously, coal), the gas grid, and large gas-burning industrial plant.
H	Hydrogen (element)	An abundant chemical element, present in most materials, including water (H_2O).
H_2	Hydrogen (molecule)	A colourless, odourless gas much lighter than air. If ignited, it can burn in air, and can be used as a fuel.
CO_2	Carbon dioxide	Gas produced from combustion of carbon-containing fuels. Main global warming gas.
CO	Carbon monoxide	Gas produced from partial burning of carbon-containing fuels, in a restricted supply of air or oxygen. Toxic to humans when inhaled. Used as a fuel or feedstock material in some industrial settings.
N_2O	Nitrous oxide	A powerful greenhouse gas that is emitted from soils, especially fertilised agricultural soils. N_2O also forms in combustion systems in smaller quantities, including in road transport. It is used as an anaesthetic (laughing gas).
NO	Nitric oxide	A colourless gas that forms in combustion systems. NO readily reacts in air, turning into the more harmful NO_2. In the human body, it is a signalling molecule in many physiological processes.
NO_2	Nitrogen dioxide	Reddish-brown (at room temperature) gas that forms in combustion systems. A major air pollutant with serious negative impacts on human health, including increased chances of lung and heart diseases and increased mortality.
NO_x	Oxides of nitrogen	A collective term for NO, NO_2 and N_2O. The principal source is combustion systems, such as power stations and traffic, which normally emit NO and some NO_2, with far smaller quantities of N_2O. Legislation limiting pollution from industrial sources generally covers the NO and NO_2 components only.

Glossary

Electricity and gas infrastructure		
Acronym/Abbreviation	Name	Description
AC	Alternating current	Electrical current which changes direction, usually at a defined frequency. It is usually produced from a turbine, which has an electrical coil rotating in a magnetic field. The frequency of the AC is the number of times per second the turbine spins round (or a multiple of it, depending upon the generator's construction). In all European electricity grids, the electrical current is AC, which changes direction 50 times per second (50 Hz). The exact frequency tends to vary and will generally be slightly different in each 'synchronous area', e.g. GB, the island of Ireland, and the main continent of Europe.
-	Blackout	Loss of electrical power. Usually taken to mean a loss of power to a large area or whole country.
-	Capacity factor	See load factor
CCGT	Combined cycle gas turbine	The most efficient type of gas-fired power station that uses the waste heat from a gas turbine to power a secondary steam circuit. Efficiencies over 50% are possible.
-	Curtail, curtailment	In relation to an electrical generator: the act of requiring the generator to reduce or cease output. In Britain, curtailment might occur for onshore windfarms that are located in areas where the electricity grid has limited capacity.
DC	Direct Current	Electrical current which flows in one direction. Many consumer electrical appliances use DC power including modern TVs, computers and anything that relies on a battery. The AC/DC converter is embedded in the appliance (e.g. the large box on a laptop charging lead).
DN	Distribution Network	A system of electrical wires or gas pipes in a local area, which delivers electricity or gas to people's homes and businesses. Traditionally, distribution systems were supplied with electricity and gas entirely from the relevant transmission system. Increasingly, distribution systems are also being supplied by small generators such as solar panels, small windfarms, or "green gas" generators in the local area. Some electrical distribution systems now export power to the transmission system, some of the time.
-	Distribution System	See Distribution Network.
DSO	Distribution System Operator	The operator of an electricity distribution network where there is a more 'active' management of generation outputs, flexible demand, voltages and network configuration than a Distribution Network Operator would typically have done.
DG	Distributed Generation	Electricity generators connected to the distribution network.

Glossary

Acronym/Abbreviation	Name	Description
-	Diversity or diversification	In relation to use of electricity, gas or heat, 'diversity' or 'diversification' of demand occurs when different households or other consumers require use at different times. Thus, the electrical, gas or heat network sees a maximum overall demand that is much smaller than the theoretical maximum demand if all consumers were to require their own maximum use at the same time. For example, a household might have a maximum electrical demand of 10-15kW, but electrical networks plan for between 1-2kW per household *after diversification maximum demand* (ADMD) (because we don't all take a shower at the same time). However, future electrification of heat may reduce diversification of demand during cold weather, if all households are using heating.
ESO	Electricity System Operator	The ESO (in GB's case, National Grid ESO) ensures that the right amount of electrical power is being produced to exactly match the country's consumption of electricity and that power flows and voltages on the transmission network and the power system's electrical frequency are within acceptable limits.
-	Electrolyser	A piece of equipment which passes an electrical current through water to split water molecules into their constituent hydrogen and oxygen parts, which can be collected separately.
-	Frequency (of the electricity grid)	The number of times per second that the AC electrical current flowing though the grid changes direction. Synchronous electrical machines such as used at large thermal generators (such as gas and nuclear power stations) or at hydro power plants spin at this frequency, or an exact fraction of it, depending upon the generator construction. The nominal GB grid frequency is 50 Hz (50 times per second). Any mismatch between the amount of electricity being generated and used will cause the grid frequency to start to change. It is essential that the grid frequency stays very close to 50 Hz, because all operating standards require this. In Britain, if the grid frequency falls below 47 Hz, or rises above 52 Hz, all generators are permitted to disconnect, and there would be a blackout. National Grid ESO's licence obligation is to control system frequency between 49.5 Hz and 50.5 Hz.
-	Frequency support/ frequency response	One of several essential grid services which the Electricity System Operator procures to help stabilise the operation of the grid. Frequency response is used following a disturbance (e.g. a generator suddenly stops working), to keep the power system's frequency very close to 50 Hz. Providers of a frequency response service are paid to be ready to suddenly deliver extra power (or suddenly reduce their power delivery) if needed.

Glossary

Acronym/Abbreviation	Name	Description
HVDC	High voltage direct current	Direct current at high voltage, typically hundreds of Kilovolts (kV).
-	Incident solar radiation	Solar radiation which falls on a particular surface or land area.
-	Linepack	Describes the total volume of gas (natural gas) within the national gas transmission system. It is usually measured in millions of cubic meters, which is the volume the gas would occupy at standard atmospheric pressure.
-	Load factor	A measure of the average use of a generator. A generator's load factor is the total energy output (MWh) in a year divided by the energy the plant would have produced (MWh) if it operated at maximum capacity all year with no interruptions. Also referred to as Capacity Factor. $\textit{Load factor} = \dfrac{\textit{Electricity actually generated in a year (MWh)}}{\textit{Electricity generated if operating continuously at full power (MWh)}}$
OCGT	Open cycle gas turbine	A simpler type of gas-fired power station without the secondary steam loop as in a CCGT (essentially a jet engine on the ground, without the high level of expensive components or safety requirement of an aerospace jet engine). As a result, efficiencies are lower (around 35-40%, compared to 50-60% for CCGTs) but capital costs are also lower. They tend to be economically preferable if the plant is only operating in peak demand conditions.
P2G	Power-to-gas	Conversion of electrical energy to a gaseous fuel (usually hydrogen by electrolysis).
P2X	Power-to-X	Conversion of electrical energy to a gaseous or liquid fuel. This is usually done by first producing hydrogen from electrolysis, followed by reaction with some other substance (e.g. a carbon-rich gas, or nitrogen) to produce a fuel that might be more useful than hydrogen for particular applications (e.g. synthetic jet fuel, synthetic methane or ammonia).
PEM	Proton exchange membrane, or polymer electrolyte membrane	A type of electrolyser. Uses electrical energy to split water into hydrogen and oxygen. Compared to the main other electrolyser type (alkaline water electrolysers), PEM electrolysers can better cope with variable electrical input (as would be the case for using surplus renewable electricity to produce hydrogen).
-	Solar irradiance	Energy from sunshine per square metre per second. It is normally measured in Watts per square metre (W/m^2). In the UK, average year-round (including night and cloud cover) solar irradiance across the year varies from around 95 W/m^2 (Edinburgh) to 110 W/m^2 (London). In sunnier places, average solar irradiance can reach over 270 W/m^2 (Nouakchott, Mauritania).
-	Transmission system	A system of electrical wires or gas pipes which transports electricity or gas, in bulk, over long distances.

Glossary

Acronym/Abbreviation	Name	Description
V2G	Vehicle-to-grid	A technology which allows electricity to flow in both directions between the electricity grid and an EV battery. This technology could allow electric vehicles to provide support to operation of the grid beyond simply stopping charging at a particular time and would return energy to the grid (see frequency support). This would help ease the energy transition and may be financially attractive to EV owners, who could sell grid services to the system operator (via an aggregator). However, it would also mean additional charging/discharging cycles of the battery.
Carbon capture, utilisation and storage		
Acronym/Abbreviation	**Name**	**Description**
BECCS	Bioenergy with carbon capture and storage	Burning of biomass (to produce electricity, heat or hydrogen) with CCS applied to capture the CO_2 emissions. This is regarded as a carbon-negative technology as the CO_2 is first sequestered by the biomass and is captured either before or after combustion.
CCS	Carbon capture and storage	Capture of CO_2 – either from combustion of fuels, or directly from industrial processes or the air – and storage (typically underground), which is intended to be permanent.
CCU	Carbon capture and utilisation	Capture of CO_2 – either from combustion of fuels, or directly from industrial processes or the air – and utilisation in other industrial processes.
CCUS	Carbon capture, utilisation and storage	Collective term for CCU and CCS.
DACCS	Direct air carbon capture and storage	Capture of CO_2 directly from the air.
Buildings, heating and cooling		
Acronym/Abbreviation	**Name**	**Description**
ASHP	Air source heat pump	Heat pump whose source of heat is ambient air. (Warm air from the output of another process could be used to increase COP).
COP	Coefficient of performance.	The performance of a heat pump (or refrigeration cycle), given by the energy (heat) out divided by the energy (electricity) in. Heat pump COP typically varies between 2-4. $$COP = \frac{Heat\ output}{Electricity\ input}$$
DH	District Heating	A heating system which transports heat, primarily in hot water pipes, i.e. a 'heat network', between multiple buildings.
EPC	Energy Performance Certificate	An EU regulation to define the energy efficiency of a building. A building is rated A-G, and being rated is a UK requirement for new buildings and the sale or rental of existing buildings.
GSHP	Ground-source heat pump	Heat pump whose source of heat is the ground.

Glossary

Acronym/Abbreviation	Name	Description
HP	Heat pump	A heat pump is an electricity-powered heating device that works by transferring heat from a source (e.g. air, ground or water) to an output (e.g. the space to be heated). As heat in the source is not zero – anything above absolute zero (-273 °C) has thermal energy – the heat energy output is greater than the electrical input. The ratio of heat out to electricity in (see COP) typically varies between 2-4, meaning the output is 2-4 times greater than the input.
-	Prosumer	A portmanteau of 'producer' (or provider) and 'consumer'. In the energy system, it refers to a consumer of energy who also produces their own energy. Typical examples include households with rooftop solar panels and EV drivers who can participate in vehicle-to-grid (see V2G).
SAP	Standard Assessment Procedure	The methodology used by the UK Government to assess and compare the energy and environmental performance of dwellings.
-	U-value	The thermal transmittance of a building material, i.e. the rate at which heat passes through the material (in Watts per square metre), per °C temperature difference across the material. Usually used to describe materials or parts of buildings, the U-value allows calculation of the rate of heat escape from walls, windows and other building parts, under different temperature conditions.
WSHP	Water-source heat pump	Heat pump whose source of heat is water (could be a river or industrial output/ sewage).
LED	Light-emitting diode	A device which emits light and can be used to provide lighting. LEDs are among the most energy-efficient types of lighting available.
Vehicles and transport		
Acronym/Abbreviation	**Name**	**Description**
BEV	Battery electric vehicle	A vehicle whose sole means of propulsion is a rechargeable battery connected to an electric motor.
Contrail (or contrail cirrus)	Condensation trail	Condensation trails from aircraft. These can form in the atmosphere when exhaust air from aircraft mixes with cold ambient air. In some conditions, a trail of ice crystals forms. These trails contribute to global warming, and are believed to have a greater global warming effect than the aircraft CO_2 emissions. The trails are sometimes called *contrail cirrus*, because they are similar to cirrus clouds which form naturally in the atmosphere.
EV	Electric vehicle	A collective term for BEVs, FCVs, HEVs and PHEVs. Increasingly, BEV and EV are used interchangeably due to i) BEVs' market dominance over FCVs and ii) PHEVs and HEVs being included in the current UK ICE car ban in 2032.
-	E-bike	A power-assisted bicycle that uses a battery and an electric motor to increase the power output of the cranks as the rider pedals.

Glossary

Acronym/Abbreviation	Name	Description
FCV	Fuel-cell vehicle	A vehicle powered by a fuel cell – which generates electricity from oxygen from the air and compressed hydrogen – connected to an electric motor.
HGV	Heavy goods vehicle	Freight vehicles exceeding 3.5 tonnes in weight. Typically refers to lorries/trucks.
HEV	Hybrid electric vehicle	A vehicle containing both an internal combustion engine and an electric powertrain in the objective of improving the vehicle's fuel economy. At the time of writing, these are included in the UK ICE car ban in 2032.
ICE	Internal combustion engine	The type of engine in conventional cars and other vehicles, normally fuelled by petrol, diesel or a similar fossil fuel.
LGV	Light goods vehicle	Freight vehicles not exceeding 3.5 tonnes in weight. Typically refers to vans.
pkm	Person-kilometre	A quantity to determine the movement of people, useful for transport planning. 5 person-kilometres can be achieved by moving 5 people one kilometre, or 1 person 5 kilometres.
PHEV	Plug-in hybrid electric vehicle	A vehicle containing both an internal combustion engine and an electric powertrain. The battery can be charged – either from an on-board generator using energy from combustion, or by being plugged in to an external electricity supply – to achieve a longer electric range than a HEV, though this is typically no longer than 30-50 km. At the time of writing, these are included in the UK ICE car ban in 2032.
SAF	Sustainable aviation fuel	An umbrella term for synthetic jet fuel (see synfuel) and biofuels: fuels that could be used in jet engines to power aircraft with very little or no modification required to the engines or aircraft. While these fuels can be carbon-neutral, they contribute to the non-CO_2 warming effects of aviation (which have been found to roughly triple the global warming effects of aircraft).
tkm	Tonne-kilometre	A quantity to determine the movement of goods, useful for transport planning. 5 person-kilometres can be achieved by moving 5 people one kilometre, or 1 person 5 kilometres.
V2G	Vehicle-to-grid	A technology which allows electricity to flow in both directions between the electricity grid and an EV battery. This technology could allow electric vehicles to provide support to operation of the grid beyond simply stopping charging at a particular time and would return energy to the grid (see frequency support). This would help ease the energy transition and may be financially attractive to EV owners, who could sell grid services to the system operator (via an aggregator). However, it would also mean additional charging/discharging cycles of the battery.

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