# Contents

**Authors** iv  
**Acknowledgements** v  
**Foreword** vi  
**Technologies A-Z** vii  
**Chapter 1** Introduction 1  
1.1 What is Net Zero? 1  
1.2 What is this Guide and Who is it for? 1  
1.3 Energy & Power: Units & Scale 1  
1.4 UK Emissions 2  
1.5 Chapter 1 Endnotes & References 3  
**Chapter 2** The UK Energy Sector 5  
2.1 UK Energy Flows 5  
2.2 UK Energy Infrastructure 6  
2.3 Chapter 2 Endnotes & References 8  
**Chapter 3** Energy Demand Technologies for Net Zero 9  
3.1 Heating & Cooling 9  
3.2 Transport 17  
3.3 Electrical Appliances, Machines & Lights 27  
3.4 Chapter 3 Endnotes & References 30  
**Chapter 4** Energy Infrastructure for Net Zero 43  
4.1 Electricity Generation 43  
4.2 Life Cycle Emissions of Electricity Generation 50  
4.3 Renewable Electricity Resources 52  
4.4 Electricity Network 53  
4.5 Fuels for Net Zero 57  
4.6 Life Cycle Emissions of Gaseous Fuels 61  
4.7 Gas/Hydrogen Network 62  
4.8 District Heating 64  
4.9 Buildings 65  
4.10 Carbon Capture, Utilisation and Storage (CCUS) 70  
4.11 Energy Storage 73  
4.12 Chapter 4 Endnotes & References 79  
**Chapter 5** Energy Systems for Net Zero 97  
5.1 Energy Carriers 97  
5.2 Pathways to Net Zero 99  
5.3 Chapter 5 Endnotes & References 112  
**Chapter 6** Conclusion: A Vision of the 2050 Energy System 113  
**Chapter 7** Annex: The Chemistry of Energy Systems 115  
7.1 The Carbon Cycle 115  
7.2 The Nitrogen Cycle 118  
7.3 Annex References 121  
**Glossary** 123  

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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

<table>
<thead>
<tr>
<th>Topic</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia</td>
<td>60</td>
</tr>
<tr>
<td>Aviation</td>
<td>25</td>
</tr>
<tr>
<td>Bioenergy for electricity generation</td>
<td>47, 59</td>
</tr>
<tr>
<td>Biofuels for transport</td>
<td>60</td>
</tr>
<tr>
<td>Bioenergy for heating</td>
<td>16, 60</td>
</tr>
<tr>
<td>Building efficiency</td>
<td>65</td>
</tr>
<tr>
<td>Building standards</td>
<td>68</td>
</tr>
<tr>
<td>Carbon capture, utilisation &amp; storage</td>
<td>70</td>
</tr>
<tr>
<td>Demand reduction - surface transport</td>
<td>22</td>
</tr>
<tr>
<td>District heating</td>
<td>13, 64</td>
</tr>
<tr>
<td>E-bikes</td>
<td>21</td>
</tr>
<tr>
<td>Electric vehicles</td>
<td>20</td>
</tr>
<tr>
<td>Electricity demand</td>
<td>27</td>
</tr>
<tr>
<td>Electricity network</td>
<td>53</td>
</tr>
<tr>
<td>Electricity storage</td>
<td>73</td>
</tr>
<tr>
<td>Emissions of electricity generation</td>
<td>50</td>
</tr>
<tr>
<td>Emissions of gaseous fuels</td>
<td>61</td>
</tr>
<tr>
<td>Fossil fuels with carbon capture &amp; storage for electricity generation</td>
<td>50</td>
</tr>
<tr>
<td>Freight</td>
<td>24</td>
</tr>
<tr>
<td>Gas &amp; hydrogen storage</td>
<td>76</td>
</tr>
<tr>
<td>Gas network</td>
<td>62</td>
</tr>
<tr>
<td>Heat pumps</td>
<td>11</td>
</tr>
<tr>
<td>Heat storage</td>
<td>77</td>
</tr>
<tr>
<td>Hydro &amp; geothermal electricity generation</td>
<td>49</td>
</tr>
<tr>
<td>Hydrogen for heating</td>
<td>14, 63</td>
</tr>
<tr>
<td>Hydrogen network</td>
<td>62</td>
</tr>
<tr>
<td>Hydrogen production</td>
<td>57</td>
</tr>
<tr>
<td>Net Zero pathways</td>
<td>99</td>
</tr>
<tr>
<td>Nuclear energy</td>
<td>48</td>
</tr>
<tr>
<td>Public transport</td>
<td>22</td>
</tr>
<tr>
<td>Renewable electricity resources</td>
<td>52</td>
</tr>
<tr>
<td>Shipping</td>
<td>26</td>
</tr>
<tr>
<td>Smart grids</td>
<td>54</td>
</tr>
<tr>
<td>Solar electricity generation</td>
<td>44</td>
</tr>
<tr>
<td>Solar thermal heating</td>
<td>16, 68</td>
</tr>
<tr>
<td>Synthetic fuels</td>
<td>61</td>
</tr>
<tr>
<td>Wave &amp; tidal electricity generation</td>
<td>46</td>
</tr>
<tr>
<td>Wind electricity generation</td>
<td>43</td>
</tr>
</tbody>
</table>
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 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’ = 1,000,000,000,000.

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

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Chapter 1 – Introduction

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 CO₂ 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 CO₂ equivalent (MtCO₂e). 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 MtCO₂e, CO₂ 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, SF₆, and NF₃.

For the remainder of this Guide, GHG emissions will be expressed in MtCO₂e.

Figure 2 UK GHG emissions in 2018 including international aviation & shipping, in MtCO₂e. Data from [1.12]

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.

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Chapter 1 – Introduction

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

1This 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.

2These 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).
Chapter 1 – Introduction

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


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.

- 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]
Chapter 2 – The UK Energy Sector

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].

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 GW² [2.5]

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).

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.
Chapter 2 – The UK Energy Sector

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


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.

Commercial & Public Sector Heating Demand

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

Heating demand by sector and end use

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

Heating demand by sector and end use

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

Relative demand

>60% reduction in gas demand, January to August

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Chapter 3 – Energy Demand Technologies for Net Zero

Industrial Heating Demand
- 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].

Future UK Heating & Cooling 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).

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].

Climate Change Impacts
- Heating (HDD) and Cooling Degree Days (CDD) 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 [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 [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 [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]
Chapter 3 – Energy Demand Technologies for Net Zero

- 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.

Heat Pump Performance
- HPs use between 2 and 4 times 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):

\[
COP = \frac{\text{Heat Out}}{\text{Electricity In}}
\]

- 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

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 16 Heat pump/refrigeration cycle](image_url)

![Figure 17 Typical rated COP of HPs by source compared to direct heating (either electric or efficient gas boiler)](image_url)
Chapter 3 – Energy Demand Technologies for Net Zero

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%

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.

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].

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.

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].

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].

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

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

Combined Heat and Power (CHP)

- 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 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].

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

- 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.
Chapter 3 – Energy Demand Technologies for Net Zero

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

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

Figure 23 Hydrogen production from water by electrolysis
Chapter 3 – Energy Demand Technologies for Net Zero

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 1/3 of heat demand from bioenergy and 2% of residential heating demand [3.1].
- Net-zero potential is limited by the time lag between CO₂ 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 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). Data from [3.45]
Chapter 3 – Energy Demand Technologies for Net Zero

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).

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

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

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)
Chapter 3 – Energy Demand Technologies for Net Zero

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. 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]
Chapter 3 – Energy Demand Technologies for Net Zero

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)
- 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%)\(^{3.51}\).
- 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\(^{3.50}\)

<table>
<thead>
<tr>
<th>Charging</th>
<th>Home</th>
<th>Workplace</th>
<th>Public</th>
<th>En route</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>3-7 kW</td>
<td>7-22 kW</td>
<td>7-22 kW</td>
<td>50-150 kW</td>
</tr>
<tr>
<td>Time to add 100 km range</td>
<td>190-450 mins</td>
<td>60-190 mins</td>
<td>60-190 mins</td>
<td>9-27 mins</td>
</tr>
</tbody>
</table>
Chapter 3 – Energy Demand Technologies for Net Zero

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 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.

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.

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.
- This will improve further as electricity decarbonisation targets are met.

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 (Figure 33).
- A UK study found that large-scale switch to E-bikes could save the UK up to 30 million tonnes CO₂ per year – around half the total emissions from cars.

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.
# Chapter 3 – Energy Demand Technologies for Net Zero

## 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. Car data from [3.57], bike and e-bike data from [3.59]
Chapter 3 – Energy Demand Technologies for Net Zero

Figure 34 Life-cycle emissions per passenger km (pkm), average occupancy and fully occupied, for cars, buses and rail (different powertrains) 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]
Chapter 3 – Energy Demand Technologies for Net Zero

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/tonne CO₂ to 2050 is recommended in one study for Net Zero road transport [3.83].

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).

Surface Transport – Freight
Low Emission Surface Freight
- UK domestic freight is mostly moved by road (79%), the remainder is shipping (13%) and rail (9%).

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

- 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%.
Chapter 3 – Energy Demand Technologies for Net Zero

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
- CO₂ 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-CO₂ warming effects from NOₓ, sulphates, aerosols and contrail cirrus – this multiplies the global warming impacts of aircraft by 3x [3.93].
- CORSIA²⁴ is the UN aviation agency’s scheme for offsetting and removing emissions from 2020 – but it does not include non-CO₂ emissions or CO₂ 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 CO₂ 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 intensive²⁵, though synfuels could be produced alongside large-scale renewable resources outside the UK (e.g. desert solar) (§4.5.4).
Chapter 3 – Energy Demand Technologies for Net Zero

**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)\[3.97\].
- 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).

**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.

**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\[3.14\].
- Higher prices for jet fuels would also encourage development of low-carbon propulsion systems (e.g. electrification, synfuels and hydrogen).

**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\(\text{§5.2}\).
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. 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]
Chapter 3 – Energy Demand Technologies for Net Zero

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 gCO₂/kWh in 1998 to 167 gCO₂/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]
Load Factors and Capacity

- Load factors – or capacity factors – (the average output relative to capacity) are lower for variable renewables than for thermal generation\(^2\). 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\(^3\)) 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 43 Projected future UK energy demand, including electricity. Reproduced from [3.32]

<table>
<thead>
<tr>
<th>Energy demand (TWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2019</td>
</tr>
<tr>
<td>Consumer Transf. 2050</td>
</tr>
<tr>
<td>System Transf. 2050</td>
</tr>
<tr>
<td>Leading the way 2050</td>
</tr>
</tbody>
</table>

- Electricity
- Fossil Gas
- Hydrogen
- Oil/Petroleum
- Biofuels + Other

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

- Smart charging can take us towards this

- Peak EV charging demand
- Average EV charging demand
Chapter 3 – Energy Demand Technologies for Net Zero

3.4 Chapter 3 Endnotes & References

3.4.1 Endnotes

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

2. 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.

3. Heating Degree Days (HDDs) is a measure of the potential heating demand based on 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 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].

4. 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/m² and ii) CO₂ increases to c. 650ppm until 2050 then stabilises.

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

6. 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].

7. 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.

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

9. 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.

10. 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.

11. This guide concerns GHG emissions (primarily CO₂) and the technological solutions to meeting Net Zero. Burning of fossil fuels and biomass also causes other emissions, including oxides of nitrogen (NOₓ), fine particulate matter (e.g. PM10, PM5 and PM2.5) and volatile organic compounds, which
Chapter 3 – Energy Demand Technologies for Net Zero

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.

2Emissions 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 gCO₂e/kWh for e-bikes and 21 gCO₂e/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/CO₂ intensity associated with their ‘fuel cycle’.

21Lifecycle emissions data for cars is the same as for Figure 32, but converted from gCO₂e/km to gCO₂e/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, gCO₂e/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 gCO₂e/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.

22A 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 CO₂ 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 CO₂; 433 litres of petrol burns to create 1,000 kg – 1 tonne – of CO₂).

23CORSIA - 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 CO₂ 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 MtCO₂/year up to and including 2019, and 1,000 MtCO₂/year from 2020 onwards, the airline must only offset the difference – 100 MtCO₂/year. Secondly, it does not include non-CO₂ emissions, which have been estimated to triple the global warming impacts of aviation [3.93].

24Net Zero-compatible synfuel would combine hydrogen made from electrolysis, or chemical processing of fuels with CCS, and carbon from CO₂ 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].

Leg 2: 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.

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 NOx 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.

Leg 3: 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.

Leg 4: 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.
Chapter 3 – Energy Demand Technologies for Net Zero

Table 2  Energy density of hydrogen, ammonia and methane at different pressures and temperatures.

<table>
<thead>
<tr>
<th>Property</th>
<th>Hydrogen (H₂)</th>
<th>Ammonia (NH₃)</th>
<th>Methane (CH₄)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calorific value per kg</td>
<td>142 MJ/kg or 39.4 kWh/kg</td>
<td>22.5 MJ/kg or 6.2 kWh/kg</td>
<td>55.5 MJ/kg or 15.4 kWh/kg</td>
</tr>
<tr>
<td>Calorific value per cubic metre, in gaseous state</td>
<td>25 °C, atmospheric pressure (1.01 Bar)</td>
<td>11.7 MJ/m³ or 3.2 kWh/m³</td>
<td>15.7 MJ/m³ or 4.4 kWh/m³</td>
</tr>
<tr>
<td></td>
<td>25 °C, compressed to 200 Bar</td>
<td>2,300 MJ/m³ or 650 kWh/m³</td>
<td>Not done. Much easier to liquify.</td>
</tr>
<tr>
<td></td>
<td>25 °C, compressed to 800 Bar</td>
<td>9,400 MJ/m³ or 2,600 kWh/m³</td>
<td>Not done. Much easier to liquify.</td>
</tr>
<tr>
<td></td>
<td>Cryo-compressed to 500 Bar, at -200 °C.</td>
<td>11,000 MJ/m³ or 3,000 kWh/m³</td>
<td>Not done. Much easier to liquify.</td>
</tr>
<tr>
<td>Calorific value per cubic metre, when liquefied</td>
<td>10,200 MJ/m³ or 2,800 kWh/m³</td>
<td>13,900 to 15,700 MJ/m³ or 3,900 to 4,400 kWh/m³ (depending on temp &amp; pressure)</td>
<td>23,500 MJ/m³ or 6,500 kWh/m³</td>
</tr>
<tr>
<td>Conditions required to turn to a liquid</td>
<td>-253 °C or below</td>
<td>-33 °C or below</td>
<td>-162 °C or below</td>
</tr>
<tr>
<td></td>
<td>at atmospheric pressure</td>
<td>Ambient temperature,</td>
<td>Not done.</td>
</tr>
<tr>
<td></td>
<td>at higher pressures</td>
<td>13 bar pressure</td>
<td></td>
</tr>
<tr>
<td></td>
<td>240 °C,</td>
<td>10-15 bar pressure</td>
<td></td>
</tr>
</tbody>
</table>

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

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.

Assuming a ‘fuel economy’ of 18 kWh/100km.

3.4.2 References


Chapter 3 – Energy Demand Technologies for Net Zero


Chapter 3 – Energy Demand Technologies for Net Zero


Chapter 3 – Energy Demand Technologies for Net Zero


Chapter 3 – Energy Demand Technologies for Net Zero


Chapter 3 – Energy Demand Technologies for Net Zero


Chapter 3 – Energy Demand Technologies for Net Zero


Chapter 3 – Energy Demand Technologies for Net Zero


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]
Chapter 4 – Energy Infrastructure for Net Zero

Cost of Wind Generation

- In the 2019 Contracts for Difference (CfD) auctions, 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) [4.5].
Chapter 4 – Energy Infrastructure for Net Zero

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.
- 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.
- 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.

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 (totaling 427 MW) and two tidal lagoon projects (totaling 530 MW) in the pipeline for operation dates between 2021 and 2030.
- 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. This leads to high costs per unit generation (Figure 54).
- While costs are forecast to reduce, these costs reflect the engineering challenges of harnessing the energy while being sufficiently robust against hostile conditions.
Chapter 4 – Energy Infrastructure for Net Zero

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 [4.14].
- Bioenergy from waste can contribute, though quantities will be limited by how much waste we produce [§4.5.2].
Chapter 4 – Energy Infrastructure for Net Zero

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.

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 CO₂ from the atmosphere by growing, and CO₂ 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 MtCO₂ 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 km² by 2050 (around 7% of current agricultural land), coupled with mass afforestation.
- Growth of BECCS to effectively remove CO₂ 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.
Chapter 4 – Energy Infrastructure for Net Zero

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.

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)\(^ {39}\), and while abundant, is also not renewable.
- Alternative fuels, such as thorium, and reactor technologies, such as fast breeders, could increase the abundance 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.
Chapter 4 – Energy Infrastructure for Net Zero

- **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].

- **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].

**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 [4.21].

**Geothermal**
- In the UK, deep geothermal would come from natural heating from radioactive rocks [4.3].
- 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 CO₂-intensive industries.

**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]**

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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:
- 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.

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 gCO₂e/kWh.
- Existing coal and gas stations are major GHG emitters of the order several hundred gCO₂e/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].

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 gCO₂e/kWh.
- BECCS has negative emissions by 2050, around -300 gCO₂e/kWh.
- GHG emissions of biomass, hydro and BECCS vary enormously according to site details and region.
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\(^\text{[4.24]}\).
- Methane can be emitted from decomposing vegetation, including in large hydro reservoirs \(^\text{[4.24]}\).

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\(^\text{[47]}\)

![Graph showing potential UK renewable electricity generation resources by technology.](image)

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

![Diagram showing comparison of UK renewable resources with 2019 electricity demand & renewable generation and two scenarios of 2050 UK electricity demand.](image)
Chapter 4 – Energy Infrastructure for Net Zero

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 significant47, 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

4.4 Electricity Network

4.4.1 Implications of Net Zero

- The GB49 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 losses50, 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).

Supplying UK electricity demand now and in 2050 from renewables is feasible. Doing so requires an appropriate electricity network (§4.4).
Figure 65: Aviation and shipping fuel demand; illustrative electricity demand if those demands were met with synthetic fuels

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.

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.

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 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.

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Chapter 4 – Energy Infrastructure for Net Zero

**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]

![Graph showing demand profile](#)

<table>
<thead>
<tr>
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<th>Capacity</th>
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**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 for a time. To date, it has been enabled through aggregators that can group energy users together to provide services (such as frequency response) to the system operator.

**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.

**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].

**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].

**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. Failure to develop the network can result in excessive curtailment of renewable generation output (Figure 68).

**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.
**Chapter 4 – Energy Infrastructure for Net Zero**

**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.

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].

**Figure 69** Hydrogen production from electrolysis of water

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.
Chapter 4 – Energy Infrastructure for Net Zero

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 CO₂ 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 CO₂-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 CO₂ 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].

**Hydrogen from Electrolysis**

- Water can be split into hydrogen and oxygen by passing electricity through it (electrolysis)².
- 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 H₂ 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 km² 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 km² of windfarm or 37 nuclear power stations equivalent to Hinkley Point C would be required.

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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 endnote60

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 endnote61
Chapter 4 – Energy Infrastructure for Net Zero

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 CO₂ 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 km² (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

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Chapter 4 – Energy Infrastructure for Net Zero

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]

![](image.png)

### 4.5.3 Ammonia

- Ammonia (NH₃) 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

![](image.png)

**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.
- Due to their high cost, effective emissions pricing is required to make them preferable to fossil fuels.

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. 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 CO₂-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.
Chapter 4 – Energy Infrastructure for Net Zero

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.

![Graph showing GHG emissions](image)

- **Fossil gas extraction & transport**
- **Combustion**
- **'Blue H₂' synthesis - CO₂ releases**
- **Bio - growth**
- **Bio - other emissions**

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.
Chapter 4 – Energy Infrastructure for Net Zero

- 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 emissions 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 work³, 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 hydrogen⁶⁴.

- 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)⁶⁵. 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 1991⁶⁶.
- 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 adaptation⁶⁷.
- The British Standards Institute has developed standards for the development of new hydrogen appliances⁶⁸, 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 scrapage.

Demonstration Project – Hy4Heat⁶⁹
- 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.

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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.

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).

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

<table>
<thead>
<tr>
<th>Source temperature</th>
<th>DH generation</th>
<th>Era</th>
<th>Primary heat source technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;50°C</td>
<td>5</td>
<td>2020+</td>
<td>Shared ambient/low temp. networks with decentralised heat pumps</td>
</tr>
<tr>
<td>&gt;50°C</td>
<td>4</td>
<td>2015+</td>
<td>Low temp. waste heat, heat pumps, heat storage</td>
</tr>
<tr>
<td>&gt;70°C</td>
<td>3</td>
<td>1980+</td>
<td>Waste heat, biomass, gas and gas CHP, potentially hydrogen</td>
</tr>
<tr>
<td>&gt;100°C</td>
<td>2</td>
<td>1930-1980</td>
<td>Waste heat, coal (oil, coal)</td>
</tr>
<tr>
<td>&gt;&gt;100°C</td>
<td>1</td>
<td>1880-1930</td>
<td>Waste heat, coal</td>
</tr>
</tbody>
</table>

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 retrofiting 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.

District Heating for Net Zero – Technology Options

- The majority of UK DH builds are ‘3rd Gen’ (70-80 °C output, predominantly gas-based and from limited low carbon sources).
- ‘4th Gen’ systems (<60 °C) can extend viability into high and medium heat density areas.
- ‘5th Gen’ 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].

Area Potential - Heat Density
- 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 [4.59].

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) assessed to be 27% of UK cooling demand [4.59].
Chapter 4 – Energy Infrastructure for Net Zero

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 m² total floor area.
- 22% retail, 16% offices, 56% industrial, 7% other.

The UK is the 2nd most gas dependent country in the OECD for heating [4.73].
Chapter 4 – Energy Infrastructure for Net Zero

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 84. Regulated energy\(^2\), SAP\(^3\) and EPC\(^3\) energy bands, UK houses and commercial buildings. Data: [4.65-4.68]

<table>
<thead>
<tr>
<th>kWh/m(^2)/yr</th>
<th>Average new UK house</th>
<th>Average UK commercial</th>
<th>Average UK house</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-75</td>
<td>(92 plus)</td>
<td>(81-91)</td>
<td></td>
</tr>
<tr>
<td>75-150</td>
<td>(69-80)</td>
<td>(55-68)</td>
<td></td>
</tr>
<tr>
<td>150-225</td>
<td>(59-54)</td>
<td>(39-54)</td>
<td></td>
</tr>
<tr>
<td>225-300</td>
<td>(38-38)</td>
<td>(21-38)</td>
<td></td>
</tr>
<tr>
<td>300-380</td>
<td></td>
<td>(1-20)</td>
<td></td>
</tr>
<tr>
<td>380-450</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>450+</td>
<td>(75-150)</td>
<td>(150-225)</td>
<td>(225-300)</td>
</tr>
</tbody>
</table>

Figure 85. Fuel share by % of heating demand, selected OECD nations. Reproduced from [4.73]
Chapter 4 – Energy Infrastructure for Net Zero

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

![Graph showing required vs. actual retrofit annual rate for different types of insulation and heating systems to achieve Net Zero.]

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

![Graph comparing residential heat demand in 2020 vs. 2050 for different heating systems, showing a significant reduction in demand.]

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].
Chapter 4 – Energy Infrastructure for Net Zero

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).

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].

Building Standards for Deep Retrofits

- Enerphit [4.80] is a stepwise retrofit to near-Passivhaus 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).

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 88 Whole house/deep retrofit visualisation

Figure 89 Stepwise Enerphit retrofit process. Data from [4.82]
Chapter 4 – Energy Infrastructure for Net Zero

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.

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 CO₂ savings are lost if high energy efficiency standards (e.g., Passivhaus) are not used in place of current buildings standards (Figure 91) [4.91].

Building Fabric Thermal Efficiency

- Construction elements’ thermal properties are rated by a U-value.
- 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.

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 [4.45] – 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].

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% CO₂ saving compared to a gas boiler over 50 years as a result of increasing grid decarbonisation [4.91]. 50% of the potential CO₂ 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].

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].

Offset Residual Emissions (‘Allowable Solutions’)

- Where carbon reduction targets for new buildings cannot be met 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].

Building Standards

- Current basis of UK building standards only includes regulated energy.
- 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/m²/year) and includes unregulated energy requirements.

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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 CO₂ 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 CO₂ 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 CO₂

• 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: CO₂ can be used to produce limestone aggregate for construction [4.94]. This stores CO₂ and displaces emissions in the sector.
Chapter 4 – Energy Infrastructure for Net Zero

Figure 92 Clockwise from top: polymers; agriculture; cargo shipping. All are potential end uses of CO₂. Sources: [4.95-4.97]

Similar operations have been used in the oil industry – injecting CO₂ into oil wells for enhanced oil extraction (EOR) – since the 1970s and 1980s. There are 13 large EOR projects, 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]

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].

CO₂ 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 GtCO₂ in old oil fields and ~78 GtCO₂ in total [4.102] – around 200 years’ worth of CO₂ 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 CO₂ sources and potential geological sources in Europe. Source: [4.104]

Figure 94 Map of CO₂ sources and potential geological sources in Europe. Source: [4.104]
Chapter 4 – Energy Infrastructure for Net Zero

UK Proposed CCS Projects
- CO₂ will be collected from industrial hubs (Figure 95) – heavy industry and power stations.
- CO₂ will be transported by pipeline or ship to North Sea storage sites.
- Existing oil & gas pipelines will be used to transport CO₂ where possible [4.105, 4.106]

There are three methods to capture CO₂ from industrial processes and power generation (Figure 96).

Post-Combustion Carbon Capture
- CO₂ 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.
- CO₂ 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)

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 CO₂. This requires a hydrogen-ready combustor.
- CO₂ 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 CO₂ concentration.
- CO₂ capture rates can be very high due to near-pure stream of CO₂ (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 CO₂ at the source.
- Compared to DACCS, CO₂ 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 CO₂ emissions from some industrial clusters.
- Emissions would continue as i) CCS is not complete (60-90% of CO₂ 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)
- CO₂ 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 CO₂ concentration in air is low, the energy demand of DACCS is significant.

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

Figure 97 GB transmission-connected electricity demand and generation mix, 31 October-6 November 2020. Data from [4.109]
Chapter 4 – Energy Infrastructure for Net Zero

### 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\(^1\), 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\(^2\).
- 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 mountain sides.
- 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\(^3\).

### 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 milliseconds-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.

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**Figure 98** Pumped hydro storage

![Pumped hydro storage diagram](image)

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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]

<table>
<thead>
<tr>
<th>Technology</th>
<th>Roundtrip efficiency (electricity → electricity)</th>
<th>Timescale suitability</th>
<th>Constraints/Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithium ion batteries</td>
<td>85-95%</td>
<td>Milliseconds → hours</td>
<td>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).</td>
</tr>
<tr>
<td>Flow batteries</td>
<td>60-85%</td>
<td>Milliseconds → hours</td>
<td>Requires more space than solid batteries; for some types, scarcity/cost of resources and toxicity of components (e.g. vanadium, bromine).</td>
</tr>
<tr>
<td>Supercapacitors</td>
<td>95-98%</td>
<td>Milliseconds → seconds</td>
<td>Few space limitations; limited energy capacity, used for rapid delivery of relatively small amounts of energy.</td>
</tr>
<tr>
<td>Compressed Air</td>
<td>55-70%</td>
<td>Seconds → days</td>
<td>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.</td>
</tr>
<tr>
<td>Flywheels</td>
<td>70-95%</td>
<td>Milliseconds → seconds</td>
<td>Few space limitations.</td>
</tr>
<tr>
<td>Pumped Hydro</td>
<td>75-85%</td>
<td>Seconds → hours</td>
<td>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.</td>
</tr>
<tr>
<td>Hydrogen/ derived fuel</td>
<td>25-45%</td>
<td>Seasonal</td>
<td>Hydrogen could be made from any water source; to ease pressure on water resources, electrolysis of seawater is the most suitable.</td>
</tr>
<tr>
<td>Thermal</td>
<td>60-70%</td>
<td>Hours</td>
<td>Few space limitations; high temperature (&gt;300 °C) or cryogenic (&lt;-100 °C) operation.</td>
</tr>
</tbody>
</table>

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\(^82\) \cite{4.113-4.115}
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].

- **Proposed geological sites for seasonal storage of gas**
  - 95,000 GWh

- **Storage in electricity system (within day)**
  - 30 GWh

- **Storage in gas system pipework (within day)**
  - 300 GWh

- **Seasonal storage capacity: geological gas stores**
  - 18,000 GWh

- **Seasonal storage capacity: LNG stores**
  - 13,000 GWh

- **About an hour** accessible per day from geological stores. (Similar daily amount from LNG stores.)

- **A few hours** 1,500 GWh

- **3 to 5 cold winter days** 2.5 to 3 cold winter days

- **3 or 4 cold winter weeks**
Chapter 4 – Energy Infrastructure for Net Zero

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** and **endothermic** 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>
<thead>
<tr>
<th>Technology</th>
<th>Advantages</th>
<th>Barriers</th>
<th>Efficiency</th>
<th>Compatibility</th>
<th>Application</th>
<th>Duration</th>
<th>Market</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensible Hot Water Tank</td>
<td>Mature, scalable, cost-effective, thermal capacity</td>
<td>Capital cost, space, heat loss</td>
<td>50-90%</td>
<td>All sources</td>
<td>District heat, residential, commercial</td>
<td>Short- medium</td>
<td>Mature</td>
</tr>
<tr>
<td>Pit</td>
<td>Large capacity, cost-effective</td>
<td>Land availability</td>
<td>&lt;80%</td>
<td>Solar thermal, district heating</td>
<td>Commercial</td>
<td>All</td>
<td>Limited</td>
</tr>
<tr>
<td>Aquifer</td>
<td>Large capacity, cost-effective</td>
<td>Location-specific</td>
<td>70-90%</td>
<td>GSP, waste heat, CHP</td>
<td>District heat, commercial</td>
<td>Long</td>
<td>Limited</td>
</tr>
<tr>
<td>Borehole</td>
<td>Scalable, expandable</td>
<td>Low capacity, duration to operability</td>
<td>40%</td>
<td>Solar thermal, GSP, CHP, waste heat</td>
<td>District heat</td>
<td>Very long</td>
<td>Limited</td>
</tr>
<tr>
<td>Latent Phase change material (organic)</td>
<td>High heat-to-volume ratio, easier to package</td>
<td>Cost, flammability</td>
<td>75-90%</td>
<td>All sources</td>
<td>District heat, residential</td>
<td>Daily</td>
<td>Prototypes</td>
</tr>
<tr>
<td>Latent Phase change material (inorganic)</td>
<td>High heat-to-volume ratio, low cost</td>
<td>Harder to package</td>
<td>75-90%</td>
<td>All sources</td>
<td>District heat, residential</td>
<td>Daily</td>
<td>Prototypes</td>
</tr>
<tr>
<td>Thermochemical</td>
<td>Compact</td>
<td>Unproven</td>
<td>&gt;90% (in theory)</td>
<td>Industrial waste heat</td>
<td>District heat, commercial</td>
<td>Daily</td>
<td>None</td>
</tr>
</tbody>
</table>

**Table 4** Summary of heat storage technologies. Data from [4.128-4.130]
Chapter 4 – Energy Infrastructure for Net Zero

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

- Tank thermal energy storage (TTES) (60 to 80 kWh/m²)
- Pit thermal energy storage (PTES) (60 to 80 kWh/m²)
- Borehole thermal energy storage (BTES) (15 to 30 kWh/m²)
- Aquifer thermal energy storage (ATES) (30 to 40 kWh/m²)

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 m³ 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].

Sizing/Storage Cycle Duration
- Determined by source/surplus availability, time to charge and time to discharge.
- Heat storage economics improve significantly with scale [4.131].
4.12 Chapter 4 Endnotes & References

4.12.1 Endnotes

3¹Contracts 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.

3²Solar 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 swaths 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.

3³Tides 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.
Chapter 4 – Energy Infrastructure for Net Zero

34A 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.

35Some 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.

36CfDs 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.

37These 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).

38This 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.

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

40The 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 decommissioning) 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 CO₂ and seawater desalination [4.136].
Chapter 4 – Energy Infrastructure for Net Zero

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/m², 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/m² × 0.1 × 2.42×10¹¹ m² [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/m², as assumed in [4.27]. UK territorial waters are 7.74×10¹² m², of which 1.2×10¹¹ m² are less than 50 m deep (taken as the limit of fixed offshore wind installations in [4.27]). If ½ of these waters are covered in offshore wind farms, leaving ¾ to allow shipping channels and fishing areas, the available resource is 3 W/m² × 0.33 × 1.2×10¹¹ m² × 8766 = 1040 TWh/yr if constrained to fixed offshore wind. If floating wind installations
Chapter 4 – Energy Infrastructure for Net Zero

are to be included, and ½ of the UK’s territorial waters were covered in offshore wind farms, the resource would be $3 \text{ W/m}^2 \times 0.33 \times 7.74\times10^7 \text{ m}^2 \times 8766 = 6710 \text{TWh/yr}$.

- **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 $0.18 \times 110 \text{ W/m}^2 = 19.6 \text{ W/m}^2$. 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 $19.6 \text{ W/m}^2 \times 0.05 \times 2.42\times10^7 \times 8766 = 2100 \text{TWh/yr}$.

- **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 $6.07\times10^9 \text{ m}^2$. 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 $0.24 \text{ W/m}^2 \times 0.2 \times 6.07\times10^9 \times 8766 = 26 \text{TWh/yr}$.

- **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 $40,000 \text{ W/m} \times 0.5 \times 0.5 \times 10,000\times10^3 \text{ m} \times 8766 = 88 \text{TWh/yr}$. 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 $0.7 \times 12,700\times10^3 \text{ m}^2 \times 8766 = 78 \text{TWh/yr}$ (this is close to the value of 80 TWh given in [4.16]).

- **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.

“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$^7$ kWh $\times 300x10^{-6}$ t/kWh = 42 MtCO$_2$ of emissions abatement per year.

“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.

50Ohm'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.

51Net Zero-compatible synfuel would combine hydrogen made from electrolysis, or chemical processing of fuels with CCS, and carbon from CO₂ 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 MtCO₂/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].

52Electricity 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.

53Conventionally, 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.

54Based 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).

55Smart 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).

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].

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].

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.

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 ºC.

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].

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 km² [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...
Chapter 4 – Energy Infrastructure for Net Zero

ranges considerably. The lowest are from around 2-2.5 MW/km² (Dogger Bank, East Anglia Array - Norfolk Boreas); several are around 3 MW/km² (including Hornsea 1 & 2, East Anglia Array - Norfolk Vanguard) with some around 4 MW/km² or over (Moray Firth, Beatrice, Neart na Gaoithe and East Anglia 3). London Array has an exceptional rated output of 6.3 MW/km². 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/km²) 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.

Net Zero-compatible synfuel would combine hydrogen made from electrolysis, or chemical processing of fuels with CCS, and carbon from CO₂ 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].

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.

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].

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].
Chapter 4 – Energy Infrastructure for Net Zero

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.

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

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.

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.

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


‘Regulated’ energy includes heating, hot water, cooling, lighting but not appliances (‘unregulated’), minus onsite generation contribution.

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.

‘Industrial’ is warehouses, distribution centres, factories etc., ‘Other’ includes hospitals, student accommodation etc.

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.

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].

The U-value of a construction material is the thermal transmittance of the material typically expressed in W/m²K. It specifies the rate of heat transfer through a material per °C (or Kelvin, K) of temperature difference.


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Chapter 4 – Energy Infrastructure for Net Zero

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].

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

UK pathways for DACCS of 25 MtCO₂/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].

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.

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].

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].

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.

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

Chapter 4 – Energy Infrastructure for Net Zero

4.12.2 References


[4.11] A. Lilleboe, "AHH's 1.5MW tidal turbine being installed at Nigg to capture green energy from ocean currents." [Online]. Available: https://shutr.bz/3mBDP5o


Chapter 4 – Energy Infrastructure for Net Zero


Chapter 4 – Energy Infrastructure for Net Zero


Chapter 4 – Energy Infrastructure for Net Zero


Chapter 4 – Energy Infrastructure for Net Zero


Chapter 4 – Energy Infrastructure for Net Zero


Chapter 4 – Energy Infrastructure for Net Zero


Chapter 4 – Energy Infrastructure for Net Zero


Chapter 4 – Energy Infrastructure for Net Zero


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 gasification).
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)
Chapter 5 – Energy Systems for Net Zero

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

(Less drastic)
Chapter 5 – Energy Systems for Net Zero

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

- **Electricity**: Majority heat pumps & district heat; hydrogen for winter peaks
- **Hydrogen**: Majority hydrogen boilers
- **Fossil fuels**:

**Heat**:
- 100% cars are EVs by 2050
- 90-95% cars are EVs by 2050

**Cars**:
- 100% cars are EVs by 2050

**Heavy road transport**:
- Mixture of electric and hydrogen HGVs
- HGVs are predominantly hydrogen

**Aviation**:
- 9% of aircraft miles (short haul) is flown in hybrid electric aircraft
- Synthetic jet fuel made from hydrogen and biomass
- Mid to long-haul aviation is 75% reliant on fossil fuels. The remainder is biofuels (17%) and synthetic jet fuel (8%)
- Aviation still reliant on fossil fuels

**Shipping**:
- Hydrogen converted to ammonia for shipping fuel
- Shipping fully reliant on hydrogen
- Synthetic hydrocarbon fuel made from hydrogen and biomass

**Industry**:
- 68-89% fuel switch to electricity; remainder is hydrogen/synthetic fuel & biomass
- 54% fuel switch to hydrogen; remainder is electricity & biomass
- Electricity, hydrogen and CCS have roughly equal shares in emissions reduction
- Majority hydrogen; some reliance on fossil fuels

### 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

Chapter 5 – Energy Systems for Net Zero

Electricity mix

Generation (TWh)

2019  ESC-C  ESC-P  FES-LTW  FES-ST  FES-CT  CAT-ZCB  CCC-B

- Other (inc. interconnectors)  - Nuclear  - Fossil fuel, CCS
- Wind - offshore  - Bioenergy, no CCS  - Fossil fuel, no CCS
- Wind - onshore  - Bioenergy, CCS  - Other renewables
- Solar PV  - Other renewables

Hydrogen production

Hydrogen (TWh)

2019  ESC-C  ESC-P  FES-LTW  FES-ST  FES-CT  CAT-ZCB  CCC-B

- Electrolysis  - Fossil gas with CCS  - Biomass gasification with CCS  - Imports

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### Table 5 Comparative analysis of selected Net Zero pathways

<table>
<thead>
<tr>
<th>Pathway</th>
<th>ESC-C</th>
<th>ESC-P</th>
<th>FES-LTW</th>
<th>FES-ST</th>
<th>FES-CT</th>
<th>CAT-ZCB</th>
<th>CCC-B</th>
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<tr>
<td><strong>Heating demand</strong></td>
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<tr>
<td>Residential heating demand in 2050 remains similar to today (-370 TWh). Efficiency improvements from retrofitting 10 million homes are countered by increased indoor temperatures.</td>
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<tr>
<td>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).</td>
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<td>60% of UK homes are EPC C or higher by 2035, leading to reduction in heating demand by 27% to -270 TWh by 2050. Heating demand falls by 16% to -310 TWh by 2050.</td>
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<tr>
<td>Less drastic program of retrofits due to lower reliance on heat pumps and higher reliance on hydrogen. Heating demand falls by 16% to -270 TWh by 2050.</td>
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<tr>
<td>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.</td>
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<tr>
<td>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.</td>
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#### 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 limits 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 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 limits 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.

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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.

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.
Comparative analysis of selected Net Zero pathways (continued)

<table>
<thead>
<tr>
<th>Pathway</th>
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<th>ESC-P</th>
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<th>FES-ST</th>
<th>FES-CT</th>
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<tbody>
<tr>
<td>Transport demand</td>
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<td>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.</td>
<td>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).</td>
<td>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.</td>
<td>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 electric cars on the road by 2050, roughly equal to today. Aviation demand decrease 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.</td>
<td>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.</td>
<td>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.</td>
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<tr>
<td>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.</td>
<td>Improvements in access to public transport and cycling &amp; walking infrastructure allow a slower uptake in car ownership. 93% of cars in 2050 are EVs. Shipping is completely decarbonised by a switch to hydrogen; aviation is still reliant on fossil fuels.</td>
<td>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.</td>
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<td>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 and biomass.</td>
<td>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 flown 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 biomass.</td>
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### 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.

- **ESC-C**: A shift towards less energy-intensive industries leads to a fall in industrial energy demand by 1/3 compared to today.
- **ESC-P**: 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.
- **FES-LTW**: Energy efficiency improvements are encouraged with strong carbon pricing. Industrial demand follows positive trajectory based on growing GDP.
- **FES-ST**: Energy efficiency improvements are pursued due to effective carbon pricing. Industrial demand follows positive trajectory based on growing GDP.
- **FES-CT**: Growth in industry leads to a 11% growth in industrial energy demand by 2050.
- **CAT-ZCB**: 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 MtCO₂e in 2050, down from 100 MtCO₂e today.

- **ESC-C**: 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 MtCO₂e in 2050.
- **ESC-P**: Industries switch fuels to electricity (68%), hydrogen (31%) and biomass (1%). Gas demand is completely phased out, and residual industrial emissions are 4 MtCO₂e in 2050.
- **FES-LTW**: Industries switch fuels to electricity (46%), 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 MtCO₂e in 2050.
- **FES-ST**: 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 MtCO₂e in 2050.
- **FES-CT**: Total industrial fuel switch to 68% electricity, 18% synthetic gas, 5% synthetic fuels and 9% biomass. Industrial emissions are Net Zero.
- **CAT-ZCB**: Large-scale fuel switches to electricity and hydrogen which, expressed in terms of GHG abatement, provide 14 MtCO₂e/year of abatement each in 2050. Significant industrial emissions remain from processes by which no decarbonisation routes have been found: around 15 MtCO₂e/year is residual before CCS and BECCS are applied to industrial processes to reduce residual emissions to around 3 MtCO₂e/year by 2050.

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

<table>
<thead>
<tr>
<th>Pathway</th>
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- 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.

- **ESC-C**: Hydrogen and carbon cap-tured 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.

- **ESC-P**: Hydrogen and carbon cap-tured 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.

- **FES-LTW**: Hydrogen and carbon cap-tured 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.

- **FES-ST**: Hydrogen and carbon cap-tured 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.

- **FES-CT**: Hydrogen and carbon cap-tured 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.

- **CAT-ZCB**: Hydrogen and carbon cap-tured 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.

- **CCC-B**: Hydrogen and carbon cap-tured 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.
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<tr>
<td>Land use/ biomass</td>
<td>14 million hectares of UK-grown biomass and 30,000 hectares of forest provides 140 TWh of domestic biomass by 2050.</td>
<td>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.</td>
<td>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.</td>
<td>Strategically managed land use and waste products leads to a UK domestic biomass resource of around 220 TWh/year by 2050.</td>
<td>Strategically managed land use and waste products leads to a UK domestic biomass resource of around 220 TWh/year by 2050.</td>
<td>75% of current livestock land is re-purposed, 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.</td>
<td>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.</td>
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<tr>
<td>Carbon capture and removal</td>
<td>Early innovation in CCS pushes capture rates to 99%. CCS is applied to heavy industries, and 28 MTCO₂e/year is captured directly from industry by 2050. DACCS scaled up to remove 25 MTCO₂e/year by 2050; BECCS provides around 15 TWh/year of electricity and 34 TWh/year of hydrogen production by 2050.</td>
<td>A failure to innovate CCS limits capture rates to 95%. CCS is applied to industry to capture 13 MTCO₂e of industrial emissions. Emissions are captured by rapid increases in tree planting. BECCS provides around 15 TWh/year electricity by 2050, but is not used for hydrogen production. Removals from BECCS are 61 MTCO₂e/year by 2050.</td>
<td>CCS capture rates reach 97% by 2050. CCS is used to capture residual emissions in industry (4 MTCO₂e/year by 2050). BECCS provides around 64 TWh/year electricity by 2050, but is not used for hydrogen production. Removals from BECCS are 61 MTCO₂e/year by 2050.</td>
<td>CCS capture rates reach 97% by 2050. CCS is used to capture residual emissions in industry (4 MTCO₂e/year by 2050). BECCS provides around 52 TWh/year electricity by 2050. BECCS provides around 55 TWh/year electricity by 2050, but is not used for hydrogen production. Removals from BECCS are 49 MTCO₂e/year by 2050.</td>
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<td>CCS capture rates reach 95% by 2050. Carbon capture and storage from industry reaches 8 MTCO₂e/year by 2050. Engineered emissions removals reach 58 MTCO₂e/year by 2050 (BECCS provides 52 MTCO₂e/year of removals across power, energy-from waste, industry and hydrogen production by 2050; DACCS provides 5 MTCO₂e/year; LULUCF provides 1 MTCO₂e/year) in addition to nature-based sinks of 39 MTCO₂e/year.</td>
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~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 reforming 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 powered by renewables; 35% is produced from biomass gasification with CCS; the remaining 6% is produced from steam reforming of methane, which is limited by the 95% CO₂ capture rate.

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

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<tr>
<td>Hydrogen/low-carbon fuels</td>
<td>-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 reforming of methane with CCS (99% capture rate). The remaining 14% is produced by biomass gasification with CCS.</td>
<td>-185 TWh/year hydrogen needed by 2050 to supply industry, peak winter heating, electricity storage and heavy-duty transport (including shipping). 59% of this is produced from electrolysis powered by renewables; 35% is produced from biomass gasification with CCS; the remaining 6% is produced from steam reforming of methane, which is limited by the 95% CO₂ capture rate.</td>
<td>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.</td>
<td>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 reforming with CCS (97% capture rate), the remaining 11% is from electrolysis powered by renewables.</td>
<td>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 reforming with CCS (97% capture rate).</td>
<td>-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.</td>
<td>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.</td>
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</table>
| Electricity demand             | Electrification of road transport, heating and industry leads to a 25% 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 an 113% 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. | Heavy electrification of road transport, heating and industry leads to a 110% increase in electricity system demand from today to 2050.
Table 5 Comparative analysis of selected Net Zero pathways (continued)

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<tr>
<td><strong>Electricity mix</strong></td>
<td>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.</td>
<td>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. 30 GW of gas with CCS and 30 GW of hydrogen turbines are required to smooth out gaps in supply and demand.</td>
<td>71% of generation is wind (54% offshore, 17% onshore), 11% is solar, 11% is BECCS and 3% is other renewables including wave &amp; tidal and geothermal. 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.</td>
<td>72% of generation is wind (65% offshore, 9% onshore), 9% is solar, 11% is BECCS and 8% is other renewables including wave &amp; tidal and hydro. 18% 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 3% of annual electricity storage and providing for long term energy demand. Gas with CCS provides some peaking plant, contributing 0.01% of electricity generation by 2050.</td>
<td>65% of generation is wind (48% offshore, 17% onshore), 10% is solar, 9% is BECCS and 7% is other renewables including wave &amp; 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.</td>
<td>78% of generation is wind (68% offshore, 10% onshore), 9% is wave &amp; 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 electrolysis using surplus energy. The synthetic fuels enable decarbonisation of shipping &amp; aviation, and provide fuel for gas plants for when demand outstrips supply.</td>
<td>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.</td>
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**Storage and Flexibility**

| Geological storage of 660 GW 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 GW smooths out peaks and troughs in supply. | Geological storage of 600 GW 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 GW 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 to 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) 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 to grid (26% 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 to 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 GW 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. |
Pathway | ESC-C | ESC-P | FES-LTW | FES-ST | FES-CT | CAT-ZCB | CCC-B
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**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 remains 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.

Table 5 Comparative analysis of selected Net Zero pathways (continued)
5.3 Chapter 5 Endnotes & References

5.3.1 Endnotes

a) 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%.

b) 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


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

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 CO₂ 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 CO₂
H – is the symbol for hydrogen
hydrogen gas is H₂
water is H₂O
O – is the symbol for oxygen
oxygen gas is O₂

Photosynthesis

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

The chemical equation of photosynthesis is:

\[ 6 \text{CO}_2 + 6 \text{H}_2\text{O} + \text{light} \rightarrow \text{C}_6\text{H}_12\text{O}_6 + 6 \text{O}_2 \]

This builds plant material, for example glucose (C₆H₁₂O₆, 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, O₂.

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 (C₆H₁₂O₆) breaks down as follows:

Respiration

The chemical equation for respiration is:

\[ \text{C}_6\text{H}_12\text{O}_6 + 6 \text{O}_2 \rightarrow 6 \text{CO}_2 + 6 \text{H}_2\text{O} + \text{heat} \]

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:

\[ \text{C}_6\text{H}_12\text{O}_6 \rightarrow 3 \text{CO}_2 + 3 \text{CH}_4 \]

Reaction products: mainly carbon dioxide and methane, CH₄.

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
Annex: The Chemistry of Energy Systems

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 $CH_4$.

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

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

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

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:

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

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.

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:

$$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$$

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:

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

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)

$$CO + H_2O \rightarrow H_2 + CO_2 + \text{a little heat}$$

(water-gas shift)

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’.
Annex: The Chemistry of Energy Systems

7.2 The Nitrogen Cycle

7.2.1 Natural Environment [7.2, 7.3]

N is the symbol for nitrogen

Nitrogen gas is N₂
Nitric oxide is NO
Nitrogen dioxide is NO₂
Nitrous oxide is N₂O

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 NO₂ Gases

A little NO and NO₂ are formed during lightning strikes, from nitrogen and oxygen in the air reacting:

\[ \text{N}_2 + \text{O}_2 \rightarrow 2 \text{ NO} \]
\[ \text{N}_2 + 2\text{O}_2 \rightarrow 2 \text{ NO}_2 \]

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

\[ \text{NO} + \frac{1}{2} \text{O}_2 \rightarrow \text{NO}_2 \]

These gases both dissolve in rainwater to make an acidic solution containing nitrates (NO₃⁻) 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 (N₂) into ammonia (NH₃), which forms (with water) ammonium compounds (NH₄⁺) ‘plant foods’.

\[ \text{N}_2 \rightarrow \text{(microbes)} \rightarrow \text{NH}_3 \leftarrow \text{(in water)} \rightarrow \text{NH}_4^+ \]

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

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

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 (NH₄⁺) and/or ammonia gas, (NH₃).

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

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:

\[ \text{NO}_3^- \rightarrow \text{NO}_2^- \rightarrow \text{N}_2\text{O} \text{ (escapes to air)} \rightarrow \text{N}_2 \text{ (escapes to air)} \]

7.2.2 Human Activity [7.3, 7.4]

Emissions of NOₓ from High Temperature Combustion

Nitric oxide (NO), nitrogen dioxide (NO₂) and nitrous oxide (N₂O) are collectively known as NOₓ.
Annex: The Chemistry of Energy Systems

Any combustion (or very high temperature conditions) causes some nitrogen in the air to react with oxygen and form NO and/or NO₂, and sometimes also N₂O gases (collectively known as ‘NOₓ’). NOₓ is normally predominantly NO and/or NO₂.

\[
\begin{align*}
N_2 + O_2 & \rightarrow 2 NO \\
N_2 + 2 O_2 & \rightarrow 2 NO_2 \\
N_2 + \frac{1}{2} O_2 & \rightarrow N_2O
\end{align*}
\]

In air: \( NO + \frac{1}{2} O_2 \leftrightarrow NO_2 \)

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

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

**Impacts of NOₓ Emissions**

NO₂ 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.

NOₓ (NO and NO₂ components) can also cause ecological damage, affecting some sensitive ecosystems, such as peat bogs in upland Britain, which are important carbon stores.

NOₓ from aircraft interacts with other substances in the upper atmosphere, which contributes to non-CO₂ warming effects from aviation [7.5].

**Formation of Nitrous Oxide in Combustion**

Small amounts of nitrous oxide, N₂O, 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 NOₓ emissions [7.6].

Catalytic converters on car exhausts aim to change the NOₓ in car exhaust fumes to nitrogen gas, N₂. However, the catalytic converters also change some of the NO and NO₂ to N₂O, which is good for air quality, but increases emissions of the greenhouse gas N₂O. 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].

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

\[
\begin{align*}
N_2 + 3 H_2 & \rightarrow 3 NH_3 & \text{ammonia production, Haber-Bosch process} \\
NH_3 + 2 O_2 & \rightarrow H_2O + HNO_3 & \text{nitric acid production, the Ostwald process} \\
HNO_3 + NH_3 & \rightarrow NH_4NO_3 & \text{ammonium nitrate, acid-base neutralisation}
\end{align*}
\]

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

Some of the excess nitrogen ends up converted to N₂O 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.

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Annex: The Chemistry of Energy Systems

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

- **Nitrogen gas, $N_{2}$**
  - Major constituent of air

- **De-nitrification increases in nitrogen-rich soil**

- **Fertiliser manufacture**

- **Fertiliser**

- **Nitrogen fixation by soil microbes**

- **Decaying plant and animal matter**

- **Nutrient cycling in the soil**

- **Leaching: nutrients washed out of soils**

- **Nitrogen fixation by soil microbes**

**KEY**

- **Nitrogen gas, $N_{2}$**
- **Oxides of nitrogen**
  - Consisting largely of $NO$ - nitric oxide, and/or $NO_{2}$ - nitrogen dioxide
- **Nitrous oxide, $N_{2}O$**
  - (Powerful greenhouse gas)
- **Nitrogen compounds in water and soils: nitrates, $NO_{3}^{-}$ and nitrates, $NO_{2}^{-}$**
- **Ammonia gas (NH$_{3}$) and ammonium compounds (NH$_{4}^{+}$)**
- **Nitrogen compounds in biomass: amino acids and proteins**
- **NO$_x$ formed during combustion**
- **NO$_x$ Mainly nitric oxide gas, NO, & nitrogen dioxide gas, NO$_2$**

**Nitrogen fixation**

**De-nitrification**

**Lightning strikes**

**Combustion**

**Nitrous oxide gas $N_{2}O$**

**Nitrates, $NO_{3}^{-}$**

**Ammonium compounds**

**Ammonia gas NH$_{3}$**

**Amino acids**

**Proteins**

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Annex: The Chemistry of Energy Systems

7.3 Annex References


## Glossary

### General terms

<table>
<thead>
<tr>
<th>Acronym/Abbreviation</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FES</td>
<td>Future Energy Scenarios</td>
<td>National Grid has developed a portfolio of Future Energy Scenarios for Great Britain, which are referenced several times throughout this guide.</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse gas</td>
<td>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.</td>
</tr>
<tr>
<td>LULUCF</td>
<td>Land use, land use change and forestry</td>
<td>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).</td>
</tr>
<tr>
<td>-</td>
<td>Net Zero</td>
<td>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.</td>
</tr>
<tr>
<td>-</td>
<td>Net zero technology</td>
<td>A technology with low enough GHG emissions to enable net zero overall emissions.</td>
</tr>
<tr>
<td>-</td>
<td>Order(s) of magnitude</td>
<td>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”.</td>
</tr>
<tr>
<td>R&amp;D</td>
<td>Research and Development</td>
<td>The process by which new knowledge is acquired in the hope of developing new technologies, products, systems or services.</td>
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### Policy Instruments

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<tr>
<td>CfD</td>
<td>Contract for Difference</td>
<td>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.</td>
</tr>
<tr>
<td>FiT</td>
<td>Feed-in-Tariff</td>
<td>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.</td>
</tr>
<tr>
<td>RHI</td>
<td>Renewable Heat Incentive</td>
<td>A UK Government policy instrument designed to encourage the provision of heat from renewable sources.</td>
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## Glossary

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<tr>
<td>RO</td>
<td>Renewables Obligation</td>
<td>A UK Government policy instrument designed to encourage the provision of electricity from renewable generators.</td>
</tr>
<tr>
<td>ROCs</td>
<td>Renewable Obligation Certificates</td>
<td>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.</td>
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### Organisations

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<tr>
<th>Acronym/Abbreviation</th>
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<tbody>
<tr>
<td>Aggregator</td>
<td>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.</td>
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<tr>
<td>BEIS</td>
<td>Department for Business, Energy &amp; Industrial Strategy</td>
<td>UK Government department responsible for national policies regarding business, energy and industrial strategy.</td>
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<tr>
<td>CCC</td>
<td>Climate Change Committee</td>
<td>Independent statutory body for advising the UK Government on climate change.</td>
</tr>
<tr>
<td>DIT</td>
<td>Department for Transport</td>
<td>UK Government department responsible for national transport policy.</td>
</tr>
<tr>
<td>DNO</td>
<td>Distribution Network Operator</td>
<td>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.</td>
</tr>
<tr>
<td>ENA</td>
<td>Energy Networks Association</td>
<td>A trade body of owners and operators of electricity and gas network infrastructure in the UK.</td>
</tr>
<tr>
<td>GDN</td>
<td>Gas Distribution Network</td>
<td>The gas network infrastructure in a local area which delivers gas to end-users through smaller, lower-pressure gas pipes.</td>
</tr>
<tr>
<td>National Grid ESO</td>
<td>National Grid Electricity System Operator</td>
<td>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.</td>
</tr>
<tr>
<td>National Grid ET</td>
<td>National Grid Electricity Transmission</td>
<td>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).</td>
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<tbody>
<tr>
<td>National Grid GT</td>
<td>National Grid Gas transmission</td>
<td>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.</td>
</tr>
<tr>
<td>Ofgem</td>
<td>Office for gas and electricity markets</td>
<td>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.</td>
</tr>
</tbody>
</table>

### Fuels and chemistry

<table>
<thead>
<tr>
<th>Acronym/Abbreviation</th>
<th>Name</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>AD</td>
<td>Anaerobic Digestion</td>
<td>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.</td>
</tr>
<tr>
<td>-</td>
<td>Bioenergy</td>
<td>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.</td>
</tr>
<tr>
<td>-</td>
<td>Biofuel</td>
<td>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.</td>
</tr>
<tr>
<td>-</td>
<td>Biogas</td>
<td>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.</td>
</tr>
<tr>
<td>-</td>
<td>Biomass</td>
<td>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.</td>
</tr>
<tr>
<td>Bio-SNG</td>
<td>Bio-synthetic natural gas</td>
<td>Methane formed synthetically, using biomass as the source of carbon.</td>
</tr>
<tr>
<td>-</td>
<td>Fossil fuel</td>
<td>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.</td>
</tr>
<tr>
<td>-</td>
<td>Fugitive emissions</td>
<td>Unintended release of a substance, usually a gas or liquid, e.g. from leaks in equipment.</td>
</tr>
<tr>
<td>-</td>
<td>Gasworks</td>
<td>Facilities for the production of town gas, normally from coal.</td>
</tr>
</tbody>
</table>
### Glossary

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<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>Gasification</td>
<td>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.</td>
</tr>
<tr>
<td>GCV</td>
<td>Gross calorific value</td>
<td>See HHV.</td>
</tr>
<tr>
<td>HHV</td>
<td>Higher heating value</td>
<td>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.</td>
</tr>
<tr>
<td>-</td>
<td>Landfill gas</td>
<td>Gas derived from landfill sites. Landfill gas contains methane and can be used as a fuel.</td>
</tr>
<tr>
<td>-</td>
<td>Latent heat of fusion</td>
<td>The energy required to melt a solid, or released when a liquid solidifies/freezes.</td>
</tr>
<tr>
<td>-</td>
<td>Latent heat of vaporisation</td>
<td>The energy required to turn a substance from liquid to gaseous state, or released when a gas condenses into a liquid.</td>
</tr>
<tr>
<td>LNG</td>
<td>Liquefied natural gas</td>
<td>Natural gas that has been converted to liquid form (by refrigeration) for ease of storage or transport.</td>
</tr>
<tr>
<td>LHV</td>
<td>Lower heating value</td>
<td>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.</td>
</tr>
<tr>
<td>-</td>
<td>Fossil gas</td>
<td>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.</td>
</tr>
<tr>
<td>-</td>
<td>Organic</td>
<td>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.</td>
</tr>
<tr>
<td>-</td>
<td>Renewable</td>
<td>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.</td>
</tr>
<tr>
<td>-</td>
<td>Synfuel</td>
<td>Synthetic fuel, made from chemical processing of a feedstock e.g. hydrogen and CO₂. Examples include synthetic methane, ethanol or kerosene.</td>
</tr>
<tr>
<td>-</td>
<td>Syngas</td>
<td>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.</td>
</tr>
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Glossary

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<tbody>
<tr>
<td>SNG</td>
<td>Synthetic natural gas</td>
<td>Methane, formed from a chemical process, e.g. combining hydrogen with CO₂.</td>
</tr>
<tr>
<td>-</td>
<td>Town gas</td>
<td>A calorific gas, historically manufactured from coal in UK towns and cities, at gasworks, 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.</td>
</tr>
<tr>
<td>CH₄</td>
<td>Methane</td>
<td>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 CO₂). 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.</td>
</tr>
<tr>
<td>H</td>
<td>Hydrogen (element)</td>
<td>An abundant chemical element, present in most materials, including water (H₂O).</td>
</tr>
<tr>
<td>H₂</td>
<td>Hydrogen (molecule)</td>
<td>A colourless, odourless gas much lighter than air. If ignited, it can burn in air, and can be used as a fuel.</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
<td>Gas produced from combustion of carbon-containing fuels. Main global warming gas.</td>
</tr>
<tr>
<td>CO</td>
<td>Carbon monoxide</td>
<td>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.</td>
</tr>
<tr>
<td>N₂O</td>
<td>Nitrous oxide</td>
<td>A powerful greenhouse gas that is emitted from soils, especially fertilised agricultural soils. N₂O also forms in combustion systems in smaller quantities, including in road transport. It is used as an anaesthetic (laughing gas).</td>
</tr>
<tr>
<td>NO</td>
<td>Nitric oxide</td>
<td>A colourless gas that forms in combustion systems. NO readily reacts in air, turning into the more harmful NO₂. In the human body, it is a signalling molecule in many physiological processes.</td>
</tr>
<tr>
<td>NO₂</td>
<td>Nitrogen dioxide</td>
<td>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.</td>
</tr>
<tr>
<td>NOₓ</td>
<td>Oxides of nitrogen</td>
<td>A collective term for NO, NO₂ and N₂O. The principal source is combustion systems, such as power stations and traffic, which normally emit NO and some NO₂, with far smaller quantities of N₂O. Legislation limiting pollution from industrial sources generally covers the NO and NO₂ components only.</td>
</tr>
</tbody>
</table>
### Glossary

#### Electricity and gas infrastructure

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>AC</td>
<td>Alternating current</td>
<td>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.</td>
</tr>
<tr>
<td>-</td>
<td>Blackout</td>
<td>Loss of electrical power. Usually taken to mean a loss of power to a large area or whole country.</td>
</tr>
<tr>
<td>-</td>
<td>Capacity factor</td>
<td>See load factor</td>
</tr>
<tr>
<td>CCGT</td>
<td>Combined cycle gas turbine</td>
<td>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.</td>
</tr>
<tr>
<td>-</td>
<td>Curtail, curtailment</td>
<td>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.</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
<td>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).</td>
</tr>
<tr>
<td>DN</td>
<td>Distribution Network</td>
<td>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.</td>
</tr>
<tr>
<td>-</td>
<td>Distribution System</td>
<td>See Distribution Network.</td>
</tr>
<tr>
<td>DSO</td>
<td>Distribution System Operator</td>
<td>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.</td>
</tr>
<tr>
<td>DG</td>
<td>Distributed Generation</td>
<td>Electricity generators connected to the distribution network.</td>
</tr>
</tbody>
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# Glossary

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<tr>
<td>Diversity or diversification</td>
<td>Diversity or diversification</td>
<td>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.</td>
</tr>
<tr>
<td>Electricity System Operator</td>
<td>Electricity System Operator</td>
<td>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.</td>
</tr>
<tr>
<td>Electrolyser</td>
<td>Electrolyser</td>
<td>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.</td>
</tr>
<tr>
<td>Frequency (of the electricity grid)</td>
<td>Frequency (of the electricity grid)</td>
<td>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.</td>
</tr>
<tr>
<td>Frequency support/ frequency response</td>
<td>Frequency support/ frequency response</td>
<td>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.</td>
</tr>
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<tr>
<td>HVDC</td>
<td>High voltage direct current</td>
<td>Direct current at high voltage, typically hundreds of Kilovolts (kV).</td>
</tr>
<tr>
<td>-</td>
<td>Incident solar radiation</td>
<td>Solar radiation which falls on a particular surface or land area.</td>
</tr>
<tr>
<td>-</td>
<td>Linepack</td>
<td>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.</td>
</tr>
<tr>
<td>-</td>
<td>Load factor</td>
<td>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.</td>
</tr>
<tr>
<td>OCGT</td>
<td>Open cycle gas turbine</td>
<td>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.</td>
</tr>
<tr>
<td>P2G</td>
<td>Power-to-gas</td>
<td>Conversion of electrical energy to a gaseous fuel (usually hydrogen by electrolysis).</td>
</tr>
<tr>
<td>P2X</td>
<td>Power-to-X</td>
<td>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).</td>
</tr>
<tr>
<td>PEM</td>
<td>Proton exchange membrane, or polymer electrolyte membrane</td>
<td>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).</td>
</tr>
<tr>
<td>-</td>
<td>Solar irradiance</td>
<td>Energy from sunshine per square metre per second. It is normally measured in Watts per square metre (W/m²). In the UK, average year-round (including night and cloud cover) solar irradiance across the year varies from around 95 W/m² (Edinburgh) to 110 W/m² (London). In sunnier places, average solar irradiance can reach over 270 W/m² (Nouakchott, Mauritania).</td>
</tr>
<tr>
<td>-</td>
<td>Transmission system</td>
<td>A system of electrical wires or gas pipes which transports electricity or gas, in bulk, over long distances.</td>
</tr>
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<tr>
<td>V2G</td>
<td>Vehicle-to-grid</td>
<td>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.</td>
</tr>
</tbody>
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### Carbon capture, utilisation and storage

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<tr>
<td>BECCS</td>
<td>Bioenergy with carbon capture and storage</td>
<td>Burning of biomass (to produce electricity, heat or hydrogen) with CCS applied to capture the CO₂ emissions. This is regarded as a carbon-negative technology as the CO₂ is first sequestered by the biomass and is captured either before or after combustion.</td>
</tr>
<tr>
<td>CCS</td>
<td>Carbon capture and storage</td>
<td>Capture of CO₂ – either from combustion of fuels, or directly from industrial processes or the air – and storage (typically underground), which is intended to be permanent.</td>
</tr>
<tr>
<td>CCU</td>
<td>Carbon capture and utilisation</td>
<td>Capture of CO₂ – either from combustion of fuels, or directly from industrial processes or the air – and utilisation in other industrial processes.</td>
</tr>
<tr>
<td>CCUS</td>
<td>Carbon capture, utilisation and storage</td>
<td>Collective term for CCU and CCS.</td>
</tr>
<tr>
<td>DACCS</td>
<td>Direct air carbon capture and storage</td>
<td>Capture of CO₂ directly from the air.</td>
</tr>
</tbody>
</table>

### Buildings, heating and cooling

<table>
<thead>
<tr>
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<tr>
<td>ASHP</td>
<td>Air source heat pump</td>
<td>Heat pump whose source of heat is ambient air. (Warm air from the output of another process could be used to increase COP).</td>
</tr>
<tr>
<td>COP</td>
<td>Coefficient of performance.</td>
<td>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.</td>
</tr>
<tr>
<td>DH</td>
<td>District Heating</td>
<td>A heating system which transports heat, primarily in hot water pipes, i.e. a 'heat network', between multiple buildings.</td>
</tr>
<tr>
<td>EPC</td>
<td>Energy Performance Certificate</td>
<td>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.</td>
</tr>
<tr>
<td>GSHP</td>
<td>Ground-source heat pump</td>
<td>Heat pump whose source of heat is the ground.</td>
</tr>
</tbody>
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<tr>
<td>HP</td>
<td>Heat pump</td>
<td>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.</td>
</tr>
<tr>
<td>-</td>
<td>Prosumer</td>
<td>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).</td>
</tr>
<tr>
<td>SAP</td>
<td>Standard Assessment Procedure</td>
<td>The methodology used by the UK Government to assess and compare the energy and environmental performance of dwellings.</td>
</tr>
<tr>
<td>-</td>
<td>U-value</td>
<td>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.</td>
</tr>
<tr>
<td>WSHP</td>
<td>Water-source heat pump</td>
<td>Heat pump whose source of heat is water (could be a river or industrial output/sewage).</td>
</tr>
<tr>
<td>LED</td>
<td>Light-emitting diode</td>
<td>A device which emits light and can be used to provide lighting. LEDs are among the most energy-efficient types of lighting available.</td>
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</table>

#### Vehicles and transport

<table>
<thead>
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<tr>
<td>BEV</td>
<td>Battery electric vehicle</td>
<td>A vehicle whose sole means of propulsion is a rechargeable battery connected to an electric motor.</td>
</tr>
<tr>
<td>Contrail (or contrail cirrus)</td>
<td>Condensation trail</td>
<td>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 CO₂ emissions. The trails are sometimes called contrail cirrus, because they are similar to cirrus clouds which form naturally in the atmosphere.</td>
</tr>
<tr>
<td>EV</td>
<td>Electric vehicle</td>
<td>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.</td>
</tr>
<tr>
<td>-</td>
<td>E-bike</td>
<td>A power-assisted bicycle that uses a battery and an electric motor to increase the power output of the cranks as the rider pedals.</td>
</tr>
</tbody>
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<tr>
<td>FCV</td>
<td>Fuel-cell vehicle</td>
<td>A vehicle powered by a fuel cell – which generates electricity from oxygen from the air and compressed hydrogen – connected to an electric motor.</td>
</tr>
<tr>
<td>HGV</td>
<td>Heavy goods vehicle</td>
<td>Freight vehicles exceeding 3.5 tonnes in weight. Typically refers to lorries/trucks.</td>
</tr>
<tr>
<td>HEV</td>
<td>Hybrid electric vehicle</td>
<td>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.</td>
</tr>
<tr>
<td>ICE</td>
<td>Internal combustion engine</td>
<td>The type of engine in conventional cars and other vehicles, normally fuelled by petrol, diesel or a similar fossil fuel.</td>
</tr>
<tr>
<td>LGV</td>
<td>Light goods vehicle</td>
<td>Freight vehicles not exceeding 3.5 tonnes in weight. Typically refers to vans.</td>
</tr>
<tr>
<td>pkm</td>
<td>Person-kilometre</td>
<td>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.</td>
</tr>
<tr>
<td>PHEV</td>
<td>Plug-in hybrid electric vehicle</td>
<td>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.</td>
</tr>
<tr>
<td>SAF</td>
<td>Sustainable aviation fuel</td>
<td>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-CO₂ warming effects of aviation (which have been found to roughly triple the global warming effects of aircraft).</td>
</tr>
<tr>
<td>tkm</td>
<td>Tonne-kilometre</td>
<td>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.</td>
</tr>
<tr>
<td>V2G</td>
<td>Vehicle-to-grid</td>
<td>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.</td>
</tr>
</tbody>
</table>