Energy Background Document

Future Energy Scenarios

July 2023

ESO

Contents

1. Document purpose

The purpose of this document is to provide supplementary content and background to underpin the main FES 2023 document.

2. Introduction

Great Britain's electricity system is one of the oldest, most complex and fast changing in the world. Every year the Electricity System Operator (ESO) moves 300 Terawatt Hours (TWh) of electricity, equivalent to four trillion kettles boiling at once around our system, all while enabling the transformation to a sustainable energy system[1].

Electricity is a form of energy that can be produced in different ways, to provide power for things to operate. At the ESO, we operate the flow of electricity all over Great Britain. We make sure that the right amount of electricity gets to the right places so that people can use it when and how they need it. We don't generate electricity ourselves; we get electricity from producers like wind farms, solar farms and gas power plants. The way electricity is generated is changing as we head towards a greener future. It's important to have different fuel sources and technologies to generate electricity to ensure a constant supply and prevent over reliance on one type of power generation. In line with this, the reliance on carbon-emitting fossil fuels of just a few decades ago, is reducing as we move from coal to cleaner sources. Renewables are key to this[2].

Electricity is transported through the transmission network, balancing supply and demand second by second, 24/7, like a network of roads and motorways. High voltage electricity runs up and down the UK on the transmission networks (the motorways) while Distribution Network Operators (DNOs) provide the local cables (the A roads) to take the electricity to our homes and businesses. Interconnectors are the cables that share Great Britain's electricity with our neighbours abroad. Aggregators help people to use electricity at the optimum times, for example, working with supermarkets to adjust their freezers to come on and off at different times rather than taking a steady supply[3].

As Great Britain's Electricity System Operator, we have our own ambitious zero carbon targets, and we are working hard to build the greener electricity system of the future[4]. We're doing this by reducing our reliance on energy sources like coal which produce high carbon emissions. Instead, we're increasing our use of sources like wind and solar power, which do not produce any carbon. By reducing the system's carbon emissions, we're helping Great Britain to reach the wider goal of net zero. We are also empowering people to make more conscious decisions about how they consume energy by making our data easily available. We have launched a carbon intensity app to show people the greenest times of day to use electricity and help them see real time information on how our electricity is being produced[5].

[1] https://www.nationalgrideso.com/electricity-explained

[2] https://www.nationalgrideso.com/electricity-explained/how-do-we-generate-electricity

[3] https://www.nationalgrideso.com/electricity-explained/how-does-electricity-move-around

[4] https://www.nationalgrideso.com/electricity-explained/how-do-we-generate-electricity

[5] https://www.nationalgrideso.com/news/introducing-our-carbon-intensity-app

3. Net Zero

The UK has a legal commitment to eliminate emissions by 2050, we call this the net zero target. Net zero is achieved when the amount of greenhouse gases going into the environment are balanced by those being removed, through negative emissions[6]. Reaching net zero greenhouse gas emissions is now widely recognised as critical to the future of our society, with climate scientists emphasising the urgent need to rapidly reduce emissions.

Emissions

Greenhouse Gas (GHG) emissions refer to the release of gases, primarily carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), into the Earth's atmosphere[7]. These gases trap heat and warm the planet, creating a greenhouse effect that causes global warming and climate change. GHG emissions are measured in Millions of tonnes of CO_2 equivalent ($MtCO_2e$) which compares the emissions from different GHGs based on their Global Warming Potential (GWP) as if it were CO_2.

The main sources of GHG emissions are human activities such as burning fossil fuels for energy and transportation, deforestation, and agriculture. The burning of fossil fuels, such as coal, oil, and natural gas, is the largest contributor GHG emissions, accounting for about 75% of all emissions.

Reducing GHG emissions is critical to mitigating the effects of climate change. Efforts to reduce emissions include transitioning to renewable energy sources, improving energy efficiency, reducing deforestation, and implementing policies and regulations to limit emissions from industrial processes and transportation.

Reaching net zero is not just an energy sector challenge, it spans all sectors. Some of these sectors, such as aviation and agriculture, cannot be entirely decarbonised. The energy sector will need to therefore reach negative emissions by 2050 to offset these sectors and achieve the net zero target, which will continue to heavily influence decisions made in the energy sector for many years to come. While the average carbon intensity for the whole network is useful to track progress, it hides regional variation. Each region has different levels of renewable resources as well as different domestic, Industrial & Commercial (I&C) demands. If we are to decarbonise the UK energy sector and wider economy, understanding the impact of these differences is critical. This approach has already contributed to national policy differences with Scotland, which has high levels of wind capacity relative to its demand.

Impact of climate change on nature and relevant targets

Net zero has become a well-known concept since the United Nations Climate Change Conference in 2015 in Paris, where an agreement was signed to limit global warming to under 2°C compared to pre-industrial levels. This is referred to as the Paris Agreement. To achieve it, GHG emissions need to be net zero by the second half of the 21st century. Signatories also agreed to pursue efforts to limit the temperature increase to 1.5°C. Net zero is important because it is now well evidenced that the increase in GHG emissions, most notably CO_2, due to human activity since the industrial revolution is linked to global temperature rise.

The Intergovernmental Panel on Climate Change (IPCC), the United Nations (UN) body for assessing the science related to climate change, has stated that the planet has already warmed by 1.1 degrees and human-induced climate change is already affecting weather and climate extremes. The consequences of this have been felt across the planet in the form of fires, droughts, hurricanes and flooding. This first-hand experience is helping to focus the world's attention, with net zero commitments now covering over 80% of the world's GDP (Gross Domestic Product). The IPCC confirmed that to limit warming to 2°C rapid, deep and in most cases immediate emission reductions are required. Globally, urgent progress towards net zero must happen and cannot wait until 2030 or beyond.

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[6] When more carbon is removed from the atmosphere than is emitted into the atmosphere, this is termed negative emissions.

[7] FES does not currently consider other emissions such as PM2.5/10, which are emitted from the combustion of e.g. biomass.

The Climate Change Committee (CCC) advises the UK and devolved governments on emissions targets, and reports progress in reducing GHG emissions to Parliament.

Prior to hosting COP26, the UK set its Nationally Determined Contribution (NDC), the limit for each country's carbon emissions, at a 68% reduction by 2030 (compared to 1990 levels). As well as setting one of the world's most ambitious NDCs, meeting the 6th carbon budget means a 78% reduction by 2035. This is aligned to the UK's 2050 net zero target and to the broader aim to keep global temperature rise below 1.5ºC.

The CCC has acknowledged that whilst the net zero strategy provides a strong foundation for delivering the target, it must proceed at pace, with credible policies in place by 2024, if these targets are to be met.

For information on policy announcements from the current FES cycle, please see the main FES document.

Decarbonisation of the power sector

Electricity supply has been responsible for much of the UK's decarbonisation to date. This resulted in the average carbon intensity of the GB transmission system falling by over 60% from 2009 to the beginning of 2021, making it the fastest decarbonising electricity transmission system in the world. Although to continue to lower emissions from electricity supply and consequently the carbon intensity of the transmission system the UK needs to continue promoting low carbon generation options.

Decarbonising the UK's power sector is vital, not only to reduce its contribution to UK emissions but also from a whole energy system perspective[8]. Many of our options for decarbonising other sectors involve electrifying them, for example heat pumps for domestic heating or Electric Vehicles (EVs) for transport, so a prerequisite of decarbonising these sectors is a low-carbon power sector. In addition, the power sector can provide negative emissions using bioenergy with Carbon Capture, Usage and Storage (CCUS) to help offset residual emissions from hard to abate sectors, such as agriculture.

As the ESO, we facilitate the continued decarbonisation of the power sector. We are already implementing future changes needed to ensure the electricity transmission system facilitates net zero as opposed to being a barrier. These include exploring energy market reforms and the development of new markets, a review of network planning processes, and innovation projects like our virtual energy system. These activities will create an environment where the latest technologies and the right supporting infrastructure can deliver a secure, low-carbon, reliable power system.

Across all our net zero scenarios, many of the most difficult sectors to decarbonise are those outside of the energy sector and not directly modelled by us. They mostly relate to non-energy emissions such as agriculture, shipping and aviation, waste and land use. Here, most technical options for reducing emissions are at an early stage and face considerable challenges. The CCC's 6th carbon budget pathways reduced emissions using methods including technical innovation (e.g., development of low-carbon fuels), policy decisions (e.g., increased tree planting and peatland restoration) and further changes to individuals' behaviours (e.g., reduction in meat and dairy consumption, reduction in food waste and reduction in flights compared to business as usual).

[8] Where we refer to the 'whole energy system', we are referring to electricity, natural gas and potentially hydrogen and biofuel networks and their users as one system. It is not a UK system in isolation as we are connected by interconnectors and energy is sold in a global market. Whole energy system thinking helps decarbonisation and energy security.

GHG removal

In this section, the main negative emissions[9] technologies are presented, and their associated challenges and opportunities are discussed.

BECCS stands for Bioenergy with Carbon Capture and Storage. It is a carbon-negative technology that combines bioenergy with Carbon Capture Use and Storage (CCUS) to prevent carbon dioxide from reaching the atmosphere and it can be applied to various applications, such as power generation and, hydrogen production. The process works by generating electricity from biomass, such as wood or crop residues, which absorb CO_2 from the atmosphere through photosynthesis. The CO_2 emitted during the energy production process is then captured and stored underground or in other long-term storage solutions, such as in depleted oil and gas fields.

DACCS stands for Direct Air Capture with Carbon Storage. It is a carbon dioxide removal technology that captures CO_2 directly from the air and stores it in long-term storage solutions, such as underground or in depleted oil and gas fields. The process works by pulling air through a filter or other device that contains a chemical solvent or material that selectively captures CO_2. The CO_2 is then separated from the solvent or material, compressed into a liquid form, and transported to storage locations for long-term storage.

LULUCF stands for Land Use, Land Use Change and Forestry. It refers to a set of activities that affect the Earth's land surface and its ability to store or emit carbon dioxide and other GHGs. LULUCF activities include changes in land use, such as deforestation or afforestation, forest management practices, and cropland and grazing land management. These activities can either emit GHGs when forests are cleared or absorb them when new forests are planted. The inclusion of LULUCF in emissions reporting is important because it recognizes the role that land use and land management practices can play in addressing climate change.

BECCS, DACCS, LULUCF are considered important solutions to address climate change, along with other approaches like renewable energy, energy efficiency, societal change, and carbon pricing. The UK is in a good geological position with ample potential for storage of captured CO_2 in offshore depleted oil and gas fields. The British geological survey estimate that significant amounts of CO_2 can be stored, which could last way beyond net zero[10].

[9] When more carbon is removed from the atmosphere than is emitted into the atmosphere, this is termed negative emissions

[10] https://www.nstauthority.co.uk/the-move-to-net-zero/carbon-capture-and-storage/

4. The Energy Consumer

This chapter covers what we mean by consumers and which consumer types are included in the FES scenarios. Consumers being willing and enabled to engage with the energy system is crucial to unlocking flexible supply and demand and achieving net zero in the most cost-effective way between today and 2050.

What do we mean by consumers?

We are all energy consumers, in our homes, workplaces and cars; energy is what our modern society runs on and is a basic need for everyone.

Today consumers use a lot of fossil fuels: petrol and diesel for cars, heating oil and gas for heating homes and businesses, and oil, gas and solid fuels in industry. This is already starting to change, and the energy used by consumers and the consumer experience will look very different in 2050.

In the The Energy Consumer we break energy consumption down into four sections:

Residential
Home heating and electrical appliances

Transport
Cars, HGV's, rail, aviation and shipping

Industrial
Heavy industry such as steel and cement production and light manufacturing such as food and textiles

Commercial
Shops, office, data centres

Consumer engagement

This section describes how the consumers can engage in the net zero transition through various ways of using energy. Adoption of smart tariffs, smart technologies, digitalisation and automation are essential for providing flexibility in the system.

We assume higher levels of societal change, i.e., residential consumers are more engaged in our scenarios. They respond to price signals from the energy system, and automation optimises energy use for residential consumers in the background. It can manage consumer energy demand, shifting the time they charge their Electric Vehicle or feeding energy back to the system using Vehicle-to-Grid (V2G). It could also manage thermal storage in the home, adjusting when their heat pump runs or staggering the use of electrical appliances in response to price signals. Commercial & Industrial consumers will also be increasingly engaged in Demand Side Response (DSR) technology, able to adjust energy DSR to electricity market signals. All these types of consumers can benefit from signing up to products/services which respond to price signals.

Use less energy	Use green energy	Change when or how they use energy
Consumers will need to stop using petrol or diesel cars and use a zero emission vehicle, take public transport, or walk or cycle.		Residential consumers will need to start engaging with Time of Use Tariffs and forms of smart control and automation of energy consumption that can shift electricity demand from times of low renewable generation to times with abundant renewable electricity supply.
Many consumers will need new insulation to improve the energy efficiency of their homes and reduce their energy costs.	Residential consumers will need to change their heating system away from fossil fuels to new technologies such as heat pumps or hydrogen boilers.	Industrial and commercial consumers will need to engage with aggregators and suppliers to provide higher levels of Demand Side Response to the energy system in response to price signals.
Businesses will need to improve energy efficiency and adopt low carbon heating systems.	Industry will need to switch away from fossil fuels to alternatives such as hydrogen or use Carbon Capture and Storage (CCS) technology to drastically reduce their emissions.	Some industrial consumers may need to re-locate in some scenarios to areas with hydrogen or Carbon Capture, Usage and Storage (CCUS) technology available to enable them to decarbonise.
	The freight industry will need to adopt electric, or hydrogen powered, Heavy Goods Vehicles (HGVs).	

Residential

We classify residential demand as energy used in the home for heating, cooking, lighting and appliances (white goods and computers) but excludes transport, even Electric Vehicles that are charged at home; the latter is included in the transport section later.

White goods include large electrical appliances, such as washing machines, dishwashers, tumble driers, fridges, freezers etc.

The different heating technologies examined in FES include:

- Gas boiler
- Direct electric
- Air-Source Heat Pump (ASHP)
- Ground-Source Heat Pump (GSHP)
- Hybrid (Air-Source Heat Pump and hydrogen boiler)
- Hydrogen boiler
- Biofuel boiler or hybrid
- District heating
- Other (Oil etc.).

We also examine smart heating and thermal storage. The extent to which consumers embrace dynamic tariffs and thermal storage will have a significant impact on balancing the energy system. By thermal storage, we mean hot water tanks or new forms of storage, such as phase change materials[11]. These are sized to meet demand at peak times. The electrification of heat has the potential to significantly increase peak electricity

[11] Phase change materials absorb or release a large amount of latent heat during the process of transforming physical properties (i.e., the phase transition process). For more information, see here: https://www.sciencedirect.com/topics/engineering/phase-change-material

demands, and so the adoption of smart controls, thermal storage and flexibility from heating systems plays an important role in mitigating this increase and reducing the need for additional generation capacity and electricity network reinforcement.

Pricing incentives will encourage consumers to alter their usage, shift their demand to a different time and help manage the peaks and troughs in supply and demand. Energy suppliers have provided tariffs like Economy 7 since the 1970s, offering consumers cheaper electricity over a set seven-hour period overnight. More recently, some dynamic tariffs or Time of Use Tariffs (ToUTs) incentivise consumers to increase or decrease their demand, by turning on or off electrical appliances, depending on the levels of demand and renewable generation on the system.

In our scenarios, we assume that the purchase of an EV or a heat pump acts as a trigger for consumers to change to a dynamic energy tariff as the increased domestic electricity demand incentivises them to pay more attention to their energy consumption. Thermal storage can then operate on a set schedule or based on forecast electricity prices or both, to store heat at times when electricity is cheap and then discharge at peak times.

Hybrid heat pumps could also play a role in shifting electricity demand away from peak, as the heating system switches to use hydrogen at peak times. District heating systems usually have a large thermal store to help manage supply and demand, and this will also play an important role in helping shift heat demand away from peak.

Transport

Transport demand covers all energy demand for transport including electricity, gas, hydrogen and petrol and diesel for road transport, rail, aviation and shipping.

For passenger cars, electrification is likely to be the dominant solution, with more variations in the solution for other forms of the transport sector. Heavy Goods Vehicles (HGVs) and vans make up a similar proportion of energy demand. The rise of online shopping and home delivery has led to increased use of vans for local deliveries. However, HGVs are still very important as they carry 90% of the UK's land-based freight. Decarbonising freight is challenging but there has been significant progress. Many companies are undertaking trials or even moved to full commercial operation of part of their fleets with low carbon alternatives, typically hydrogen or battery electric solutions. Any HGV solution needs to be compatible with solutions for cross-border freight, as international freight vehicles typically travel continuously from the UK to Europe and vice versa. This is a crucial part of the global supply chain which includes the UK. We split HGVs into two main categories: above and below 26 tonnes. In all scenarios, battery electric becomes the most widespread technology for vehicles under 26 tonnes. In vehicles over this threshold we see greater uncertainty, as the technical challenges for these are greater.

Availability of public charge points is a reason often given by consumers who are reluctant to switch to an EV. The locations of public charge points will be important and have implications on regional demand variations and locational requirements on the electricity network.

Types of charging

Residential charging (3-7 kW)

Typically for those with off-street parking who can install their own home charger and charge from their domestic electricity supply. This could also be via communal chargers in private car parks for blocks of flats or on-street parking close to homes that have an overnight domestic charging pattern.

Workplace and destination charging (7-22 kW)

Using employer-provided EV chargers in workplace car parks, typically plugged in during the daytime, or charging in consumer locations such as retail parks, supermarkets and other commercial premises.

Rapid charging (50-150 kW)

High power chargers, typically 50 kW or greater, that can charge car batteries back to 80% or above in 20-40 minutes. Currently these are primarily found in motorway service stations, however there may be greater uptake of local rapid charging hubs.

There is variation in the future years in how Electric Vehicles are charged, reflecting the differences in infrastructure development and consumer preferences in each scenario. In all scenarios the majority of those who can charge at home do so where possible, however a range of options is needed to ensure solutions for all consumers. Consumers are already, and will be increasingly, encouraged to engage with Time of Use Tariffs and automated vehicle charging to reduce their costs and shift electricity demand away from peak times and periods of low renewable output. We assume the purchase of an EV is a trigger point for consumers to increase engagement in the energy system and move towards smart charging.

A smart charging system considers the best time to charge a vehicle based on current prices, forecasts of future prices, and renewable generation availability. It will enable consumers to participate in Vehicle-to-Grid (V2G) or Vehicle-to-Home (V2H) services where their car batteries send power back to the electricity grid, or the house at peak times, and charge up again later. This requires technology deployment of e.g., bi-directional charging, but also electricity market change so consumers are rewarded for participating in the energy system to optimise system costs for everyone.

Industrial

Industry is spread around the country and often provides the backbone of local or regional economies. Some energy intensive industrial users are clustered together for historic reasons including resource availability and transportation links. High energy use and high reliance on fossil fuels, such as in the shipping sector, mean the sector will be particularly difficult to decarbonise; but finding decarbonisation solutions for these areas is crucial to meeting net zero. Electrification is one avenue that will enable decarbonisation of some industrial demand as the electricity system decarbonises, however it will not be suitable for all end users. Whilst there is opportunity for further electrification of industry, other solutions are needed to tackle industrial fossil fuel demand such as switching from natural gas to hydrogen or biofuel combustion. Some sectors also use fossil fuels as feedstocks for their processes which will be particularly hard to displace and therefore require Carbon Capture Usage and Storage.

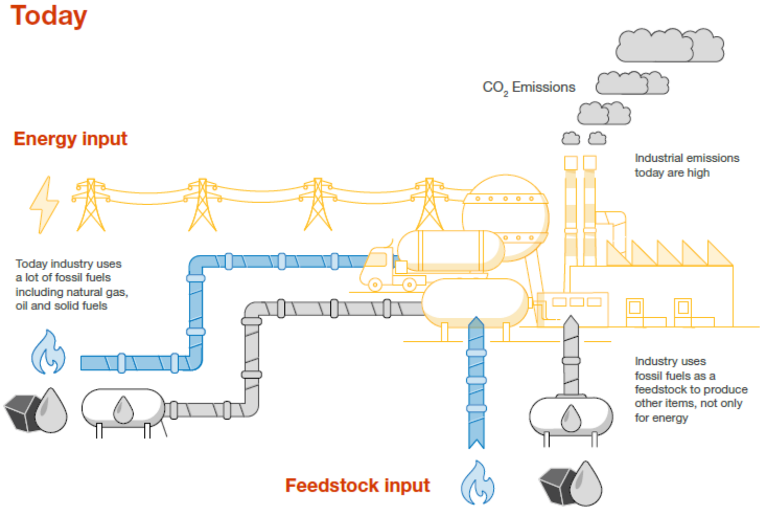
Industrial demand refers to:

1. Highly energy intensive industries producing things like steel, cement, and pharmaceuticals
2. Manufacturing of vehicles, machinery, food, textiles, furniture, books and paper, electronics
3. Mining and quarrying.

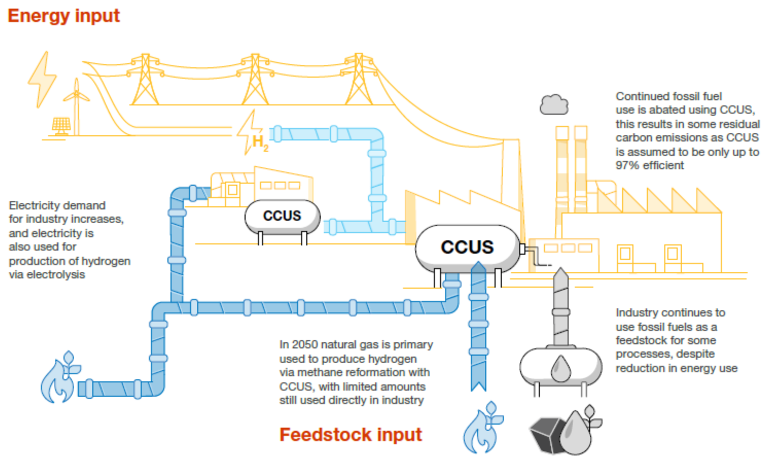
Regional clusters with energy and carbon intensive heavy industry located in proximity to one another, particularly manufacturing of chemicals, glass, steel, ceramics and cement would benefit from a strategic investment into hydrogen and CCUS infrastructure which could help stimulate decarbonisation through exploiting economies of scale and sharing the costs of infrastructure investment across different types of users. We expect hydrogen supply to be developed in these clusters, and that industries located there which can use hydrogen as a fuel, will adopt technologies to use this as a source of energy. Industries will be able to test and embed decarbonisation strategies, including manufacturing of chemicals, iron and steel.

CCUS infrastructure based in the industrial cluster sites will enable the decarbonisation of industrial processes that are unable to switch away from fossil fuels or that use fossil fuels as a feedstock. This will be particularly important for areas such as chemicals and cement production. It will also enable the production of blue hydrogen within industrial clusters to supply hydrogen to other clusters. Industrial sites located outside of clusters that are less energy-intensive such as the automotive or food production industries typically use natural gas for their industrial processes. If available, hydrogen is therefore a potential replacement to supply this industrial process heat, however there will be cases where these sites would need to electrify their heat requirements, and therefore, transport the captured carbon to the location it would be stored.

Today



2050



Recent government policy announcements and strategies have led to more ambitious pathways for industrial decarbonisation. Fuel switching is expected to ramp up in the 2030s as sources of hydrogen become more widely available and the electrification of energy intensive processes becomes more attractive driven by technology cost reductions and carbon taxes.

Industrial Demand Side Response is currently a mixture of behind the meter generation offsetting demand (typically diesel generators), Combined Heat and Power (CHP) plants, batteries, and ‘pure’ Demand Side Response where the demand itself is shifted or postponed to another time. Response using behind the meter generation is typically more expensive to operate, and so these generators are where we have seen lower DSR. Changes to transmission network charging regimes, i.e., TRIAD removal, have also shifted down though the incentives for participation in Demand Side Response.

Water pumping

The water industry uses a lot of electricity to pump water around the country, the timing of this demand may be able to be shifted.

Multi-stage production processes

Some industrial processes with more than one stage are not time critical and may be able to be staggered around times when energy is most expensive in between energy intensive production stages.

Infrequent processes

Some industrial processes occur less regularly and can be rescheduled around signals from the energy system.

Heating Ventilation and Cooling (HVAC) systems

Thermal storage can be used to shift heating loads for commercial systems. Air conditioning systems could respond to signals by adjusting their target temperature by 0.5-1 degrees, reducing demand.

Response from on-site battery storage or generation

Some large sites may have their own backup generation that could kick in and meet some of their demand at peak times.

Different types of industrial demands have their own characteristics, with variations in the capacity of response they can provide, the notice period required for response and the duration they can respond for. There are several ways that industrial consumers could engage in DSR. These include engaging with smart tariffs and switching demand from times when energy prices are high to times when they are low and when renewable energy generation is abundant. Others may be through engagement with aggregators or direct participation in flexibility markets to provide dynamic response to price signals.

Encouraging greater consumer participation will require appropriate market signals to be put in place to ensure it is worthwhile for these customers to participate in flexibility markets. In addition, it is vital to ensure they are compensated for the value they bring to the system through reduced peak demand requiring lower levels of future generation and associated network reinforcement. While some types of manufacturing such as steel or ceramics can require consistent high temperatures and energy demand to support them and have limited options to provide flexibility, other types of industrial users will be able to participate in flexibility markets.

Commercial

Commercial demand covers heating, hot water, catering, cooling and ventilation, lighting, computing and other activities.

The commercial sector encompasses a wide variety of different types of business and public and private sector operations. These include:

1. Offices
2. Retail: shops and shopping centres
3. Education: schools and universities
4. Hospitals and other healthcare services
5. Military sites
6. Hospitality: pubs, bars and restaurants
7. Public sector: national and local government buildings
8. Community and the arts: museums and community centres
9. Leisure: swimming pools and gyms
10. Data centres
11. Large refrigeration units.

Data centres are physical facilities that organisations use to accommodate their computing applications and data. They range from private facilities that are owned and located within individual businesses, to large standalone commercial data centres offering services such as ‘cloud’ and ‘managed’ computing services. Data centres host core Information Technology (IT) infrastructure that supports much of today’s digital activity, and so are fundamental to our modern way of living. Our dependence on them is only set to increase as our consumption of data continues to grow. Every time we send an email, buy something online, save something to the ‘cloud’, or play online video games we are exchanging information with a data centre. We expect a high level of growth in data centre capacity in the coming years. Stakeholder engagement indicates there is a strong pipeline of new data centres seeking to connect to the electricity network, particularly in London and the Southeast. Data centres require electricity both to run the equipment – computers, servers, and electronics – but also for cooling. Up to 40% of electricity consumption is spent on keeping the facilities temperature controlled and optimised to prevent IT equipment overheating, with the rest used to power the equipment itself.

The dominant source of energy demand and emissions in the commercial sector is for heating and hot water, which is today largely met by natural gas. This means decarbonisation solutions follow similar patterns to residential heating and face similar challenges. There are a range of low carbon technologies that can contribute to decarbonisation in this sector. The most appropriate technology for different consumers will be dependent on factors including cost, availability of infrastructure and building type. Thermal energy efficiency is an important first step in tackling emissions for these demands.

Historically, large commercial consumers have participated in DSR in relation to triad avoidance, i.e., aiming to reduce the network charges they pay by minimising their demand at peak times in the winter. DSR in the commercial sector will become increasingly important in a net zero world. Changes to transmission network charging regimes have shifted down the incentives for participation in this kind of activity.

Commercial demands have their own characteristics, with variations in the capacity of response they can provide, the notice period required for response and the duration they can respond for.

The large share of energy demand for heat and hot water represents the biggest opportunity for commercial load shifting. Electrification of some of this energy demand will lead to increased peak demands but also presents an opportunity to reduce costs to commercial consumers and stress on the electricity network by incentivising DSR. This can be delivered using thermal storage alongside heat pumps or district heating, the use of load shifting in hybrid systems from electricity to hydrogen or biofuel, or the use of electric storage heaters.

Forms of commercial demand suitable for engaging in Demand Side Response include:

Heating Ventilation and Cooling (HVAC) systems

Thermal storage can be used to shift heating loads for commercial systems. Air conditioning systems could respond to signals by increasing their target temperature by 0.5-1 degrees, reducing demand.

Refrigeration loads

Commercial fridges and freezers can be turned off for short periods with only minimal impact on the internal temperature.

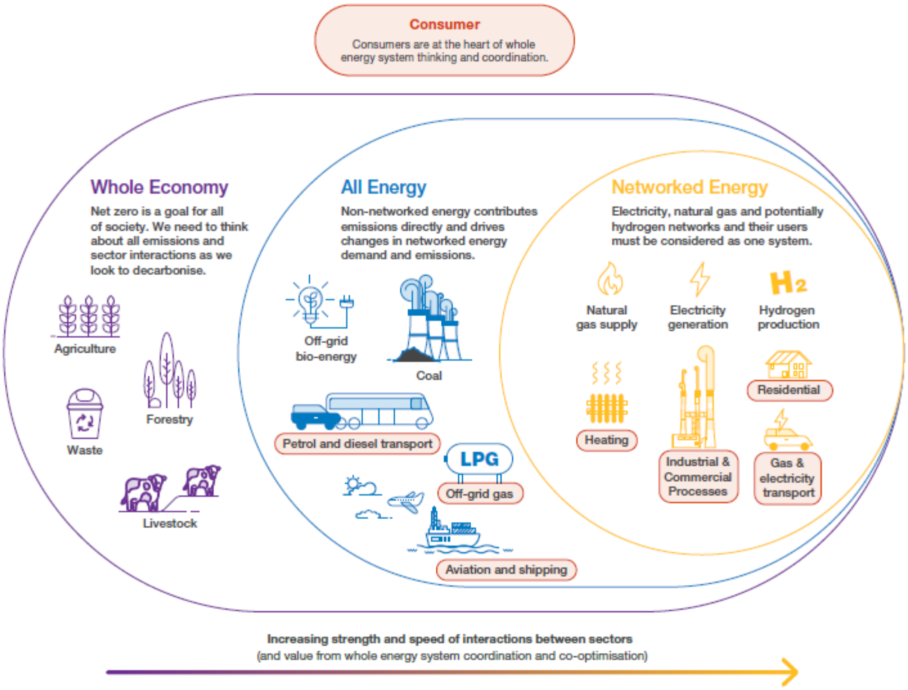
Response from on-site battery storage or generation

Some large sites may have their own backup generation that could kick in and meet some of their demand at peak times.

In the future we expect flexible demand to be increasingly important in the commercial sector. End users will be able to respond to market signals to vary some portion of their demand. This will require appropriate market signals to be put in place to encourage participation in these markets. Many commercial consumers are small businesses without the capacity to engage in the energy market themselves, so they will need an appropriate consumer proposition to allow them to participate with as few barriers as possible. This could involve the use of automation of response to signals and targeted campaigns from energy suppliers or aggregators to engage consumers. There are several ways that commercial consumers could engage in DSR. This includes engaging with smart tariffs and switching demand from times when energy prices are high to times when they are low and renewable energy generation is abundant. Other options might be through engagement with aggregators or direct participation in flexibility markets to provide dynamic response to price signals.

5. The Energy System

Where we refer to the ‘whole energy system’ in this section, we are referring to electricity, natural gas and potentially hydrogen and biofuel networks and their users as one system. It is not a UK system in isolation as we are connected by interconnectors and energy is sold in a global market. Whole energy system thinking helps decarbonisation and energy security.



The energy system of the future won’t just be about getting energy from point A to point B in the right quantities. Each piece of the future energy system comes with new challenges and opportunities. On their own, these are difficult to solve but when thought of as a whole system, strengths in one area can offset challenges in another or unlock new options entirely. Different energy uses are interconnected in a net zero world, such as transport sector which is electrified, biofuels used for planes and hydrogen heating our homes and buildings. This whole energy system view, where all uses of energy are considered alongside each other, also creates an energy system which is as efficient as possible.

Whole system thinking and coordination across energy networks provides greater efficiency and co-optimisation. However, whole system thinking should also be applied to the wider economy.

- **Networked energy** – This is energy transported from where it is produced to where it is consumed using transmission and distribution networks, such as electricity and gas, that interact closely with each other every day (e.g., gas-fired electricity generation)
- **All energy** – This includes areas where energy demand is met outside of the networked energy system such as by oil or petroleum-based products. This demand may potentially be met by the networked energy system in the future (e.g., as the transport sector decarbonises)
- **Whole economy** – This includes non-energy sectors which have an indirect interaction with energy decarbonisation. This is seen most clearly in the complex role of bioenergy and its implications for land use, but also includes how societal change impacts energy and emissions.

We also consider non-networked energy use for aviation and shipping, agriculture and Land Use, Land Use-Change and Forestry for example. For these sectors where we don’t have deep expertise, or where we do not yet have strong stakeholder evidence, we use inputs from published analysis from the Climate Change Committee and engagement with their experts.

Transformation of the whole energy system is achievable, and can deliver energy that is clean, secure, affordable, and fair. This requires strategic and holistic development of the networks, markets and technologies required, in a coordinated and timely manner, to ensure we make the most of the abundant renewable energy we could use to meet energy demand.

This chapter explains the necessary information for the energy system and the main ways that energy is produced to meet demand, i.e., electricity, hydrogen, natural gas and bioenergy. We must always ensure that supply and demand balance and that system peak demand can be managed. With the decarbonisation of the electricity system this is becoming more complex with more challenges from the periods of peak as we move to a system with more renewables and demand flexing to meet supply.

Electricity

Decarbonisation of GB's whole energy system, and reducing the country's exposure to global energy markets, cannot be done without investing in our electricity system and our ability to accurately match demand to a weather-dependent supply. We have seen a significant increase in the proportion of electricity from low carbon and renewable generation in recent years and this has spearheaded the wider emission reductions across the economy. A range of technologies with different characteristics can, in combination, help deliver secure, affordable low carbon electricity supplies and harness the potential of domestic renewable resources. More electricity from wind and solar is vital to help UK meet its target for net zero by 2050.

The electricity system today is built around the core principle of being able to adjust supply smoothly to match demand as it changes through the day and year. Fossil fuel generation is dispatchable, meaning it can be turned on and off to match demand. In winter, coal generation plants have been used to help meet peak demand, but coal use has been declining sharply in recent years, bringing carbon emissions down as a result, and leaving more room for flexibility from both the supply and demand sides.

Renewable generation capacity, primarily wind and solar, keeps increasing. This growth has been supported by government subsidies, such as the Feed-In Tariff (FIT), the Contracts for Difference (CfD) scheme and the Renewable Obligation but has also been driven by rapid reductions in cost that have allowed them to start competing in a subsidy-free environment. In Britain, we are managing one of the fastest decarbonising electricity systems in the world, while also being one of the most reliable. Today, we are well on track to being able to operate the electricity system with periods of no carbon emissions by 2025, and continuously by 2035.

For the UK to meet its legal commitment of net zero carbon emissions by 2050, the whole energy system must enable the entire economy to decarbonise. This includes providing some negative emissions to offset emissions from sectors which are difficult to decarbonise. In all net zero scenarios, carbon neutral or carbon negative electricity generation has a significant part to play but comes with its own challenges for operating the system. Thermal generation plants such as nuclear or natural gas provide essential ancillary services to the electricity network. As we move towards more renewables, we need to find alternative sources of ancillary services[12].

In recent years, decarbonisation has been the main driver for future change to the electricity system, joined by an urgent effort to improve energy security and reduce energy costs for consumers by reducing exposure to the wholesale gas price. In simple terms, the wholesale cost of natural gas often sets Britain's marginal electricity price because of the role natural gas generation plays as the marginal generator. Natural gas prices, and therefore electricity prices, have increased rapidly due to demand exceeding supply following the COVID-19 pandemic and the global response to Russia's invasion of Ukraine. While transitioning from generation that relies on imported fossil fuels to domestic renewables significantly improves future energy security, reduces carbon emissions and reduces exposure to global gas prices, there are also things we can do to reduce demand today. The high-level case for change is clear but how this change is delivered remains uncertain.

We create our generation backgrounds for each scenario to meet its energy demand ensuring security of supply [13]. Therefore, the level of peak demand drives the capacity we need, and the scenario framework helps shape what type of capacity we add. We assume a full and intact network for our analysis, which means we do not

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[12] https://www.nationalgrideso.com/electricity-transmission/news/operability-strategy-report-2023

[13] https://www.nationalgrideso.com/industry-information/codes/security-and-quality-supply-standards

model network constraints or outages. Constraint modelling is carried out as part of the Network Options Assessment (NOA) process[14]. We create the generation backgrounds to ensure that security of supply is met.

Load factors

Load factors are measures of utilisation of an electricity generator over a given time period. It is calculated by dividing the generation output over the maximum possible output in that time period. They vary across the scenarios according to the mix we assume in FES, with the amount of renewable generation capacity influencing load factors across the whole energy system. They also depend on the technology, weather, and merit order. For example, the load factor of a wind turbine is dependent on wind speed whereas the load factor of a gas generator is driven by market needs and how much this defines that it operates.

- Some technologies have low load factors, such as gas generation, but stay on the system for security of supply. Natural gas load factors keep reducing as renewable generation increases and other solutions to maintaining grid stability are developed.
- Nuclear typically runs with higher load factors, running as baseload generation.
- Hydrogen generation operates with very low load factors in the net zero scenarios, as does unabated gas in Falling Short, indicating their role is primarily to support security of supply.
- Bioenergy with Carbon Capture and Storage plants run close to their full output when they are used, with a greater proportion being turned on in winter months to meet higher peak demands.
- BECCS operate as baseload for operational reasons.
- Load factors for offshore wind are increasing, as technological advances improve efficiencies and as their locations become more diverse and therefore less dependent on local weather effects. Load factors for solar remain low, but total generation output increases due to a large increase in installed capacity. Load factors for renewable generation are capped by the variable nature of renewable energy resources.
- As capacity for wind generation increases, so too does the challenge of managing excess generation. In the Flexibility chapter, we discuss and how we can manage this through flexible demand, but we are still likely to have some curtailment of generation. Our modelling assumes it is wind that is curtailed but this would depend on future market arrangements.
- Though our modelling focusses on the load factors of generation, it is important to note that utilisation of the network also varies by scenario. Coordinated planning ensures that location of key infrastructure and generation assets can be as efficient as possible for the whole energy system.

The generation mix coming from electricity supply in FES consists of:

- Renewable sources (wind, solar and marine)
- Nuclear plants
- Some remaining capacity from fossil fuels
- Bioenergy and BECCS
- Nuclear generation
- Hydrogen
- Interconnectors[15]

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[14] https://www.nationalgrideso.com/research-publications/network-options-assessment-noa

[15] Currently, we do not model multi-purpose interconnectors in FES. For more information on this, please see here: https://www.nationalgrid.com/stories/energy-explained/what-are-multi-purpose-interconnectors#:~:text=Multi-purpose%20interconnectors%20%28known%20as%20MPIs%29%20are%20subsea%20electricity,operate%20separately%20and%20connect%20to%20the%20shore%20individually

- Electricity storage.

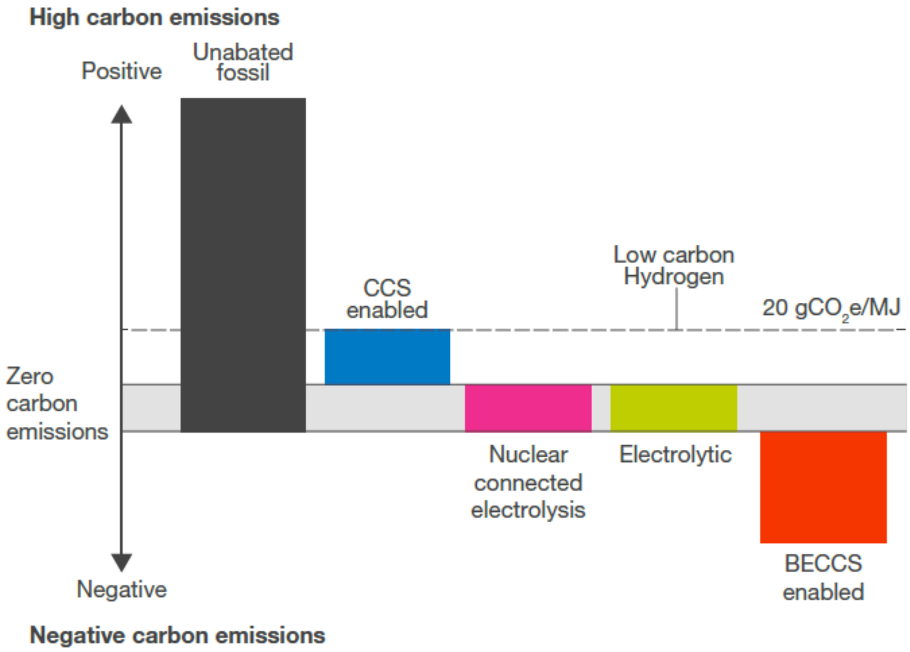
Low carbon hydrogen

Low carbon hydrogen is a vector that plays a key role in all our FES net zero scenarios.

In addition to being able to replace almost all uses of natural gas in the energy mix as well as its use in non-energy needs such as transportation, low carbon hydrogen production via electrolysis and ability to be stored over long time periods can help to overcome the challenges and harness the opportunities that come with increased renewable generation in the electricity system. However, despite being an essential part of the future energy system, its credible range in terms of both how much energy demand it meets and how it is produced is very wide.

Hydrogen is already commonly used worldwide for refining oil and in the production of ammonia for fertilisers. Almost all current UK hydrogen production uses methane reformation[16] without CCUS (grey hydrogen). Capturing CO_2 emissions from production or using renewable electricity could bring that very close to being carbon neutral, or even negative[17].

There are various ways of producing low carbon hydrogen with varying emissions. These are explained below. Low carbon hydrogen is defined within the Government's Low Carbon Hydrogen Standard as emitting less than 20gCO_2e per Mega Joule produced.



[16] A method for producing hydrogen, ammonia or other useful products from hydrocarbon fuels such as natural gas. In addition to Steam Methane Reforming (SMR), this could include Autothermal Reforming (ATR) which uses a pure stream of oxygen to drive the reaction and increase the hydrogen production and CO2 capture.

[17] https://www.nationalgrideso.com/document/263951/download

Unabated fossil hydrogen

Hydrogen made by methane reformation without any means to capture emissions or through gasification of coal. Sometimes referred to as grey hydrogen.

Electrolytic hydrogen

The process of using electricity to split water into hydrogen and oxygen. Sometimes referred to as green hydrogen if the electricity used to power the process is renewable.

Nuclear connected electrolysis

As electrolytic hydrogen but where electricity generated by nuclear is used to power the process. For this year's FES we have focused on low temperature electrolysis which can be combined with large or small nuclear reactors because it has the greatest commercial and technical readiness levels of all the options. Other potential ways of pairing nuclear technologies with hydrogen production include high temperature electrolysis such as solid oxide electrolysis (using heat as well as electricity from a nuclear power plant) or thermochemical production (using high temperature chemical reactions and heat from the nuclear plant). Sometimes referred to as pink hydrogen.

CCS enabled hydrogen

This is the same as unabated fossil fuel hydrogen except when it is produced, up to 97% of carbon emissions are captured and either stored or used. It still involves the extraction of fossil fuels, and the associated emissions this brings, and its status as low carbon technology is dependent on the effectiveness of carbon capture. Sometimes referred to as blue hydrogen.

BECCS enabled hydrogen

Through gasification, biomass can be used to produce hydrogen. When this is combined with carbon capture, the CO_2 produced as a by-product is stored, making the overall process negative in terms of carbon emissions. This is also sometimes referred to as blue hydrogen.

Hydrogen plays a key role in the whole energy system development. Pure low carbon hydrogen produces no carbon emissions at the point of combustion and hydrogen fuel cells can generate electricity with no emissions besides water, which potentially makes it a perfect fuel for a net zero world. There are many ways we can take advantage of it but to do so, we must overcome some technical and commercial challenges, as shown in the table below.

Advantages and disadvantages of hydrogen

Advantages	Disadvantages
Hydrogen provides us with **flexibility** to meet demand. It can be stored and used in electricity generation, helping to manage peak demand when fossil fuels are no longer available.	Characteristics of hydrogen, like its energy density and molecular structure, have implications for **transportation and storage**. Pipes may need to be upgraded and salt cavern storage modified to store hydrogen.
Hydrogen can replace natural gas in **heat** applications, with comparatively simple modifications to appliances (both domestic and industrial).	Currently there are no **regulations** nor market for hydrogen supply at scale, both of which are fundamental to the growth of hydrogen use.
The existing national gas **pipe network** could be repurposed for hydrogen.	Due to the process of producing, transporting and storing both hydrogen and CO_2, hydrogen is a **less energy efficient** way of heating, compared to natural gas.
Hydrogen can also be **blended** into the natural gas network (approximately 20% by volume) to reduce its carbon impact. This could be done on a regional basis as hydrogen production is gradually increased.	Given higher production costs for hydrogen in comparison to natural gas, the final product to the customer will be more expensive.
Electrolysis could produce green hydrogen using surplus **renewable electricity** at times of low demand. This avoids shutting off wind generation, which incurs costs to end-consumers.	The **costs** of producing hydrogen vary greatly, dependent on factors such as the wholesale cost of electricity and the cost of electrolysers and methane reformers.
With careful placing of electrolysers and associated hydrogen infrastructure, some electricity **network constraints** could be significantly reduced.	If the **location** of electrolysers is not carefully considered, they could add to network constraint issues caused by the increase in renewable electricity.
Producing hydrogen from the UK's natural gas supplies and renewable electricity would reduce our **dependency** on energy imports.	There is uncertainty about worldwide plans for hydrogen. A **global hydrogen market** may develop, which could supplement demand but also leave us exposed to hydrogen price volatility.

Hydrogen can help to address many of the hardest parts of the transition to net zero. It can meet end user demand to replace fossil fuels with minimal change to the user's experience as well as help to balance supply and demand in the electricity system. All the different use cases come with their own combination of the challenges and benefits, with the hydrogen for heating application depending on upcoming government decisions.

Hydrogen also helps to operate the electricity system. Specifically, it helps us to:

1. **Balance the electricity system:** electricity supply and demand need to be always carefully balanced and hydrogen can help on both sides of that equation. Producing hydrogen via electrolysis can create additional demand when needed to avoid curtailing wind and solar generation and this hydrogen can then be used to generate power at times of peak demand or low renewable output
2. **Overcome network constraints:** strategic siting of electrolysers has the potential to reduce networks constraints that occur at times of high renewable output by providing price-responsive demand.

The different ways of using hydrogen and their associated costs are compared. Overall costs of the different production methods are equally important, and we have worked with Delta-EE on an innovation project to understand what influences costs. Some of the main findings are summarised below[18]. The report highlights how any analysis of the potential market and costs associated with hydrogen would have to consider the whole energy system. Costs of electrolysers and methane reformation with CCUS are fundamentally linked to the electricity and natural gas markets and any incentives for carbon capture. This emphasises the need for market reform to improve price signals and for strategic whole system thinking.

Hydrogen Production

- Costs are dominated by fuel costs. Electricity for green hydrogen, natural gas for blue.
- A reliable forecast of fuel costs throughout the life of the production facility is therefore highly valuable for an operator to know. This can be provided through clear pricing mechanisms and by reducing exposure to uncertain energy markets.
- If large volumes of electricity can be accessed at low cost, and hydrogen can be stored efficiently, then a strategy of oversizing electrolysers can reduce the average hydrogen price despite lower load factors.
- Using fuel costs correct as at the start of 2022, the project found that the levelised cost of delivered hydrogen could be roughly the same for blue and green hydrogen if the latter was being used to avoid curtailment (implying lower electricity costs). For other forms of electrolysis, the equivalent cost would be around two or three times as high as blue hydrogen. The delivered cost of blue and green hydrogen (which isn't solely produced using electricity which would otherwise be curtailed) is expected to reach parity over the coming decades.

Hydrogen Storage

- Costs are highly variable depending on how frequently the storage is used, its location and how quickly it can be filled and discharged.
- A heavily utilised storage facility would add roughly 20% to the cost of hydrogen at point of delivery but this could be much higher if utilisation of the facility is lower (e.g. more strategic inter-seasonal storage).

Using hydrogen to produce electricity

- Generation load factors are the main variable affecting cost of electricity produced from hydrogen.
- Electricity prices drop significantly when load factors increase. Electricity prices for hydrogen fuelled peaking plants can be up to six times as expensive as when hydrogen is used for electricity generation at other times.
- At very low load factors, capital investment costs have a significant impact on cost of electricity produced, so retrofitting of natural gas generation plants may be favoured over new plants.

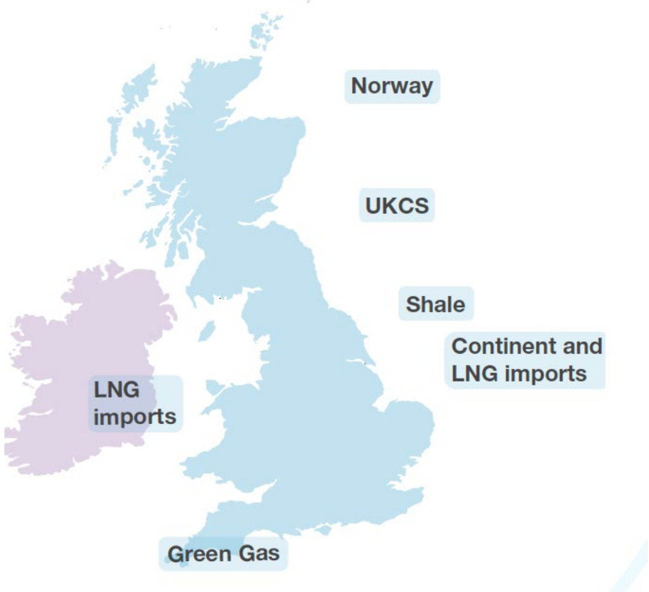
[18] https://www.delta-ee.com/report/report-summary-hydrogen-as-an-electricity-system-asset/

Natural gas

The design of the energy system we have in Great Britain today has been shaped by the previous dominant sources of energy (coal, and then later natural gas) – from the way we provide heat for homes and industry, all the way to generation of electricity. Transitioning towards net zero while maintaining a reliable and affordable energy system for all will require a continued, if different, role for natural gas as it cannot be used in a net zero world without its emissions being captured, i.e., used as unabated gas.

Our scenarios explore the variety of natural gas supplies into Great Britain between now and 2050. We have modelled how the different sources may change over the coming decades in response to evolving demand profiles and levels.

Below, the sources of natural gas used in Great Britain are illustrated and explained.



Norway: its large and flexible reserves mean it could keep supplying gas to the UK for longer than our own UK Continental Shelf (UKCS). For some scenarios the UK may stop importing gas from Norway because of reduced demand coming from increased electrification.

UKCS: refers to extracting natural gas from new wells, which will be uneconomical for the future and therefore, any natural gas needed for either a feedstock for hydrogen, in a power station or industrial process with carbon capture fitted, will have to be imported in the future.

Shale: though there is currently a moratorium on fracking projects, Cuadrilla has until 2023 to evaluate options for the UK's two shale gas wells. The British Energy Security Strategy (BESS) suggests shale gas may be considered as a viable source. However, high levels of public scrutiny would be expected, and support may be tempered by an extracted gas likely still being priced at global market value without significant intervention in the market.

Liquefied Natural Gas (LNG) & continental imports: a second wave of liquefaction projects in the mid-2020s results in more LNG being available globally. Demand for LNG may also rise globally as countries shift away from coal to decarbonise. Imports from the continent via existing gas interconnectors continue to play a key role in the supply of natural gas and LNG imports are seen in all our scenarios. As LNG is shipped to Britain from abroad, its lifecycle emissions are higher than natural gas supplied from indigenous sources.

Green gas: is made from bioresources and is considered carbon neutral. It refers to biomethane and Bio-substitute Natural Gas (BioSNG). It is injected into the gas network to reduce the overall carbon intensity of the gas used in homes and businesses. Some green gas is assumed to be used off grid to provide fuel for remote and otherwise hard to decarbonise sectors. This is largely produced from waste processes, such as anaerobic digestion, rather than from other bioresources which are prioritised for other uses.

As we transition to net zero, there are multiple possibilities for the future role of the natural gas network. The gas National Transmission System (NTS) is over 7,500 km long and transports gas at high pressure around the country. It supplies gas to approximately 85% of homes in Great Britain through its connections to the gas distribution networks and local distribution zones. How homes and buildings are heated in future will determine the role of this extensive transmission and distribution network. That decision is dependent on factors including security of supply, the cost of retrofitting homes and the willingness of consumers to change. Our scenarios cover several possibilities to examine this.

One possibility, included as an example examined in System Transformation, is that the network may be fully repurposed to carry hydrogen as homes and buildings use it for heat in boilers like the natural gas ones they have today. However, in other scenarios such as Leading the Way, the NTS could be converted to a 'hydrogen backbone', transporting hydrogen between industrial clusters and potentially to interconnectors at the Bacton Gas Terminal as well as other locations as further interconnection develops. Project Union, from National Grid Gas Transmission & Metering aims to get there by developing blending of hydrogen across the NTS in parallel to a strategic roll-out of new pipeline sections designed for hydrogen alone. Across the scenarios, some gas distribution network will also need to be converted to carry hydrogen.

In Leading the Way and System Transformation, we assume the gas system is used to transport hydrogen blends before the transition to 100% hydrogen. Assets that are not required to transport natural gas may be used to carry carbon captured from power generation and other processes to be stored.

Some network assets may be decommissioned if it becomes uneconomical to transport very small volumes of gas.

Bioenergy

Bioenergy has an important role to play. Most of the required emissions reduction across the economy between now and 2050 will come from reducing demand and replacing fossil fuels with renewables or low carbon alternatives. Negative emissions from Bioenergy with Carbon Capture and Storage and other Greenhouse Gas Removal methods are still required to offset emissions from sectors of the economy which are 'hard to abate'. Reaching net zero by 2050 without BECCS would either require higher levels of lifestyle change (e.g., in relation to diet) or improvements in other GGR technologies to an extent that we consider challenging at this time.

Bioenergy comes from bioresources. These include renewable, organic feedstock like wood, using cooking oil, agricultural waste and energy crops (like elephant grass). This can be used as solid (biomass), liquids (biofuel) or gas (biogas). We use Intergovernmental Panel on Climate Change international carbon accounting standards to determine the carbon footprint of energy crops. As they grow, energy crops absorb carbon which is released when they are burned to produce heat or power.

Bioenergy is considered to have no net carbon emissions in our scenarios. Capturing and storing the carbon emitted from burning biomass therefore results in negative emissions. This helps achieve net zero by offsetting emissions from those sectors currently deemed unlikely to completely decarbonise, like agriculture and aviation.

Bioenergy can also reduce emissions in the following areas:

1. Avoiding emissions: by using the emissions from decomposing waste as a fuel rather than emitting it directly to the atmosphere (which would otherwise be the case), we can use it to displace fossil fuels
2. Providing negative emissions: under the Renewable Energy Directive, Anaerobic Digestion of some slurries and wastewater can be carbon negative
3. Displacing artificial fertilisers: recycling the nutrients in bioresources avoids a normally very energy and carbon intensive manufacturing process
4. Reducing demand for industrial gases elsewhere: stored CO2 from bioresources can be used to reduce CO2 demand from the food and drink industry, which is normally met with a by-product of fertilizer manufacture. It can also be converted to gas such as methane or Sustainable Aviation Fuel (SAF).

We already use bioenergy from many sources for many purposes. There is interest in using more as a key enabler for decarbonisation as well as an alternative to fossil fuels which are becoming increasingly volatile in price and have a finite supply.

In our modelling, we assume that all biomass is sustainably sourced, according to biomass considerations used in CB6 analysis, which was done by the CCC. The bioenergy value chain is illustrated below.

Feedstock	Processing		Outputs		End Use	
Biomass Energy crops agricultural and forest residues (GB and imported)	**COMBUSTION - Generation** (with/out CCUS)		**ELECTRICITY** negative carbon emissions if CCUS		**APPLIANCE USE LIGHTING, ELECTRIC TRANSPORT ETC.**	*Both combustion processes and outputs can be combined in e.g. Combined Heat and Power (CHP)*
	COMBUSTION - Heat (biomass boilers)		**HEAT**		**HEAT** (residential/industrial)	
	VARIOUS CONVERSION METHODS		**BIOLPG**	Combustion	**HEAT** e.g. rural buildings	
			LIQUID FUELS e.g. BIOETHANOL, SYNFUELS		**ROAD TRANSPORT AVIATION**	
Dry waste Such as commercial and industrial waste	**COMBUSTION - Generation and/or heat** (with/out CCUS)		**HEAT/ELECTRICITY** (negative carbon emissions if CCUS)		**HEAT, APPLIANCE USE LIGHTING, ELECTRIC, TRANSPORT ETC.**	
	GASIFICATION into **biogas**	**Combust locally**	**HEAT/ELECTRICITY**		**HEAT, APPLIANCE USE LIGHTING, ELECTRIC, TRANSPORT ETC.**	
		Process into biomethane which can be injected into grid	**BIOMETHANE**		**HEAT** (residential/industrial)	
		Conversion e.g. SMR (with/out CCUS) to create hydrogen	**HYDROGEN** negative carbon emissions if CCUS	H_2	**HEAT, ROAD TRANSPORT, SHIPPING**	
Wet waste Such as food waste, wet agricultural waste, slurries, Used Cooking Oil (UCO)/ tallow and other oils	**ANAEROBIC DIGESTION** into biogas	**Combust locally**	**HEAT/ELECTRICITY**		**HEAT, APPLIANCE USE LIGHTING, ELECTRIC TRANSPORT ETC.**	
		Process into biomethane which can be injected into grid	**BIOMETHANE**		**HEAT** (residential/industrial)	
		Conversion e.g. Small Modular Reactors (SMR) (with/out CCUS) to create hydrogen	**HYDROGEN** negative carbon emissions if CCUS	H_2	**HEAT, ROAD TRANSPORT**	
	VARIOUS CONVERSION METHODS		**BIOLPG**	Combustion	**HEAT** e.g. rural buildings	
			LIQUID FUELS e.g. BIODIESEL		**ROAD TRANSPORT AVIATION**	

Below, the different areas that can contribute to increased bioenergy use are elaborated.

Theme	Bioenergy use is more likely if...
Amount of societal change	We haven't been able to reduce emissions in other ways
	We need direct replacements for oil, coal and gas for which other options do not exist
	Demand for low carbon sources of methane is high (because there is greater concern over carbon footprint or greater demand for hydrogen production)
An enabler to decarbonisation	Current carbon accounting methods continue to count lifecycle emissions in country of origin/supply
	Energy crops are assumed to be replenished quickly with negligible difference in overall carbon sequestration in the long term and short-term loss of a carbon sink is acceptable to policymakers
	Bioenergy is shown to have net positive impacts on land use and biodiversity
	The carbon price is higher rather than lower
	Carbon capture rates improve significantly[9]
Supply chain and energy crops	Bioresource supply is domestic or from a reliable partner country
	Land use for bioresources can be accommodated with minimal impact on other important areas such as food production

Theme	Bioenergy use is more likely if...
Utilising a waste product	Restrictions on unabated waste to landfill get tighter
Lifecycle cost	BECCS is less expensive compared to Greenhouse Gas Removal alternatives
	Electricity price is high (because BECCS generation becomes more profitable and can compete effectively against DACCS, which becomes more expensive with a higher electricity price)
	Bioenergy feedstock is cheap
	Government subsidies promote bioenergy
Electricity generation and efficiency	Electricity generation from bioenergy becomes more efficient
	We need more dispatchable synchronous thermal generation

6. Flexibility

This chapter explains why we need flexibility, how flexibility is currently being managed and what options are available from both the supply and demand sides.

What is flexibility and why do we need it?

Energy systems need to match supply and demand, we call this energy balancing. Energy system flexibility is the ability to adjust supply and demand to achieve that balance. For the electricity system this needs to happen in real time whilst for the gas network it can be over a slightly longer timeframe. Flexibility also allows us to keep the flows of energy through the networks within safe limits. FES models energy flows on unconstrained networks, but the network impacts of these flows are analysed in other ESO and industry publications[19].

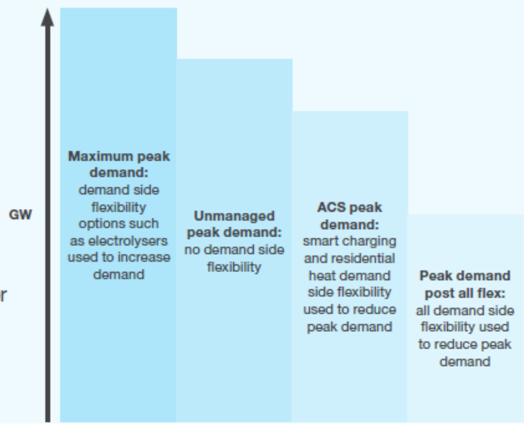
Flexibility is crucial to operate the system where the supply and demand of energy needs to be balanced over different timescales, from minutes or less to seasons or even years. Demand and supply can both vary for different reasons. Some parts are flexible, and their flexibility levels can also vary, such as CCGT and EV charging, and some parts are inflexible, such as solar output and lighting. Demand varies according to the needs of energy consumers. Supply depends on factors like the availability of fuels and weather conditions affecting renewable generation output. Therefore, the flexible supply and demand elements of the system are needed to balance the inflexible parts of the system, and this tends to be achieved through pricing in the markets. Prices are high when supply is scarce but low when it is plentiful (and vice versa for demand).

Interactions between different forms of energy on the system are important. Current peak heat demands in winter are several times higher than peak electricity demands so natural gas provides a significant amount of flexibility by meeting most of this heat demand. As sectors such as heat and transport electrify there will be higher electricity peaks, while electricity generation will become more variable as levels of wind and solar generation increase. So, electricity supply and demand will become more weather sensitive, so a larger relative level of flexibility will be required.

Peak electricity demand definitions

There are several types of peak electricity demand referred to in this chapter:

- **Maximum peak demand:** as well as using demand side flexibility to reduce demand, it can also be used to increase demand when electricity supply is very high, for example by running electrolysers when it is windy. In this report this is referred to as maximum peak demand.
- **Unmanaged peak demand:** refers to the maximum electricity demand before any demand side flexibility takes place to reduce demand. This does include a degree of natural diversity.
- **ACS peak demand:** this is the maximum electricity demand over an average winter after smart charging and residential heat demand side flexibility have been applied.
- **Peak demand post all flex:** this refers to the maximum electricity demand after all demand side flexibility has been applied.



[19] https://www.nationalgrideso.com/research-publications/network-options-assessment-noa

Up until now flexibility has been largely about adjusting energy supply to meet demand. This has been enabled by a reliance on flexibility from fossil fuels which are easy to store. In the case of gas, flexibility comes from storage and the ability to compress or expand gas within the network, known as linepack[20]. As the energy system transitions away from gas to renewables and the electricity supply becomes more weather sensitive, demand will increasingly have to be enabled to adjust to meet supply. When supply is high, demand will need to increase to consume or store additional energy, and when supply is low demand will need to reduce.

Historically, meeting security of supply has been most challenging during times of peak demand, when increased energy supply was needed to meet this demand. However, as more demand side flexibility becomes available, and demand can ramp up or down in response to price signals, this is likely to change. We may see periods of high renewable generation output with higher demands than our traditional winter peak. As more of our energy demand is electrified this makes flexibility more important in keeping costs down by minimising peak demand. Other challenging system situations may arise, such as summer minimum demand and rapid alternations between maximum and minimum demand.

Security of Supply standards

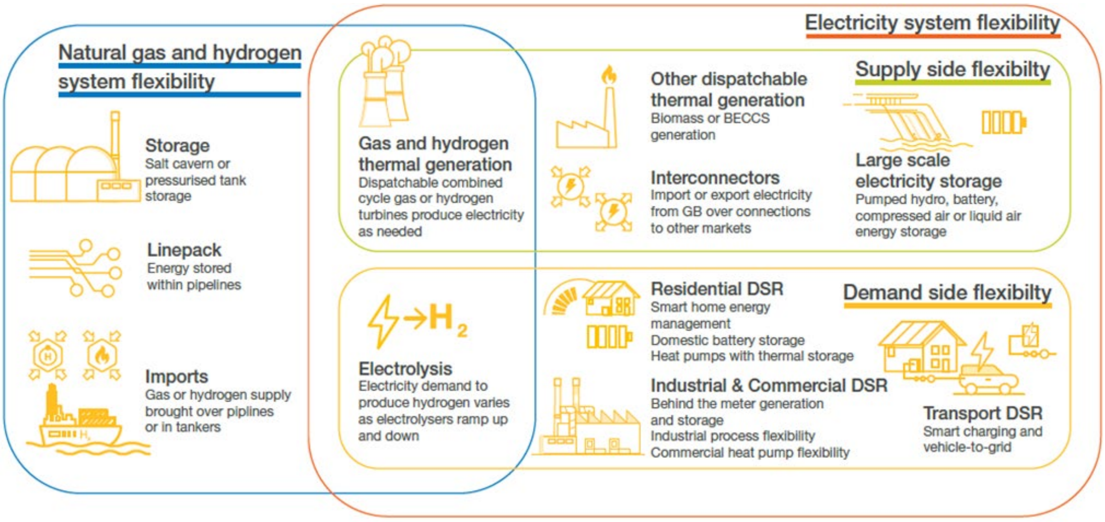
At all times the electricity and gas systems must meet Security of Supply standards, ensuring our energy supplies are reliable. These standards are different for gas and electricity due to the different challenges of operating each system, for example a greater link between cold temperatures and demand in the case of the gas network:

- For electricity, a reliability standard is set by the Secretary of State – currently three hours per year Loss of Load Expectation (LOLE). This measures the risk, across the whole of winter, of demand exceeding supply under normal operation. When considering peak electricity demand, the Average Cold Spell (ACS) definition of electricity demand is used[1].
- For natural gas, there must be enough supply to meet the peak demand on a very cold day (a 1-in-20 peak winter day[2]) even if the single largest piece of supply infrastructure were to fail (known as the N-1 scenario)[3].

Our analysis ensures these standards can be met in all years and all scenarios. As more sectors are electrified, we may need to consider whether these standards are still fit for purpose. As more heat demand is met by the electricity system, electricity demands will become more sensitive to the weather, and our standards must be robust enough to meet these new challenges. As we saw in Texas in 2021, extreme weather events can be extremely challenging for energy systems and careful planning is needed to prepare for them.

New sources of flexibility bring opportunities. Alongside demand side flexibility, other technologies which support a transition to net zero such as interconnectors and energy storage can provide flexibility from the supply side. In some scenarios we can use hydrogen for flexibility, absorbing excess wind and storing energy to meet peak demand later. It can also help network investment and operability constraints, reducing the need for electricity network reinforcement by producing hydrogen close to generation and then moving it around the country or exporting it.

[20] Amount of gas in the network at any given time. The acceptable range over which this can vary and the ability to further compress and expand this gas is called 'linepack' flexibility. Throughout the day, gas supply and demand are rarely in balance. If demand exceeds supply, levels of linepack in the National Transmission System (NTS) will decrease, along with system pressures. The opposite is true when supply exceeds demand.



Traditionally, risks to meeting electricity security of supply (i.e. meeting all electricity demand at any given time) have been at times of high demand, particularly peak demand. Flexibility is used to help manage these periods, normally in the form of dispatchable gas plants being switched on, with relatively small contributions from pumped storage and (mainly industrial) DSR.

As we move away from fossil fuelled generation to renewables, alternative methods for managing peaks in demand will be required; these could include replacing natural gas power plants with equivalent hydrogen power plants, Long Duration Energy Storage (LDES), DSR, and batteries for shorter, less sustained peaks. In the future high demand will not be the only risk to security of supply managed by flexibility as increased renewable generation will result in supply determining periods of risk. For example, high demand during periods of high renewable supply will pose less risk than periods of lower demand but with much lower levels of renewable generation. These periods of undersupply are typically short: hours or a few days and can be managed by options including several energy storage technologies: interconnectors, DSR and EV smart charging (or V2G).

More extreme, though rare, are extended periods of low renewable generation which are often referred to as dunkelflaute events. These can last up to several weeks and have the potential to pose a security of supply risk. There is still considerable uncertainty around the length and regularity of these events. Their level of impact will be determined by how low renewable generation is and how much it fluctuates relative to demand.

To manage these dunkelflaute events, low carbon dispatchable thermal power plants (gas and/or hydrogen), depending on the scenario and year, are likely to be required. There is also potential for some combination of LDES (e.g., compressed air energy storage, liquid air energy storage, pumped hydro storage) and interconnectors. However, we note here that weather patterns can be strong enough to affect neighbouring countries as well and therefore, in this case, interconnectors alone cannot solve the problem. We are working with academic partners to improve our understanding of the potential impact of dunkelflaute periods in future FES iterations.

Oversupply can also be an issue as, at periods of high renewable generation and low regular demand, additional energy will need to be consumed (either by increasing demand or using energy storage) or generation will need to be curtailed. As with undersupply, oversupply can occur daily or last for a longer period. Electrolysers may be particularly useful for managing longer periods of electricity oversupply as they can increase demand by using electricity to produce hydrogen.

Current flexibility provision

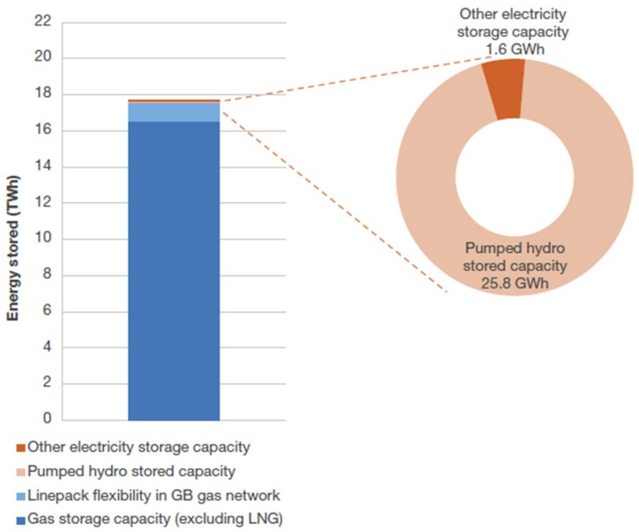
Gas

Today, most of our flexibility is delivered through the gas system. Gas can be easily stored and can provide flexibility over a range of timescales and volumes for both the gas and electricity networks. Broadly this can be split into two types of flexibility categorised by duration:

1. **Real-time:** the flexibility provided by linepack means demand on the gas network can be met even if gas supply doesn't match gas demand in real time. This in turn allows gas fired power stations to be ramped up and down to ensure electricity supply can meet electricity demand in real time

2. **Seasonal:** gas supply can be increased during winter to meet the seasonal peak demand, largely for heat. It can then be reduced during summer when demand is lower.

This flexibility is delivered by storage on the gas network from linepack, but also by additional connected storage sites and the ability to vary upstream production.



Oil

In the UK, most of the oil demand is typically for transport. The UK has commitments to the International Energy Agency (IEA) to hold oil stocks to offset the impact of any significant disruptions to the global oil market.

As the transport sector electrifies, the ability to maintain this level of reserve will reduce considerably. Electricity is much more difficult to store and, whilst some of this storage may be replaced, it is unlikely that most of it will be. While this means electrification increases the exposure of the transport sector to disruptions in the electricity market, the move to a more renewables-based UK energy system makes us less vulnerable to global commodities markets overall.

Electricity

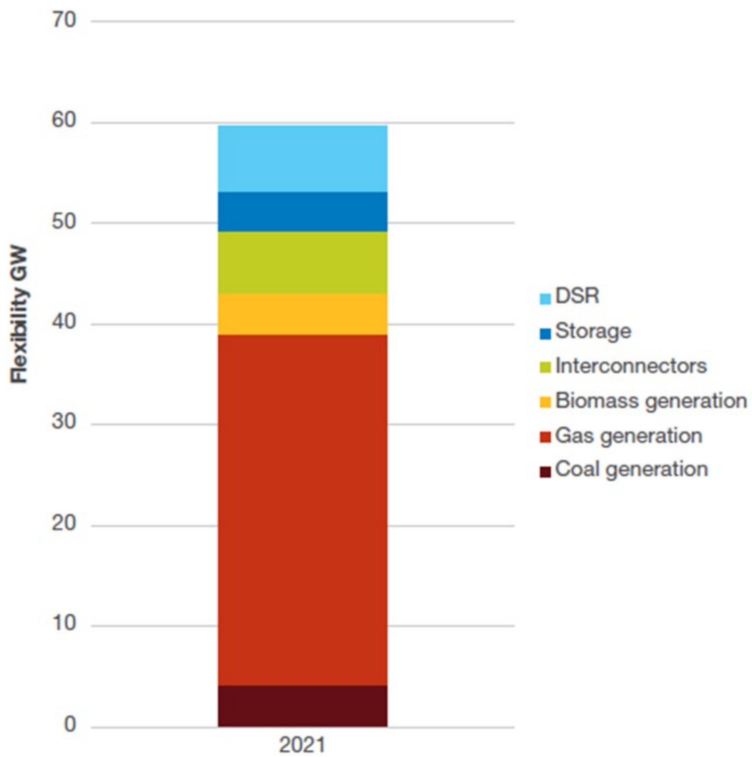
In the future there will be an increased need for electricity system flexibility, for two main reasons:

1. The increase in variable renewable electricity generation which requires additional flexibility to ensure supply and demand are balanced

2. The electrification of other sectors such as heat and transport will increase total electricity demand, but especially peak demand. It will also expose the power sector to new variability trends (e.g., the increased charging of Electric Vehicles prior to a bank holiday).

To meet both these effects, additional flexibility is required. Electricity system flexibility today is predominantly delivered on the supply side. As demand varies through the day, different sources of electricity can be turned up or down to varying degrees. Some, nuclear for example, operate more as 'baseload' generation, running constantly although ramping up and down within pre-set limits, while others such as natural gas turbines are more flexible. There is also some demand side flexibility where demand can shift to meet an increasingly weather dependent supply. Some of this is due to residential consumers shifting demand but the majority is I&C consumers switching to onsite generation. This doesn't change total underlying demand but does reduce the level of demand seen at transmission level.

Different sources of electricity flexibility are shown in the figure below. This includes storage, but also dispatchable electricity generation, and is shown in terms of instantaneous power output: energy delivered per second as opposed to just energy stored. It shows that demand side flexibility currently makes up a small proportion; the majority of electricity system flexibility today comes from fossil fuels, especially natural gas, with gas power stations able to modulate up and down, supported by gas network flexibility.



Although gas will remain important to the broader energy system as a transitional fuel, by 2035 unabated gas usage in the power sector makes up only a small percent of domestic generation under all our net zero scenarios. This reduction is required not only to achieve the 2035 net zero power sector target, but also to allow other sectors such as heat and transport to decarbonise through electrification.

This combination of an increasing need for electricity system flexibility and a reduced reliance on gas means additional sources of flexibility for the power sector need to be deployed. Strong market signals and the correct enabling conditions, such as increased digitalisation, are needed to ensure the right types of flexibility are in the right places, at the right time.

Flexibility types

This section highlights the examined flexible technologies, the issues they can help manage, the duration over which they must act and the scale of requirement. The role of these technologies will be investigated further in the following sections.

As the UK moves towards net zero, more renewable generation, which is weather-dependent, alongside increased electrification, will increase the importance in ensuring a reliable and low-carbon energy system. Flexibility is needed for a range of activities, including storing energy over years, covering extended periods of extremes in high demand or low supply, and charging and discharging over minutes or less to maintain operability of the electricity network. This increased need for flexibility over a range of durations and scales presents a challenge to future energy systems and, as the UK approaches net zero, it won't be able to use natural gas to provide flexibility. However, innovation is leading to a range of new technologies which can help provide this flexibility, often over a range of scales and durations.

As shown above, flexibility can be provided by both the demand (DSR, V2G, electrolysis) and supply (interconnectors, dispatchable thermal generation, electricity storage) sides. Our FES scenarios do not model specific flexibility services or a constrained network. As such these graphics are indicative only and do not directly align to FES modelling and the Data Workbook.

Residential, Industrial & Commercial demand side flexibility

Roles for demand side flexibility:

- Balancing daily variations in supply and demand
- Reserve for unplanned outages/forecast error
- Reducing network constraints

Demand side flexibility, including contracted Demand Side Response and price related load shifting, will play an important role in balancing supply and demand and mitigating peak demand increases. However, it should be recognised that some demand cannot be moved, and this still needs to be met. It should also be recognised that if demand side flexibility is to be deployed at scale, market changes are required. These changes must facilitate flexible tariffs, support innovation and reduce barriers to participation for new market entrants from the Industrial & Commercial sector or in the form of aggregated residential demand. A demand side strategy should identify strategic priorities and incentivise more flexible electricity consumption, as well as long duration storage and early hydrogen uptake.

Industrial & commercial demand side flexibility can be split into two broad categories:

- Demand side flexibility from processes: an industrial process is carried out earlier or later to shift its energy demand
- Demand side flexibility from heat: as Industrial & Commercial heat is electrified; heating demand can be moved to match supply using either smart storage heaters or thermal storage alongside heat pumps.

There are several avenues for consumers to provide demand side flexibility, from appliances, electric heating or Electric Vehicle charging. EVs and smart charging demand are covered later in the document. Much of this flexibility will be delivered without direct consumer involvement – consumers would simply opt into a smart tariff and use smart devices in their homes. These devices would then turn on and consume power in the background when supply is high relative to demand, within any parameters pre-set by the consumer. Smart technology can minimise the impact on the consumer experience.

Flexibility from appliances presents a smaller but still significant opportunity. Smart appliances automatically responding to price signals from smart tariffs to shift electricity demand away from peak periods for appliances such as washing machines, dishwashers and, even for short periods of time, refrigerators or freezers.

We expect the move to flexible EV charging to act as a trigger point for consumers to begin to engage in this type of demand shifting as elements such as time varying EV tariffs are already available in the current market.

Domestic heat flexibility has an important role to play in shifting some of this heat demand away from peak times. As well as thermal storage technologies (including storage heaters) discussed here, there are several other thermal flexibility options. At times of peak demand, hybrid heat pumps can switch from electricity to hydrogen or biofuels for heating.

On very cold days some households using Air Source Heat Pumps without thermal storage may switch to a resistive heating mode, operating at less than half their usual efficiency and increasing their electricity demand. In highly insulated homes the heating can be switched off completely for short periods, reducing demand over peak times without leading to noticeable drop in temperature.

District heat networks can also have centralised thermal storage attached, allowing them to shift demand.

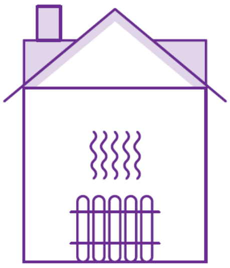
Residential thermal energy storage

Thermal energy storage refers to a series of technologies which store heat energy and includes hot water tanks and solid storage (including storage heaters) as well as newer technologies.

The input to thermal energy storage can be heat, usually from a resistive heater or heat pump, or in the case of some new technologies, electricity directly. Domestic thermal energy storage can be used to reduce electricity demand at times of low supply or peak times, or to increase it at times of higher supply. For example, a heat pump charges up a hot water tank or a dedicated thermal store when prices are low, this then supplies heat to the house for 3-4 hours over the peak evening period[21]. Increased electrification of domestic heat demand occurs across all scenarios, and so thermal storage will become increasingly important.

Storage heaters were adopted in the 1960s and 70s to make the most of surplus electricity overnight, when demands were lower. Although use has declined, there were still around 1.6 million households using storage heaters in 2020. While storage heaters can shift electricity demand away from peak evening demand periods, providing over 4 GW of nominal peak shaving in 2021, they are mostly 'dumb' devices with only basic controls that cannot adjust according to system needs, and so their ability to balance supply and demand more broadly

[21] Thermal energy storage has typically operated within daily cycles, and this is how it is modelled in FES. However, some new technologies can store heat for longer, up to several days at a time.



is limited. However, a new generation of 'smart' storage heaters is now available that could unlock greater flexibility in future.

Transport flexibility

Smart charging and Vehicle-to-Grid behaviour will play an important role in the future energy system. Across all scenarios, cars are primarily electrified, increasing electricity demands and requiring strategies to manage how they are charged and how system costs are distributed. However, this presents an opportunity to increase system flexibility, integrate renewables and better match supply and demand. With suitable incentives and automation, drivers will be able to reduce their transportation costs at the same time as reducing the costs of operating the energy system. The reduction from unmanaged charging to smart charging is the electricity flexibility provided by smart charging.

Roles for Electric Vehicle flexibility:

- Managing several days of oversupply or undersupply
- Balancing daily variations in supply and demand
- Reserve for unplanned outages/ forecast error
- Reducing network constraints

Most of the flexibility value provided by EVs comes from vehicles charging at home overnight; although commercial vehicle fleets or workplace EV chargers can play a greater role at other times of day. During the daytime we expect some commuters to plug in their cars at work. Smart optimisation of EV chargers can benefit consumers and the energy system, ensuring that vehicles maximise the use of low carbon and low-cost electricity. Commercial fleet operators are also incentivised to keep running costs low and providing flexibility from smart charging and V2G can support this. Increasing demand through smart charging at times of high renewable output could be as valuable to the energy system as reducing peak demands.

Electrolysis

Electrolysis plays an important role as a source of flexibility in the net zero scenarios. It can ramp up demand rapidly to match renewable output, producing hydrogen that can be stored until it is needed.

At times of low electricity demand, or high renewable output, nuclear-connected electrolysis increases to absorb excess power while allowing the reactor to continue to operate at baseload (i.e. providing electricity flexibility).

Roles for electrolysis flexibility:

- Managing several days of oversupply or undersupply
- Balancing daily variations in supply and demand
- Reducing network constraints

High levels of renewable generation, particularly offshore wind, are needed in this year's net zero scenarios to meet annual electricity demands. Its variable nature means we will often see times when renewable output exceeds demand. If demand cannot be increased via one or more of the sources of flexibility discussed in this chapter, then more generation will be curtailed. Electrolysis can reduce curtailment as the hydrogen produced is easier to store than electricity, and can, if needed, be stored across seasons. Electrolysis will be incentivised to operate and respond to electricity prices and market conditions, including times of potential curtailment. Similarly, we don't expect electrolysis to be incentivised to run at times of peak demand other than at times of high levels of renewable generation. This is a key part of the transformation of our electricity system from being demand-led to being supply-led, with demands shifting to make use of available electricity.

The locations of electrolysers are also key and must be considered to maximise value to the energy system. There must be hydrogen storage nearby or a connection to a network or infrastructure to transport the hydrogen. Locating electrolysers close to renewable generators could also minimise the need for electricity network reinforcement to transport this energy. However, sub-optimal siting could potentially increase network costs and constraints.

Efficient price signals will be important to not only ensure that electrolysers are incentivised to run when we want them to and not when we don't (i.e. to run when supply is high relative to demand), but also to ensure they are optimally sited in locations where flexibility can provide the most benefit to the system. To do this, efficient market design is needed, for example the introduction of locational pricing. Our Net Zero Market Reform work looks at this and is discussed in more detail here.

Hydrogen storage

Roles for hydrogen storage flexibility:

- System resilience
- Managing seasonal differences in supply and demand
- Managing extreme weather periods
- Managing several days of oversupply or undersupply

Natural gas is both relatively easy to store and able to provide flexibility across the whole system, either used directly as a fuel, for example in gas boilers or for industry, or via gas turbines to produce electricity. As we move towards net zero, natural gas consumption, and consequently natural gas storage, reduces significantly. As another gaseous fuel, hydrogen can provide similar flexibility benefits across the whole system and is needed to replace some of the flexibility provided by natural gas.

In the net zero scenarios in 2050, whole energy system flexibility is provided primarily using electricity or gas to produce hydrogen. The hydrogen is stored, and then used, either in the power sector, converted to other fuels or to meet end user demand directly. Producing hydrogen through electrolysis offers demand side flexibility to the electricity system and converting it back to power offers supply side flexibility. If hydrogen is not used immediately for heat or transport, it can be compressed and stored, in potentially very large volumes. This allows energy generated in windy periods to be used in calm periods, or to be stored between summer and winter. The overall 'round cycle' efficiency of this process is low due to losses at the production, compression and combustion stages but must be weighed up against the potential value of the electricity at times of low renewable output. Hydrogen storage will be important to support energy security of supply as well as to accommodate electrolysed hydrogen at times of excess wind or solar.

Hydrogen storage

One of the advantages of transporting hydrogen through pipelines is that the pipelines provide relatively low-cost storage. This will be useful for daily flexibility but will not meet all storage needs. For seasonal variations in demand much larger scale storage will be required.

Salt caverns are one of the most viable options for long-term, large-scale storage of hydrogen. The reuse of these facilities (previously used for natural gas storage) is a relatively well-proven commercial option. The amount of hydrogen lost through long-term storage in this way is believed to be minimal and not increase over time, but there may be some limitations on the rate of injection/discharge due to the geology of storage sites. Alternative larger scale hydrogen storage possibilities include decommissioned oil and gas fields. For smaller-scale storage, hydrogen can be kept as a gas in pressurised tanks.

To store hydrogen in liquid form it is best converted into ammonia, methanol or Liquid Organic Hydrogen Carriers. Options are also being investigated for solid-state storage. This would allow storage of a higher concentration of hydrogen and would involve solid materials that can either physically absorb the gas or chemically combine with it.

Dispatchable sources of supply

Roles for dispatchable (thermal) supply flexibility

- System resilience
- Managing seasonal differences in supply and demand
- Managing extreme weather periods
- Managing several days of oversupply or undersupply
- Balancing daily variations in supply and demand
- Reserve for unplanned outages/forecast error
- Real-time operability

Demand Side Response will be crucial to help manage peak demands, but some demand is inflexible (hospitals, for example, need a constant supply of energy) and needs to be met by sources of supply under all conditions, even when renewable generation output is low. Today the bulk of dispatchable capacity comes from natural gas generation. In the future a much greater share will come from other sources, such as electricity storage and interconnection with other countries and electricity markets. As renewable generation capacity is rising sharply in the future, this dispatchable supply may be required to run for several hours at a time, potentially over several days and so it is important that the energy storage deployed includes a suitable capacity of longer duration technologies. More broadly, this highlights the importance of ensuring these alternative dispatchable technologies are supported now so they are deployed at the required scale in the future and with the necessary carbon removal technology.

Electricity Storage

Electricity storage will need to increase significantly to support the decarbonisation of our electricity system, with as much as twelve-fold and seven-fold increases in capacity (GW) and volume (GWh) respectively from 2021 to 2050.

We see a combination of electricity storage technologies being deployed out to 2050:

• pumped hydro

• large-scale, residential and industrial behind-the-meter batteries, and

• Compressed Air Energy Storage (CAES) and Liquid Air Energy Storage (LAES).

Energy storage is a rapidly developing sector and there are several emerging technologies such as gravitational storage and flow batteries which are not included as there is very limited information on future sites. However, as they develop, it is possible they may displace some of the capacity and volume we currently allocate to other technologies. We will continue to review our modelling assumptions and update future FES iterations as more market information becomes available.

The ratio between storage capacity and volume dictates the amount of time a technology can discharge for at full power, and this in turn influences the type of flexibility the technology can provide. Batteries typically have a 1:1 or 1:2 ratio of capacity to volume, although stakeholder feedback suggests this is partly market driven and could increase to at least 4 hours. Pumped storage, CAES and LAES all typically see much more energy stored compared to power output (up to a ratio of around 1:14 in FES scenarios) and can charge or discharge at maximum output for a longer period.

Different durations of energy storage provide different benefits to the energy system. Two to four-hour storage typically helps meet short intra-day variations in demand and supply, provide short term reserve or help manage the real-time operability of the network. Longer duration storage can help secure the system over longer periods of high or low renewable generation output. However, non-electrical storage in other fuels such as hydrogen or gas is better suited to very long term or inter-seasonal storage.

Roles for electricity storage flexibility

- Managing seasonal differences in supply and demand (longer duration storage)
- Managing several days of oversupply or undersupply (longer duration storage)
- Balancing daily variations in supply and demand (longer and shorter duration storage)
- Reserve for unplanned outages/forecast error (shorter duration storage)
- Real-time operability (shorter duration storage)

Interconnectors

Aside from importing at peak, interconnectors are also used to move energy between GB and its neighbours throughout the year. In recent years there are typically net imports over our interconnectors with continental Europe throughout the year, particularly at peak times, although this is partially offset by export to Ireland and Northern Ireland. The movement of power over the interconnectors will continue to be primarily driven by price differentials between electricity markets. However, exporting over the interconnectors is not a solution for all excess power. Sometimes there may not be excess demand to consume the power in Europe, or at other times there may be network constraints restricting its movement within GB. Post-2030 the growth of integrated offshore networks will help manage the flow of power between GB, offshore wind farms in the North Sea and northern Europe, as offshore transmission infrastructure is shared, and supply is balanced across the network.

Roles for interconnector flexibility

- Managing seasonal differences in supply and demand
- Managing extreme weather periods
- Managing several days of oversupply or undersupply
- Balancing daily variations in supply and demand

Curtailment

As increasing levels of renewable generation are deployed, particularly wind, there will be times (i.e. windy days) when supply is significantly higher than demand. As discussed throughout this chapter, flexibility can be used to store some of this supply, or to shift demand to consume it. After flexibility options have been utilised, if supply still exceeds demand, then some generation will be asked to stop generating (curtailment); this could be any generation type but tends to be the cheapest to turn off at the time. Generation can also be curtailed due to network constraints but that isn't included here as FES models energy flows on unconstrained networks. The impacts of network constraints on energy flows are analysed in other ESO and industry publications, for example our Network Options Assessment and Electricity Ten Year Statement (ETYS). Whilst several flexibility technologies (e.g., interconnectors or demand side flexibility) can help to reduce curtailment to some extent, electrolysis is particularly useful in this respect. This is because hydrogen is much easier to store than electricity and so can hold significant volumes of curtailed energy for long times, potentially across seasons.

The high levels of curtailment before highlight the need for co-ordinated future energy planning. As renewable capacity is rapidly increased, flexibility options such as interconnectors, electrolysis and demand side flexibility should be developed simultaneously as much as possible, rather than in later years.

When supply is high compared to demand, we would then expect these flexibility options to respond to low electricity prices and market conditions and begin operation.

Whilst this occurs in our scenarios there is still significant curtailment - opportunities to utilise this curtailed energy through earlier and additional deployment of these flexibility options should be investigated and where appropriate, incentivised. This may include additional demand side flexibility, increased interconnector export, or potentially the development of a hydrogen export market.

Looking across the scenarios from a whole energy perspective, it seems clear that higher levels of hydrogen demand to support more electrolysis would be beneficial in Consumer Transformation. Similarly for System Transformation, a greater share of electrolysis compared to methane reformation could deliver whole energy system benefits that should be considered in policy development.