July 2020

Future Energy Scenarios

nationalgridESO

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Page navigation explained

Back a page

Forward a page

Return to contents

From here you can navigate to any part of this publication - for example, this will allow you to find your place quickly and easily after you have followed an internal link

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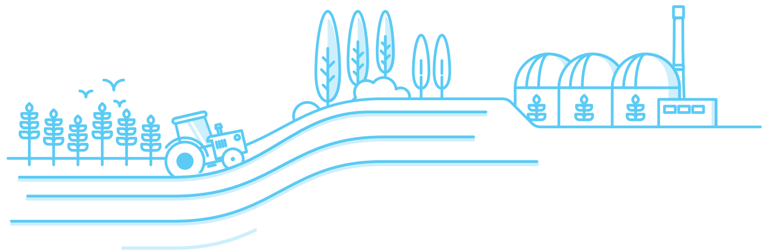
Contents



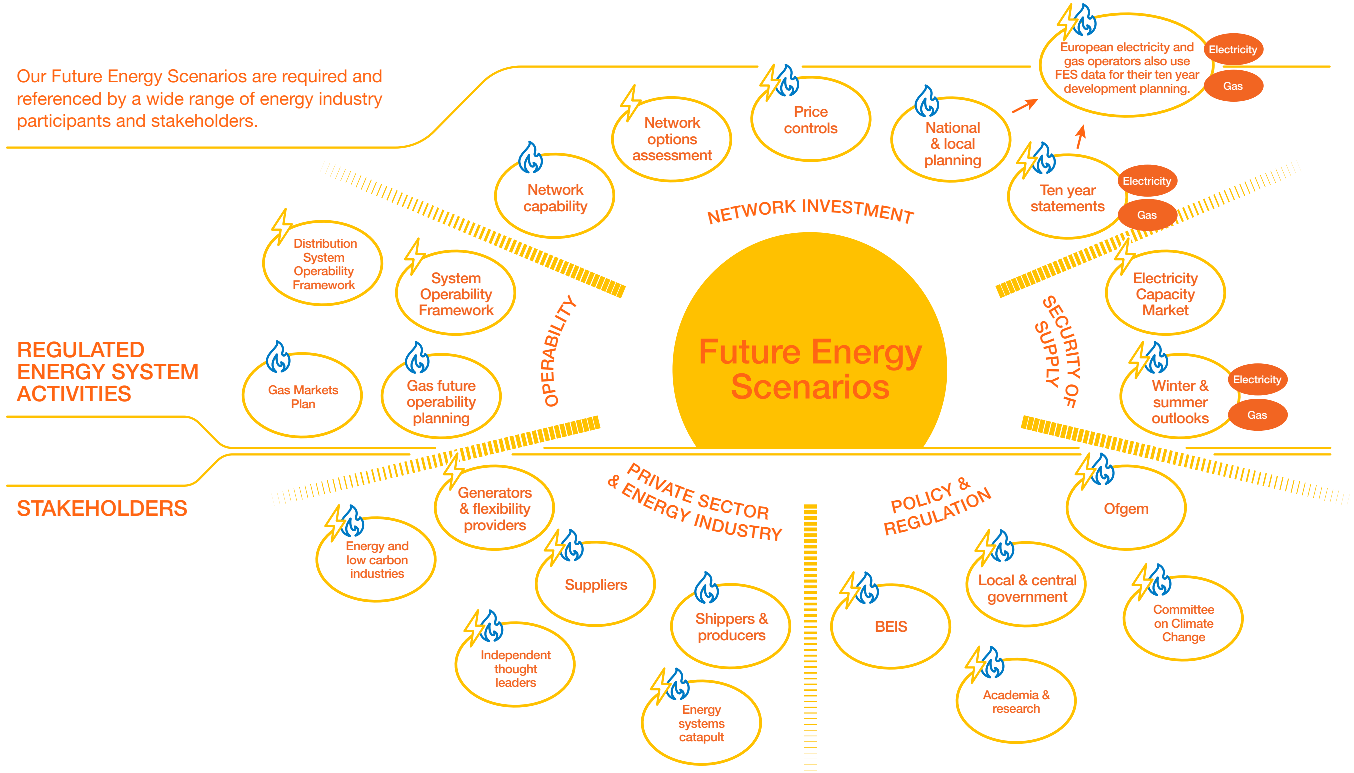
Executive summary

Introduction

The energy system must evolve while safely and reliably delivering low carbon energy to end consumers; when and where they need it to meet net zero. This will involve increasing scale, complexity and interdependency of energy conversions from one fuel to another as well as the importance of flexibility to manage differences in when and where energy is produced and consumed.

With just 30 years before the net zero deadline, FES 2020:

- Informs urgent investment in energy infrastructure;
- Supports energy policy decisions; and
- Explores the impacts of changes in how we consume energy every day between now and 2050[1].



Click to jump to enlarged diagram

1 FES directly informs investment in regulated energy networks in GB, and is also provides important input to decisions and further work across policy, private sector, and research sectors.

FES 2020 / Executive summary 05

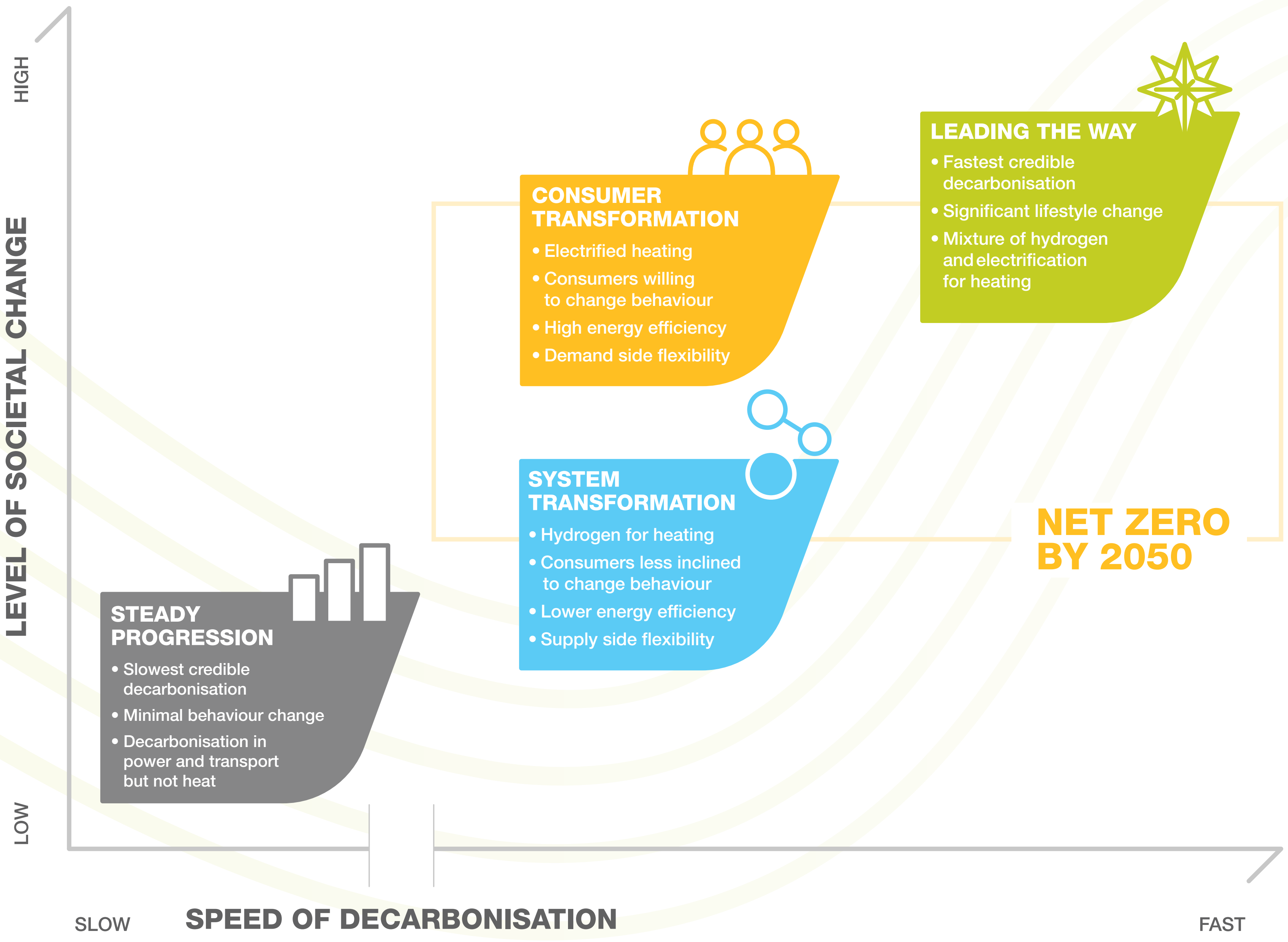
FES 2020 scenarios

This year we have developed a new set of scenarios through extensive industry collaboration.

These have net zero at their core and explore how the level of societal change and speed of decarbonisation could lead to a range of possible future pathways.

This report explores the assumptions and conclusions from the extensive modelling, research, and stakeholder engagement we have undertaken and is supported by the suite of FES documents and data sets[2]. The headline messages from FES 2020 are:

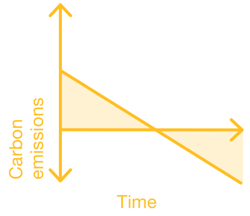
1. **Reaching net zero carbon emissions by 2050 is achievable. However, this requires immediate action across all key technologies and policy areas, and full engagement across society and end consumers.**
2. **Hydrogen and carbon capture and storage must be deployed for net zero. Industrial scale demonstration projects need to be operational this decade.**
3. **The economics of energy supply and demand fundamentally shift in a net zero world. Markets must evolve to provide incentives for investment in flexibility and zero carbon generation.**
4. **Open data and digitalisation underpin the whole system thinking required to achieve net zero. This is key to navigating increasing complexity at lowest cost for consumers.**



2 https://www.nationalgrideso.com/future-energy/future-energy-scenarios/fes-2020-documents

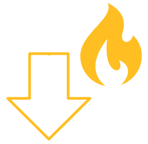
Key message 1

Reaching net zero carbon emissions by 2050 is achievable. However, it requires immediate action across all key technologies and policy areas, and full engagement across society and end consumers.

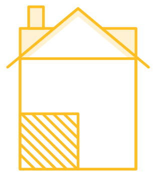


Net emissions from the power sector are negative by 2033 in net zero scenarios

At least 40 GW of new capacity is connected to electricity system in the next 10 years



Levels of natural gas burned unabated halves by 2038 across all net zero scenarios



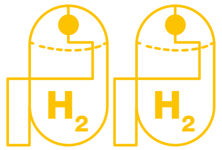
The input energy required to heat an average house could drop to as little as a quarter of what it is today

What this means

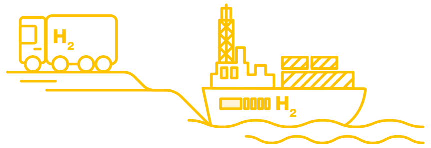
- Cross-sector regulations and services are needed to simplify the changes consumers need to make.
- Improving energy efficiency across all sectors is a no regret action. It enables low carbon technologies - and supports meeting peak and annual demands.
- Significant investment in low carbon electricity generation will be required across all net zero pathways.
- Heat decarbonisation requires urgent policy decisions to drive change across the whole energy system.

Key message 2

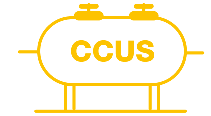
Hydrogen and carbon capture and storage must be deployed for net zero. Industrial scale demonstration projects need to be operational this decade.



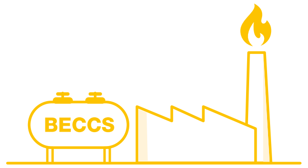
Hydrogen provides between 21% and 59% of 2050 net zero end-user energy needs



A minimum of 80 TWh of hydrogen is required by 2050 to decarbonise shipping and HGV sectors in net zero scenarios



CCUS and methane-reformed hydrogen infrastructure develops in industrial clusters by 2030 in all net zero scenarios, expanding beyond clusters in some scenarios



CCUS is paired with bioenergy to generate up to 62 $MtCO_2e$ of negative emissions by 2050 as well as being important for production of low carbon hydrogen from natural gas

What this means

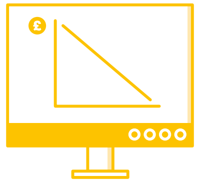
- Many different technologies can be used to produce hydrogen. Policy support is required as market signals do not currently provide strong enough investment signals to scale the technology at the pace required. Strategic direction is required to deliver at lowest cost for consumers.
- Carbon Capture Usage and Storage (CCUS) development requires support and coordination across policy, regulation, and industry.
- Hydrogen electrolysers can support integration of renewable generation. When paired with hydrogen storage and power generation, they can also provide seasonal flexibility which is important for whole system planning.

FES 2020 / Executive summary 07

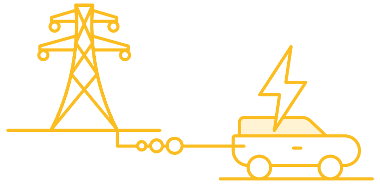
Key message 3

The economics of energy supply and demand fundamentally shift in a net zero world. Markets must evolve to provide incentives for investment in flexibility and zero carbon generation.

At least 3 GW of wind and 1.4 GW of solar need to be built every year from now until 2050



Zero marginal cost generation will provide up to 71% of generation output in 2030, and up to 80% in 2050



Vehicle-to-grid (V2G) services could provide up to 38 GW of flexibility from 5.5m vehicles

What this means

- Future markets must reflect the economics of zero marginal cost generation and the value of flexibility in supply and demand.
- Current market arrangements for renewable investment need to evolve to deliver the generation capacity required for net zero in 2050.
- The concept of peak electricity demand and how it is applied in planning and operating the system is changing as the ability of demand to ramp up to take advantage of low prices increases.

Key message 4

Open data and digitalisation underpin the whole system thinking required to achieve net zero. This is key to navigating increasing complexity at lowest cost for consumers.

By 2050, up to 80% of households smart charge their electric vehicle (EV) and up to 45% actively provide V2G services

As many as 8.1m homes actively manage heating demand with residential thermal storage and load shifting by 2050

There could be over 8m hybrid heat pumps responding to market signals and shifting demand between hydrogen and electricity systems by 2050

What this means

- The complexity of energy system decisions is increasing. Transparent and advanced analysis is critical in making the best decisions for energy consumers.
- The number of energy market participants is rapidly expanding and open data access is fundamental to ensuring efficiency.
- Whole system interactions will increase, and progress towards net zero must be made in a way that includes all impacted parties.
- Consumer technology choices today will influence decarbonisation pathways and options for efficient whole system operation in the future. Visibility and interoperability standards must be embedded to maintain options for smart management and market participation.

Consumer View

Part of the challenge of the 2050 target is that the energy system alone cannot deliver decarbonisation. It exists to serve consumers and its evolution will reflect their behavioural changes over the next 30 years.

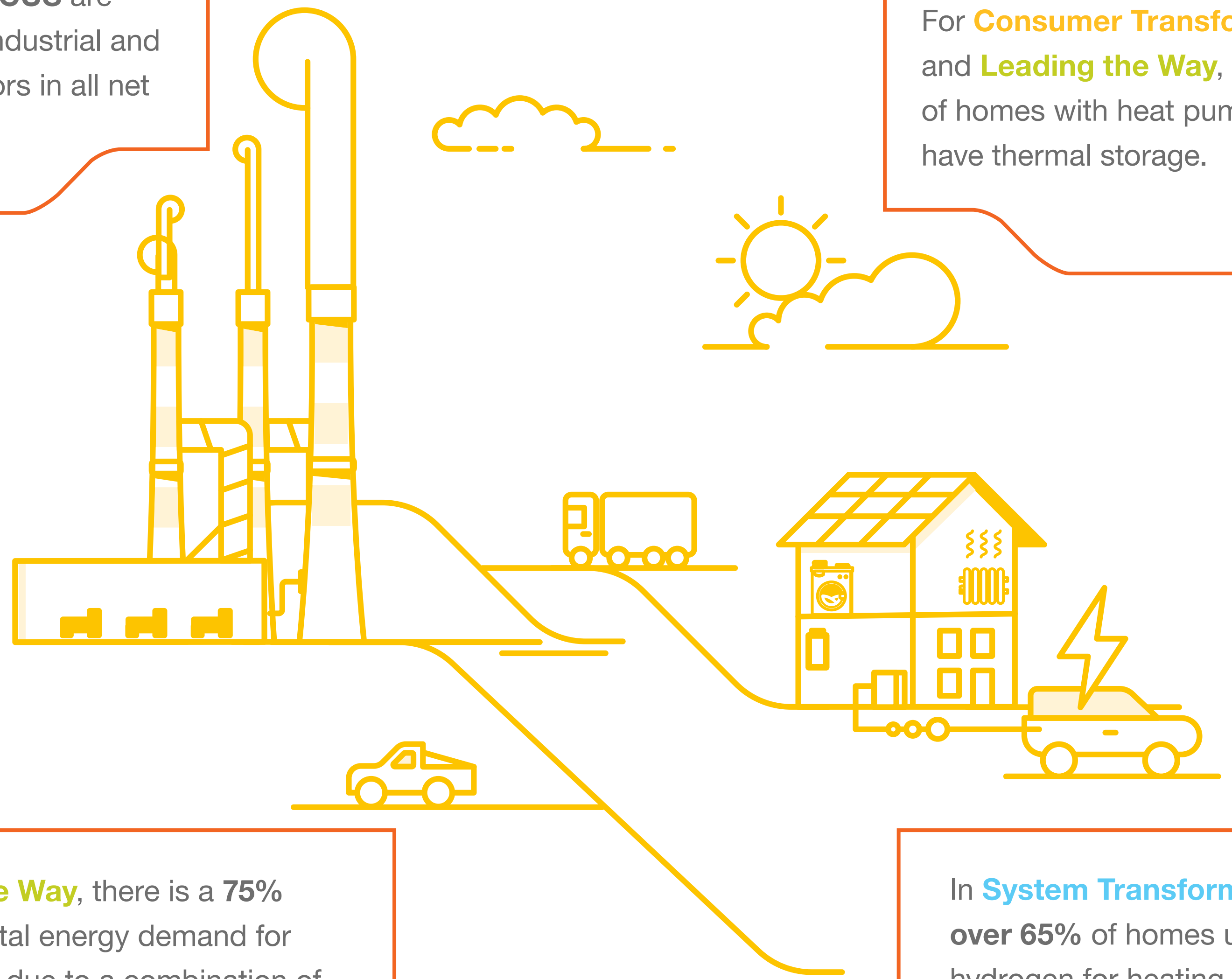
Industrial and Commercial:
High levels of energy efficiency help to manage demand and enable industrial consumers to decarbonise by switching to new technologies and fuels.

Transport:
Electrification is key to the decarbonisation of transport. Even in the slowest decarbonising scenario, there will be no new cars sold with an internal combustion engine after 2040.

Residential:
Changes to all homes are needed to enable decarbonisation in the residential sector. Energy efficiency measures, low carbon heating systems and smart energy management all play a part in net zero homes.

Hydrogen and **CCUS** are required for the industrial and commercial sectors in all net zero scenarios.

For **Consumer Transformation** and **Leading the Way**, **40%** of homes with heat pumps will have thermal storage.



In **Leading the Way**, there is a **75%** reduction in total energy demand for road transport due to a combination of electrification, automation and changing consumer behaviour.

In **System Transformation**, **over 65%** of homes use hydrogen for heating.

FES 2020 / Executive summary 09

System View

The net zero target makes it more important than ever to consider all aspects of the whole energy system. This includes how different energy sources combine to provide negative emissions and whole system flexibility.

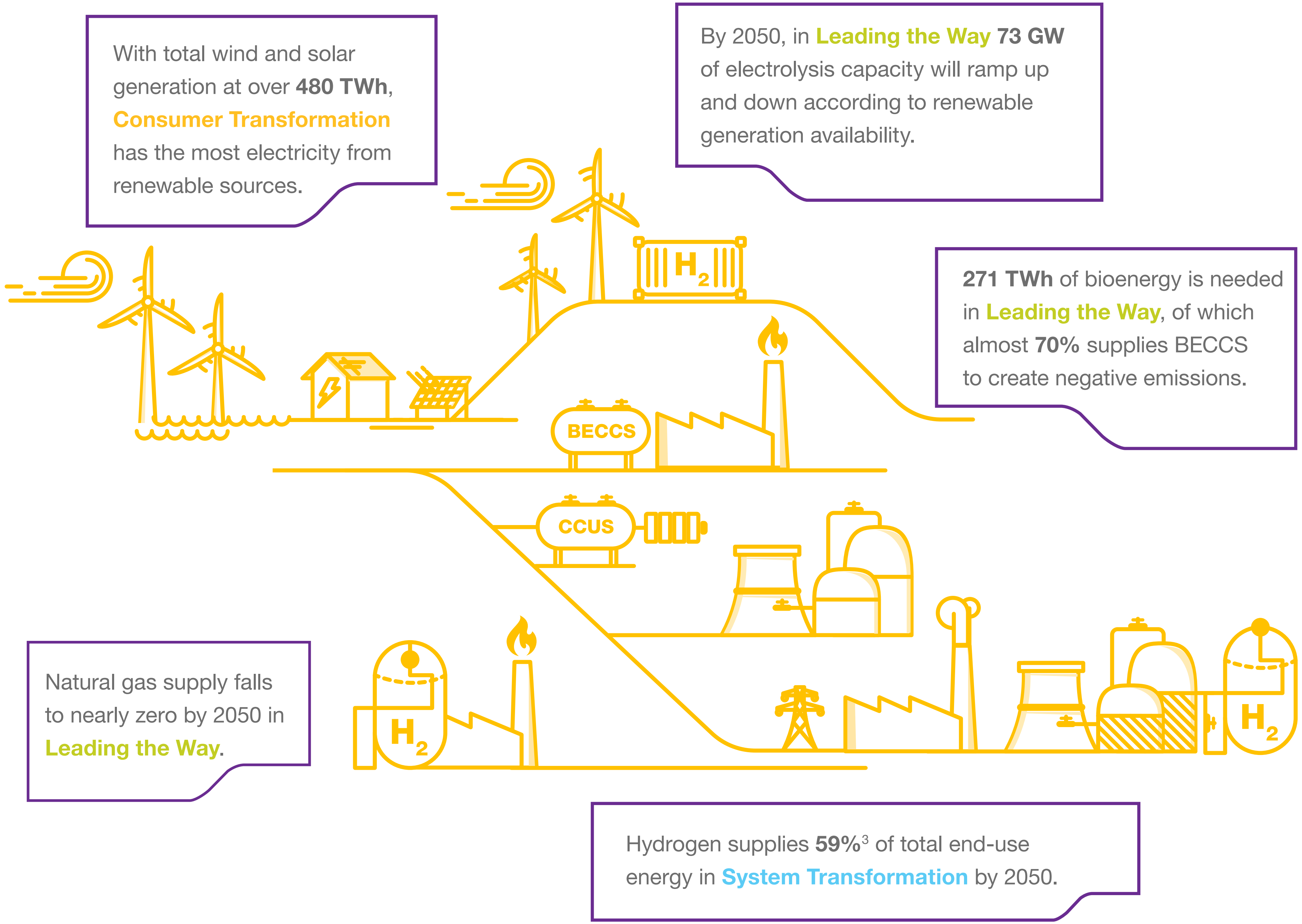
Bioenergy
Without negative emissions from bioenergy with carbon capture and storage (BECCS), net zero cannot be achieved.

Natural Gas
Natural gas remains central to all scenarios for heating into the 2030s, after which its use changes significantly.

Hydrogen
Hydrogen plays a role in every net zero scenario. It can be produced from either renewable electricity or from natural gas.

Electricity
By the mid-2030s, the net carbon intensity of electricity generated in GB has become negative in all net zero scenarios.

Flexibility
Increases in renewable generation capacity will require greater flexibility across the whole system.



3 This total energy demand excludes aviation

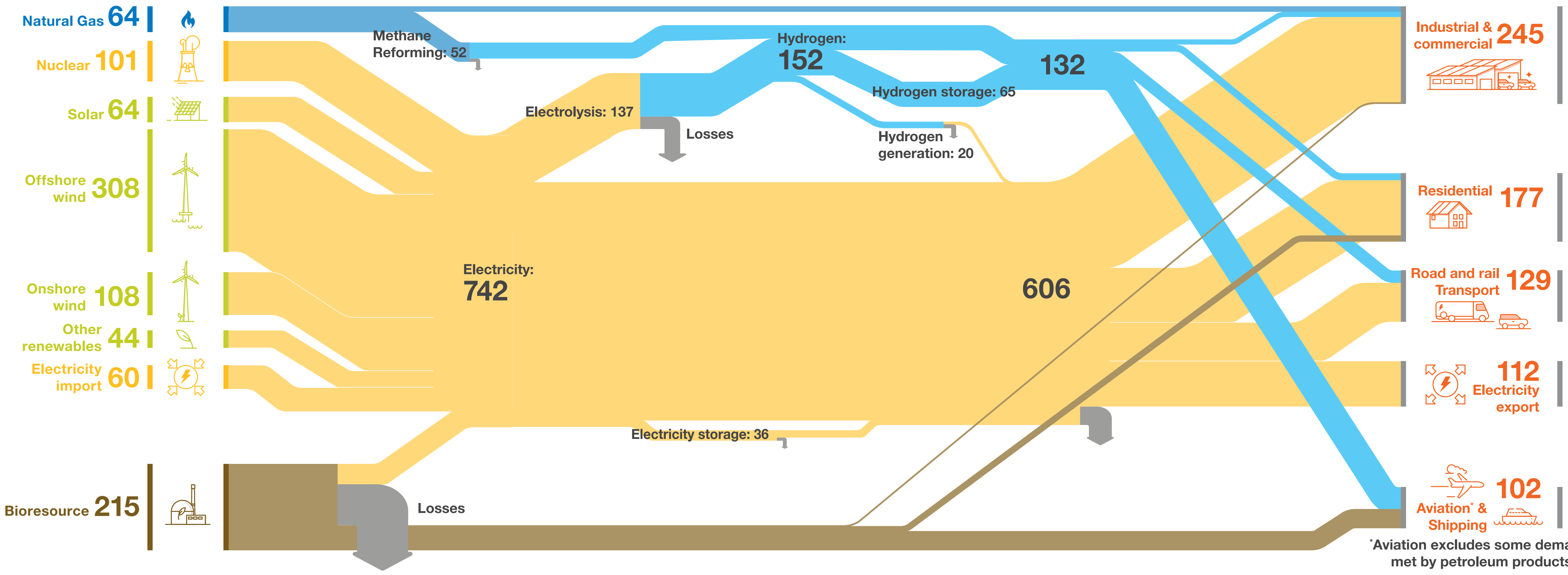
FES 2020 / Executive summary 10

2050 energy flows

Consumer Transformation

2050 energy flows in Consumer Transformation (TWh)

- Home heating, transport and industry largely electrified
- Hydrogen produced in the UK, primarily through electrolysis
- Electricity generation capacity is highest in this scenario
- Substantial increase in energy efficiency measures, lowest end-user energy demand
- Small amounts of natural gas used with CCUS to decarbonise industry, due to lower availability of hydrogen



*Aviation excludes some demand met by petroleum products

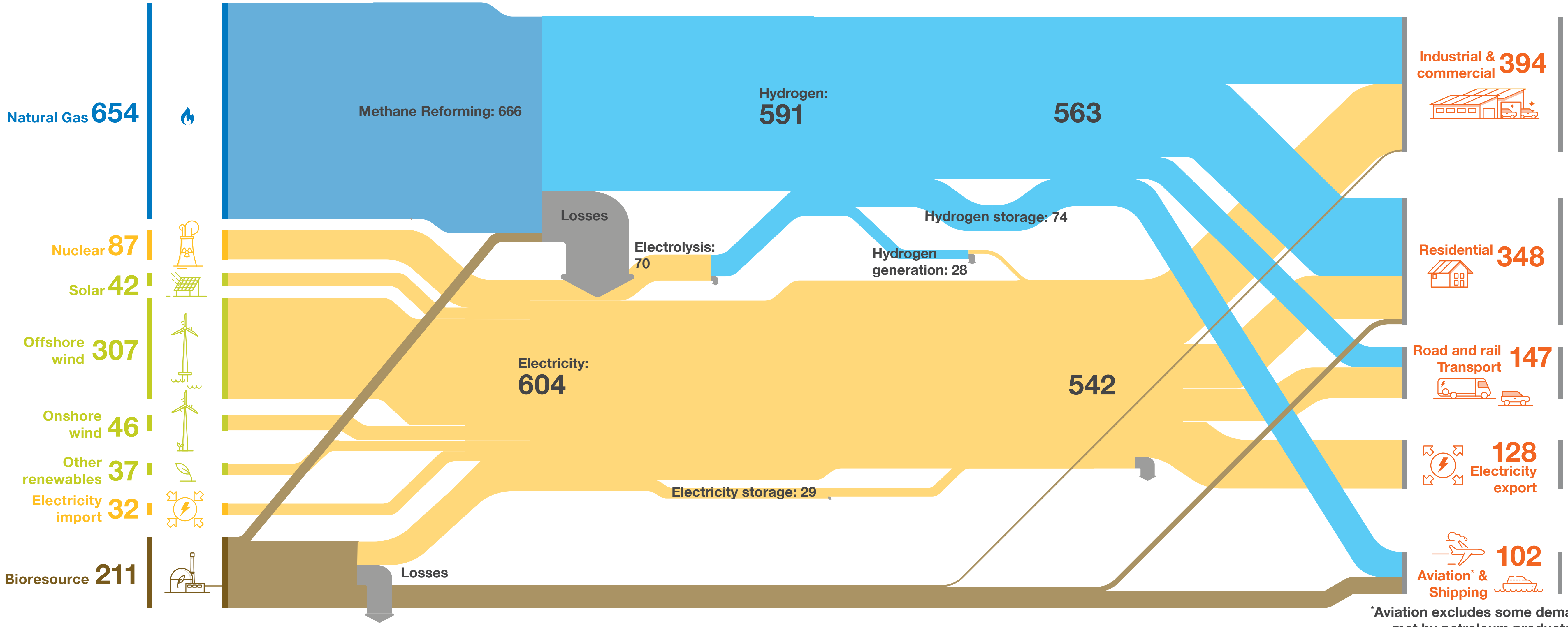
FES 2020 / Executive summary 11

2050 energy flows

System Transformation

2050 energy flows in System Transformation (TWh)

- Highest proportion of hydrogen with widespread use for home heating, industry and HGVs
- Hydrogen produced in the UK, mainly through methane reforming, with large requirement for natural gas with CCUS
- Some negative emissions from hydrogen production from bioresources with CCUS
- Less energy efficiency improvements than other net zero scenarios



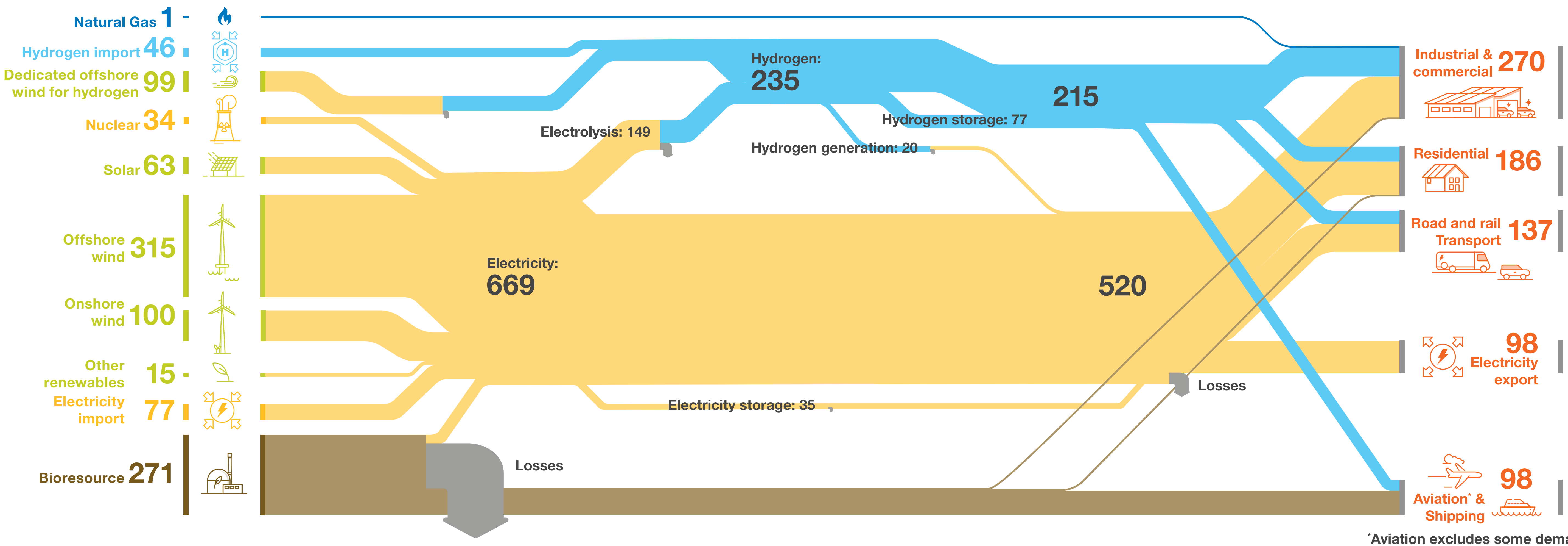
*Aviation excludes some demand met by petroleum products

2050 energy flows

Leading the Way

2050 energy flows in Leading the Way (TWh)

- Combination of hydrogen and electricity used in industry and to heat homes using hybrid heat pumps
- Hydrogen produced in the UK with electrolysis along with some imports
- Significant amounts of hydrogen are produced from dedicated, non-networked offshore wind
- Highest bioresource use, deployed mostly for BECCS, aviation and shipping
- Highest utilisation of hydrogen storage to manage variable production of hydrogen from electrolysis



*Aviation excludes some demand met by petroleum products

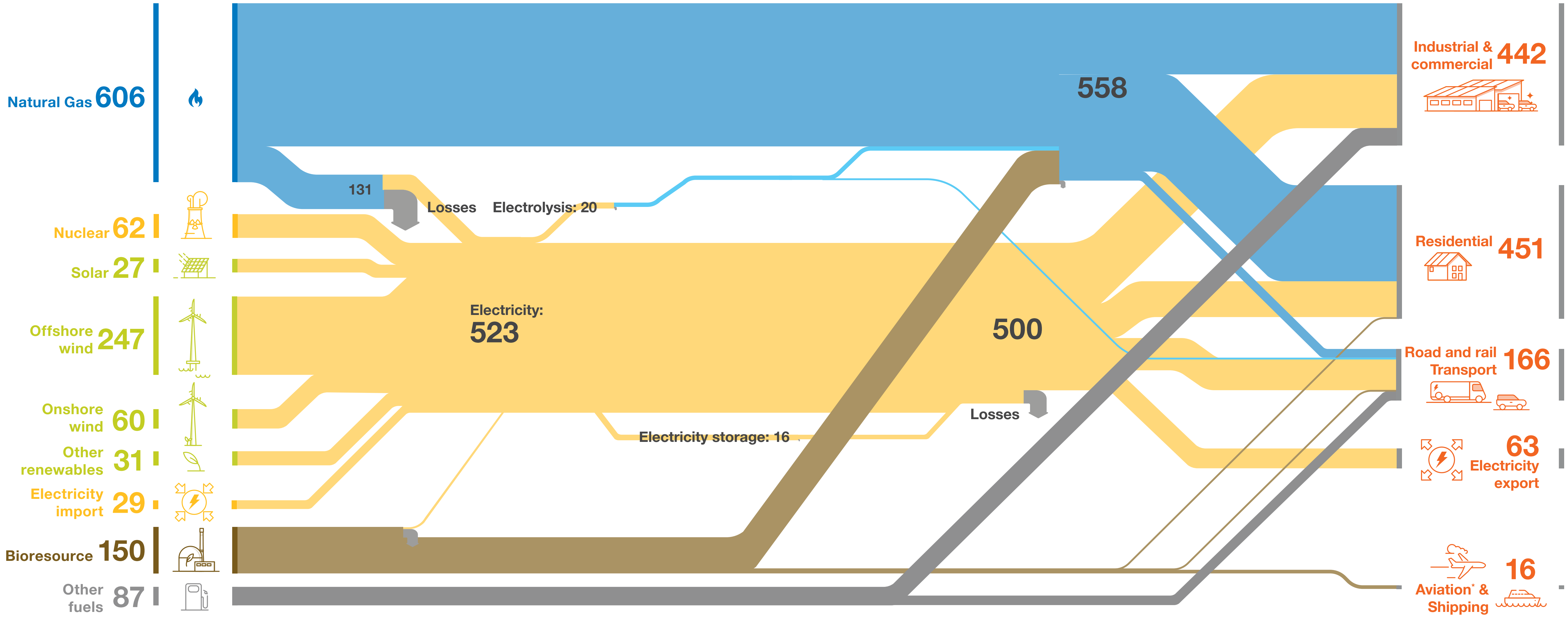
FES 2020 / Executive summary 13

2050 energy flows

Steady Progression

2050 energy flows in Steady Progression (TWh)

- High levels of natural gas, particularly for domestic heating and industry
- No negative emissions technologies
- Small private vehicles fully electrified (including some plug-in hybrids) whilst HGVs rely on fossil fuels
- Highest total end-user energy demand, due to minimal increase in energy efficiency measures



*Aviation excludes some demand met by petroleum products

FES 2020 / Executive summary 14

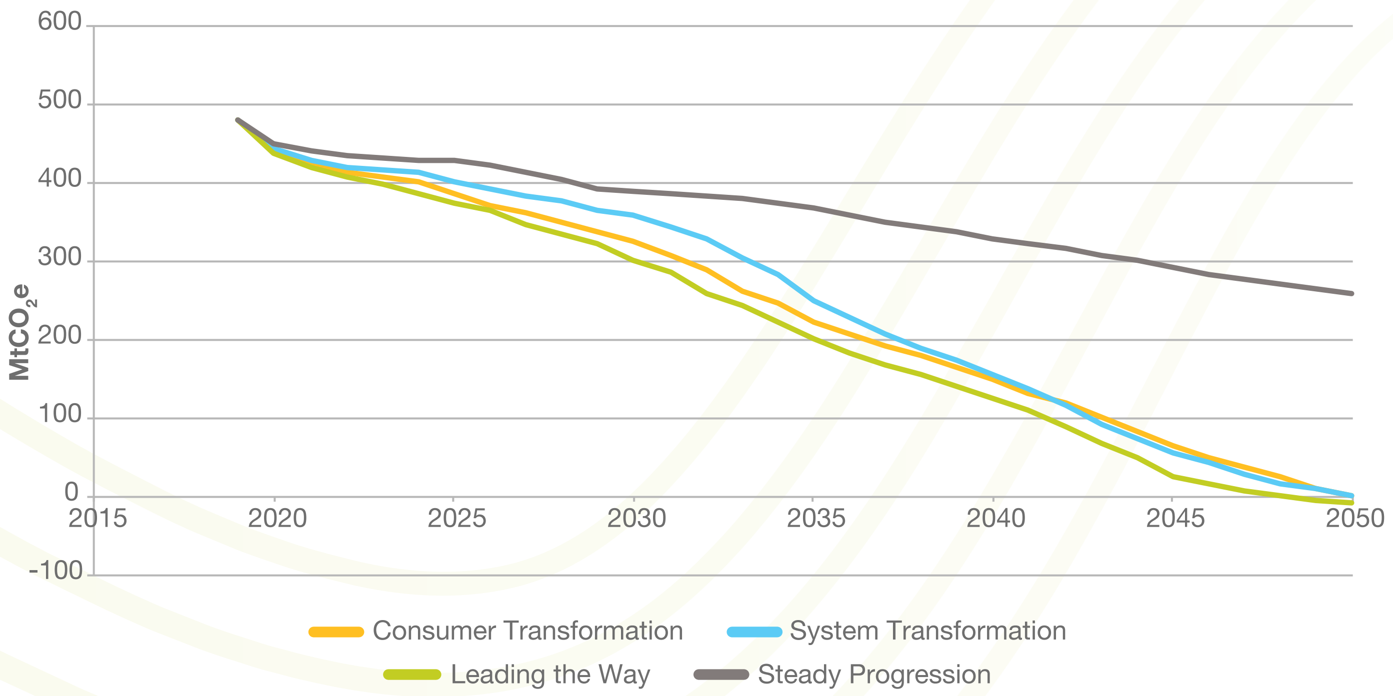
Reaching net zero by 2050

The UK net zero decarbonisation target is a challenging – and critical – goal for all sectors of the economy.

Our scenarios have net zero at their core, and explore different pathways to achieve this. UK greenhouse gas emissions in 2019 were 480 $MtCO_2e$, and have reduced by an average of 19 $MtCO_2e$ each year from 2008 to 2018. A similarly rapid rate of change of more than 15 $MtCO_2e$ each year must be maintained from now to 2050 to meet the net zero target.

As designed in the scenario framework, **Consumer Transformation** and **System Transformation** both hit the target of net zero emissions in 2050. **Leading the Way** achieves net zero slightly before this in 2048 whereas **Steady Progression** still emits 258 $MtCO_2e$ in 2050. This equates to a reduction of 68% compared to the level in 1990.

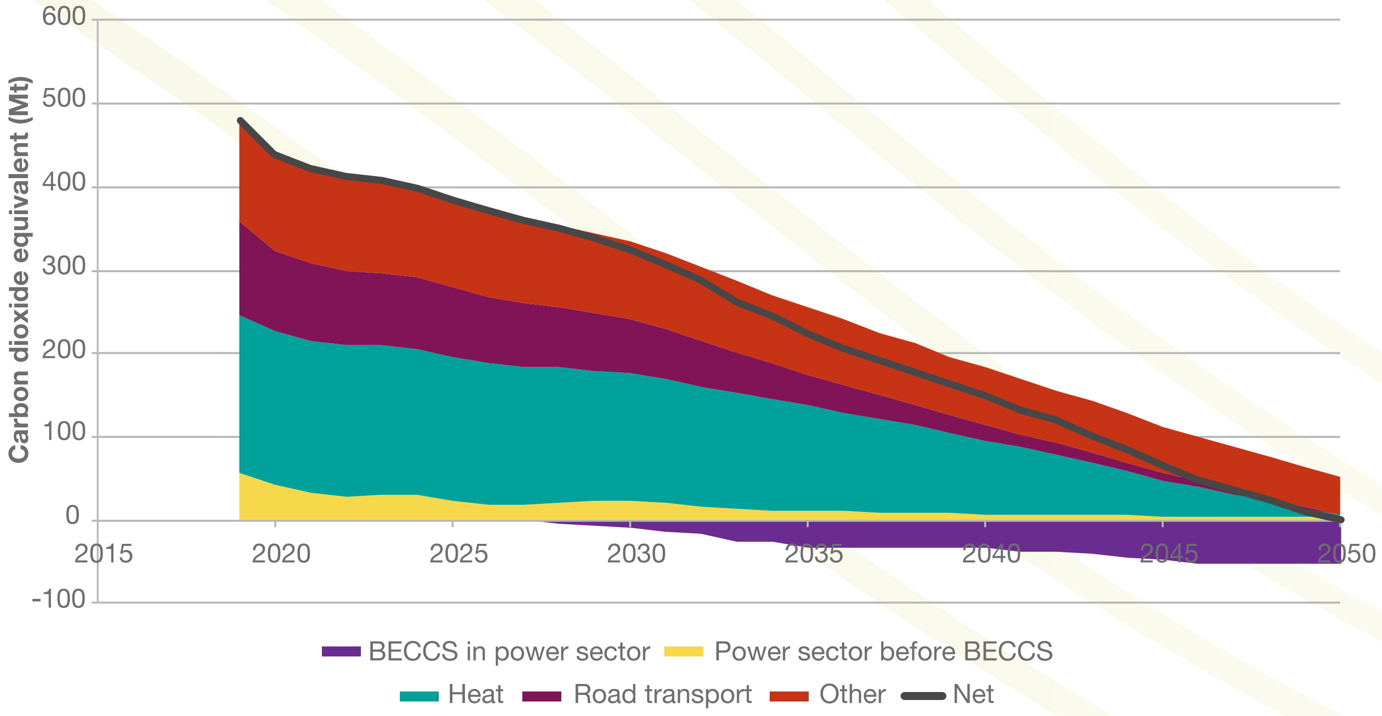
Total net greenhouse gas emissions



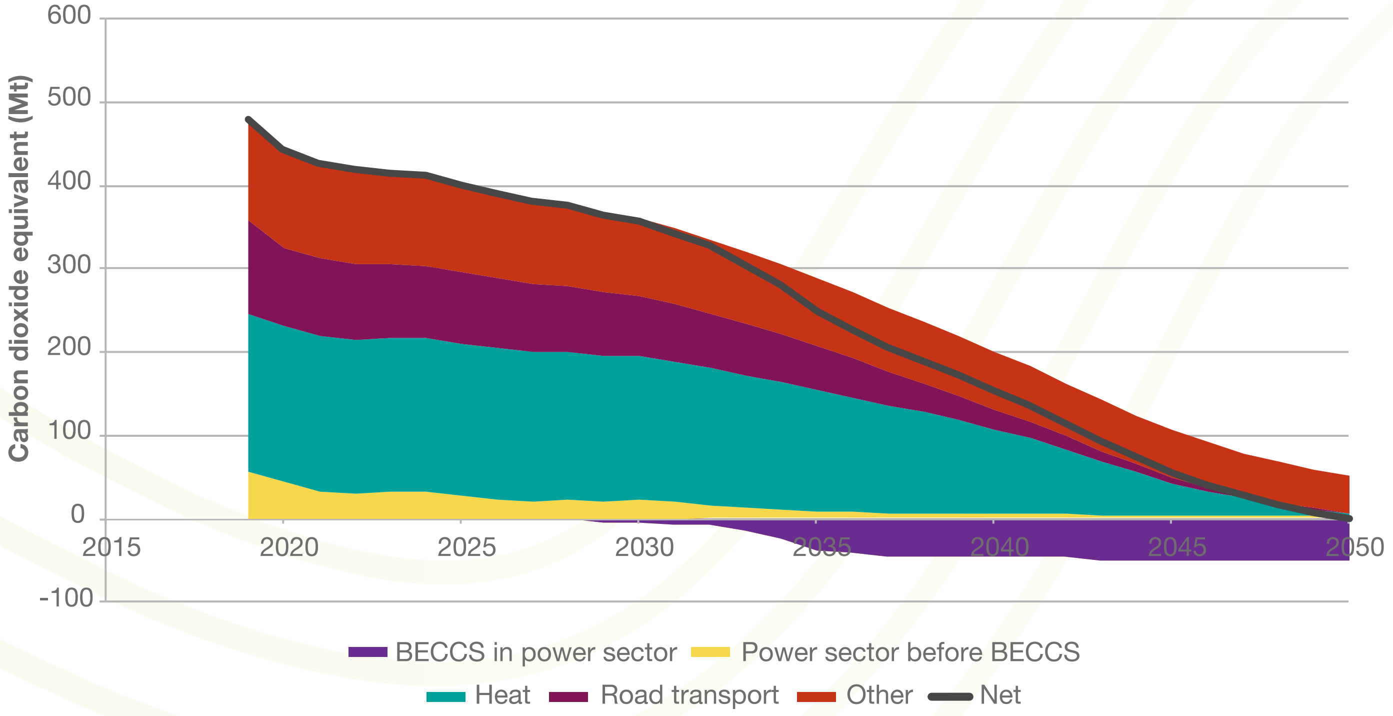
FES 2020 / Executive summary 15

Reaching net zero by 2050

Total net greenhouse gas emissions (Consumer Transformation)

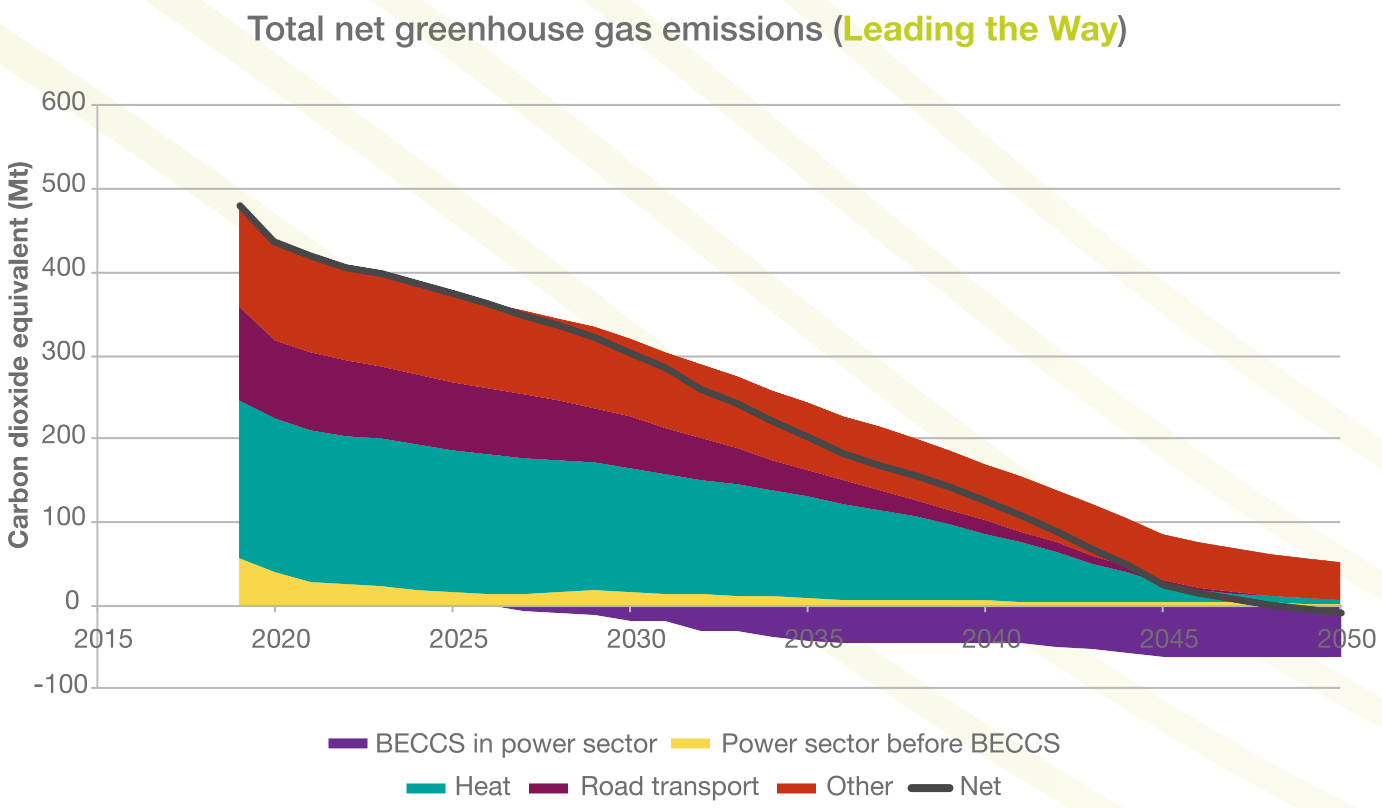


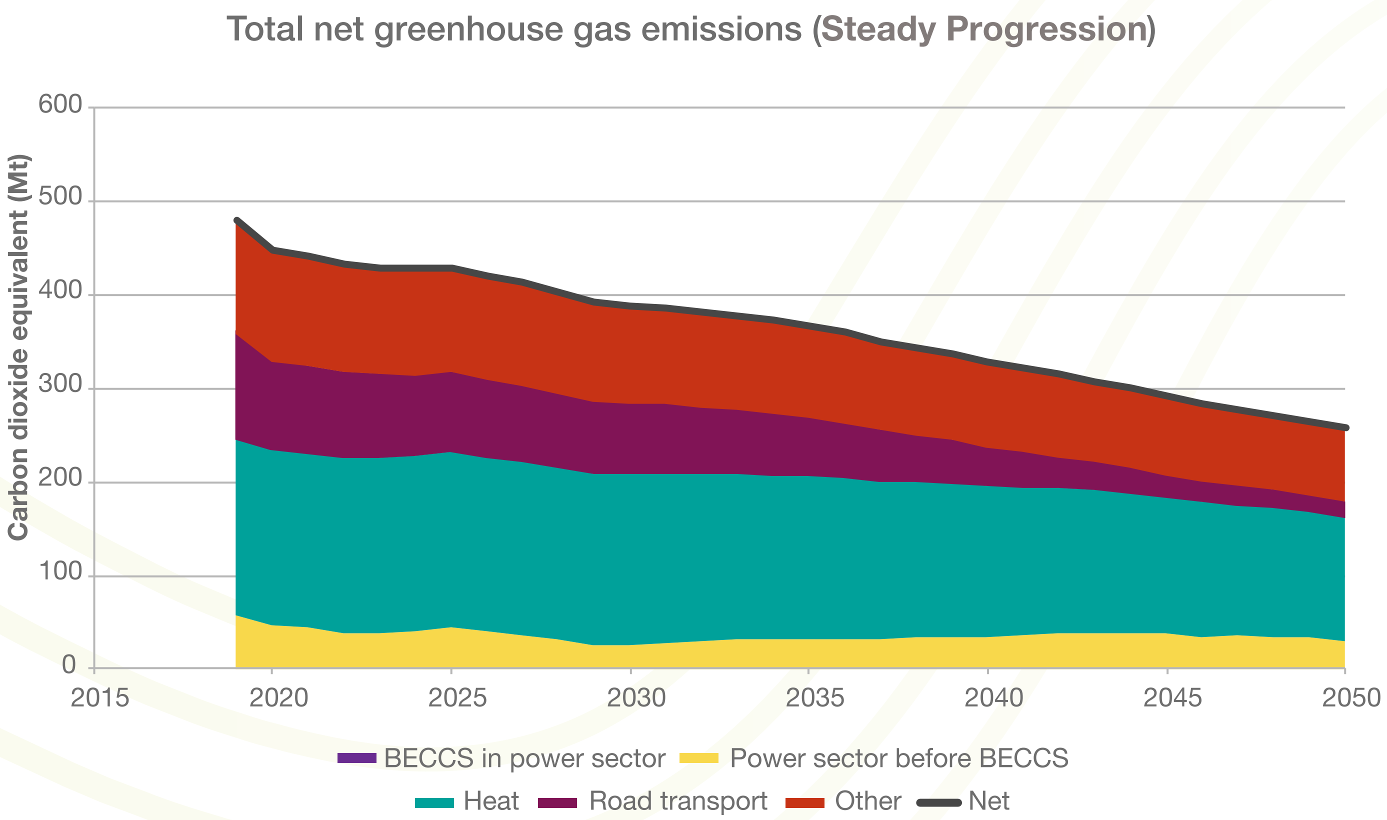
Total net greenhouse gas emissions (System Transformation)



FES 2020 / Executive summary 16

Reaching net zero by 2050





FES 2020 / Executive summary 17

Working together in the future

Beyond FES 2020 we will continue to look at how the market needs to adapt to deliver a more affordable, greener future. We are facilitating the journey to net zero by sharing insights and analysis, running world-first innovation projects, and communicating with the industry about how we need to plan and develop the energy system.

We welcome your feedback and questions on this report, and hope to engage with stakeholders from all corners of the energy industry and beyond through our future programmes.

We will be launching the second iteration of the Bridging the Gap to Net Zero programme in autumn 2020, which will focus on some of the key uncertainties identified in FES 2020 and identify key actions and recommendations for policy and industry in collaboration with stakeholders.

We will also begin research and industry engagement for FES 2021 in autumn 2020, and will be sharing details on how to get involved on our website.

FES 2020 / Executive summary 18

Introduction to the FES

With an ambitious target for net zero carbon emissions in the UK by 2050, the energy system around us is rapidly transforming. We have adapted and broadened our 2020 Future Energy Scenarios (FES) to accommodate even more changes driven by political, economic, environmental and consumer pressures. We have 30 years before the net zero deadline, which is not long in terms of investment cycles for gas networks, electricity transmission lines and even domestic heating systems. FES has an important role to play in helping to make the UK's ambition a reality.

COVID-19 impact

Covid-19 will impact many aspects of the future of energy. However the uncertainty and lack of evidence of this impact at the time of analysis means it has not been included in FES 2020. The impact of Covid-19 will be discussed with stakeholders in the second half of 2020 and will form part of FES 2021.

This year FES uses the lenses of decarbonisation and societal change to develop possible pathways for what the future of energy may be and how we could decarbonise our energy system.

Our four scenarios represent the credible range of uncertainty and are not themselves forecasts of expected pathways.

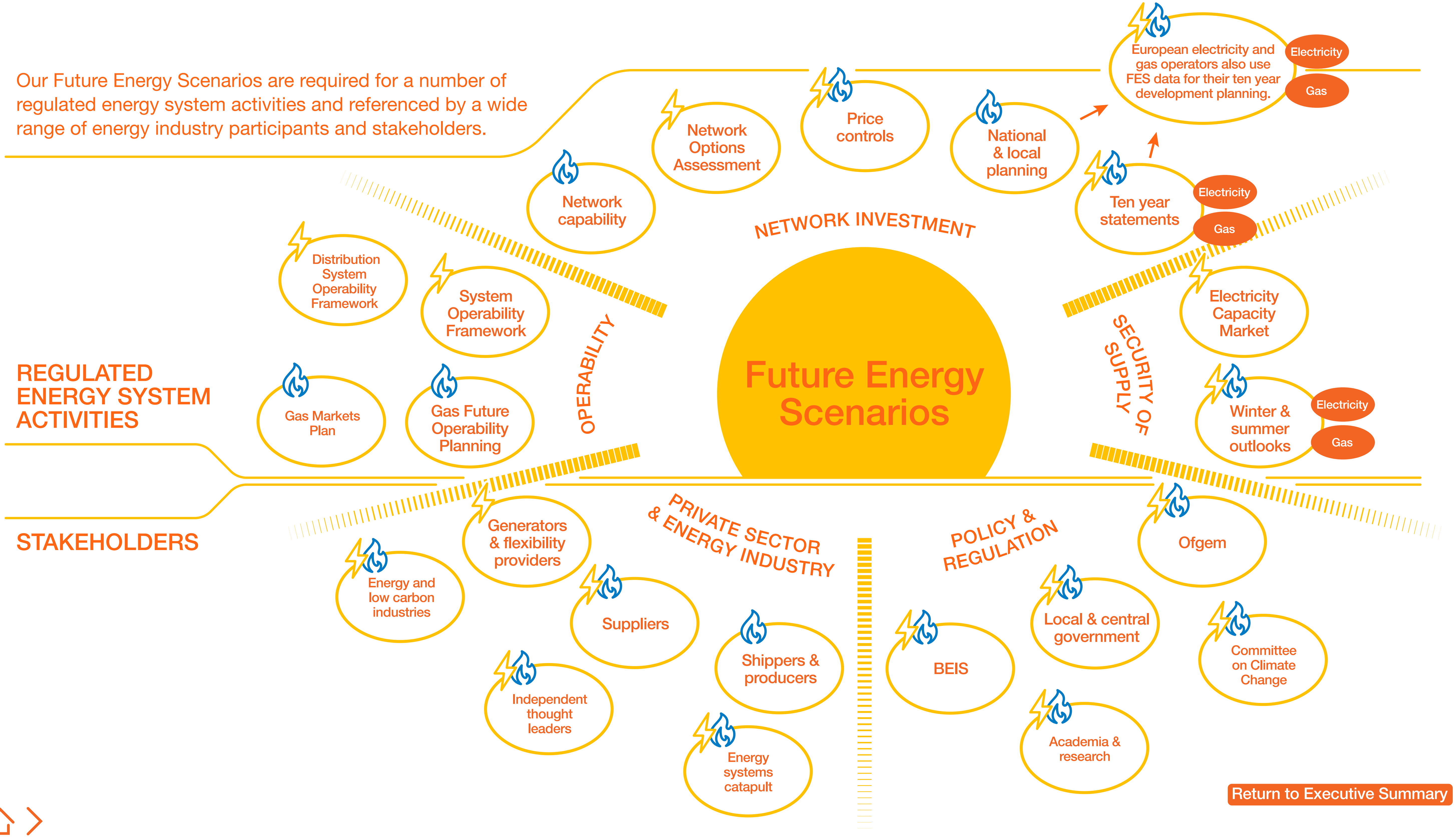
FES is used as a fundamental part of annual network planning and operability analysis. For example, if the scenarios show an increase in heat pumps, growth in renewable capacity or the closure of fossil fuel plant, network planning activities will reflect these changes.

Additionally, our stakeholders use FES for a variety of purposes:

- **for investment and pre-investment decisions, e.g. for transmission and distribution network operators;**
- **to gain insight into the energy industry;**
- **to identify future opportunities;**
- **as a reference point or to compare with industry forecasts;**
- **as a starting point for academic studies.**

Drawing on information, insight and data from all sectors of the energy industry, we have developed a whole system view, which helps us and our stakeholders to understand how we can deliver low-carbon solutions for the consumer of the future.

FES 2020 / Introduction to the FES 20



Return to Executive Summary

FES 2020 / Introduction to the FES 21

Sphere of Influence

NETWORK INV ESTMENT

Network capability
Assessment of the capability of the gas network

Network Options Assessment
NOA uses the scenarios in its economic analysis of network reinforcements. It also uses them to calculate the optimum levels of interconnection between GB and European markets.

Price controls
Ofgem and RIIO2

National & local planning
National Grid Gas has a licence obligation to forecast gas demand for the National Transmission System and the Local Distribution Zones. FES data informs this process.

European electricity and gas operators also use FES data for their ten year development planning.
Electricity: ENTSOE
Gas: ENTSOG

Ten year statements
Electricity and Gas Ten Year Statements are used for investment planning by SOs and DNOs

SECURITY OF SUPPLY

Electricity Capacity Market
Electricity Capacity Report recommends to BEIS the amount of capacity to secure through auction.

Winter & summer outlooks
The outlook reports look at the coming six months, assessing any potential issues or opportunities for both gas and electricity.

POLICY & REGULATION

Ofgem
FES is a licence obligation of National Grid Electricity System Operator set by Ofgem, to help them understand how the energy industry may develop in Great Britain.

Local & central government
For example, OLEV, DfT, Defra.

BEIS
The department of Business, Energy and Industrial Strategy refer to FES when considering new energy policy.

Committee on Climate Change
CCC also produce pathways for decarbonisation

Academia & research
Universities are active contributors to the development of FES and our work also informs their research.

PRIVATE SECTOR & ENERGY INDUSTRY

Shippers & producers
Gas shippers and producers look at FES to understand how their markets may evolve over time.

Suppliers
Energy suppliers look at FES to understand how their markets may evolve over time.

Generators & flexibility providers
FES is used to help assess how much investment to make in generation and flexibility facilities.

Energy systems catapult
Energy Systems Catapult works towards ways to decarbonise energy

Independent thought leaders
Changes to energy supply and use is a topic of much debate by independents observers and think tanks.

Energy and low carbon industries
This includes a wide range of stakeholders and activities such as R&D and innovation. Industries include major energy users (incl. power stations, ceramics etc), vehicle manufacturers heat pumps, insulation thermal stores, house builders, investment banks, etc…

OPERABILITY

Gas Future Operability Planning
Gas network operability planning by National Grid

System Operability Framework
SOF combines insight from FES with technical assessments to identify medium-term and long-term requirements for operability.

Gas Markets Plan
GMaP considers market change over a ten year time frame

Distribution System Operability Framework
Distribution Network Operators also produce SOFs

FES 2020 / Introduction to the FES 22

What's new in FES?

This year we make some ground-breaking assumptions. Where last year we only had a sensitivity analysis on net zero, this year we have three scenarios in which net zero is met, two by 2050 and one as early as is credibly possible.

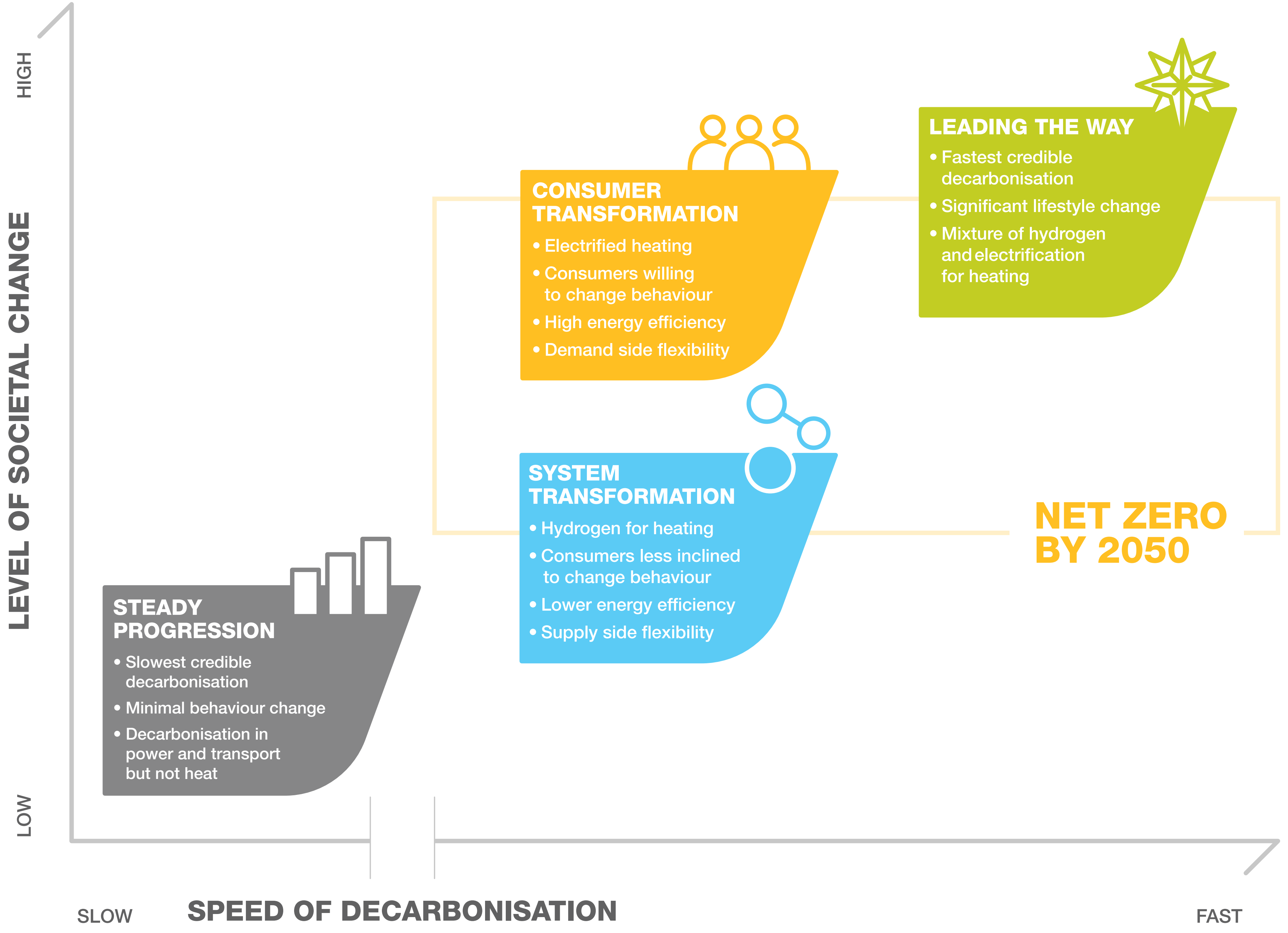
We have also improved the document's structure to reflect our differing audiences. There is a section looking at energy demand from the point of view of the end-consumer and a section showing how energy might be supplied in terms of total as well as peak demand.

To test possible outcomes, we've changed one of the scenario framework variables from the **level of decentralisation** to the **level of societal change**. This reflects the impact of an engaged, end-consumer on the possible routes to net zero. It also shows the scale of change required to meet net zero.

This year the FES report has a reduced carbon footprint by being available online only. It has also been designed to be digital-first, allowing each reader to choose their own path through the interactive format.

FES 2020 / Introduction to the FES 23

Scenario framework



FES 2020 / Introduction to the FES 24

Consumer view

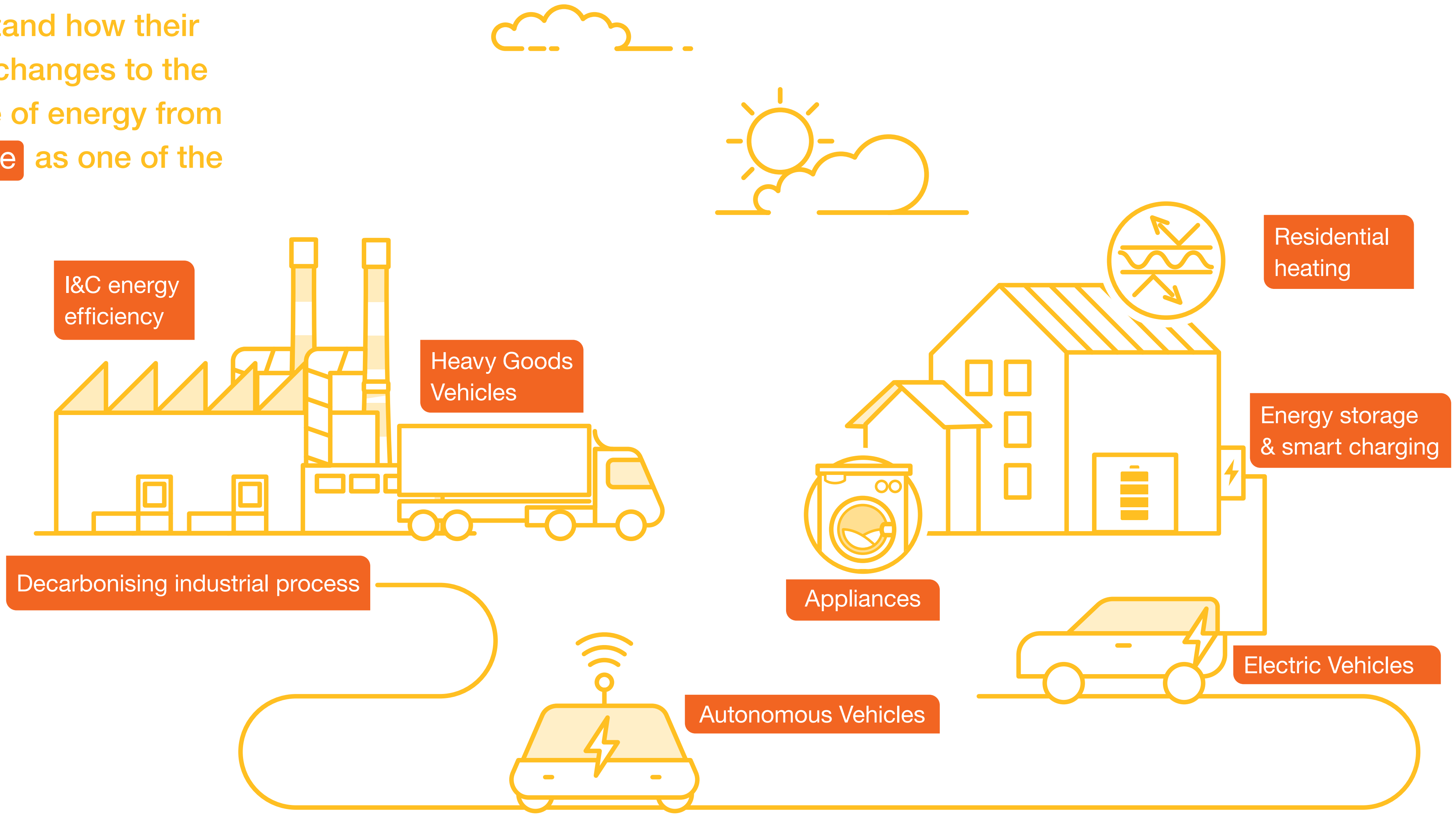
Introduction

Part of the challenge of the 2050 target is that the energy supply system alone cannot deliver decarbonisation. As the system exists to serve consumers, we need to understand how their behaviour might change in order to anticipate changes to the system. This is why we are exploring the future of energy from an end-user perspective, using societal change as one of the axes in FES 2020.

The Consumer View chapter covers the way people consume energy and how this may change over the coming decades.

It covers the consumption of energy from three different perspectives: **industrial and commercial (I&C)**, **residential** and **transport**, which account for the vast majority of the UK's energy demand and carbon emissions. Specifically, it looks at:

- How heat and power are used in industry and business;
- How homes and buildings are heated;
- How transport is fuelled;
- How end consumers changing their behaviour can help balance supply and demand on the energy system.



Click label to jump to section.

FES 2020 / Consumer view / Introduction 26

All change!

Societal change – what does that mean exactly?

It is about how we all change our behaviour to reduce our carbon footprint and support the transition of the energy system. It could be change imposed by government or change led by consumers.

In a net zero world, end consumers are likely to consider the impact of their consumption beyond their immediate energy usage. The Committee on Climate Change outlines actions for people to reduce their emissions in their Speculative net zero scenario. These include choices about transport, diet and products.
For example:

1. Take public transport or cycle to work
2. Minimise flying
3. Eat less beef, lamb and dairy
4. Buy products which last and repair them, instead of throwing away
5. Share infrequently used items like power tools.

In FES, we do not account completely for these kinds of changes. However, we can see that certainly in **Leading the Way**, they would be consistent with the assumptions of this scenario and could help to reduce carbon emissions further.

FES 2020 / Consumer view / Introduction 27

What we've found

In a net zero world, fossil fuels need to be replaced by electricity and hydrogen for transport and heating. At the same time, consumers must be willing to change how and when they use energy and be prepared to change to more energy efficient technologies.

Across the three end-consumer sectors (industrial and commercial, residential and transport), there is one common thread to decarbonisation, energy efficiency:

I&C

Innovative decarbonisation technologies will be more efficient than today's

Residential

Energy efficiency is a prerequisite to enable fuel switching from natural gas boilers to low carbon heating solutions

Transport

Electric vehicles convert energy into miles travelled far more efficiently than internal combustion engines and use of autonomy makes vehicles more efficient again.

The level of energy efficiency is different in the net zero scenarios. It is higher in the more electrified scenarios, which leads to overall energy demand being lower than today and also lower than in **System Transformation**, where hydrogen dominates. This is mainly down to the efficiency of electric vehicles and heat pumps (both natural gas and hydrogen boilers are less efficient than heat pumps). However, whilst overall energy demand is less in these scenarios, the level of electricity demand is much higher than today's.

FES 2020 / Consumer view / Introduction 28

What we've found

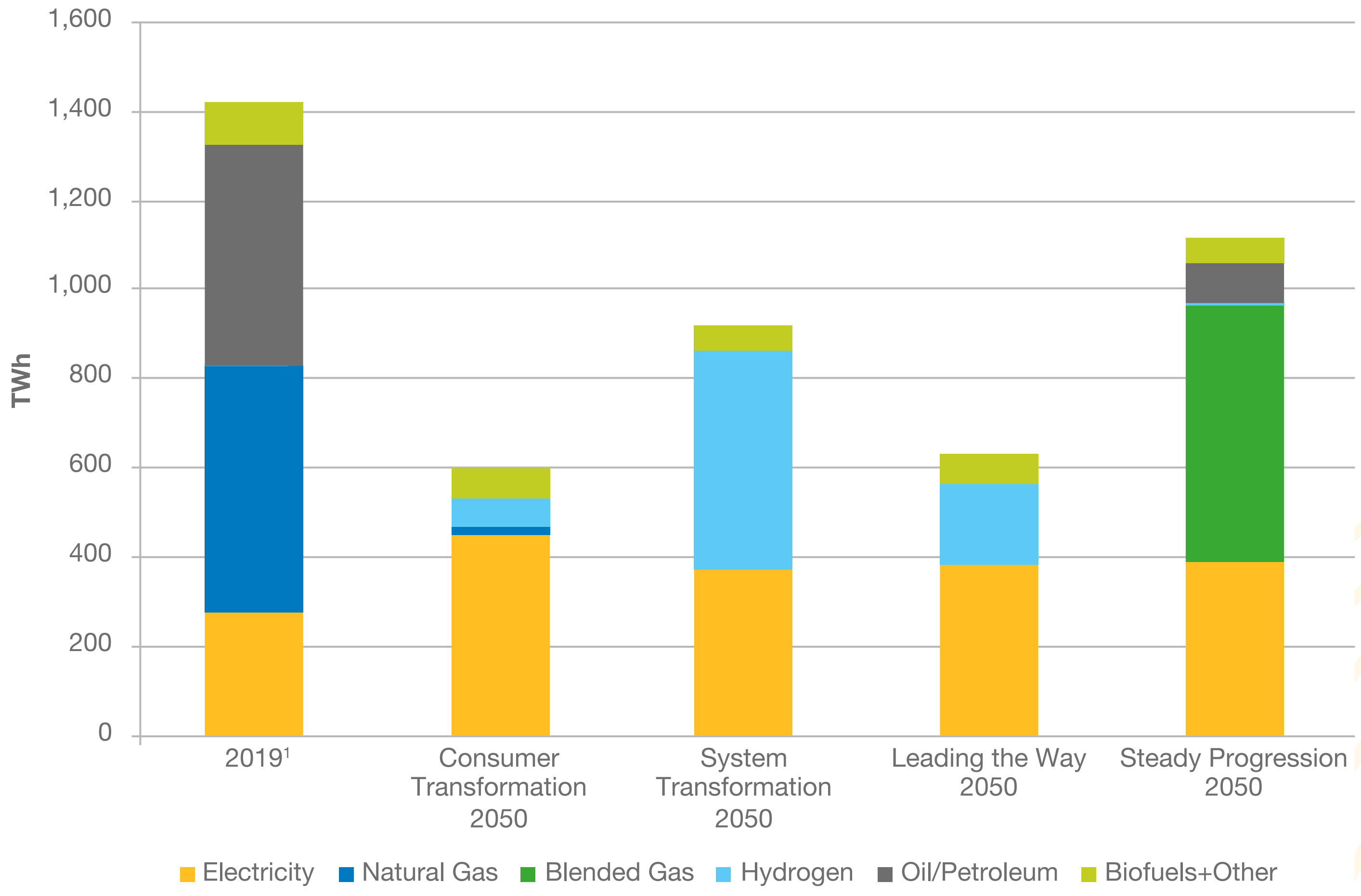
The scenarios with a greater acceptance of societal change have the lowest energy demand, illustrating the impact behavioural change can have on the energy system. It relies on people being willing to change the way they use energy, most likely motivated by wanting to reduce their own environmental impact.

In **Leading the Way**, we expect:

- People to upgrade their homes to fit a heat pump;
- Individuals to fit energy storage in their homes;
- Heating systems to respond to market signals as well as the home owner's control;
- Smart appliances in people's homes helping to manage energy demand;
- More people using public transport to get to work, whether an autonomous vehicle, a bus, tram or train;
- Private cars to be electric and plugged into the home's smart charging point whenever it's not being used, to provide additional electricity as required;
- Businesses embracing the need to switch fuels, to change industrial processes and even to relocate to take advantage of hydrogen and CCUS facilities;
- Consumer choice influencing products on offer, helping to support a more circular economy with a lower carbon footprint.

Whilst this is in our most ambitious scenario, elements of these behavioural changes are seen in all three net zero scenarios.

Figure CV.1 Annual end consumer energy demand in 2050

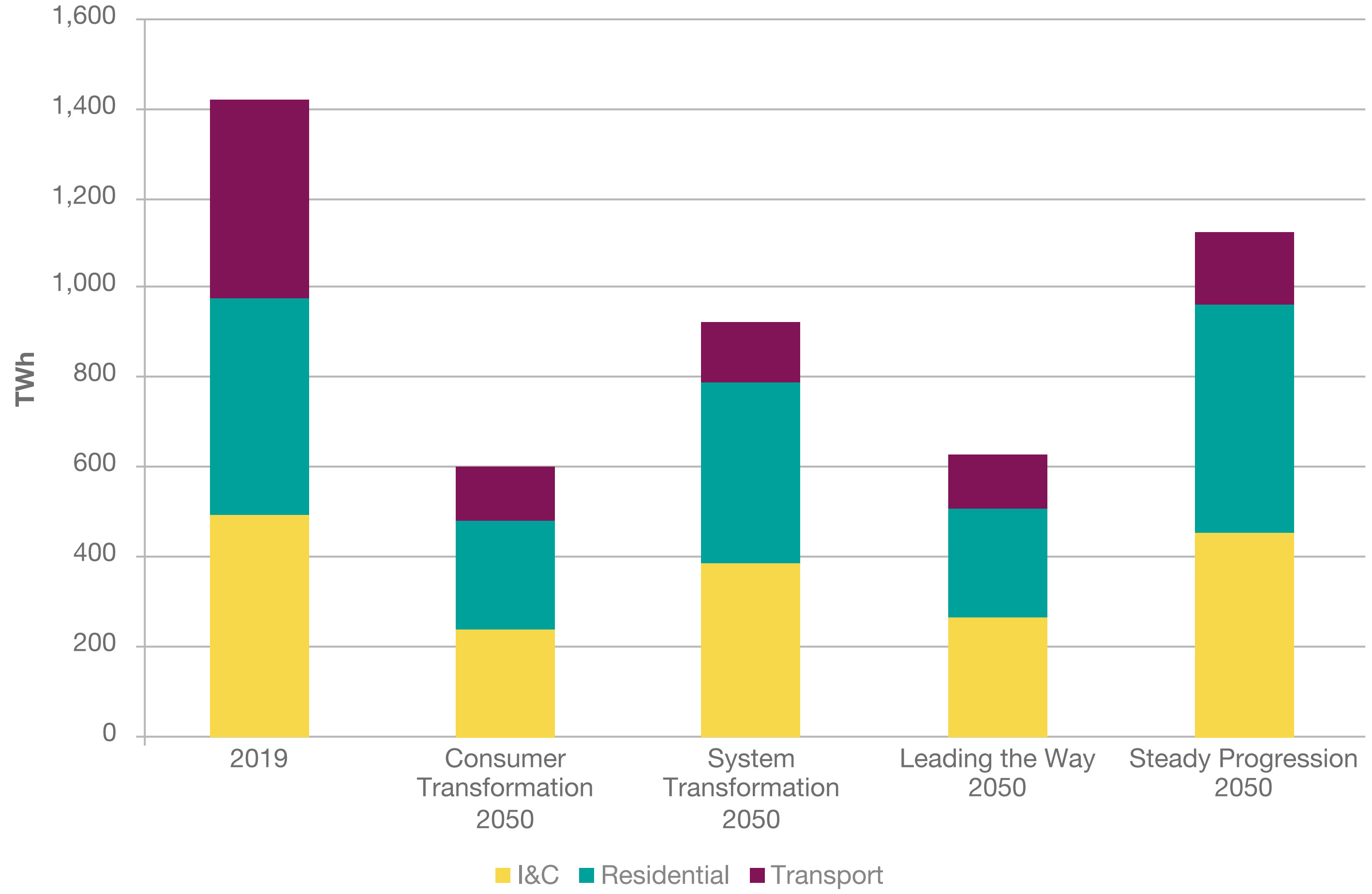


Customer Demand by Fuel

1 The energy demand figures stated here show the amount of energy consumed by the end user in each sector. They do not include how much primary energy may be required to meet this demand. Because of losses and energy conversion efficiency, this will always be larger than the demand from end consumers. The 2019 data is primarily made up of our modelled data for natural gas and electricity. However, some 2018 demand data from ECUK was used in order to provide a complete, whole system view of end consumer demand.

FES 2020 / Consumer view / Introduction 29

Figure CV.1 Annual end consumer energy demand in 2050



Customer Demand by Sector

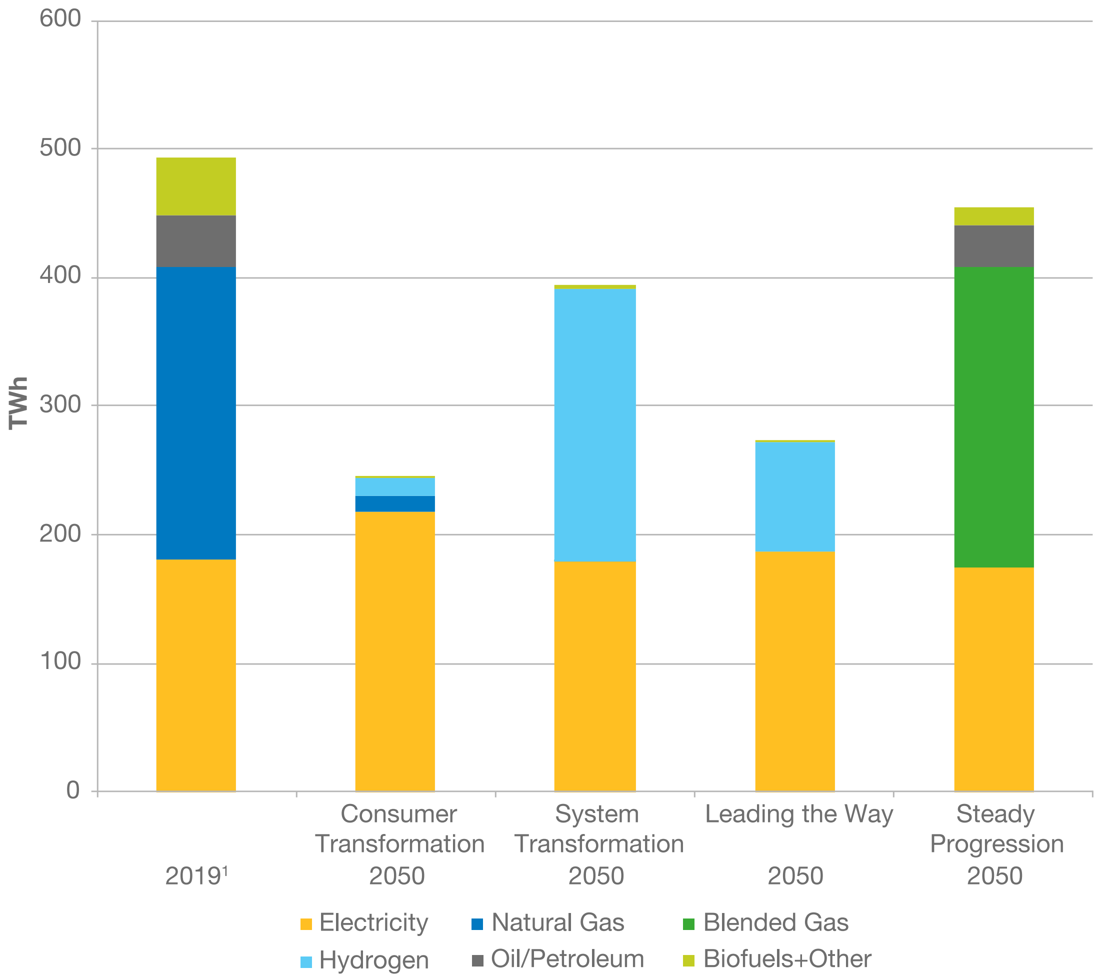
FES 2020 / Consumer view / Introduction 30

Industrial and Commercial

Key insights

- Energy efficiency measures implemented before 2030 are a fundamental step in our modelling to get to net zero in **Consumer Transformation**. Here, the high efficiency levels of appliances and the use of heat pumps reduce total energy demand to more than 30% lower than in **System Transformation** by 2050.
- Decarbonisation of the industrial sector will require a diverse range of actions including energy efficiency, fuel switching and negative emissions. For the commercial sector, it will need energy efficiency and adopting low carbon heating systems.
- Some industrial processes will not be fully decarbonised even in net zero scenarios. A mix of hydrogen, electricity and biomass can replace gas and coal to provide heat but some process emissions remain.
- Industrial clusters of complementary technologies are part of the solution for net zero. This may mean relocation for some manufacturing plant for efficient use of resources (such as hydrogen) and collaboration between companies. These industrial hubs will include carbon capture, utilisation and storage (CCUS) infrastructure, required for some hard-to-decarbonise processes.

Figure CV.2: Annual industrial and commercial energy demand in 2050



1 The 2019 data is primarily made up of our modelled data for natural gas and electricity. However, some 2018 demand data from ECUK was used in order to provide a complete, whole system view of end consumer demand. www.gov.uk/government/statistics/energy-consumption-in-the-uk

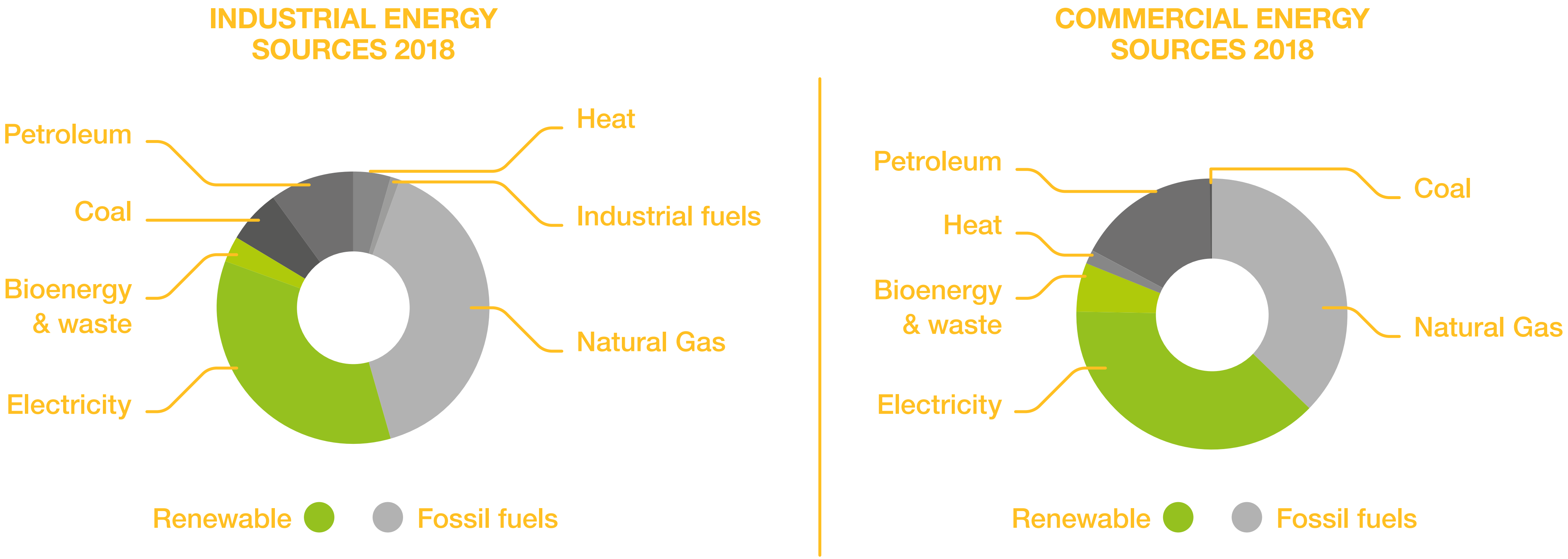
FES 2020 / Consumer view / Industrial and Commercial 32

Where are we now?

In 2018, industrial and commercial (I&C) consumers accounted for approximately 500 TWh of energy demand and 90 $MtCO_2$. This accounts for 31% of total energy demand in the UK (63% of total electricity demand and 39% of total natural gas demand) and a quarter of the UK's emissions. I&C includes some of the hardest to decarbonise sectors, such as steel, chemicals, and cement production.

Fossil fuels in this sector are used for a wide range of activities, not just for heat and power but also as feedstocks in some processes.

Figure CV.3: Industrial and Commercial energy sources (2018)[2]



2 2018 Data taken from ECUK, Consumption Data Tables: www.gov.uk/government/statistics/energy-consumption-in-the-uk

FES 2020 / Consumer view / Industrial and Commercial 33

Industrial and commercial

Industrial and commercial

The definition of this sector follows the UK's standard industrial classification structure, set out by the Office for National Statistics. Industrial sectors include iron steel production, cement, glass, pharmaceuticals, engineering and vehicle manufacturing amongst others. Commercial sectors include agriculture, construction, offices, government bodies, retail and hospitality amongst others. Energy used for embedded power generation is not included in the demand figures here.

FES 2020 / Consumer view / Industrial and Commercial 34

What we've found

For the commercial sector, decarbonisation relies on increased energy efficiency and a choice between hydrogen and electrification as unabated natural gas is phased out and biomass availability is assumed to be limited. These options also apply to some parts of the industrial sector, but the use of bioenergy and CCUS may be needed in some hard to decarbonise processes.

Modelling net zero for the I&C sector explores the impact of the following aspects, whilst keeping economic growth fixed across all scenarios:

- Pursuit of energy efficiency
- Sensitivity of consumer behaviour to energy prices
- Increased electrification for heating.

Steady Progression

System Transformation

Consumer Transformation

Leading the Way

Leading the Way

With the urgency for decarbonisation widely accepted by the public and government, action in the early 2020s increases the price of energy (both electricity and natural gas) and the cost of carbon for industrial processes. This prompts end consumers to pursue high levels of energy efficiency and the UK's Clean Growth target is met earlier than the 2030 target. Tariffs also encourage I&C customers to adjust demand to help match supply and on-site energy storage (for both heat and electricity) is widespread.

Alongside large-scale network investment to electrify heat, an investment programme in electrolysis uses renewable electricity generation to create hydrogen by 2026. This is supplemented by a small amount of hydrogen imports. Industrial clusters capture any carbon emissions from the industrial combustion of biomass or natural gas.

FES 2020 / Consumer view / Industrial and Commercial 35

What we've found

Consumer Transformation

The high price of both retail and wholesale gas and an effective carbon price encourages energy efficiency in the 2020s, provide incentives to choose low carbon processes and products. The Clean Growth Strategy 2030 target for energy efficiency is met. Increased levels of renewable generation and demand from transport prompt large-scale investment in electricity networks, which encourage industrial switching to electric processes from 2026. With business consumers willing to decarbonise, they install renewable energy generation onsite wherever possible, which combines with batteries to provide flexibility to the grid.

Industrial consumers unable to electrify locate themselves in industrial hubs around the country over the course of the 2040s. At these hubs they can access hydrogen for certain processes as well as CCUS for any carbon emissions resulting from the breakdown of some raw material.

System Transformation

Energy efficiency is encouraged with increases in the wholesale and retail energy prices. Strengthening carbon pricing in the 2020s encourages low carbon I&C activity. Alongside the carbon prices, smart pricing tariffs incentivise large energy consumers to participate in demand side response activities and to install their own renewable energy generation (mainly solar PV) and batteries by 2030.

Industrial customers adapt their heat incentivise processes to use hydrogen where possible, starting with hydrogen boilers in industrial clusters in 2026. Switching to hydrogen is gradual however, dependent on the development of the network, with some customers still changing fuels in the 2040s. CCUS is used to capture any unavoidable process emissions, either on site or as part of an industrial hub. For commercial customers, natural gas heating gradually shifts over to energy efficient, hydrogen-based systems starting in 2030, with no discernible impact on the end-product.

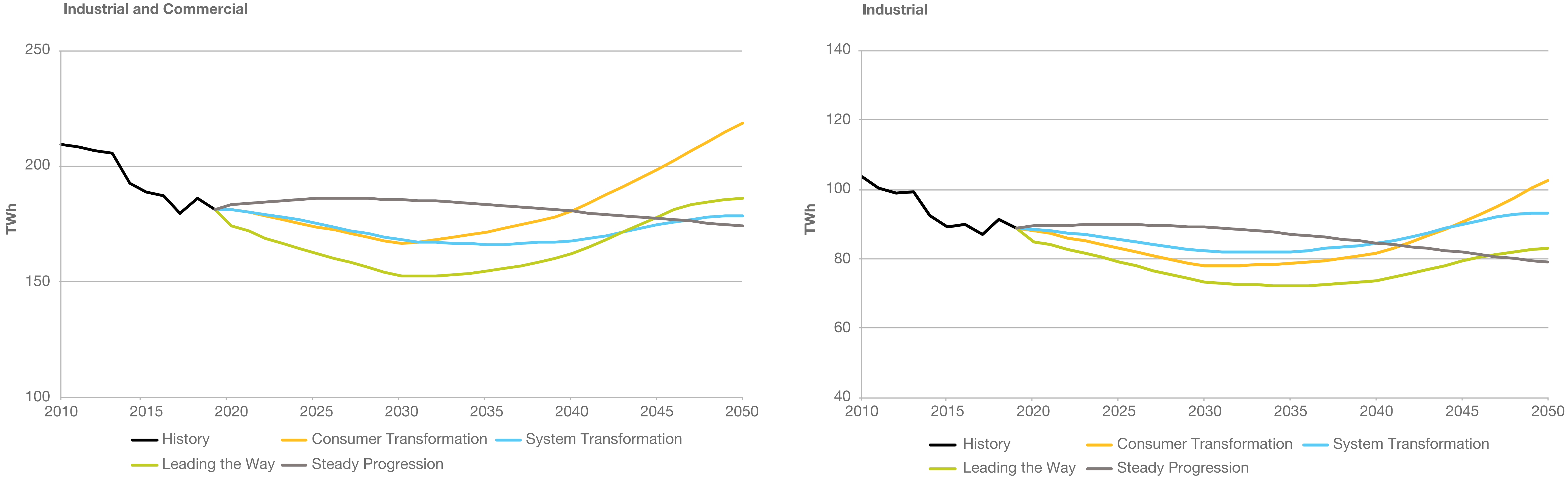
Steady Progression

The I&C sector only reduces electricity demand slightly by 2050 compared to today and natural gas demand remains the same. Energy prices are kept low and carbon pricing has not been included beyond the limited impact of the emissions trading scheme (i.e. the EU ETS). Most I&C customers continue to use energy in the same way. Energy efficiency is not actively pursued beyond incremental improvements to technology as older kit is replaced.

FES 2020 / Consumer view / Industrial and Commercial 36

What we've found

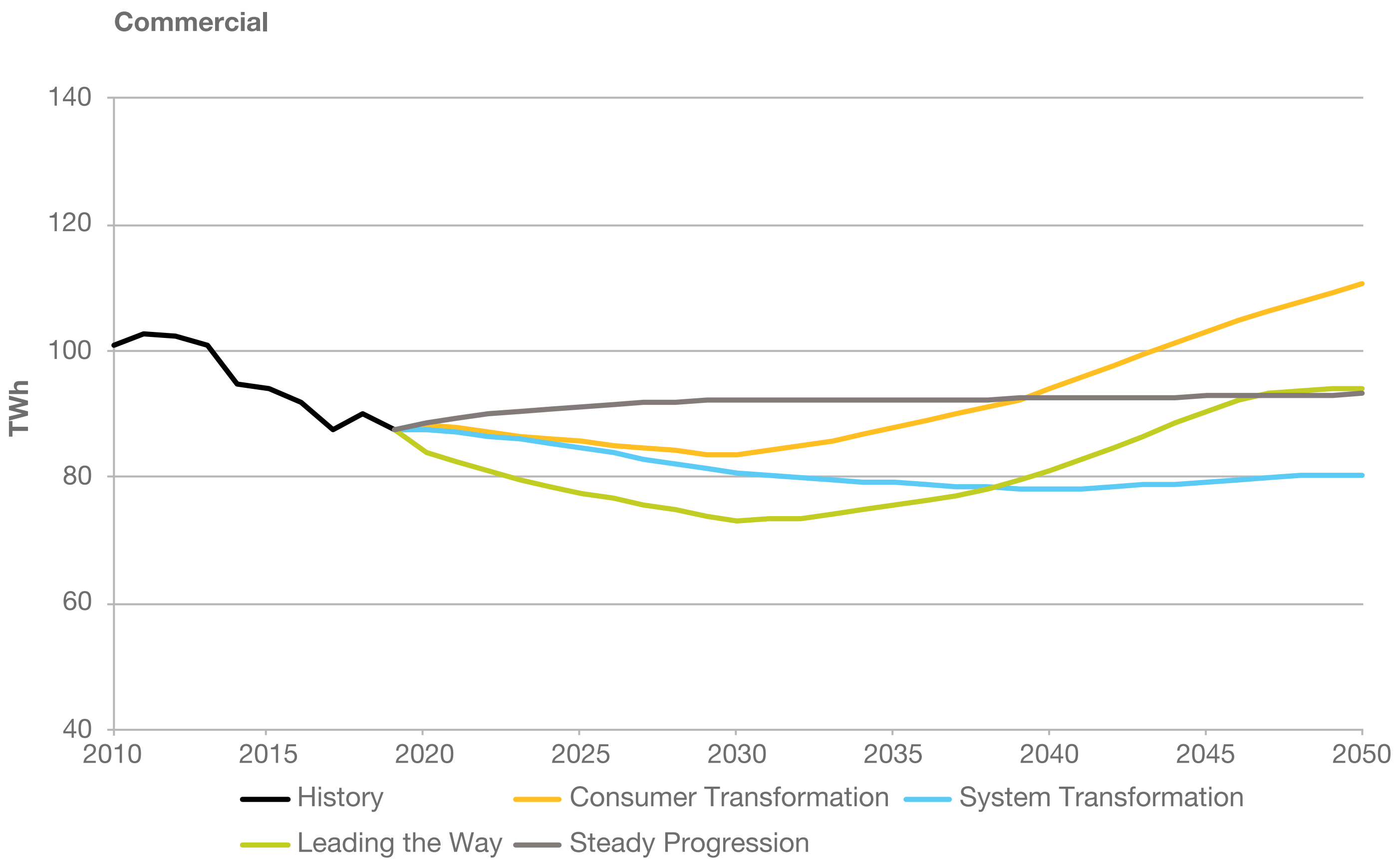
Figure CV.4: Annual electricity demand for the industrial and commercial sectors (excluding hydrogen production)



FES 2020 / Consumer view / Industrial and Commercial 37

What we've found

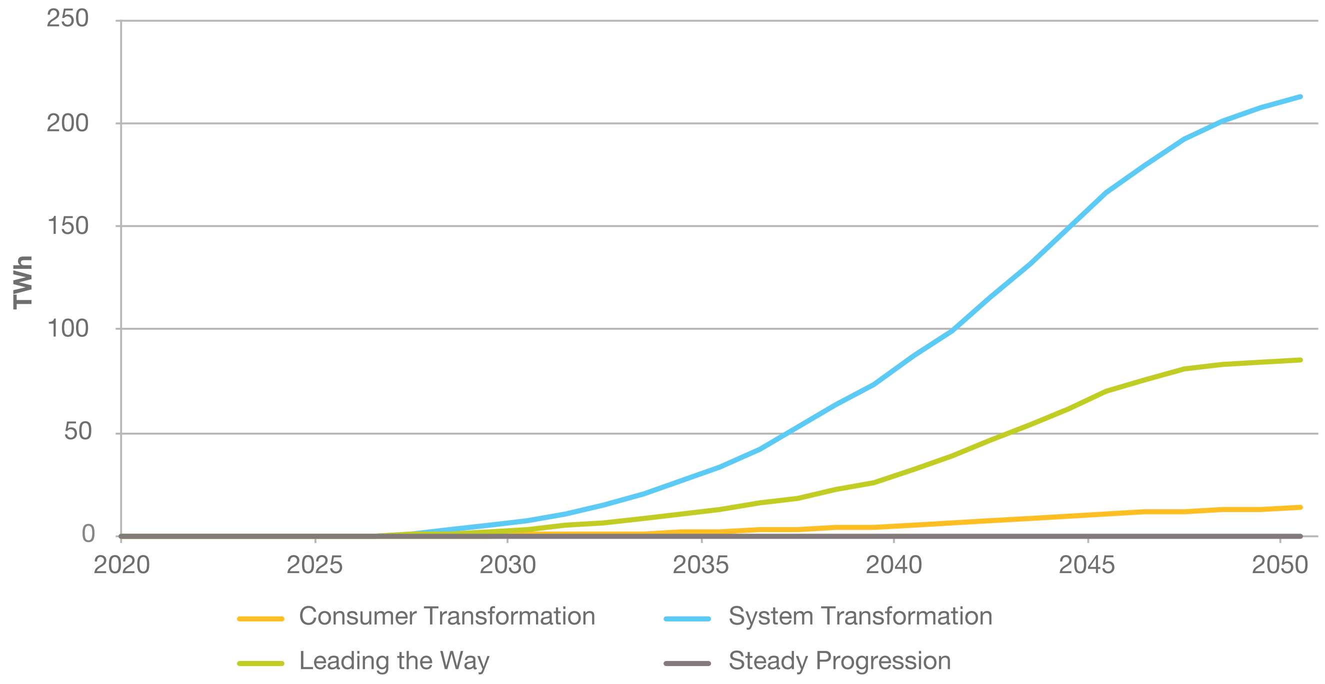
Figure CV.4: Annual electricity demand for the industrial and commercial sectors (excluding hydrogen production)

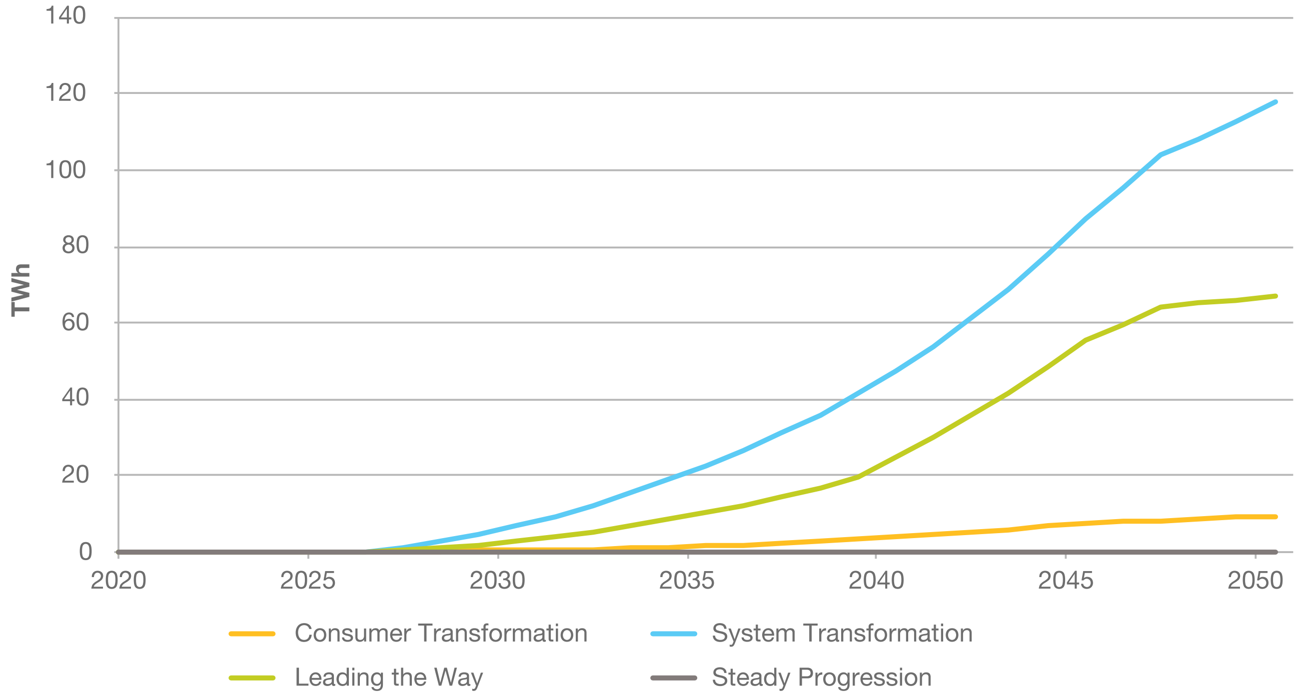


FES 2020 / Consumer view / Industrial and Commercial 38

What we've found

Figure CV.5: Annual hydrogen demand for the industrial and commercial sectors

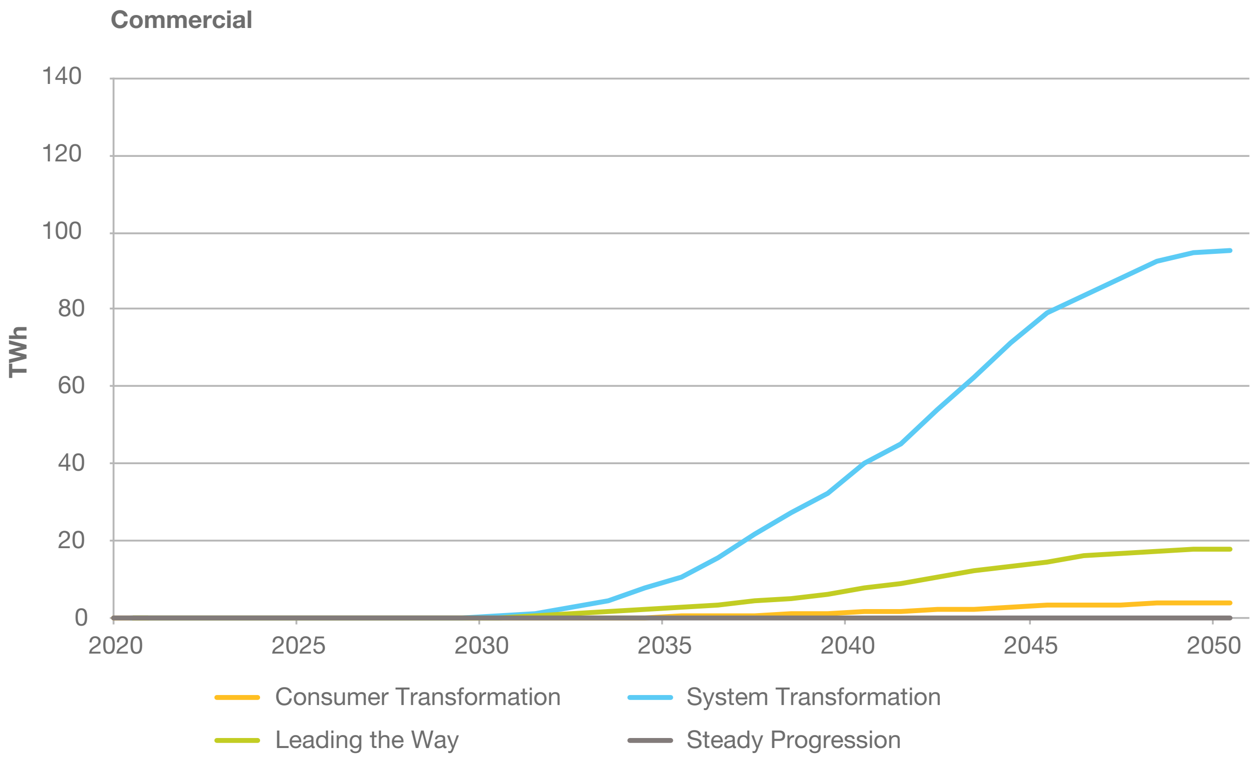




FES 2020 / Consumer view / Industrial and Commercial 39

What we've found

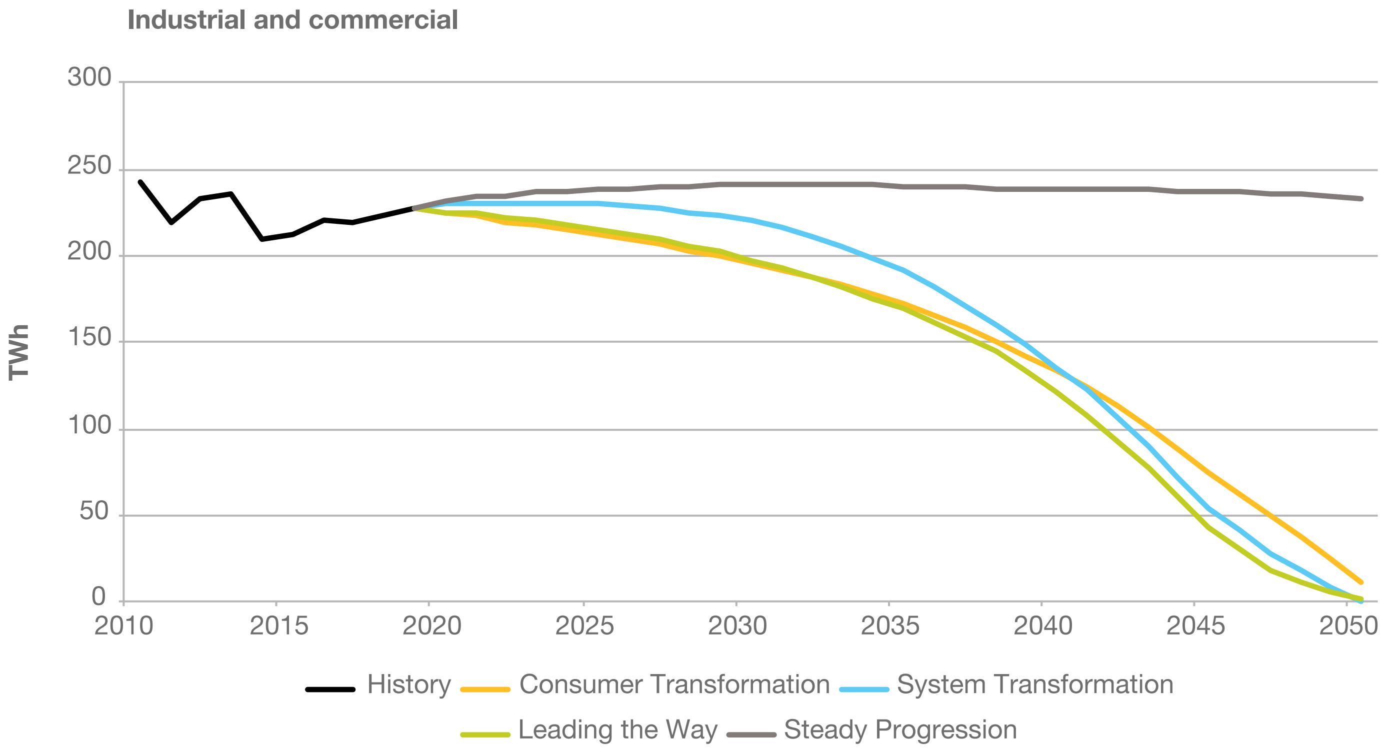
Figure CV.5: Annual hydrogen demand for the industrial and commercial sectors

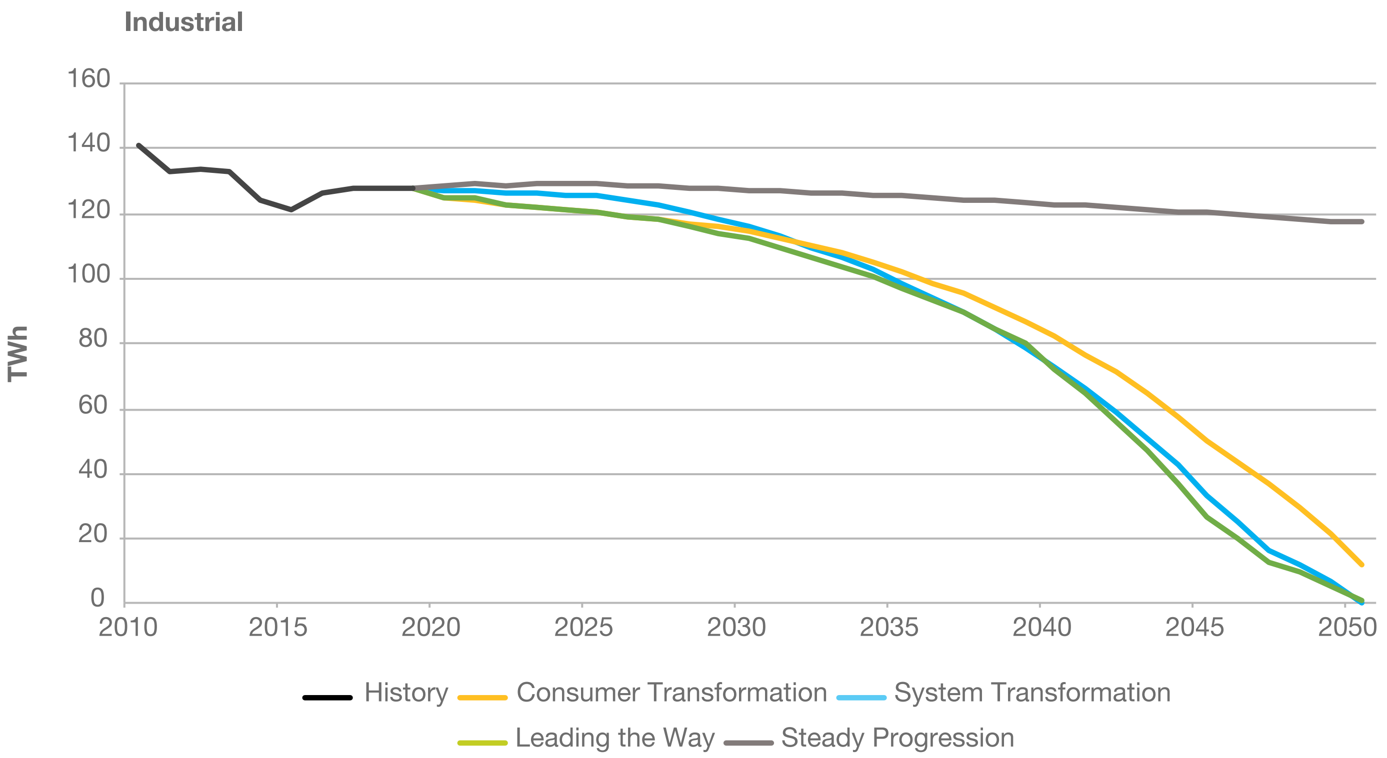


FES 2020 / Consumer view / Industrial and Commercial 40

What we've found

Figure CV.6: Annual natural gas demand for the industrial and commercial sectors

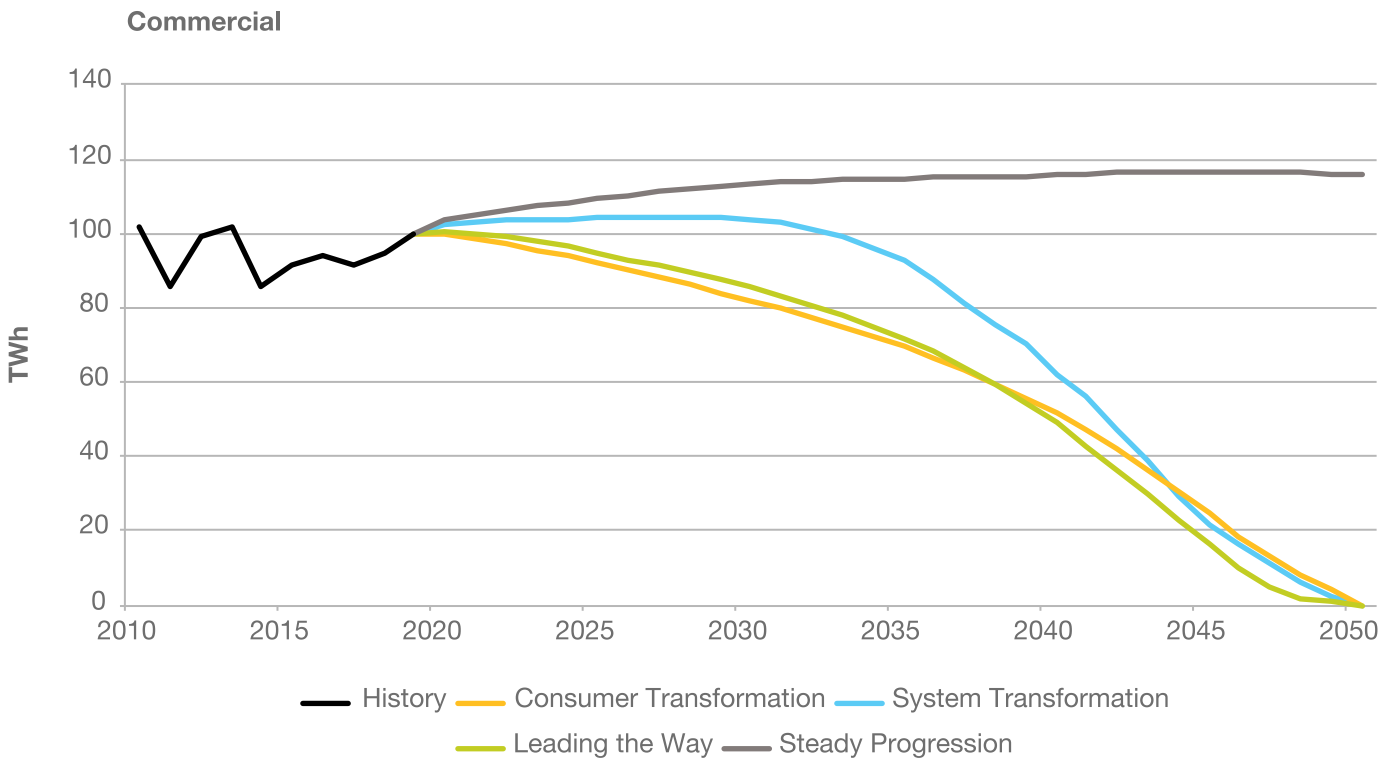




FES 2020 / Consumer view / Industrial and Commercial 41

What we've found

Figure CV.6: Annual natural gas demand for the industrial and commercial sectors



FES 2020 / Consumer view / Industrial and Commercial 42

Decarbonising industrial processes

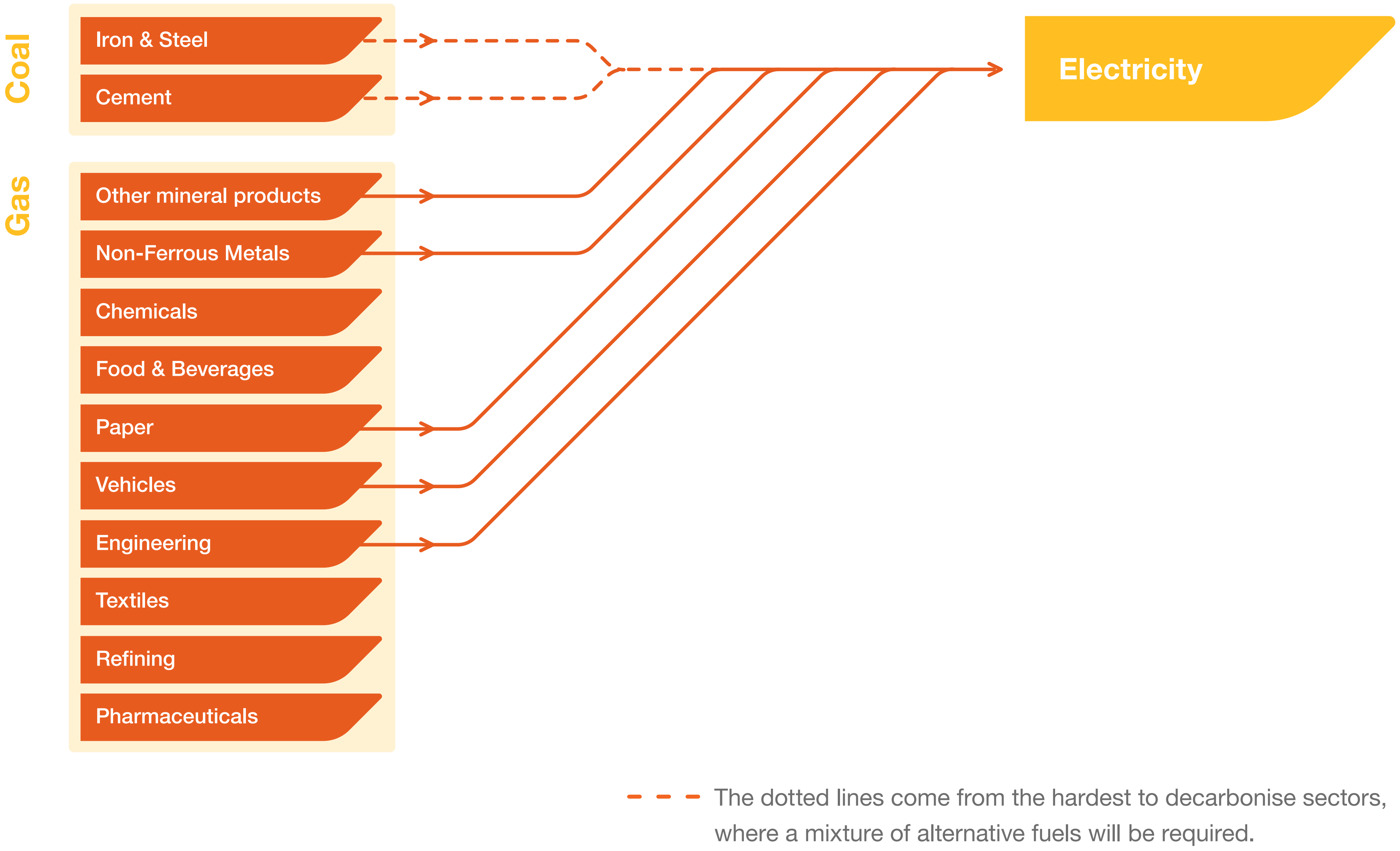
CO_2 emissions are unavoidable in some industrial processes

Unless alternative production methods are found (like for the production of clinker for cement), currently the only solution is to fit carbon capture and storage. This will require significant investment and possibly relocation to transport the carbon to somewhere suitable for storage or use.

Other industries can switch to hydrogen if they can connect to a hydrogen network. Depending on the scenario, this could be a re-purposed gas grid in **System Transformation** or in **Consumer Transformation**, connection to an industrial hub where hydrogen production, storage and CCUS are all located.

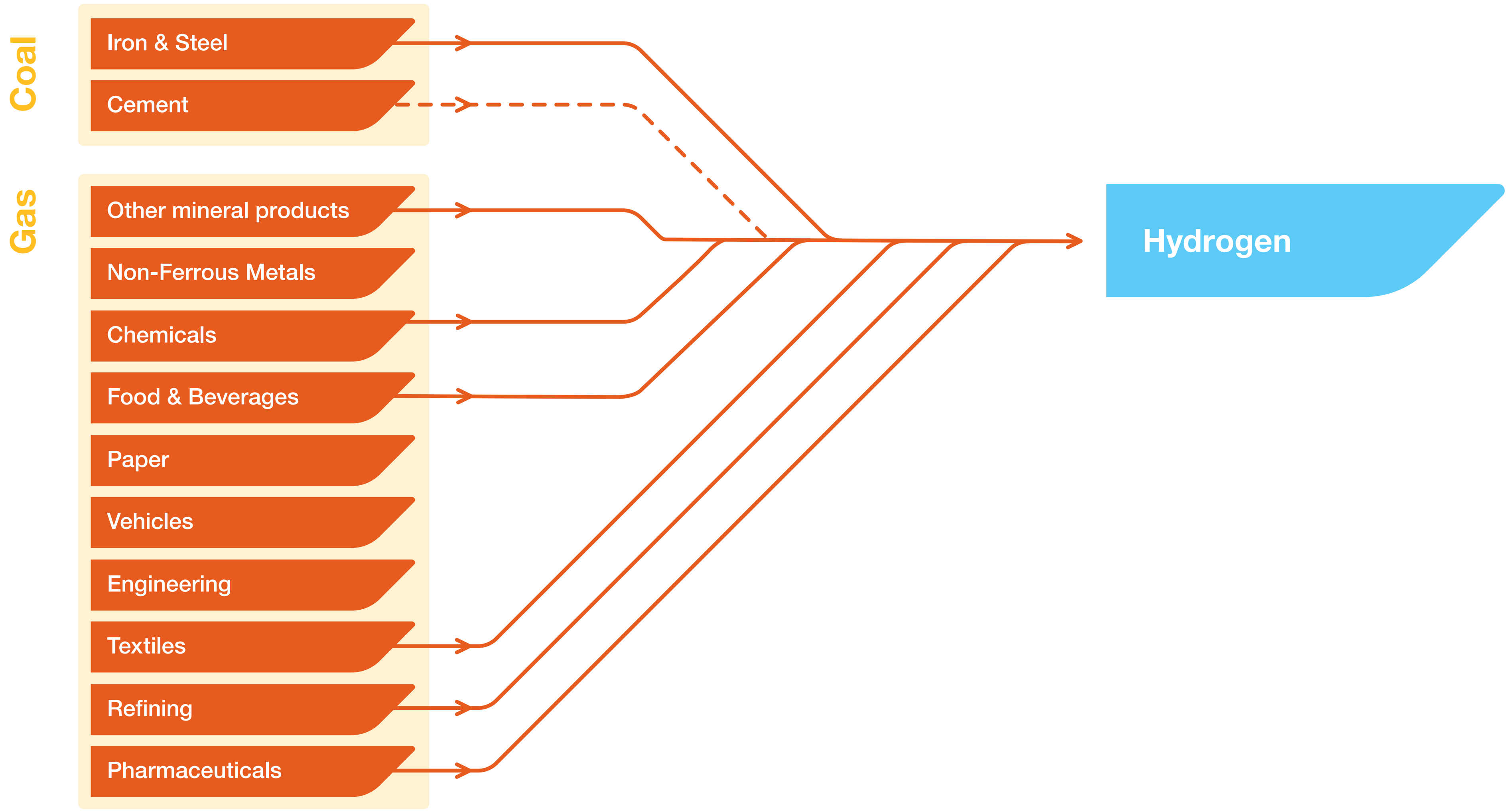
Finally, any industrial processes where the use of hydrogen is unsuitable will be electrified, for example in kilns for ceramics and cement manufacture.

Figure CV.7: Industrial fuel switching options for decarbonisation



FES 2020 / Consumer view / Industrial and Commercial 43

Figure CV.7: Industrial fuel switching options for decarbonisation

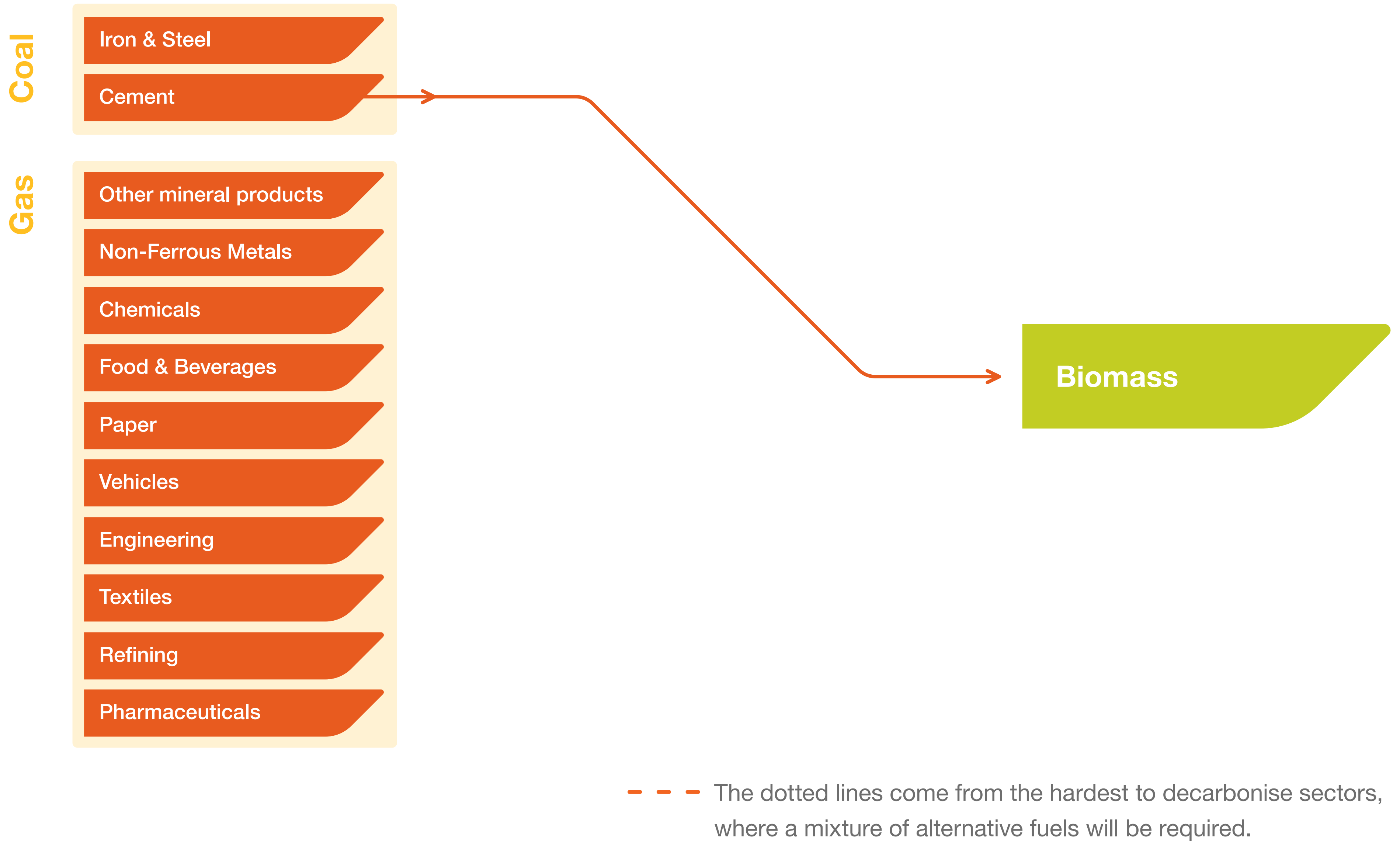


The dotted lines come from the hardest to decarbonise sectors, where a mixture of alternative fuels will be required.

FES 2020 / Consumer view / Industrial and Commercial 44

Decarbonising industrial processes

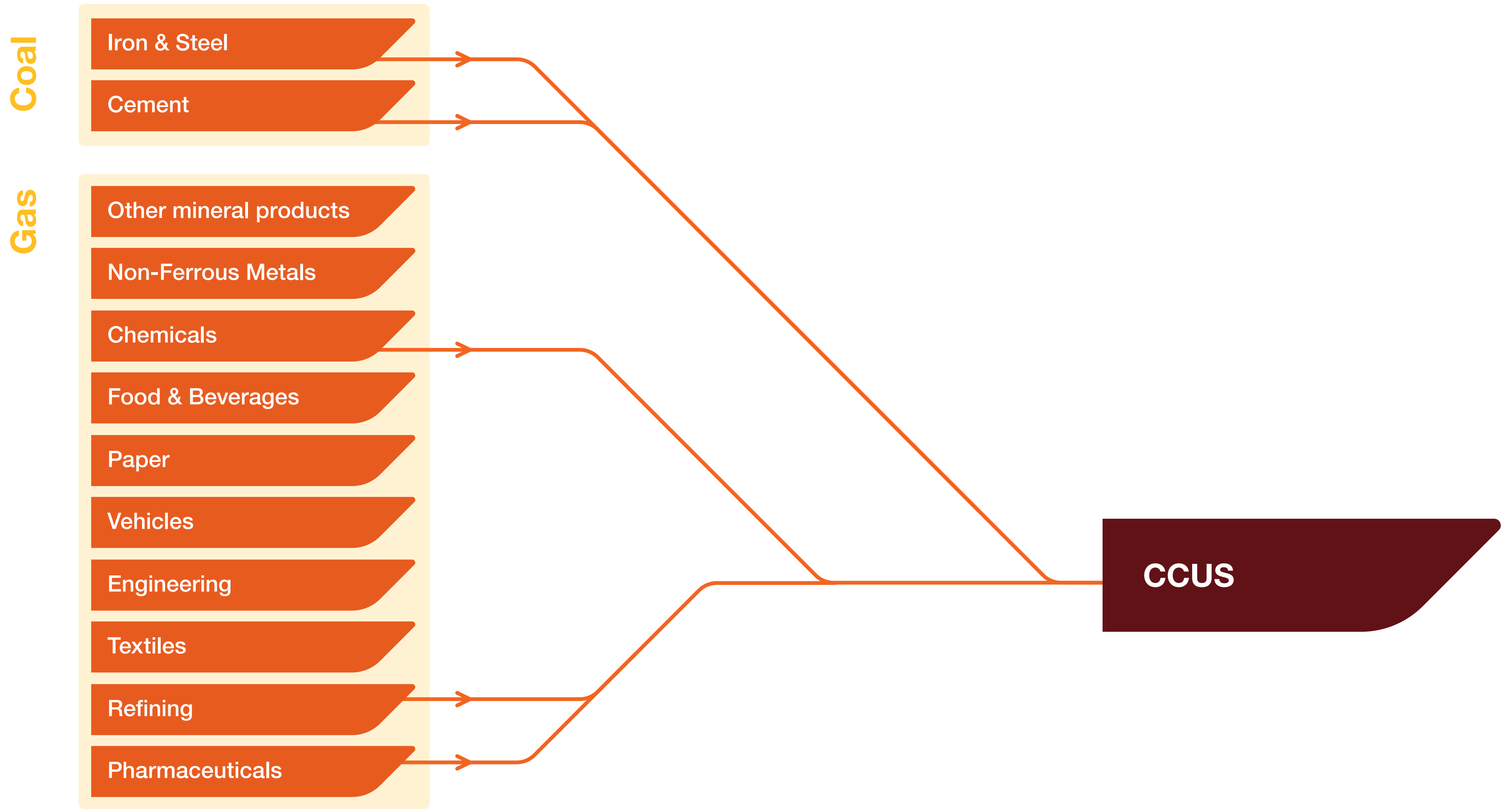
Figure CV.7: Industrial fuel switching options for decarbonisation



FES 2020 / Consumer view / Industrial and Commercial 45

Decarbonising industrial processes

Figure CV.7: Industrial fuel switching options for decarbonisation



The dotted lines come from the hardest to decarbonise sectors, where a mixture of alternative fuels will be required.

FES 2020 / Consumer view / Industrial and Commercial 46

Energy efficiency

Use of different fuels in the I&C sector is varied and there is no single solution to how energy can be used more efficiently.

Our modelling uses sensitivity to higher prices to encourage energy efficiency measures as a first step. With the highest level of consumer engagement, **Leading the Way** assumes higher energy prices in the early 2020s, combined with a sustained effort to improve energy efficiency through changes in behaviour and technology out to 2050. Along with **Consumer Transformation**, it meets the UK's Clean Growth Strategy target of a 20% increase in energy efficiency by 2030. **Leading the Way** in fact goes further and achieves a 25% increase by 2030. Achieving this target means replacing equipment before the end of its life.

System Transformation achieves this 20% target only by 2050, relying on hydrogen to decarbonise and some energy efficiency activity (i.e. only replacing equipment with a more efficient model once it has come to the end of its life). In **Steady Progression**, energy efficiency activity is minimal and the energy efficiency target is not met by 2050.

Both industrial and commercial sectors have opportunities for simple energy efficiency measures, such as LED lighting and changes to heating systems. Energy intensive industries also have more complex needs, which may require more difficult changes. Examples of new technologies which could improve efficiency and the switch from high carbon fuels include:

- Electric plasma gas heaters for iron and cement processes;
- Hydrogen boilers in the food and drink, chemical, and paper industries;
- Microwave heaters for ceramics.

Commercial organisations tend to have simpler energy needs. Electricity is needed for lighting, appliances and heating and cooling, all of which can use less energy with more efficient technologies. Heating demand, whether met by electricity or natural gas, can also be reduced by improving insulation. For agriculture (which we include in our analysis of this sector), focus needs to be on using energy efficient machinery and avoiding diesel as a fuel for farm vehicles.

FES 2020 / Consumer view / Industrial and Commercial 47

Data Centres
Our changing lives are changing demand

It is hard to remember life without the internet or without mobile phones, tablets and computers. Online services such as on demand TV, music, video calling, maps, file sharing, mobility services, and retail require data which need to be physically processed and stored. As we progress to 2050, data requirements and the number of data centres will grow.

Our research indicates an almost 70% growth in the communication sector, equating to at least an equivalent increase in demand for data centres between now and 2050, for which energy will be required to run the servers and for cooling.

In **Consumer Transformation** and **Leading the Way**, any excess heat from cooling is re-used in a heat network, but this can only work when data centres are located close to suitable areas.

> Our research indicates an almost 70% growth in the communication sector

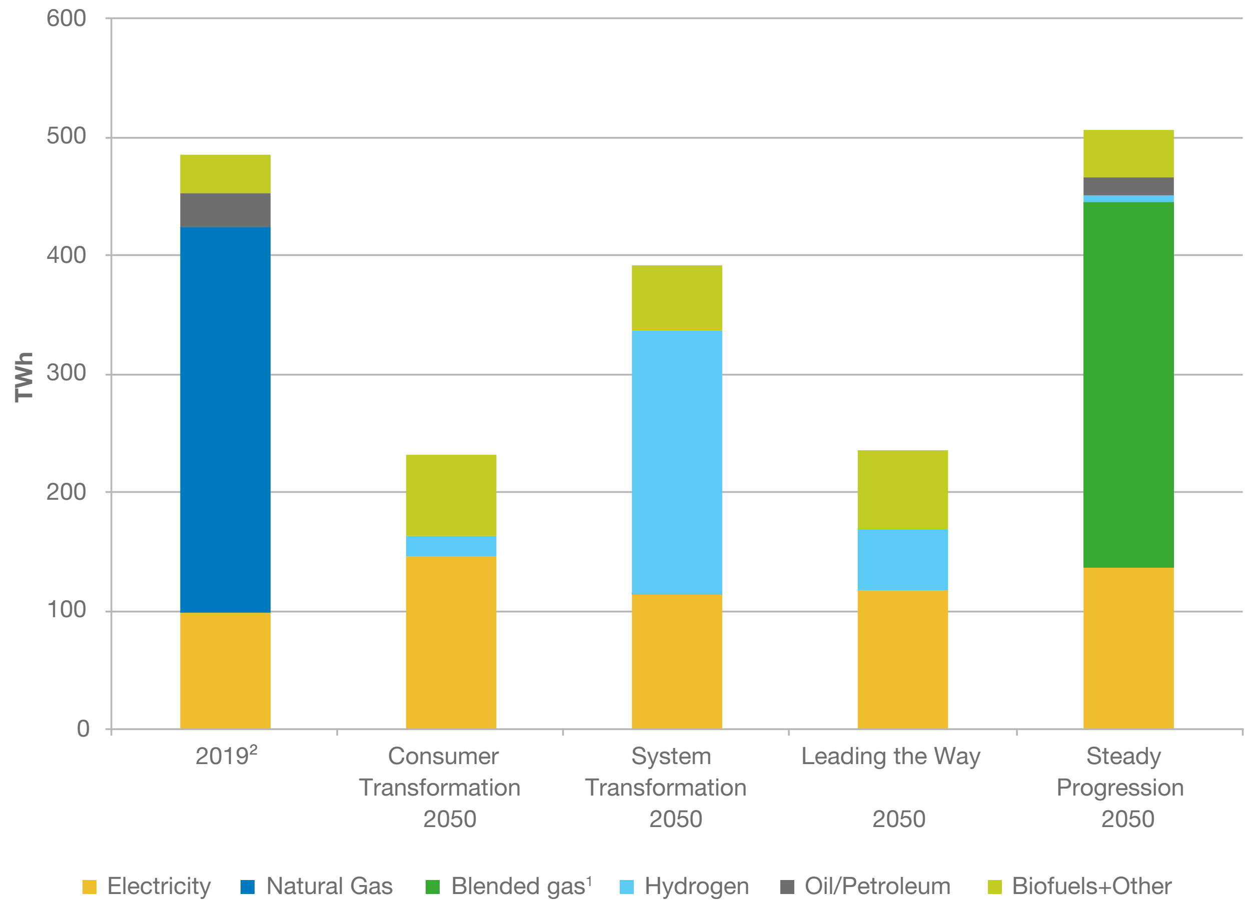
FES 2020 / Consumer view / Industrial and Commercial 48

Residential

Key insights

- For net zero, all GB homes need to improve their energy efficiency through better insulation and by more energy efficient appliances. This reduces overall energy demand and will enhance the operation of heat pumps, if fitted.
- Natural gas boilers are not part of a net zero world. Homes with natural gas boilers today will need to switch by 2050 in our net zero scenarios.
- Changes to decarbonise residential heating will need government action to support the installation of low and zero carbon heating. In both **Consumer Transformation** and **Leading the Way**, the sale of natural gas boilers is assumed to end in 2035.
- Decarbonising the residential sector will require coordinated behavioural change at an individual level. This means encouraging consumers to upgrade their homes' insulation, to choose energy efficient technology and to operate appliances 'smartly' – when electricity is in least demand. Many of these choices are interdependent (for example, heating technology and level of insulation).
- The energy required for residential heating in a net zero world could be over 50% lower by using high levels of insulation and electric heat pumps (**Consumer Transformation**) rather than hydrogen boilers (**System Transformation**). Better insulation contributes one-third of the reduction, two-thirds is down to heat pumps.

Figure CV.8: Annual residential energy demand (for heat and appliances) in 2050



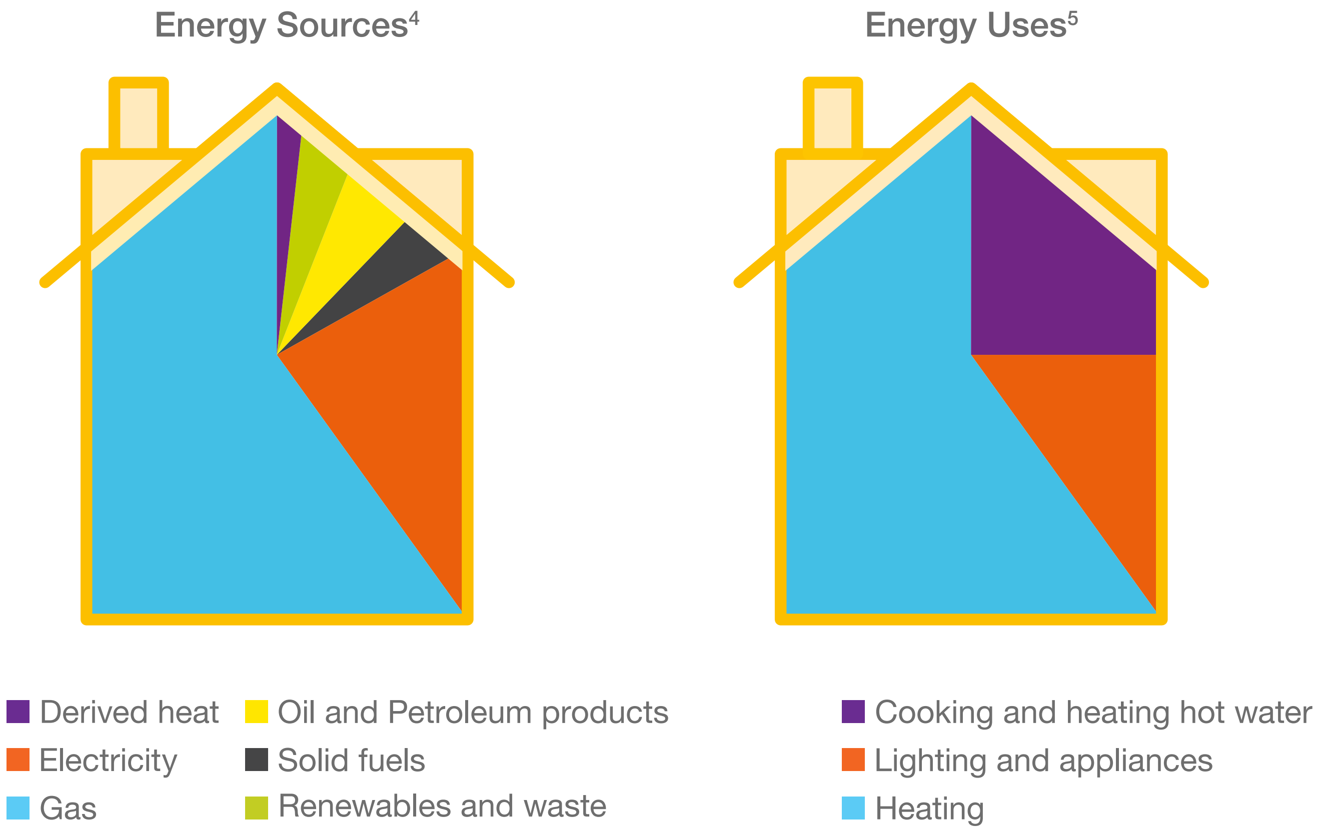
1 In Steady Progression, any natural gas is assumed to be blended with low levels of hydrogen and biomethane, to lower its carbon intensity.
2 The 2019 data is primarily made up of our modelled data for natural gas and electricity. However, some 2018 demand data from ECUK was used in order to provide a complete, whole system view of end consumer demand.
2018 Data taken from ECUK, Consumption Data Tables: www.gov.uk/government/statistics/energy-consumption-in-the-uk

FES 2020 / Consumer view / Residential 50

Where are we now?

Currently, residential demand for electricity and natural gas from the UK's 29.1 million homes makes up almost 15% of the UK's total carbon emissions[3], consuming approximately 415 TWh/annum. On average, each home is responsible for emitting four tonnes of CO_2 each year, predominantly through how the home is heated and from numerous electrical appliances, ranging from dishwashers and washing machines to TVs and tablets.

Figure CV.9: Energy sources and uses in a typical British home



3 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/790626/2018-provisional-emissions-statistics-report.pdf
4 2018 Data taken from ECUK, Consumption Data Tables: www.gov.uk/government/statistics/energy-consumption-in-the-uk
5 https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_consumption_in_households#Energy_consumption_in_households_by_type_of_end-use%20using%20data%20work%20book

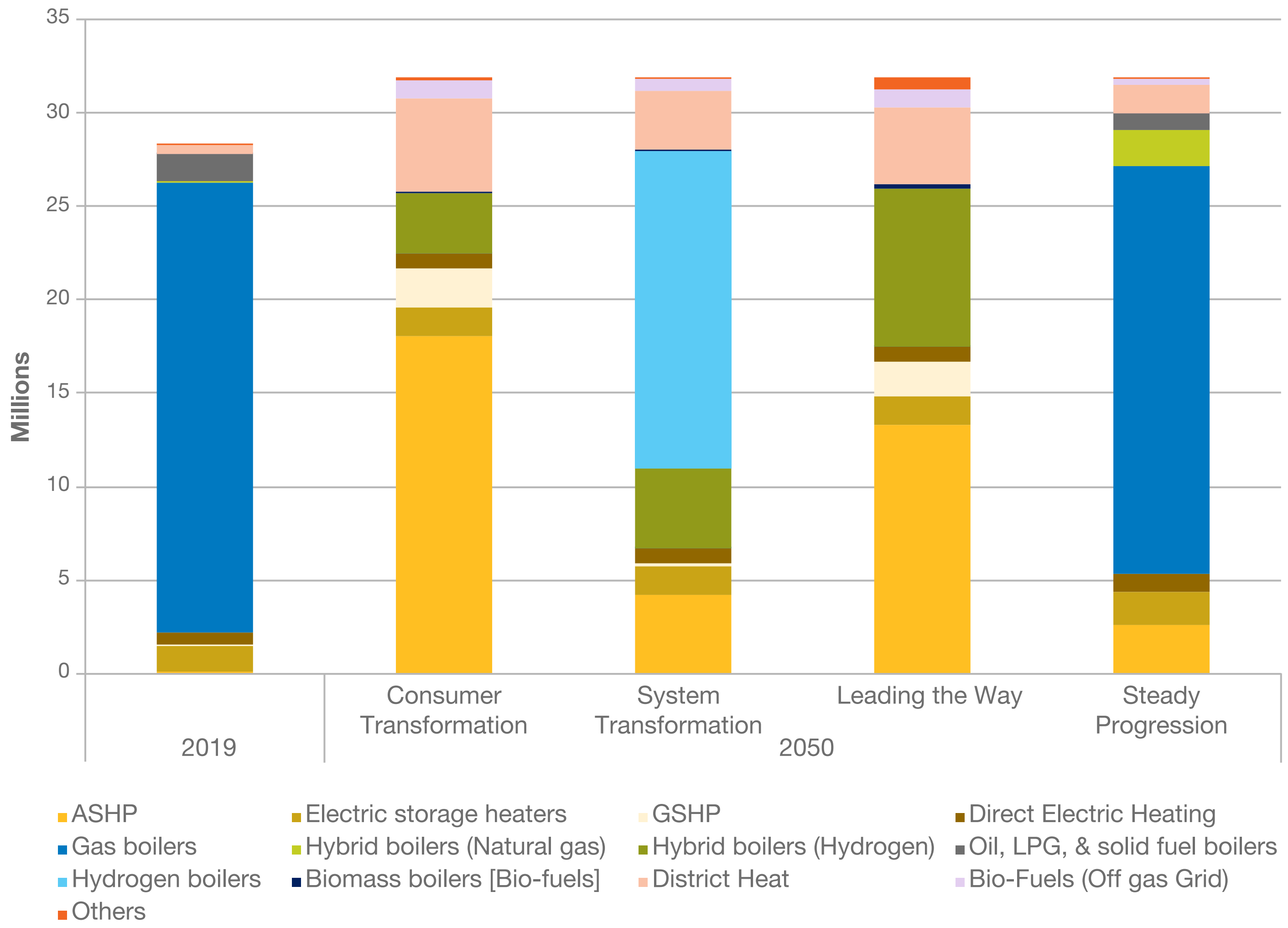
FES 2020 / Consumer view / Residential 51

What we've found

For residential heating, our net zero scenarios use either predominantly hydrogen boilers for heating (**System Transformation**), electric heat pumps (**Consumer Transformation**) or a mix of both, using hybrid heating systems (**Leading the Way**). The number of homes heated by electricity more than doubles by 2050 in all scenarios, with almost four times as many in **Consumer Transformation**. However, this does not mean an equivalent increase in energy demand, as the greater use of electric heat pumps means much less energy is required, due to their higher efficiency.

In **System Transformation**, hydrogen replaces natural gas in most cases for heating and cooking, using boilers with similar efficiency to today's natural gas boilers. The supply of hydrogen is explored in more depth in the System View chapter *(See page 82)*. In **Leading the Way**, overall energy demand for heating is higher than in **Consumer Transformation** as there are more hybrid heat pumps and hydrogen boilers.

Figure CV.10: Overall home heating technology mix in 2050



FES 2020 / Consumer view / Residential 52

What we've found

Hydrogen Boiler

Hydrogen Boiler

Hydrogen has one distinct advantage over a heat pump – it provides high energy heat, around which most homes' heating systems are already designed. However, changes are needed before we can switch over to hydrogen. Our current boilers cannot burn hydrogen safely without modifications to the burner. Changing the burner or the entire boiler (to either a hydrogen or hydrogen ready boiler) can be done relatively quickly. In comparison, a heat pump requires changes to the radiators and to the insulation levels to operate effectively. While more insulation is advisable, swapping the burner or boiler is the only change necessary to make hydrogen a suitable, decarbonised alternative. There are many other changes needed, in terms of how hydrogen is produced and transported around the country as well as how it is billed. But, for the natural gas consumer, it offers the least disruption to their home to meet net zero.

Electric Heat Pumps

Electric Heat Pumps

Heat pumps are not a new technology and are common in countries like Sweden, where there is a ready supply of renewable electricity (in the form of hydropower). Heat pumps are very energy efficient; for each kWh of electricity they consume, they deliver about 3 kWh of thermal energy. At maximum efficiency, they produce lower flow temperature (for example 45 degrees C) than a typical gas boiler in the UK (70 degrees C). This means the heating system is more likely to be underfloor or use larger radiator panels. It also means the house needs to be well insulated. Over time and with the incentive of a very cold climate, homes in Sweden are now well insulated and work well with heat pumps. In fact, over 80% of heating in Swedish homes is from low carbon or renewable sources.

So, why don't we all have them? Homes designed to have a heating system based around a gas boiler are not simple to adapt to a heat pump. This would involve first insulating the home well, possibly changing windows and doors. Then radiators would likely need to be replaced with larger ones compatible with a heat pump or with underfloor heating. All these changes will come at a cost. When this is multiplied by the approximately 28.5 million homes, the cost is significant. Heat pumps are also fairly large units (compared to a regular natural gas boiler), which need to be wall mounted on the exterior of a home or placed in the garden. Air source heat pumps are normally installed outside, on a wall or the floor, while ground source heat pumps need space outside for a long loop of pipe underground.

FES 2020 / Consumer view / Residential 53

What we've found

For each scenario, we have assumed improvements in energy efficiency in almost every home for both buildings and appliances.

While the level of insulation required varies at house level in each scenario, the overall scale of the challenge to improve every home's energy efficiency is similar across the scenarios. **Consumer Transformation** and **Leading the Way** assume the most ambitious home insulation levels, with all existing homes retrofitted to their maximum potential. We have assumed government support for a nationwide improvement programme to significantly increase the rate of retrofits from current levels.

Figure CV.11: Networked fuel mix for heating homes in 2050

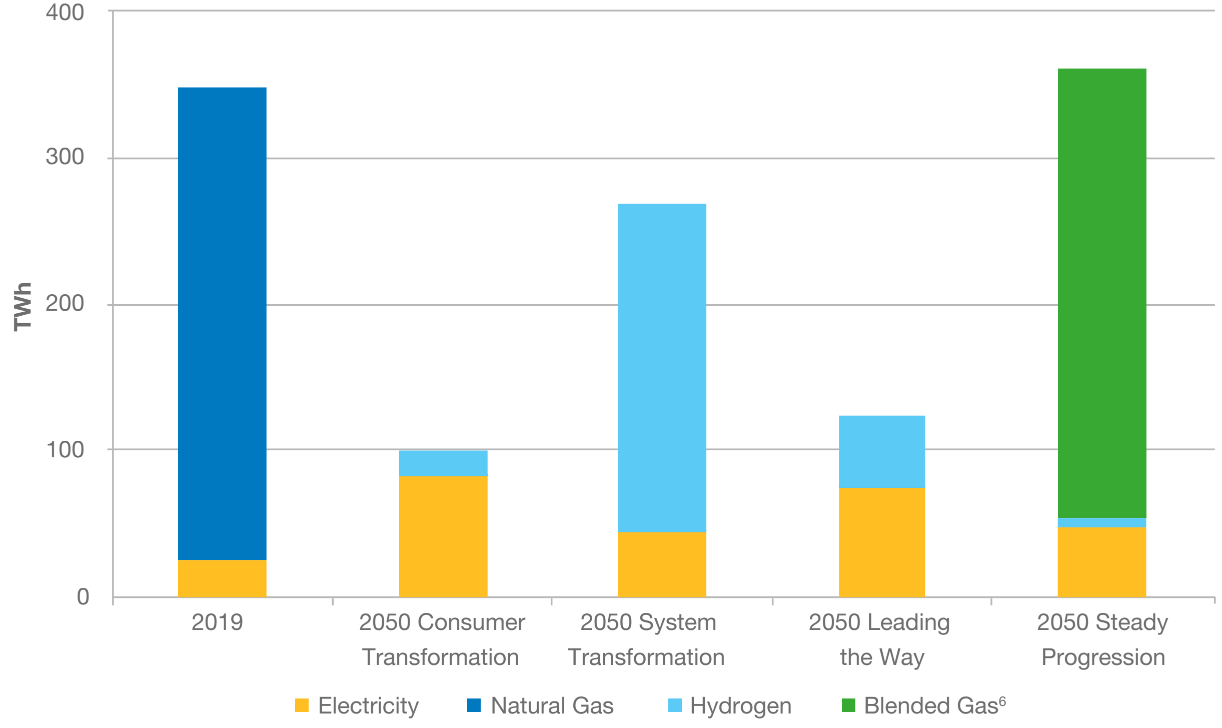


Figure CV.12: Annual electricity demand for heating homes

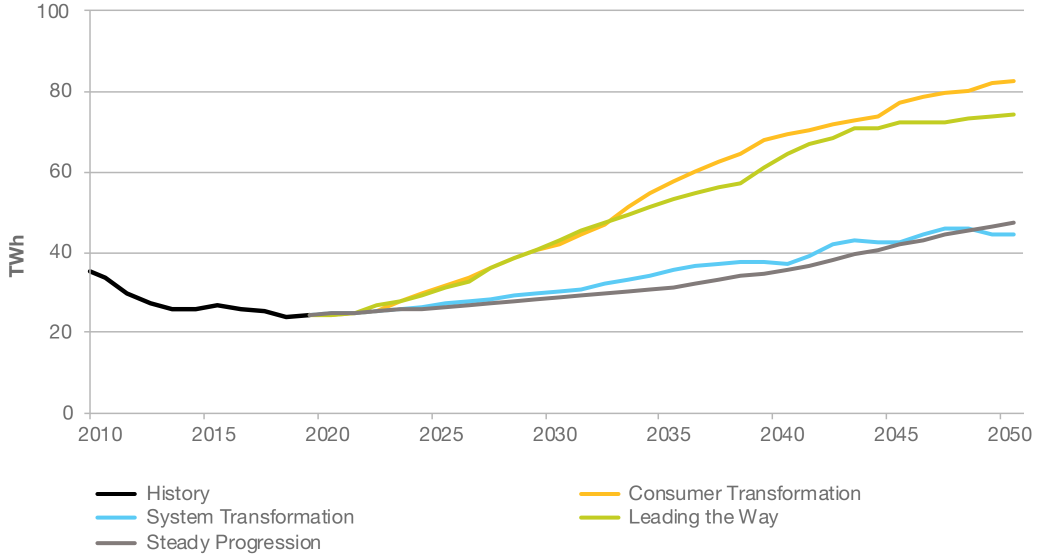
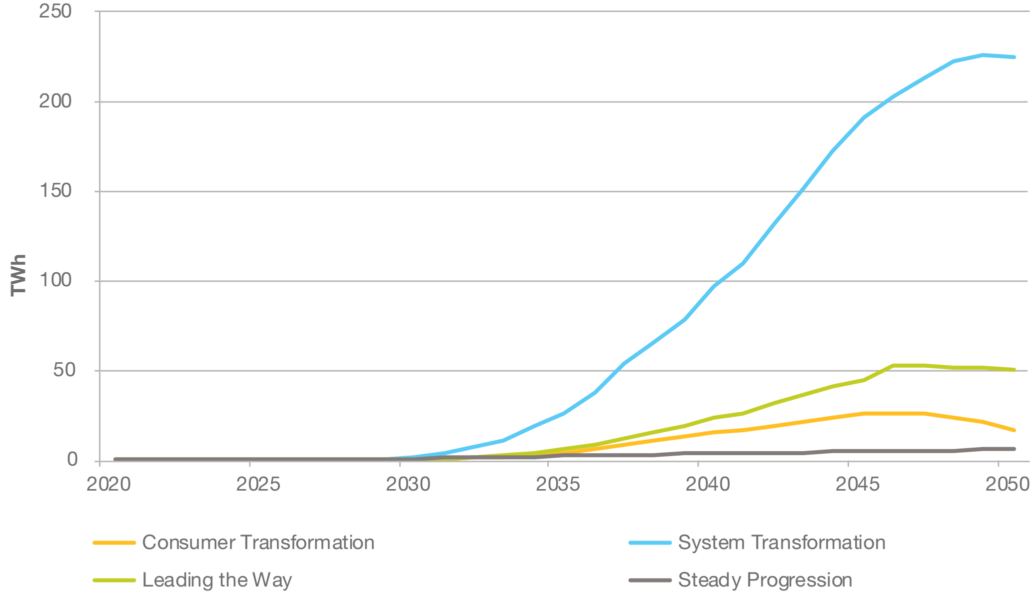
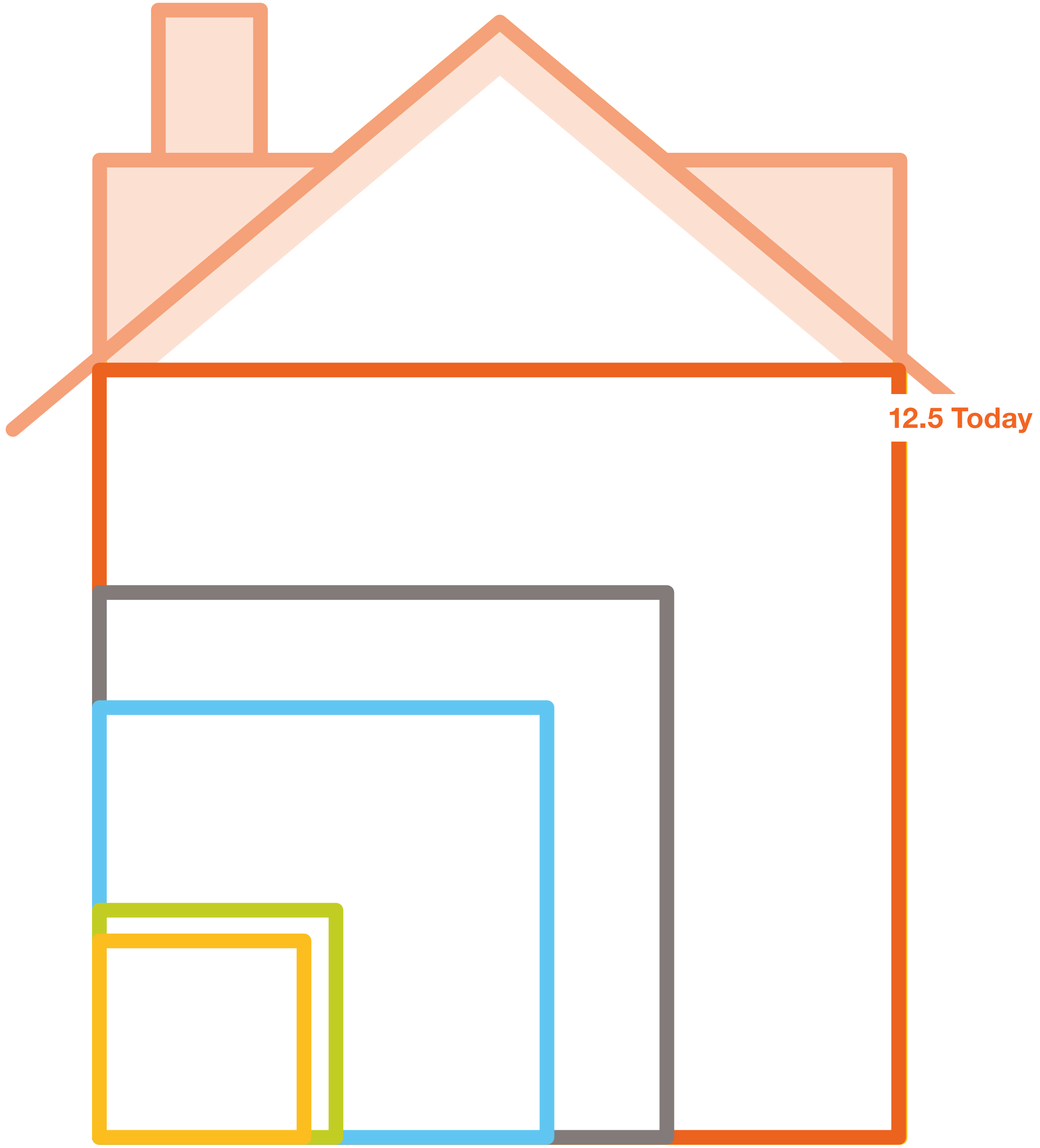


Figure CV.13: Annual hydrogen demand for heating homes



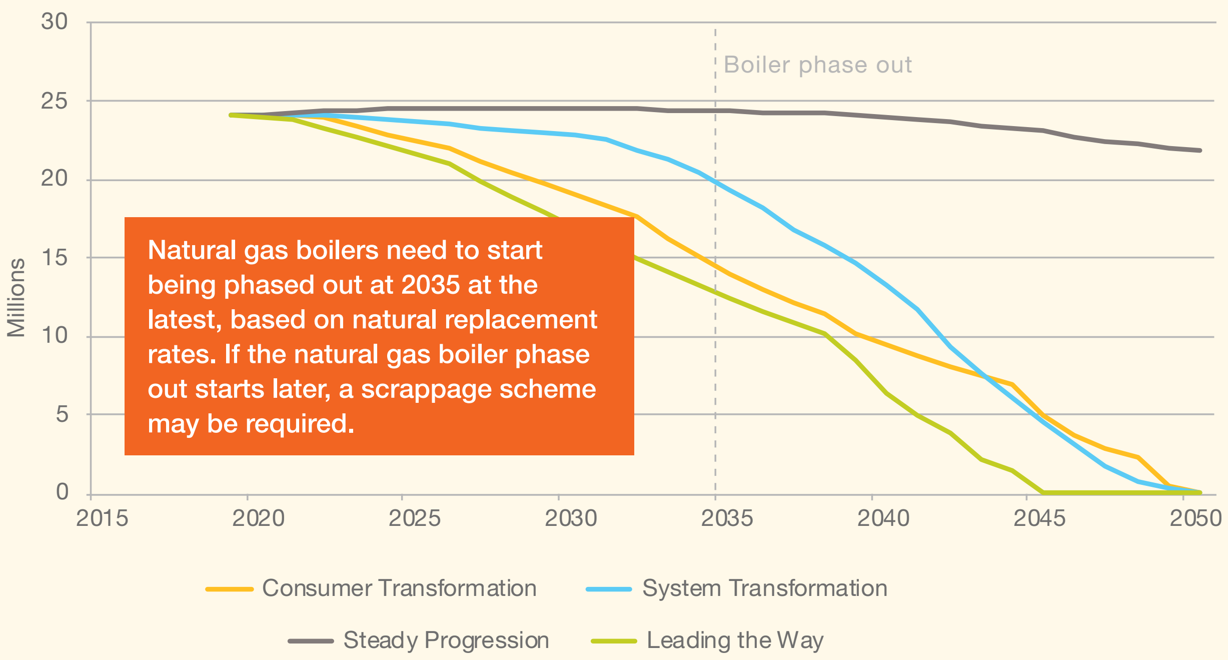
6 In Steady Progression, any natural gas is assumed to be blended with low levels of hydrogen and biomethane, to lower its carbon intensity.

Figure CV.14: Average energy demand required by household heating appliances in 2050 (MWh/annum)



Natural gas boilers for hot water and heating are phased out over time to 2050, with hydrogen boilers, heat pumps, or district heat connections increasing to meet this demand. In our two most electrified scenarios, Consumer Transformation and Leading the Way, no new natural gas boilers will be sold after 2035.

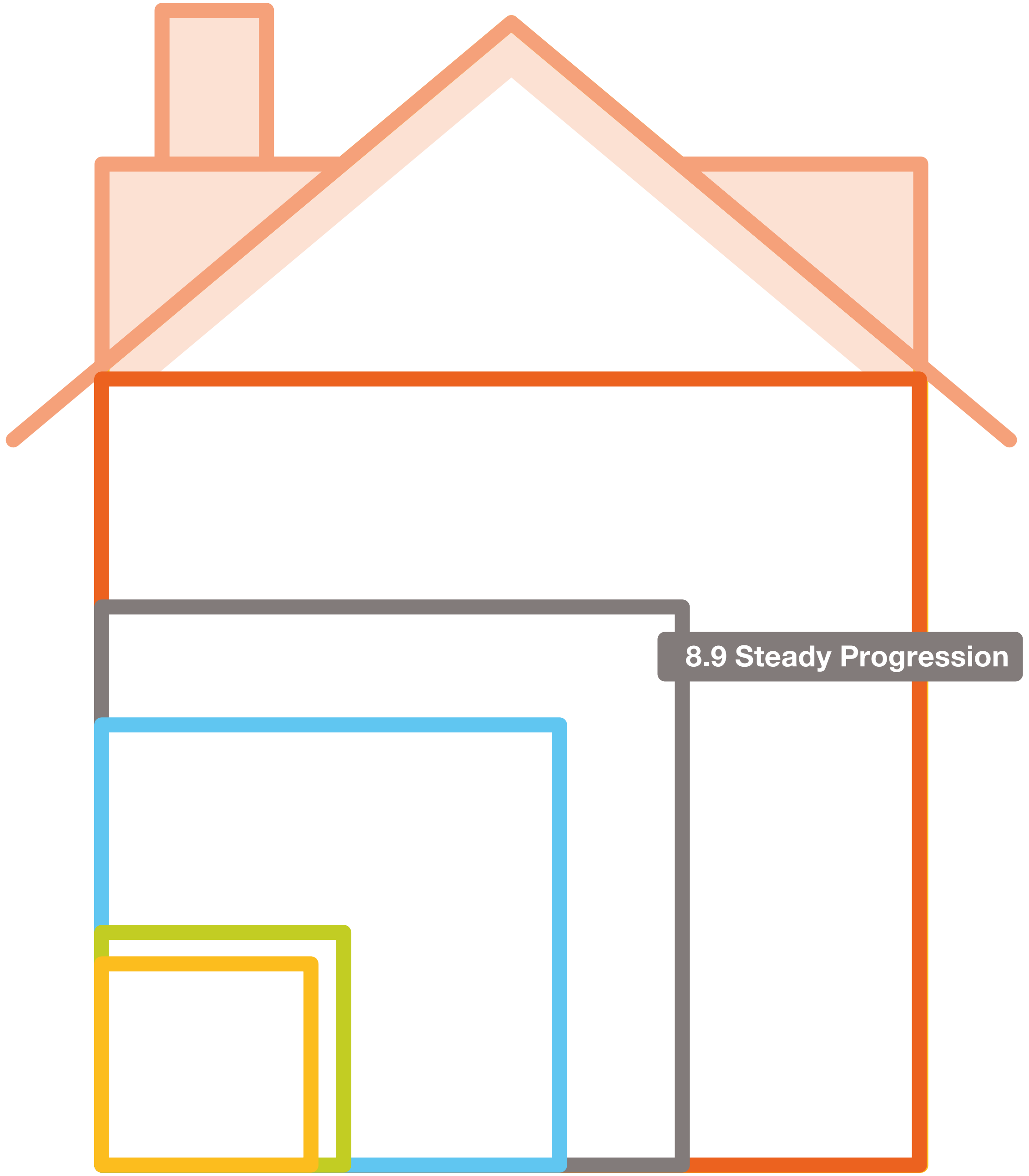
Figure CV.15: Number of gas boilers installed in homes



Note: phasing out does not occur in Steady Progression and in System Transformation, natural gas boilers would be replaced by hydrogen ready boilers or retrofitted with hydrogen burners.

FES 2020 / Consumer view / Residential 55

Figure CV.14: Average energy demand required by household heating appliances in 2050 (MWh/annum)

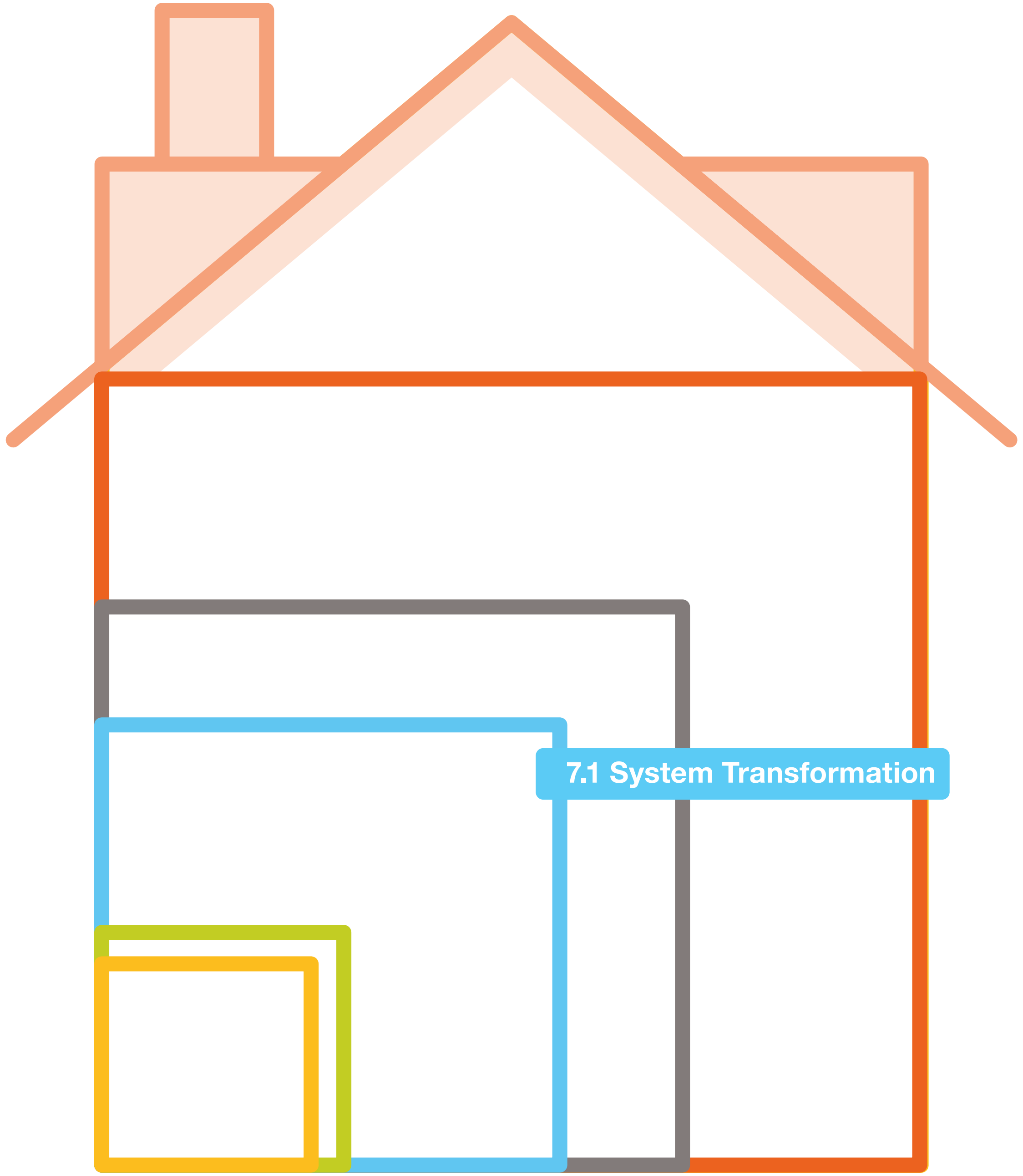


Steady Progression

Improved thermal efficiency is down to some improved insulation on homes and energy efficient natural gas boilers replacing older ones.

FES 2020 / Consumer view / Residential 56

Figure CV.14: Average energy demand required by household heating appliances in 2050 (MWh/annum)

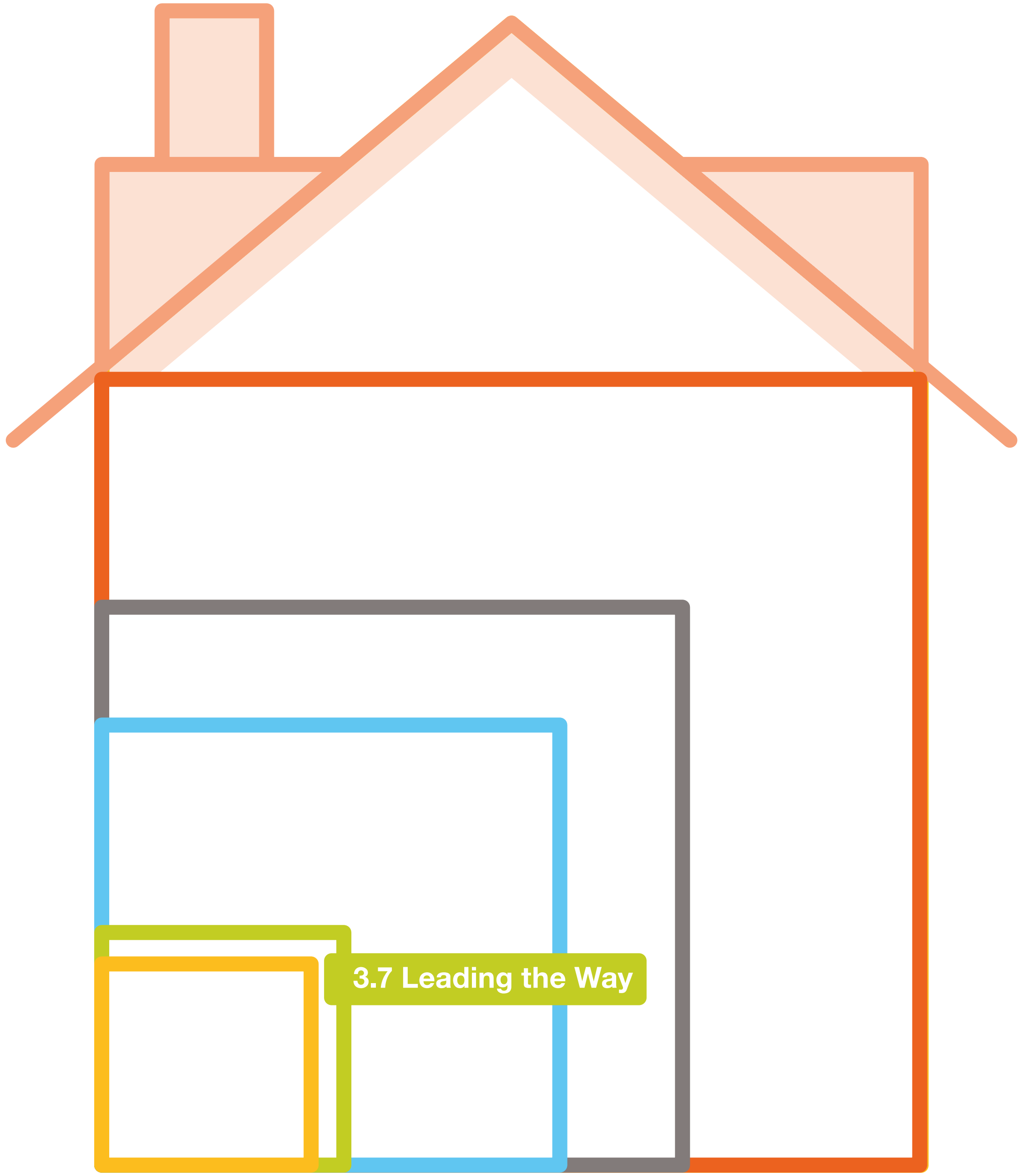


System Transformation

Average thermal efficiency in homes is improved by additional insulation to help reduce demand for hydrogen as well as fitting very energy efficient hydrogen boilers.

FES 2020 / Consumer view / Residential 57

Figure CV.14: Average energy demand required by household heating appliances in 2050 (MWh/annum)

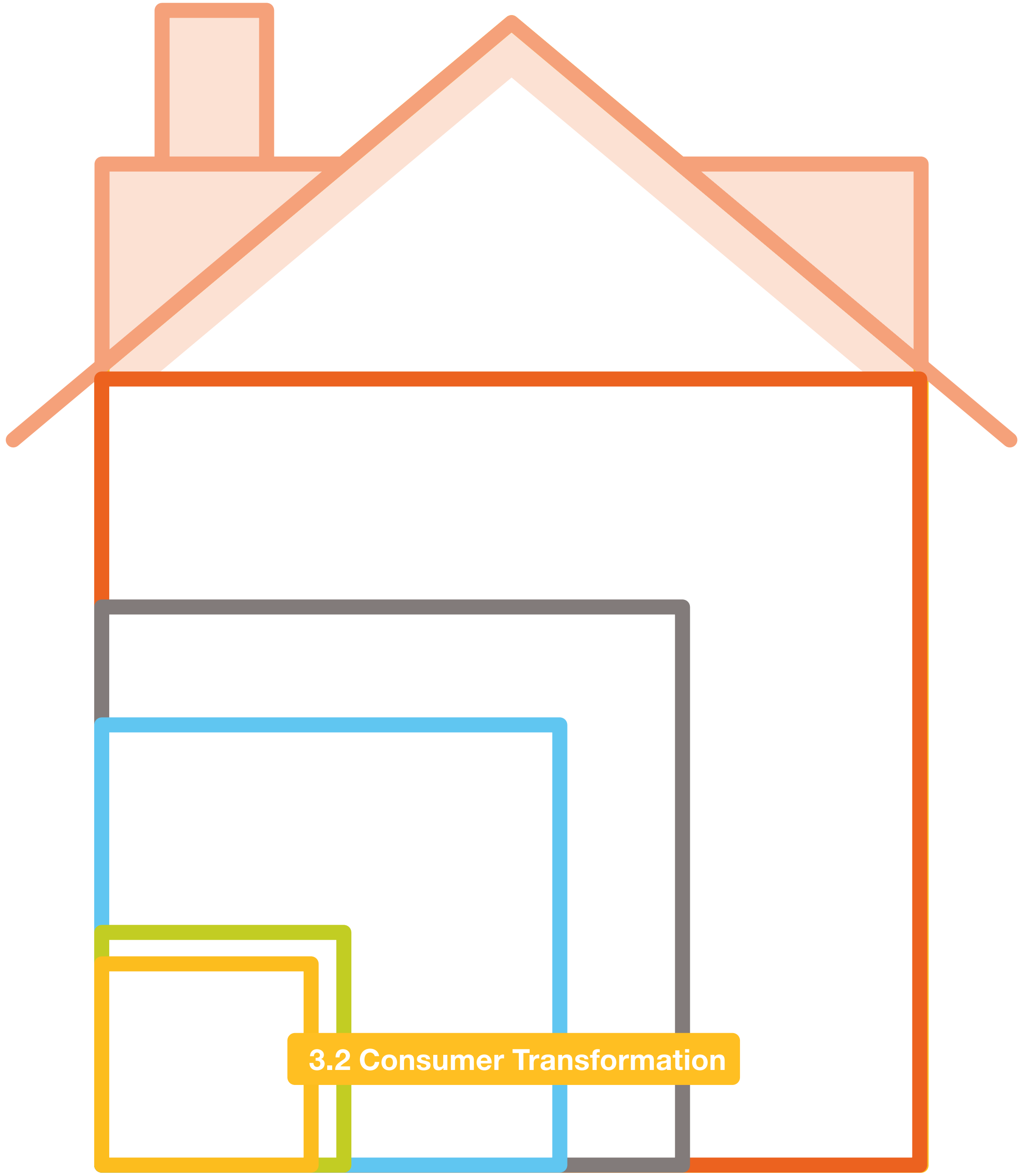


Leading the Way

High levels of insulation reduce the overall energy demand. However, as the dominant heating system is a hybrid heating system, with a mix of an electric heat pump and a hydrogen boiler, the energy demand is slightly higher than in CT with just a heat pump.

FES 2020 / Consumer view / Residential 58

Figure CV.14: Average energy demand required by household heating appliances in 2050 (MWh/annum)



Consumer Transformation

The lowest energy demand for heating in CT is because the homes are the most improved in terms of insulation as well as having a heat pump fitted. Occupants are also heating their homes to slightly lower temperatures.

FES 2020 / Consumer view / Residential 59

Heat Demand

To help manage peak heat demand (See page 183), our thermal storage assumptions for households using heat pumps have changed in FES 2020.

We assume using thermal storage for space heating becomes much more common where there are electric heating solutions.

For **Consumer Transformation** and **Leading the Way**, we have assumed that 40% of homes with heat pumps (not hybrid solutions) will have thermal storage that supports heating. In **Consumer Transformation**, where there is the highest number of homes with heat pumps, this will be approximately 8.1 million homes. There are also 2.4 million homes with electric storage heating.

In **System Transformation**, 25% of homes with a heat pump will have thermal storage (approximately 1 million homes). The storage capacity per home is assumed to be between two and four hours of heat demand on a peak winter's day (approximately 8 kWh). This means these homes will require much less electricity for heating at peak times, reducing demand on the local and national network.

To facilitate this, price incentives will be given through time of use tariffs, which will already be used to promote smart charging of EVs. However, finding enough space for thermal storage will be difficult in some homes and will be reliant on new, high density solutions such as phase change materials to minimise the amount of space required.

Our modelling assumes changes to nearly every home in the UK. This includes **homes off the gas grid**, for example in rural areas and flats. Flats tend to be in urban areas, with a robust electricity supply network and already using electric heating.

For rural areas, the switch to decarbonisation is harder as there is no one obvious solution for homes on either oil, solid fuel or LPG. Heat pumps can work, if the home is well insulated and importantly, if it is cost effective to upgrade the local electricity network to cope with the increase in peak demand. However, this is often not the case, so we've assumed that biofuels will be available for some rural homes.

For **new homes** built between 2025 and 2050, which will account for 8% of housing stock in 2050, heating will be provided via either energy efficient electrical appliances or hydrogen in our scenarios. These homes will need to accommodate energy storage, have in-built solar PV generation and be able to charge an EV. Thermal storage will provide system flexibility when heat pumps are installed. These features will help the home provide flexibility to electricity network operators when they need to manage peak demand or intermittent renewable electricity generation. We have assumed that no new homes will be connected to the gas grid from 2025 in our two most electrified scenarios, **Leading the Way** and **Consumer Transformation**. In **System Transformation**, new homes continue to be connected to the gas grid from 2025 but the boilers are hydrogen-ready to facilitate a smooth switchover from natural gas.

FES 2020 / Consumer view / Residential 60

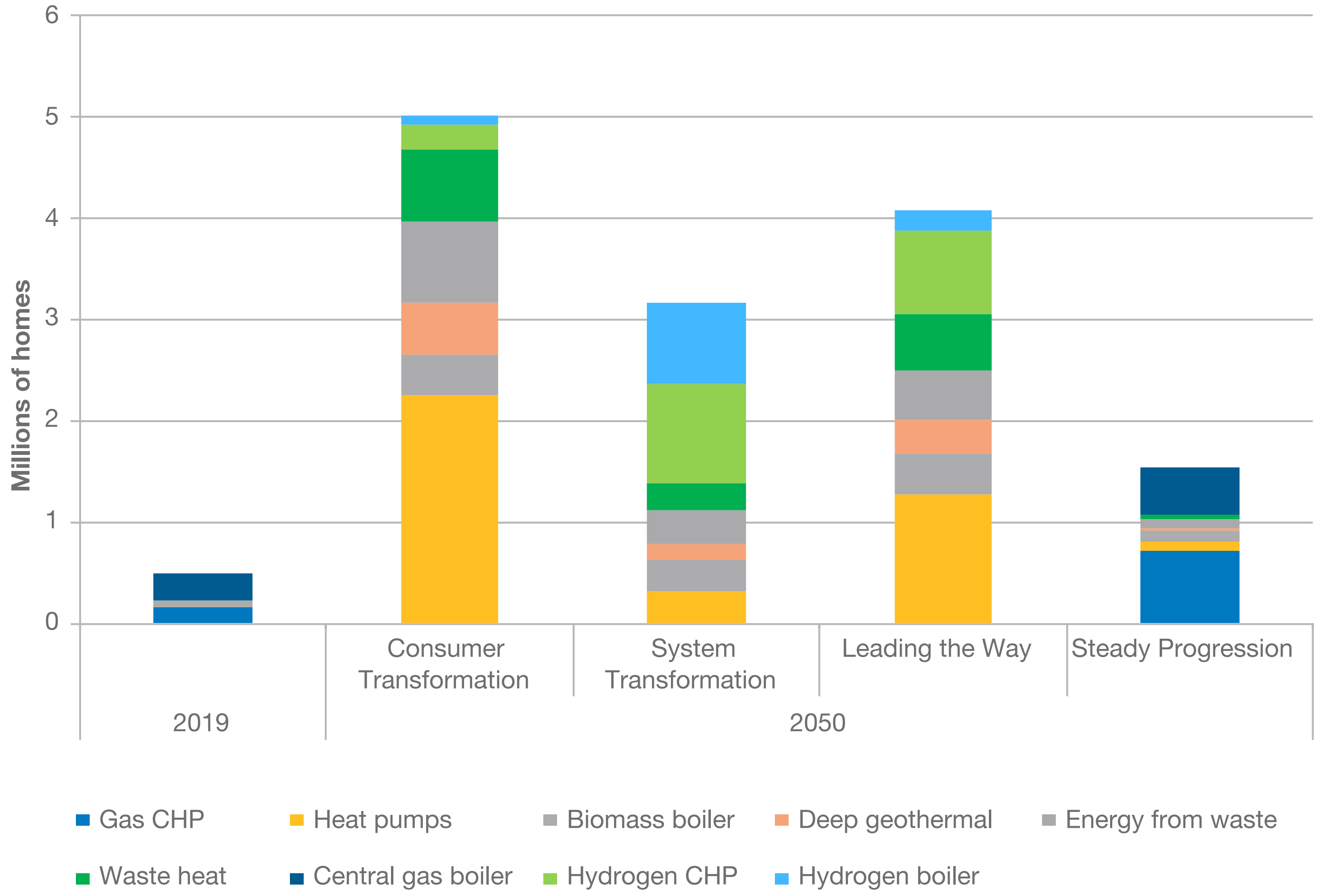
District heat networks

District heat networks feature in all scenarios, with up to five million homes (both new build and existing) connected in **Consumer Transformation**. Connecting homes to hot water pipes removes the need for individual heating systems.

A central energy centre generates hot water in its local area and can be adapted as required. From a consumer perspective, this requires minimal disruption, although it removes individual choice of heating technologies.

In **Consumer Transformation**, large electric heat pumps would be used (probably using ground or water sources), while in **System Transformation** heat would come from hydrogen initially, with a possible switch to electric heat pumps. However, there will also be heat networks which use heat from industrial processes, deep geothermal, data centres and biomass boilers where available.

Figure CV.16: District heat network technologies in 2050



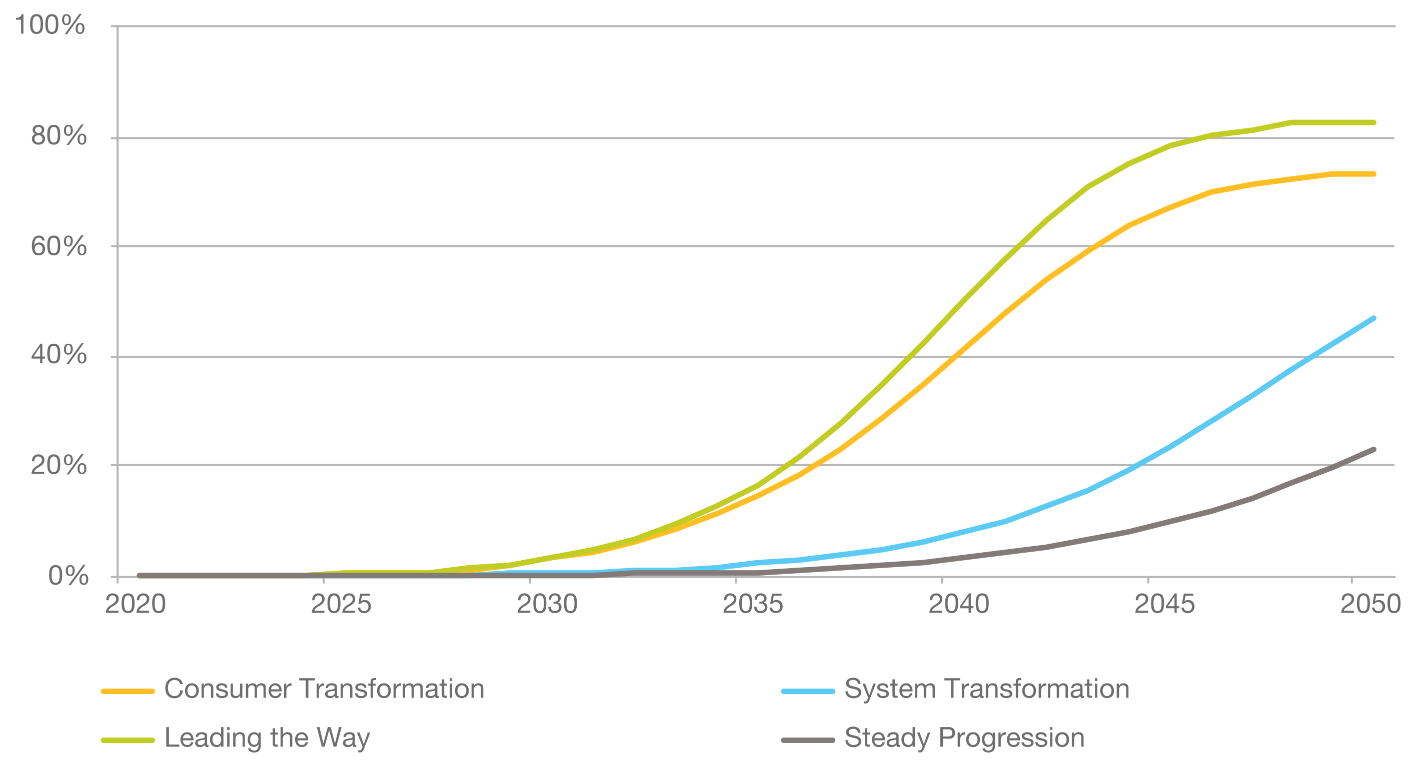
FES 2020 / Consumer view / Residential 61

Appliances

In our net zero scenarios, we have assumed appliances will become more efficient. This reflects international policies, including the EU's energy efficiency targets for 2030 and the fact that many producers will be supplying the UK and the EU with the same products.

New appliances will also be 'smarter', so can respond to external signals in terms of when to turn on, turn down, or turn off. In our modelling we have assumed the uptake of smart appliances won't increase until the 2030s, triggered by more widespread time of use tariffs for charging EVs.

Figure CV.17: Smart appliance uptake in each scenario



FES 2020 / Consumer view / Residential 62

Appliances

Appliances include:

Air conditioning, lighting, refrigeration, washing machines, TV, consumer entertainment, computing, cooking appliances, vacuum cleaners, power supply units.

Smarter

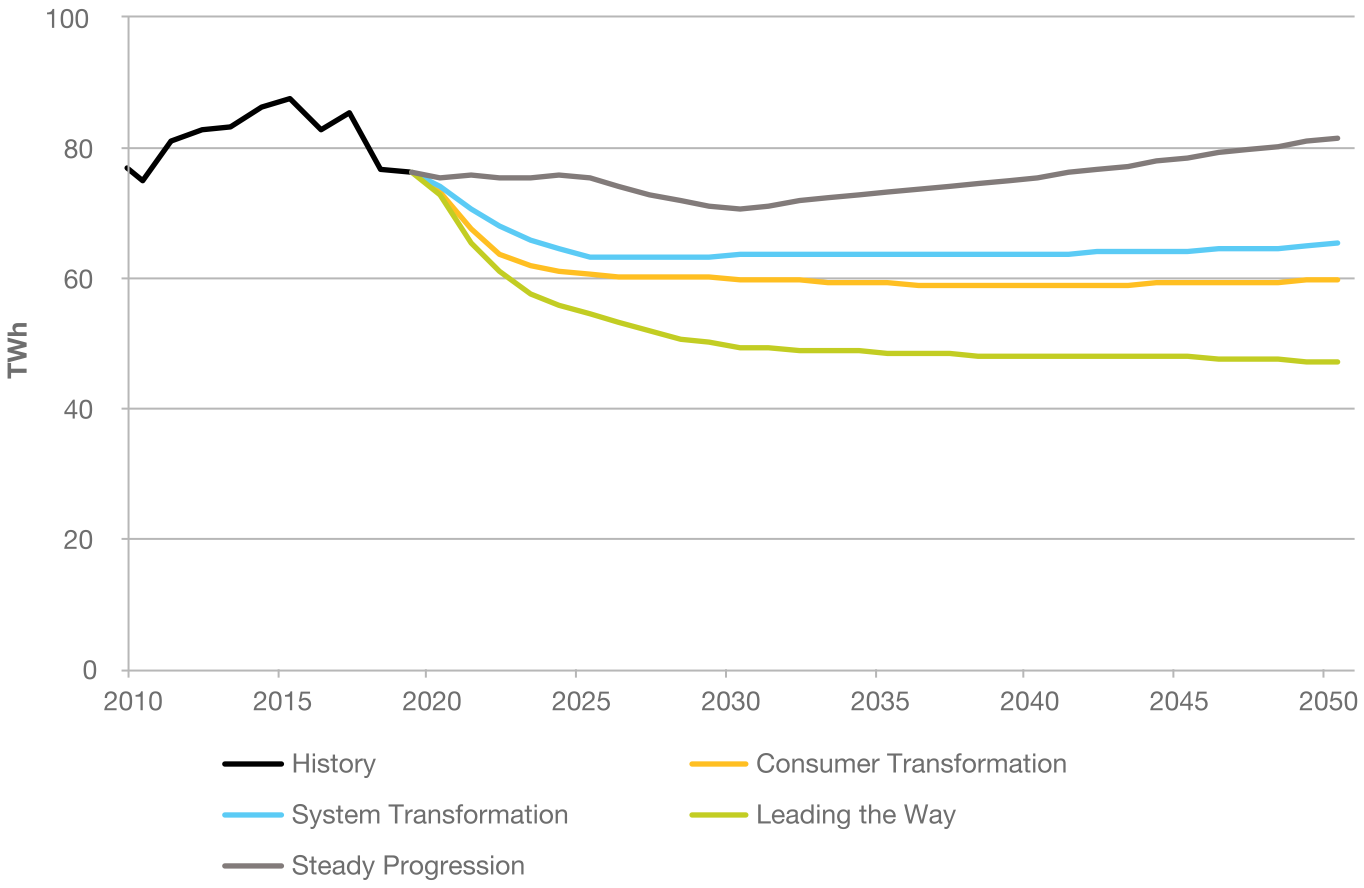
Smart Appliances

Our homes are full of appliances which improve our lives. Whether it's the dishwasher, the washing machine or the large, flat screen TV, it is hard to imagine a world without them. In our scenarios, we assume that they will all be in use, probably along with some appliances yet to be invented. However, their use is likely to be different to today. We are already seeing the number of hours watching TV is falling, replaced by streaming on smaller tablets or phones. In future, smart devices will operate or charge up based on external price signals. For example, washing machines may run when there is excess electricity on the grid and prices are low, and fridges or freezers may be turned down during peak demand.

FES 2020 / Consumer view / Residential 63

Appliances

Figure CV.18: Annual residential electricity demand for appliances



The impact of smart appliances and how we use them makes a difference to the overall electricity demand of households. We have assumed that EU Energy efficiency targets for appliances are met by **Consumer Transformation** and **Leading the Way**. **Leading the Way** in fact exceeds the target with a 40% improvement. To meet this target, we assume changes in policy and industry happen in the early 2020s. For lighting, the timing of a ban on halogen bulbs is varied between the scenarios to reflect uncertainty around consumer acceptance and stockpiling.

For example, in **Steady Progression** energy demand increases in the short term due to halogen bulbs still being bought until stocks run out in 2025. After this point, it continues to rise to reflect increasing numbers of appliances in people's homes, which are less efficient than in the net zero scenarios.

FES 2020 / Consumer view / Residential 64

Appliances

EU Energy efficiency

EU Energy Efficiency

32% improvement in energy efficiency by 2030

Halogen bulbs

Halogen bulbs

Halogen bulbs can have a big impact on overall household electricity consumption. On average, they are seven times more energy hungry and only last for two years, compared to up to 20 years for LEDs. From September 2018, the sale of halogen light bulbs was banned under EU legislation. As lighting currently accounts for 15% of a household's electricity consumption, the impact of this could result in significantly lower demand.

FES 2020 / Consumer view / Residential 65

How the level of societal change could affect a typical, suburban house in 2050

Low societal change

- Some insulation in the loft
- Smart meter
- 1 EV charge point
- 2 Battery electric vehicles
- Natural gas boiler with radiators
- Appliances' energy efficiency not greatly improved from today

Medium societal change

- Some insulation in the loft
- Smart meter
- Hydrogen hob
- Hydrogen boiler
- Smart fridge, A++ washing machine and dishwasher
- 1 EV charge point
- 1 Battery electric vehicle and 1 autonomous vehicle outside of home

High societal change

- High levels of insulation throughout home
- Smart meter
- Electric hob and oven
- Air source heat pump
- Thermal storage
- All appliances are smart and A+++
- Underfloor heating
- Home energy management system
- Battery storage in house
- 1 EV charge point
- Triple glazed windows
- Solar panels on roof
- 1 Battery electric vehicle, bicycles and use of autonomous vehicles for mobility services

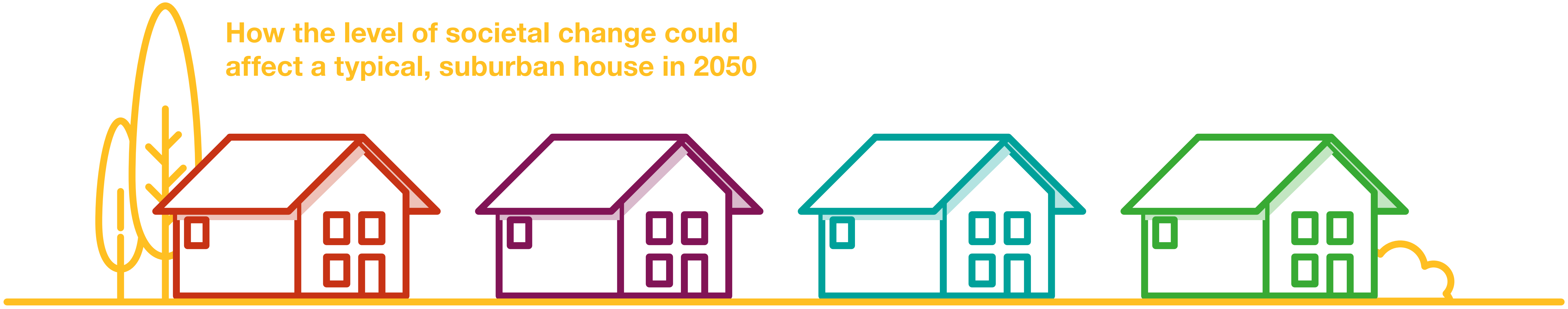
High and fast societal change

- High levels of insulation throughout home
- Smart meter
- Electric hob and oven
- Smart Hybrid heat pump
- All appliances are smart and A+++
- Home energy management system
- Battery storage in house
- 1 EV charge point
- Triple glazed windows
- Solar panels on roof
- Bicycles and use of autonomous vehicles for mobility services

SOCIETAL CHANGE INCREASING IN SPEED AND SCALE

FES 2020 / Consumer view / Residential 66

How the level of societal change could affect a typical, suburban house in 2050



Low societal change

The heating system
The house is still heated using the same natural gas boilers that most of us have in our homes in 2020. The gas supplied to the house is a mix of natural gas blended with a small amount of hydrogen or biogas in the gas transmission network.

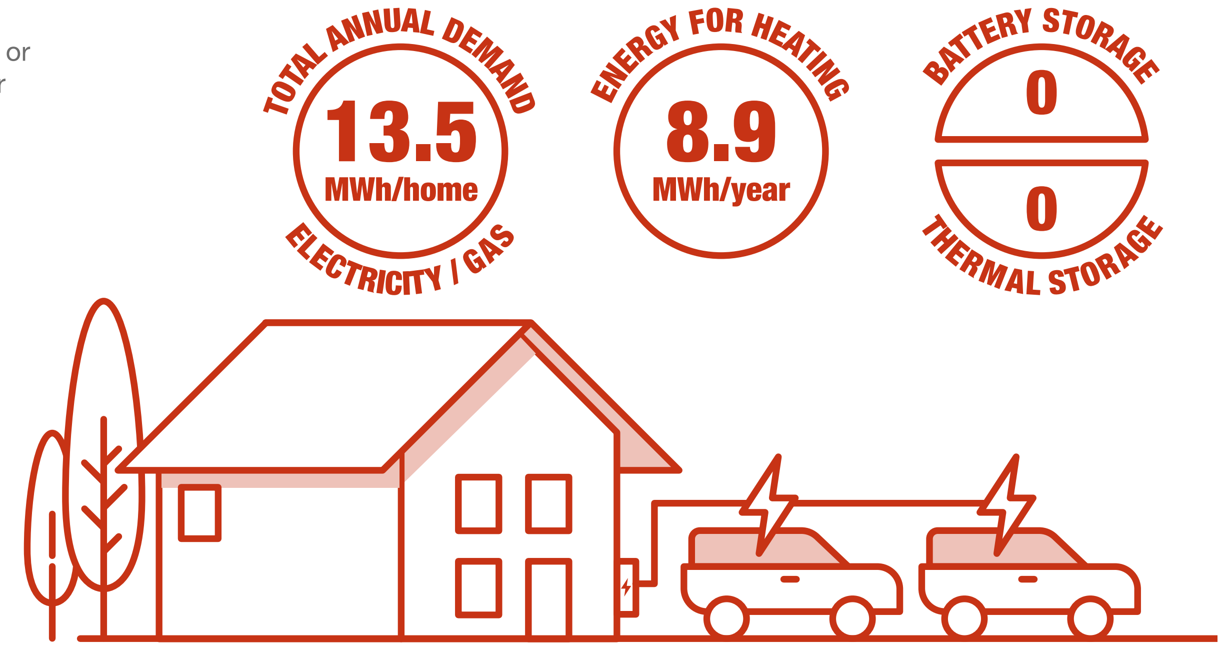
Energy Efficiency measures
There have been some retrofits of insulation, improving thermal efficiency by 14%.

Appliances
There are many appliances in the house, which are relatively efficient. The household fridge, dishwasher and washing machine are not smart enabled.

Transport
There are two cars in this house, which are both privately owned Battery Electric Vehicles (BEVs).

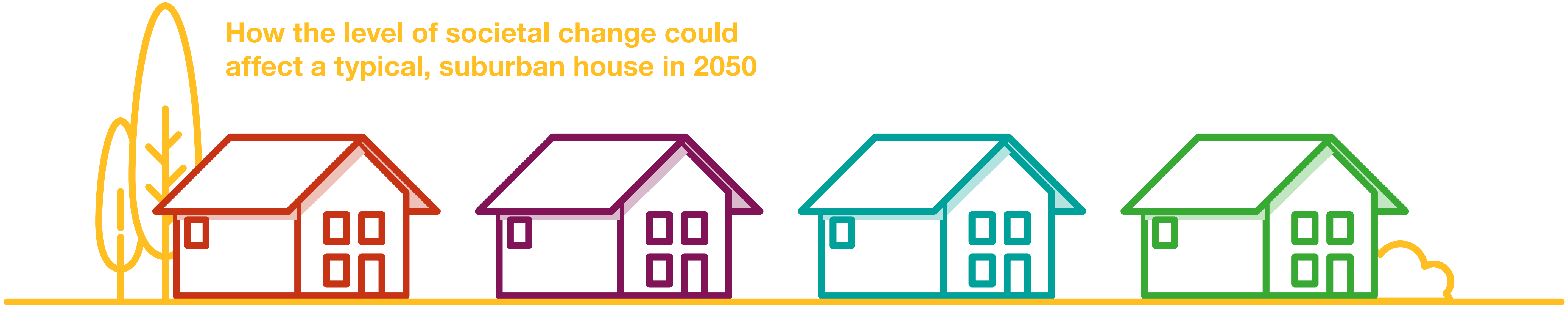
Vehicle Charging
There is one EV smart charging point available.

Household behaviour/engagement
Smart meters are in the house, but aren't well understood or used. As a result, the people in the house don't monitor or change their behaviour to reduce their electricity demand



FES 2020 / Consumer view / Residential 67

How the level of societal change could affect a typical, suburban house in 2050



Medium societal change

The heating system
The heating system inside looks and works like central heating in 2020, with radiators and a gas boiler. The boiler was retrofitted with a different burner in the 2040s to convert it from burning natural gas to hydrogen. Cooking is done on a hydrogen hob or electric oven.

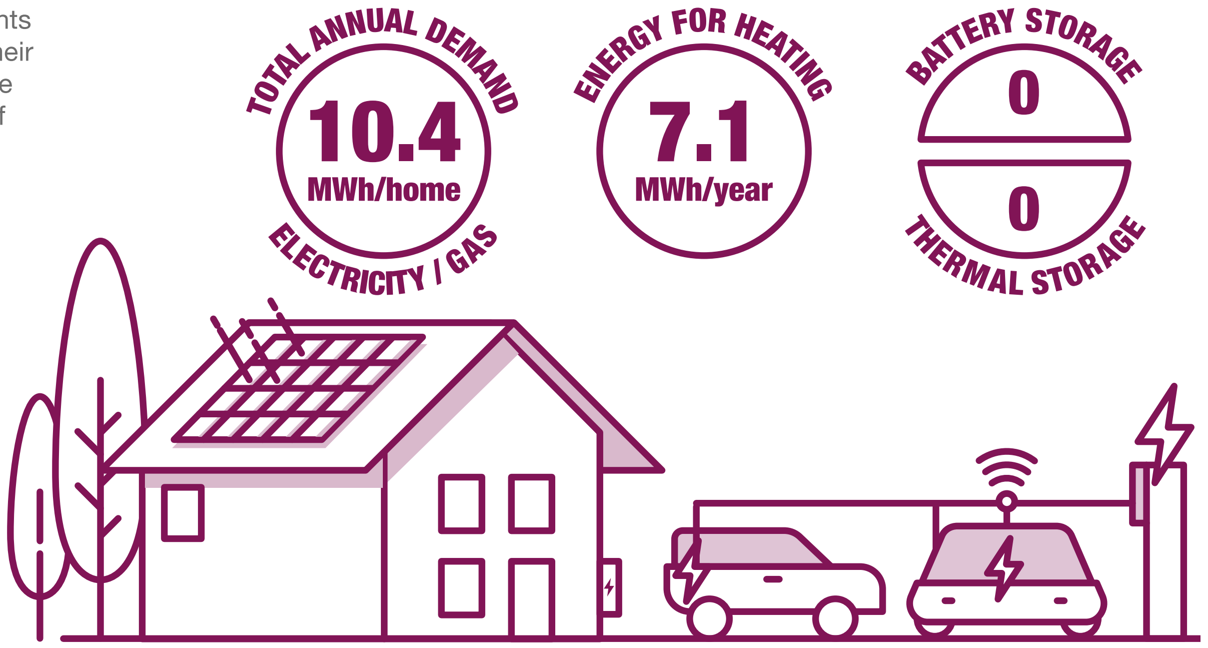
Energy Efficiency measures
The house is well insulated to reduce overall demand for hydrogen and keep bills down. The house is not as comprehensively retrofitted as in other scenarios, as the hydrogen boiler works well with slightly lower levels of thermal efficiency.

Appliances
There are some smart appliances in the home, running at times when electricity prices are lowest. A few of these are more efficient appliances compared to today's standards, but there are no reductions in the quantity of appliances bought.

Transport
The household has two privately owned cars; 1 BEV and 1 autonomous EV. The autonomous EV is used frequently for commuting and leisure use.

Vehicle Charging
The cars are generally charged at work or a rapid public charging point, so there's only one charging point at the house.

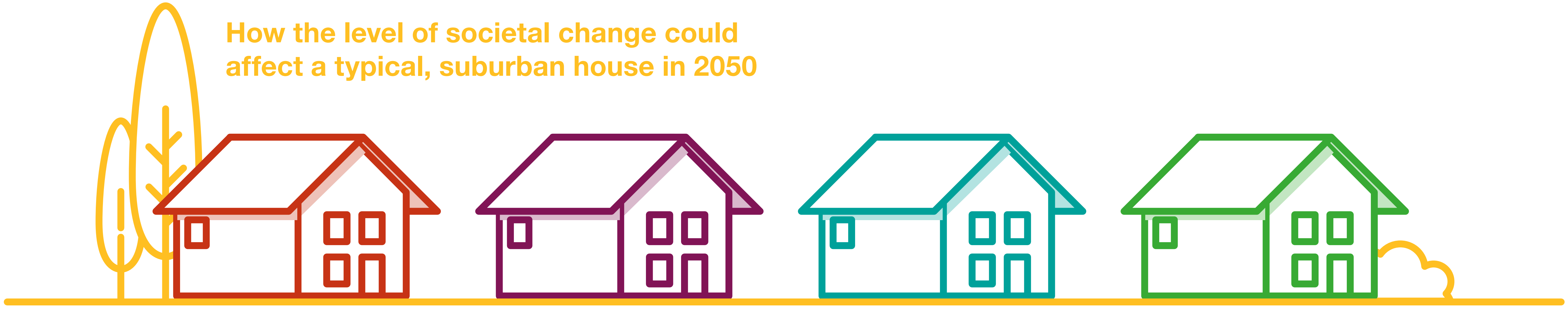
Household behaviour/engagement
The smart meter provides visibility of electricity prices and gives the occupants the information they need to manage their electricity demand. By showing the time of use tariff, they decide when to use of appliances to reduce their energy bills



SOCIETAL CHANGE INCREASING IN SPEED AND SCALE

FES 2020 / Consumer view / Residential 68

How the level of societal change could affect a typical, suburban house in 2050



High societal change

The heating system
The Air Source Heat Pump (ASHP) heating system uses either large panel radiators, underfloor heating or heated air flow around the building. When it's cold, the smart heating controls will either heat the home or charge thermal storage, so that there is warmth when the homeowner gets back from work. Hot water is also heated during the day and the thermal store was used in order to be ready to meet any demand in the evening.

Energy Efficiency measures
This home has high levels of insulation in the roof, inside the walls and externally. The windows are triple glazed, with shutters on the outside which help reduce heat loss as well as heat gain in summer. This helps the heat pump to run as efficiently as possible but required disruption during the late 2030s to bring the building up to standard.

The front entrance has two doors in order to create a buffer zone between the external environment and inside.

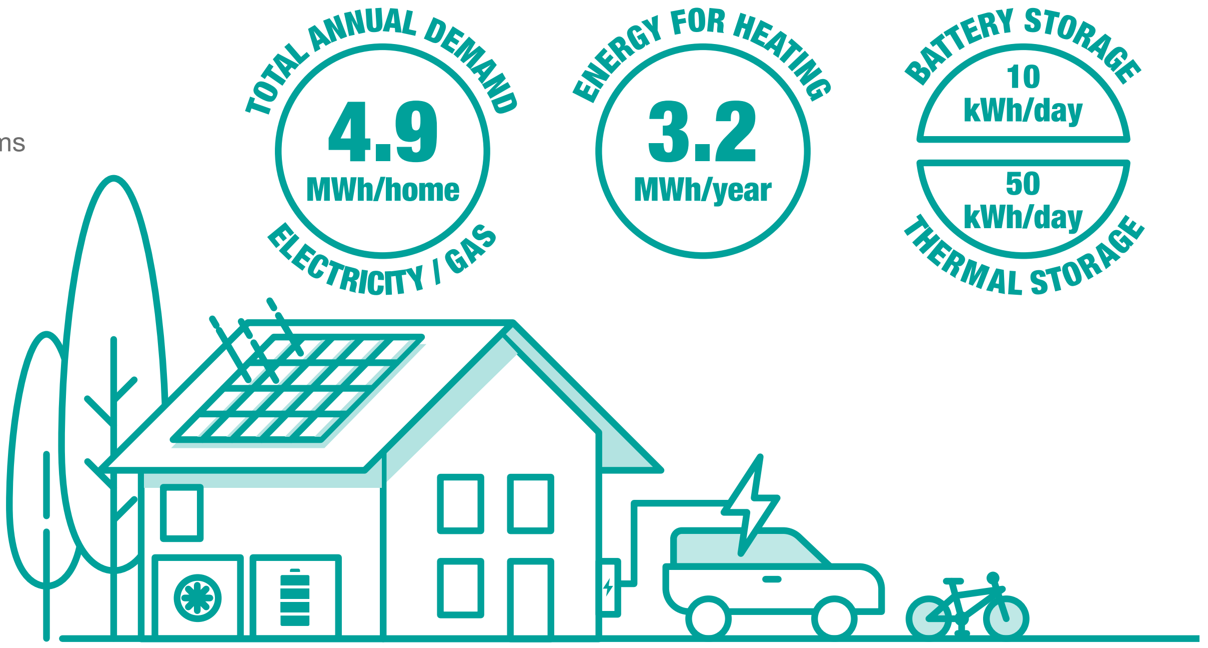
Battery storage
A battery has stored any surplus electricity generated by the solar PV panels on the roof during the day, so that it can be used in the evening peak for heating and appliances.

Appliances
There are many smart appliances in the home, running at times when electricity prices are lowest. Most of these are highly efficient.

Transport
The household has one car (an EV) and makes use of public transport (usually electric buses) and/or cycling or walking whenever possible. Ride hailing services delivered by autonomous vehicles are also used for longer journeys.

Vehicle Charging
The EV is charged at home and is kept plugged in to provide flexibility for the electricity system vehicle-to-grid.

Household behaviour/engagement
The home energy managements systems provide visibility of electricity prices, showing time of use tariffs. They don't always need the householders to make a decision based on this information; the energy management system can be set to automated so they can turn on appliances when there is less demand on the electricity system, or use electricity generated during the day by the solar PV array, for example doing the washing or dishes.



SOCIETAL CHANGE INCREASING IN SPEED AND SCALE

FES 2020 / Consumer view / Residential 69

How the level of societal change could affect a typical, suburban house in 2050

High and fast societal change

The heating system
This home assumes that a retrofit programme is undertaken as soon as possible. This enables the use of hybrid heat pumps, which will only use gas (natural gas in the short term, hydrogen in the long term) for times of peak electricity demand. When it's cold, the smart heating controls will heat the home during the day. If additional warmth is required, either during the evening electricity peak, or when external temperatures are very low, the hydrogen boiler kicks in.

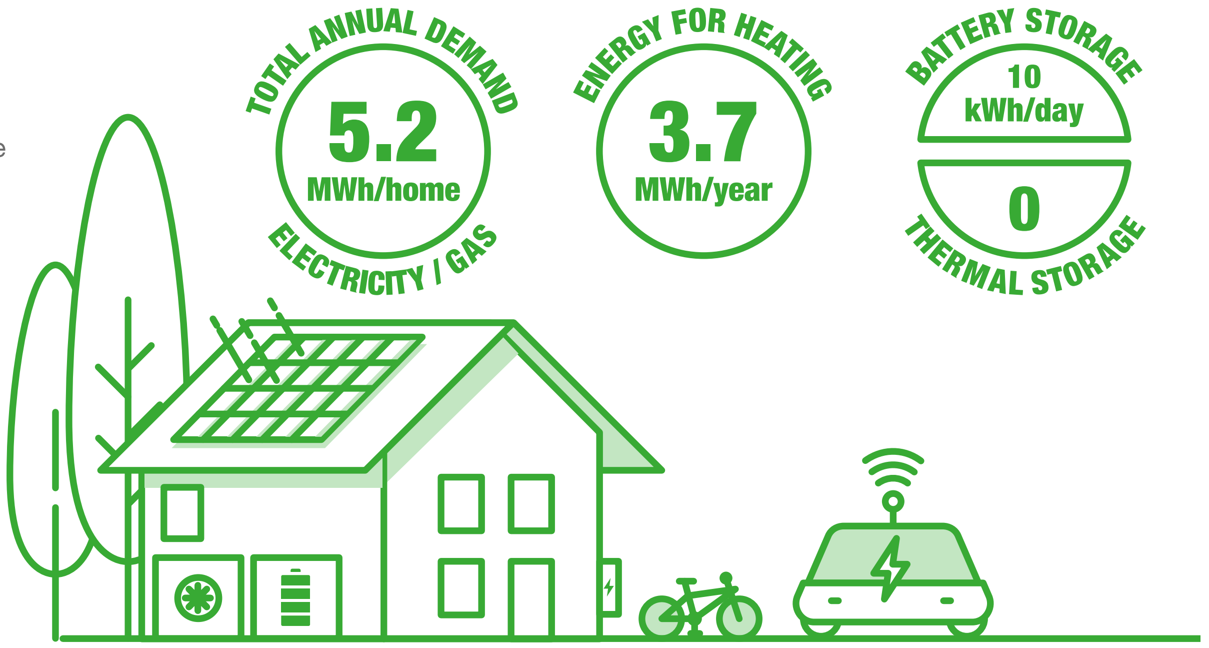
Energy Efficiency measures
The house is as energy efficient as possible, with high levels of retrofitted insulation and triple glazed windows. The front entrance has two doors in order to create a buffer zone between the external environment and the inside.

Battery storage
A battery has stored any surplus electricity generated by the solar PV panels on the roof during the day, so that it can be used in the evening peak for appliances.

Appliances
The household contains only smart appliances, which are very energy efficient. The household has actively reduced the number of appliances through buying multifunctional devices where possible.

Transport
The people in the household walk, cycle or use public transport where possible, or use mobility services provided by autonomous vehicles.

Household behaviour/engagement
The home energy managements systems provide visibility of electricity prices, showing time of use tariffs. They don't always need the householders to make a decision based on this information; the energy management system can be set to automated so they can turn on appliances when there is less demand on the electricity system, or use electricity generated during the day by the solar PV array, for example doing the washing or dishes.



SOCIETAL CHANGE INCREASING IN SPEED AND SCALE

FES 2020 / Consumer view / Residential 70

Transport

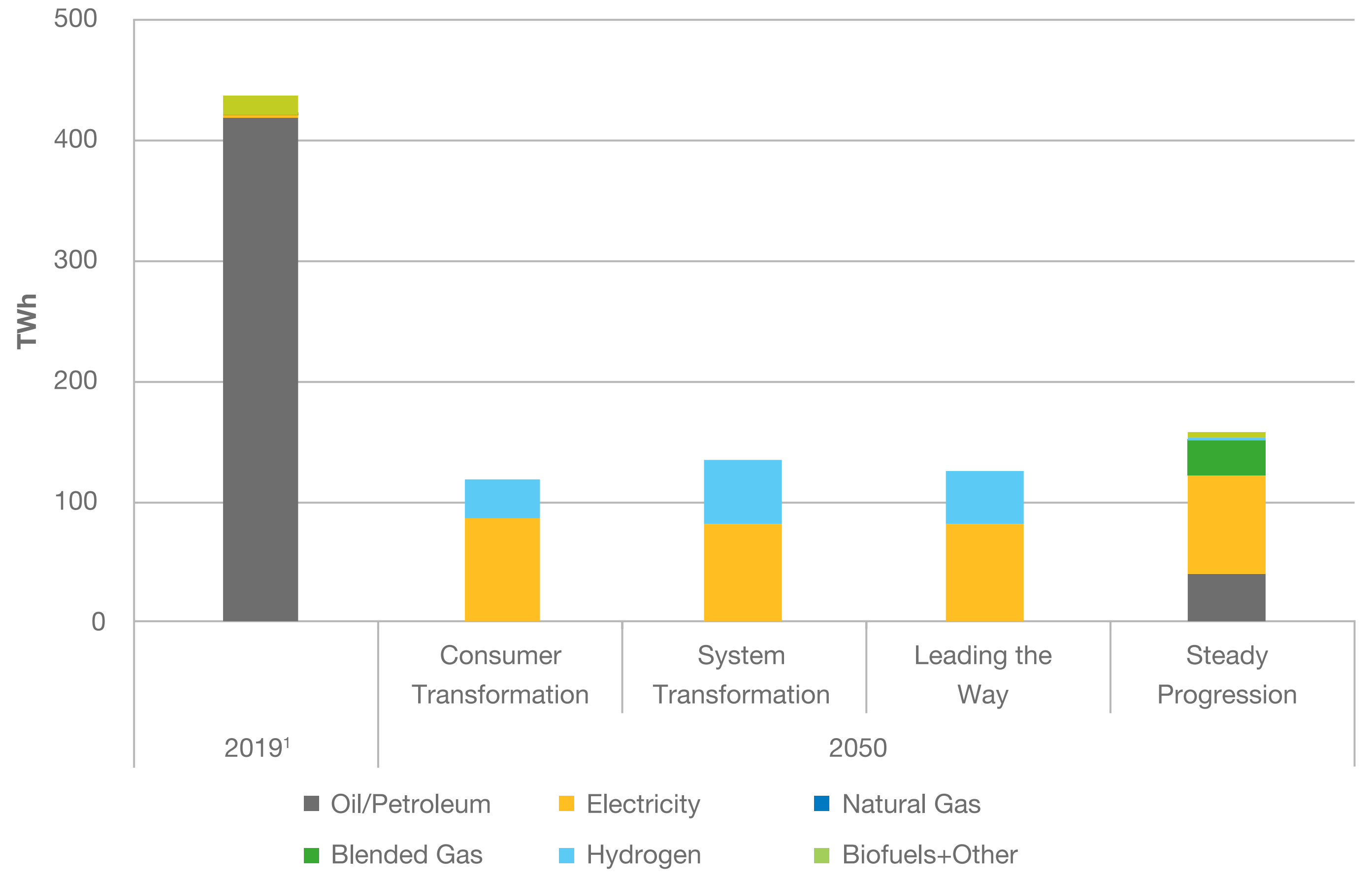
Key insights

Electrification is key to decarbonising transport, with at least 60% of all road transport being electrified in our net zero scenarios.

- Even in the slowest decarbonising scenario there will be no new cars sold with an internal combustion engine after 2040. This results in all cars on the road being ultra-low emission by 2050 at the latest, and up to 75% reduction in total energy demand for road transport, as EVs are more efficient than petrol and diesel vehicles.
- For larger vehicles net zero means either hydrogen or bioresources in our scenarios. HGVs use predominantly hydrogen, whilst shipping uses a combination of hydrogen and biofuels. Aviation is reliant on a combination of biofuels and negative emissions elsewhere to achieve net zero.
- Electrified transportation will be critical in providing flexibility to the electricity system, facilitating integration of renewables and helping to manage peak demand. This will be done through time of use tariffs and vehicle-to-grid technology.

In FES 2020, we look at how transport, and, in particular road transport as the largest sub-sector, can be decarbonised and the impact on energy demand.

Figure CV.19: Total annual demand for road transport[1] in 2050



1 The 2019 data is primarily made up of our modelled data. However, some 2018 demand data from ECUK was used in order to provide a complete, whole system view of end consumer demand. www.gov.uk/government/statistics/energy-consumption-in-the-uk

FES 2020 / Consumer view / Transport 72

Transport

Transport includes:

road, rail, domestic and international aviation and shipping.

FES 2020 / Consumer view / Transport 73

Where are we now?

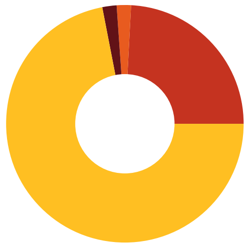
As the sector with the largest carbon emissions, transport will need fundamental changes before 2050. Currently, transport accounts for approximately a third of all UK emissions and consumes 640 TWh per annum[2]. The size of the transport sector's carbon footprint is down to the prevalence of the internal combustion engine, but it is also influenced by the individual choices we make in how we want to travel and live our lives.

In the UK, a small proportion of lorries use natural gas or biomethane, but most lorries and vans still use diesel. Deliveries by vans have increased by 67% since 1990, so their emissions are now equivalent to those from lorries. The rest of the transport sector has seen little change. 70% of passenger trains are electric (and an even higher percentage in the densely populated South East) but many freight trains use diesel locomotives. Aviation and shipping are completely reliant on fossil fuels.

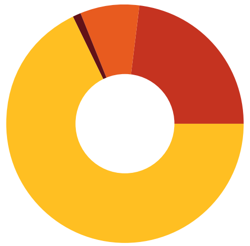
Energy, carbon and how we travel in the UK today.[3]

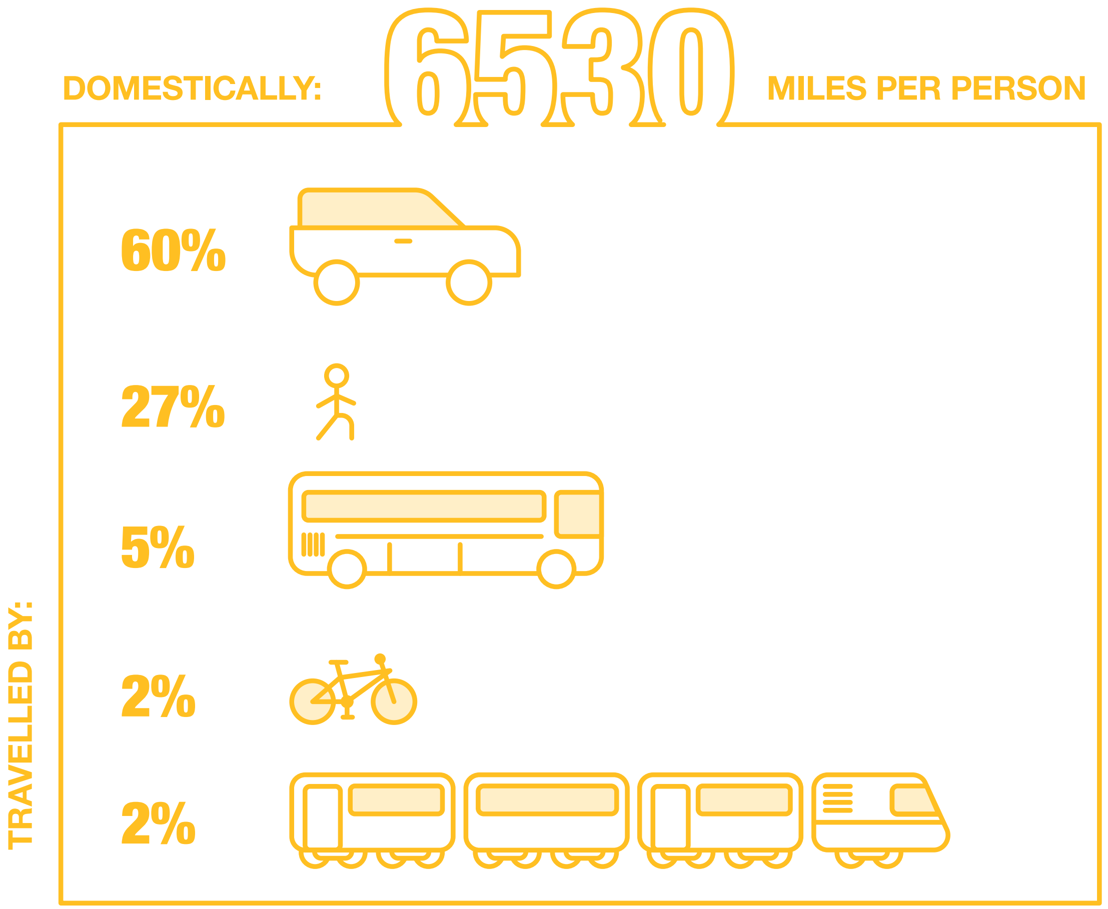
ENERGY AND CARBON FOR TRANSPORT IN THE UK (2018):[2]

ENERGY	
Road	72%
Rail	2%
Shipping	2%
Aviation	24%



CARBON	
Road	68%
Rail	1%
Shipping	8%
Aviation	23%





2 2018 Data taken from ECUK, Consumption Data Tables: www.gov.uk/government/statistics/energy-consumption-in-the-uk
3 Remaining 4% split between aviation and maritime, not modelled in FES. Data taken from DfT National Travel Survey – www.gov.uk/government/collections/national-travel-survey-statistics

FES 2020 / Consumer view / Transport 74

Where are we now?

In 2019, battery electric vehicles (BEVs) and plug in hybrid electric vehicles (PHEVs) made up just over 3% of all new vehicle sales. While overall numbers of EVs are low, the recent increase in sales has been steep and gives us a strong indication that they will continue to grow, reinforced by changes in company car tax in April 2020 that further incentivise EVs as company cars (which make up 9% of cars)[4].

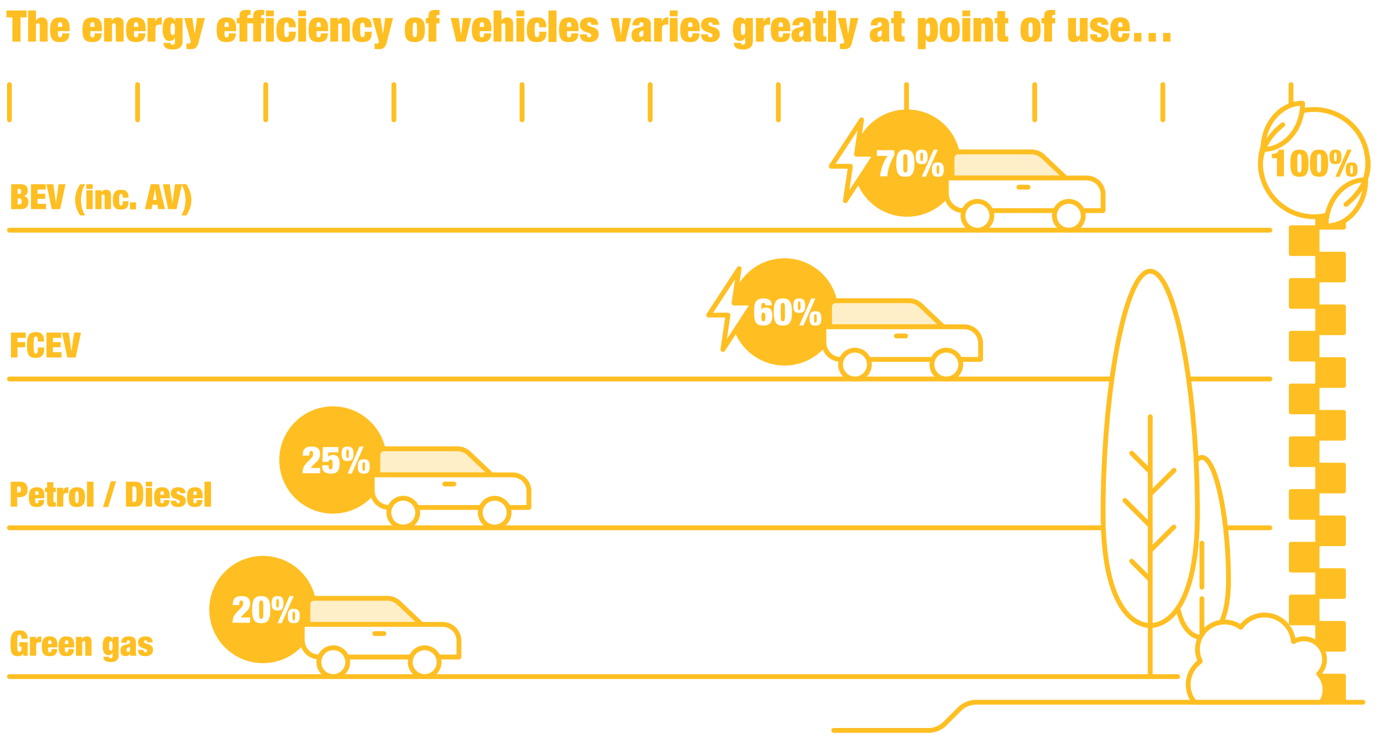
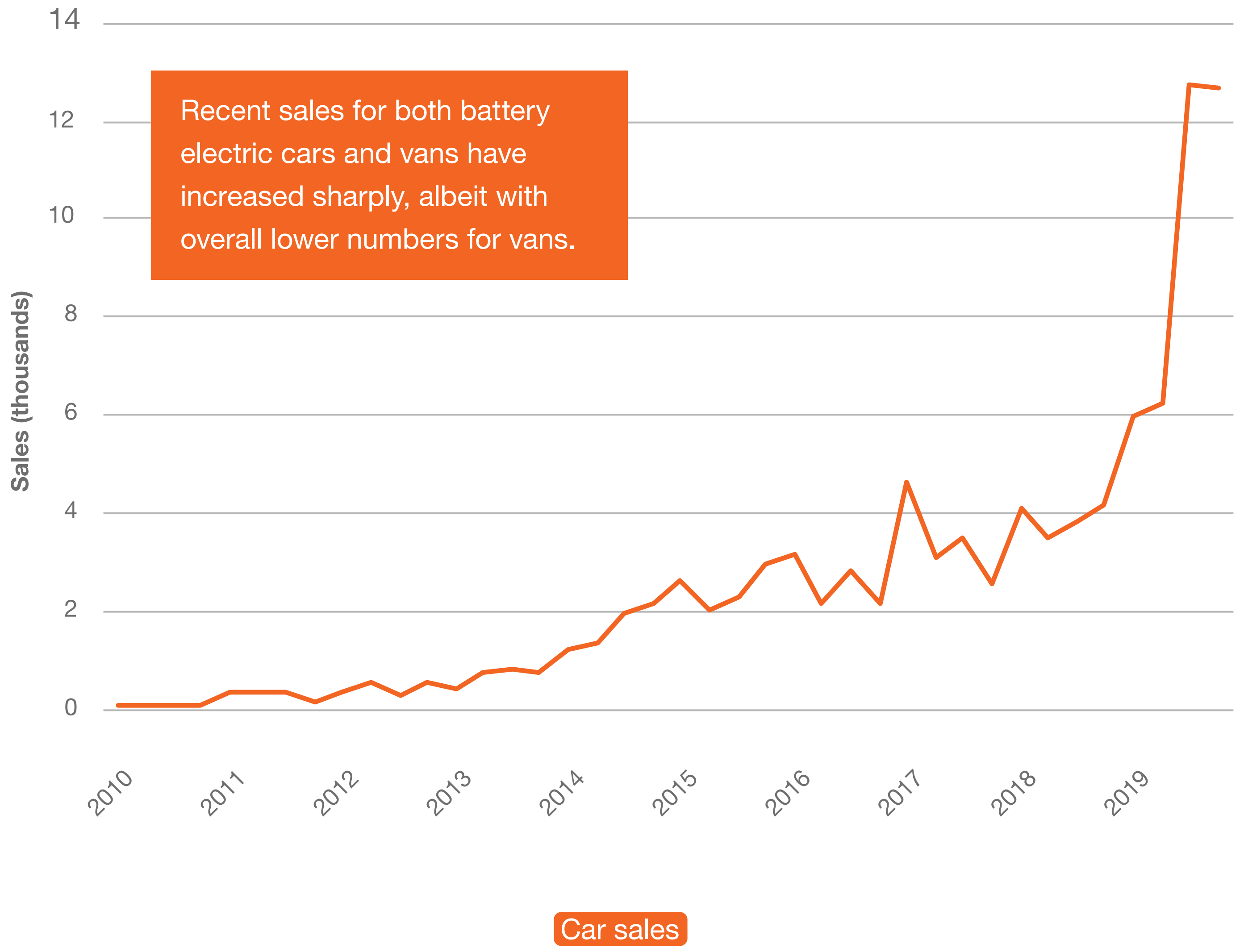


Figure CV.20: Sales of electric cars and vans in Great Britain

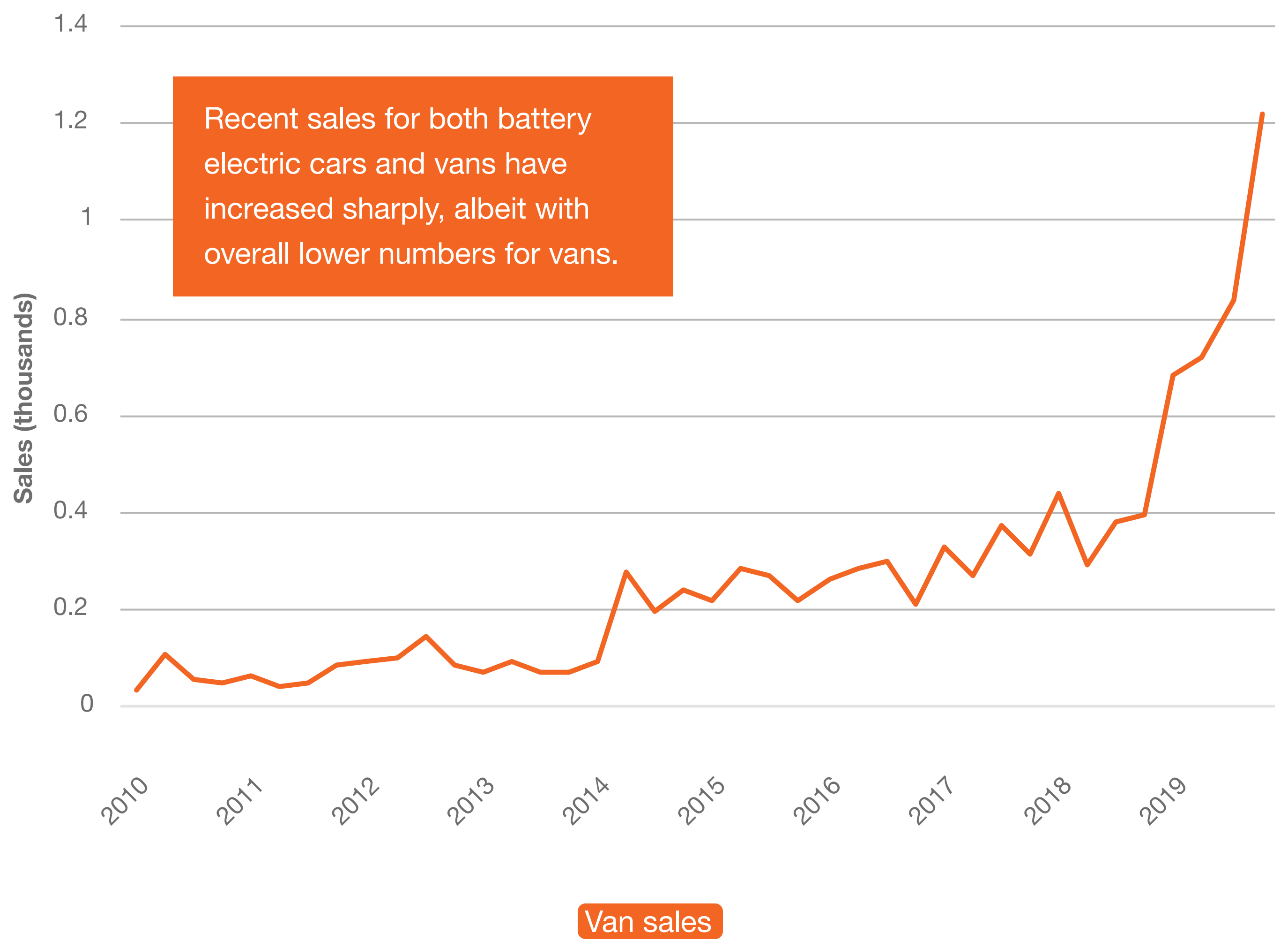


4 www.assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/800502/vehicle-licensing-statistics-2018.pdf

FES 2020 / Consumer view / Transport 75

Where are we now?

Figure CV.20: Sales of electric cars and vans in Great Britain



FES 2020 / Consumer view / Transport 76

What we've found

We have made different assumptions about consumer behaviour across our scenarios about the use of public transport and the uptake of electric vehicles.

We have also varied the number of buses, choice of fuel for HGVs, subsidies for ultra-low emission vehicles and the overall number of pure BEVs and plug-in hybrids.
We have assumed plug-in hybrids will form part of the government's proposed ban and that the ban is implemented as follows:

1. 2032 in **Leading the Way**
2. 2035 in **Consumer Transformation** and **System Transformation**
3. 2040 in **Steady Progression**

Rail travel is an important element of a decarbonised future, and there is already a government target to remove diesel from the tracks by 2040; however in **Steady Progression** this is missed and there are still diesel trains on the tracks in 2050. In **Consumer Transformation** and **Leading the Way**, we have assumed growth in rail traffic for public transport and freight and that the trains are electric (combined with batteries in some places). As there is a ready supply of hydrogen in **System Transformation**, growth in rail traffic has been met in part using hydrogen trains, however, there is still more electrification than today.

We do not directly model aviation and shipping in our Future Energy Scenarios; instead we refer to the Committee on Climate Change's[5] assumptions for their Speculative Net Zero scenario. These project **aviation** demand to be limited to a 20% increase on 2005 levels (currently forecast to be 90% in a business as usual scenario). Emissions are further reduced with more efficient planes and sustainable biofuels. However, most planes still use fossil fuels and emit carbon.

For **shipping**, we have not modelled any limits to demand. Our net zero scenarios assume hydrogen (converted to ammonia) will be used but in **Leading the Way**, biofuels are also used. For both shipping and aviation, we have included all fuels for domestic journeys (within the UK) as well as any fuels stored here and used to refuel international journeys. The residual emissions from aviation and shipping (approximately 23 $MtCO_2e$) are offset by using BECCS *(See page 103)* (bioenergy with carbon capture and storage).

The approach to decarbonising transport may be different across regions. We expect local authority approaches to managing transport to be tailored; for example some may choose hydrogen buses because of local resources. Others may decide to opt for pedestrianised town and city centres, not only to reduce carbon but to improve the health of the local population with improved air quality and by promoting cycling and walking.

5 https://www.theccc.org.uk/publication/net-zero-technical-report/

FES 2020 / Consumer view / Transport 77

What we've found

Ultra-low emission vehicles

Definition:

1. uses low carbon technologies
2. emits less than 75g of CO_2/km from the tailpipe
3. Includes BEVs/PHEVs/FCEVs

FES 2020 / Consumer view / Transport 78

Road Transport

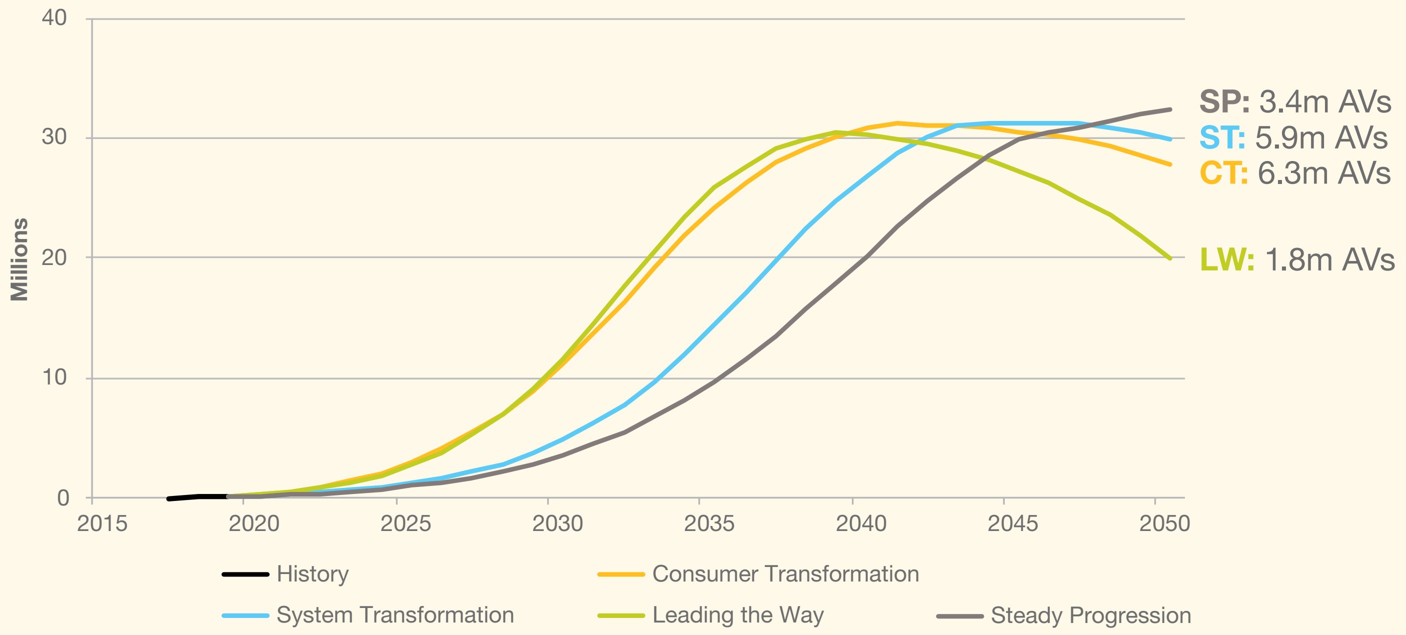
Electric vehicles everywhere – but how and where are they used?

One of the interesting aspects of the road transport scenarios relates to the number of vehicles. Our graph shows the gradual transition to BEVs in every scenario out to 2050. We have approximately 32 million cars on the road now. Our population is predicted to grow but the number of vehicles doesn't necessarily grow with it. With the use of autonomous vehicles (AVs) commonplace by 2050, our modelling has assumed that in some cases AVs might reduce the total number of vehicles, dependent on the level of societal change and an increase in the use of public transport.

Table CV21: Total number of cars on the road and miles travelled by each AV in 2050

Cars in 2050	Total Cars (millions)	Autonomous Vehicles (millions)	Shared Automated Miles Per Car
Consumer Transformation	27.9	6.3	17,000
System Transformation	30.9	5.9	14,800
Leading the Way	20.1	1.8	90,500
Steady Progression	33.4	3.4	12,300

Figure CV.22: Number of BEVs on the road



Steady Progression assumes autonomous vehicles will be privately owned. In this scenario, this increases average miles travelled, as they can make longer commutes less effort or run errands during the working day.

System Transformation assumes that in some cases a two car household becomes a one car household, where shared autonomous vehicles meet some transport needs. However, most households still have two vehicles, which leads to a modest decrease of only 8% in the number of vehicles compared to **Steady Progression**.

In **Consumer Transformation** autonomous vehicles, acting as a taxi service, often replace the need for a second car. They are used by consumers to commute to work or for leisure trips. Combined with greater use of public transport, this results in a 15% decrease in vehicles in this scenario, compared to **Steady Progression**.

In **Leading the Way**, the high levels of societal change have led us to assume that use of autonomous vehicles and public transport reduces the overall number of cars as many homes opt to have no car at all, relying instead on shared mobility solutions, using AVs, which can accommodate four people. Total number of cars is one third less in 2050 than in **Steady Progression**.

FES 2020 / Consumer view / Transport 79

Autonomous vehicles

Definition:

we're assuming an autonomous vehicle to be fully self-driving under certain or all conditions (i.e. Level 4 or 5).

FES 2020 / Consumer view / Transport 80

Road Transport

Figure CV.23: Annual energy demand for road transport in Consumer Transformation

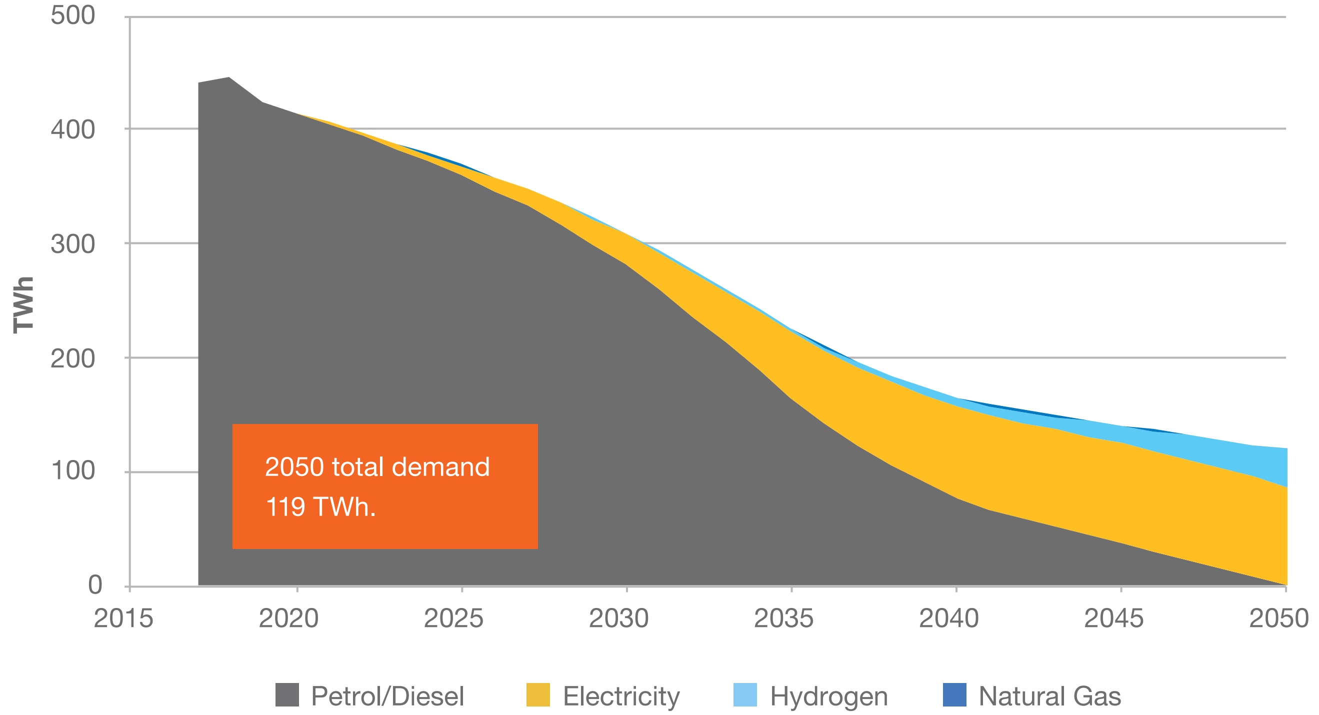
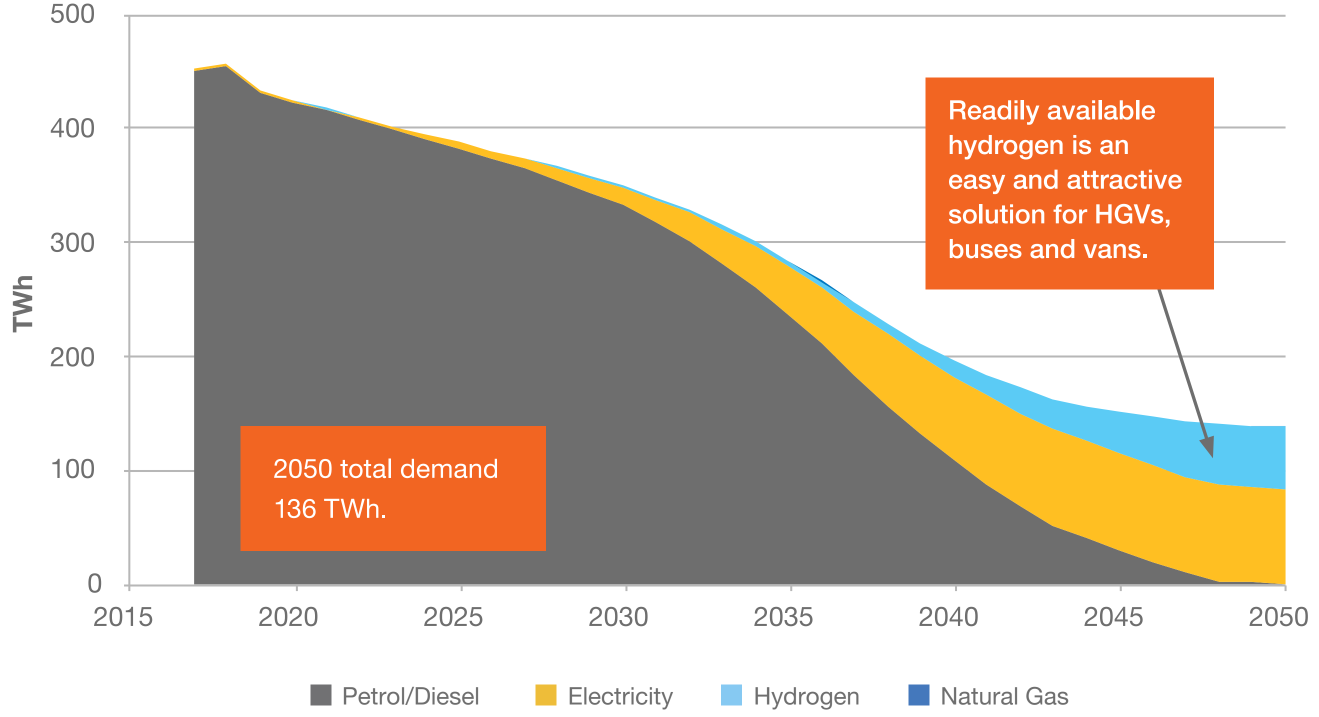


Figure CV.24: Annual energy demand for road transport in System Transformation



Consumers engage with energy efficiency as well as decarbonisation and switch to using public transport and shared mobility, as well as cycling and walking. Buses are electric thanks to government support and are well used. High levels of consumer engagement mean private electric vehicles are plugged in at home to provide flexibility for the electricity system, incentivised by time of use tariffs. HGVs mainly use green hydrogen, with some electrification. Vans have mainly switched to BEVs, thanks to government policy.

Private vehicles and most vans will switch to BEVs, supported by a government-led roll out of rapid charging points. However, there are also over a million hydrogen fuel cell cars and a million other fuel cell vehicles on the road in 2050. While there are some subsidies for electric and hydrogen buses, to help in part with tackling air pollution, there is a low level of uptake as consumers prefer to drive their own electric cars.

FES 2020 / Consumer view / Transport 81

Million hydrogen fuel cell cars

What about hydrogen cars?

The current focus for decarbonisation of cars is on battery electric vehicles. However, this is not the only route and hydrogen fuel cell electric vehicles (FCEV) are also a potential solution to lower carbon and NOx emissions (responsible for air pollution). Creating the demand for FCEVs in the UK will be hard in the short term given the current momentum behind electric vehicles and the lack of a hydrogen supply chain and refuelling network (there are currently 14 hydrogen refuelling stations in the UK). But by 2050, in a net zero scenario like **System Transformation** where hydrogen is widely available, it is possible to see how using FCEVs may become more appealing.

A hydrogen fuel cell works with an electric motor, however the electricity needed to power the motor comes from the fuel cell, used either directly or stored in a small battery. A FCEV has a range of about 300 miles, so further than today's average EV. Refuelling takes about five minutes, similar to a typical ICE car. The vehicles emit only water vapour when they are running and if they use green hydrogen, the carbon emissions are also zero.

FES 2020 / Consumer view / Transport 82

Road Transport

Figure CV.25: Annual energy demand for road transport in **Leading the Way**

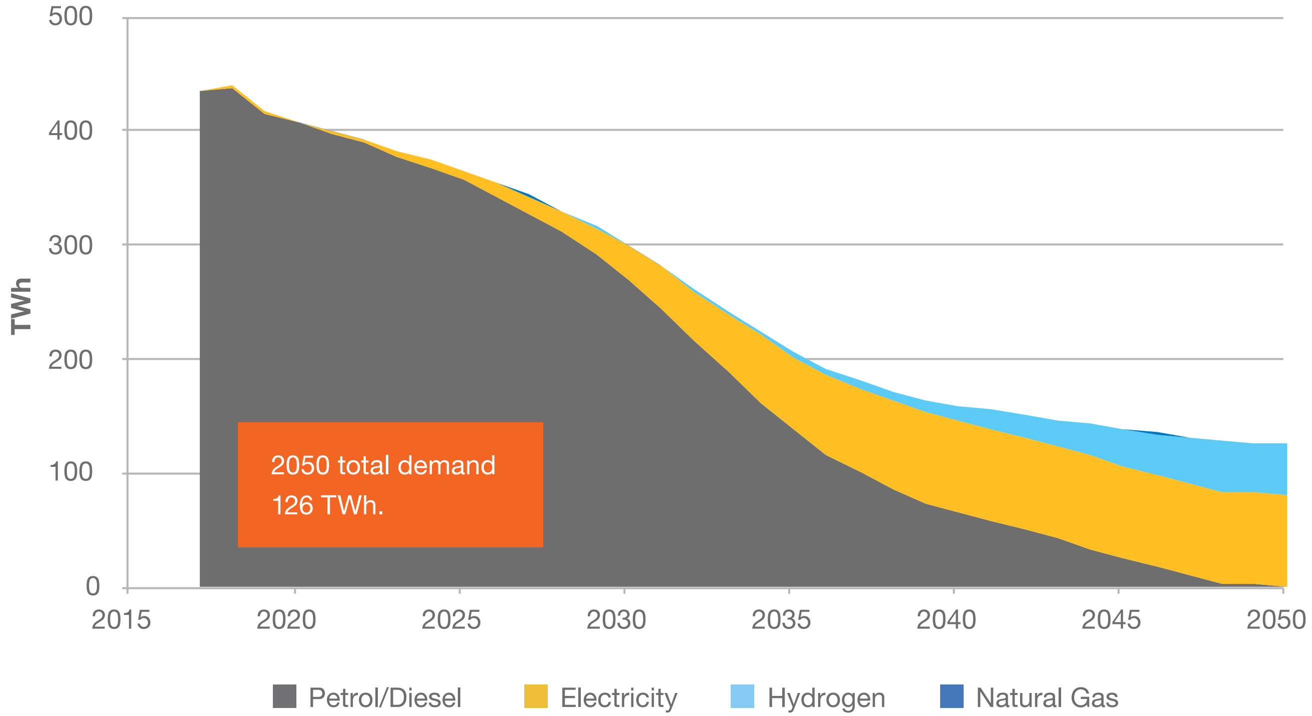
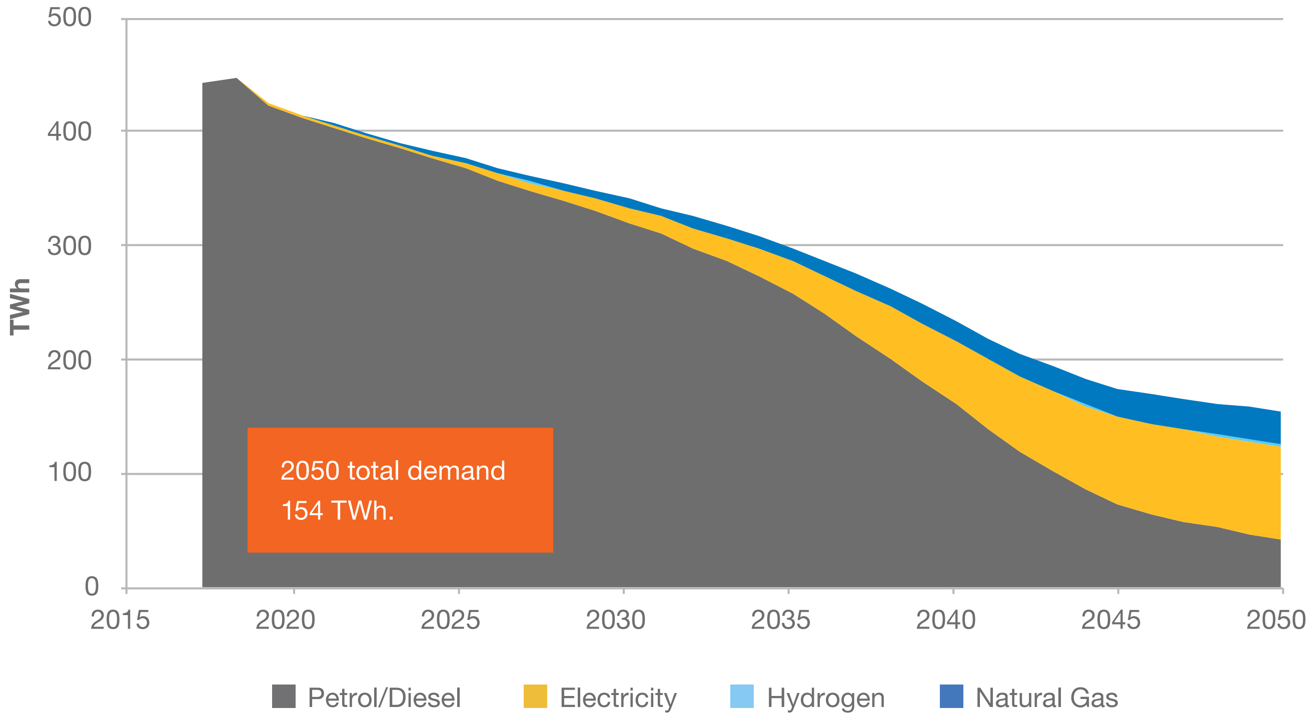


Figure CV.26: Annual energy demand for road transport in **Steady Progression**



The rapid change in consumer behaviour sees demand for public transport increase. Buses are mainly electric, but green hydrogen is also used by where feasible. Government supports decarbonisation of buses, cars, vans and HGVs, which mean all vehicles quickly switch over to zero emission alternatives. Our analysis doesn't specify what this looks like, but it may take the form of scrappage schemes, subsidies for new vehicles or delivery hubs to improve the efficiency of logistics.

Fuel cell and BEVs sales reach 100% by 2040.

By 2050, all traditional internal combustion engines have been replaced; however there are still about a million plug-in hybrids on the road. For other road transport, there is limited progress. With HGVs, there is a mix of some hydrogen, some electric, a fair amount of methane, but mainly diesel engines.

FES 2020 / Consumer view / Transport 83

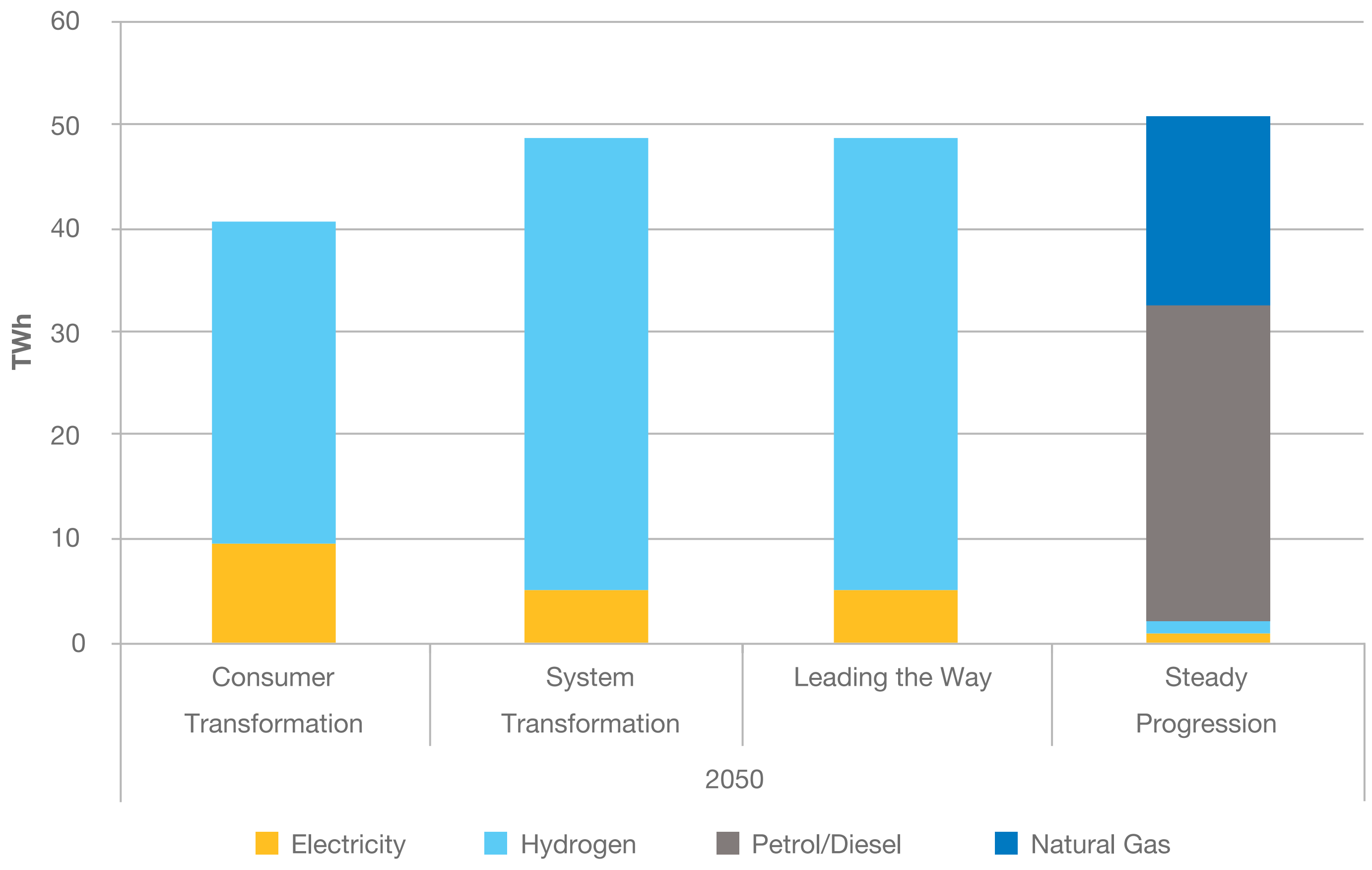
Low carbon lorries

The distances covered by lorries and the capacity and weight of the battery are challenges to using electricity for road freight. Gas, whether biomethane or hydrogen fuel cells, is an alternative, but there is currently an inadequate supply and no refuelling network. As lorries move goods across borders, solving this part of the puzzle relies on international compatibility as well as innovation in truck design and improvements in complementary infrastructure like rail and refuelling points.

Hydrogen is the most common solution for trucks in all the net zero scenarios. Electrification is greatest in **Consumer Transformation** but is limited by high infrastructure costs for HGV charging facilities (such as catenary wires on motorways), and current weight and volume considerations mean batteries are not feasible for the largest vehicles.

In **System Transformation** HGVs use a nationwide hydrogen network to refuel; for **Leading the Way**, green hydrogen is available for HGV use.

Figure CV.27: HGV fuel mix in 2050



FES 2020 / Consumer view / Transport 84

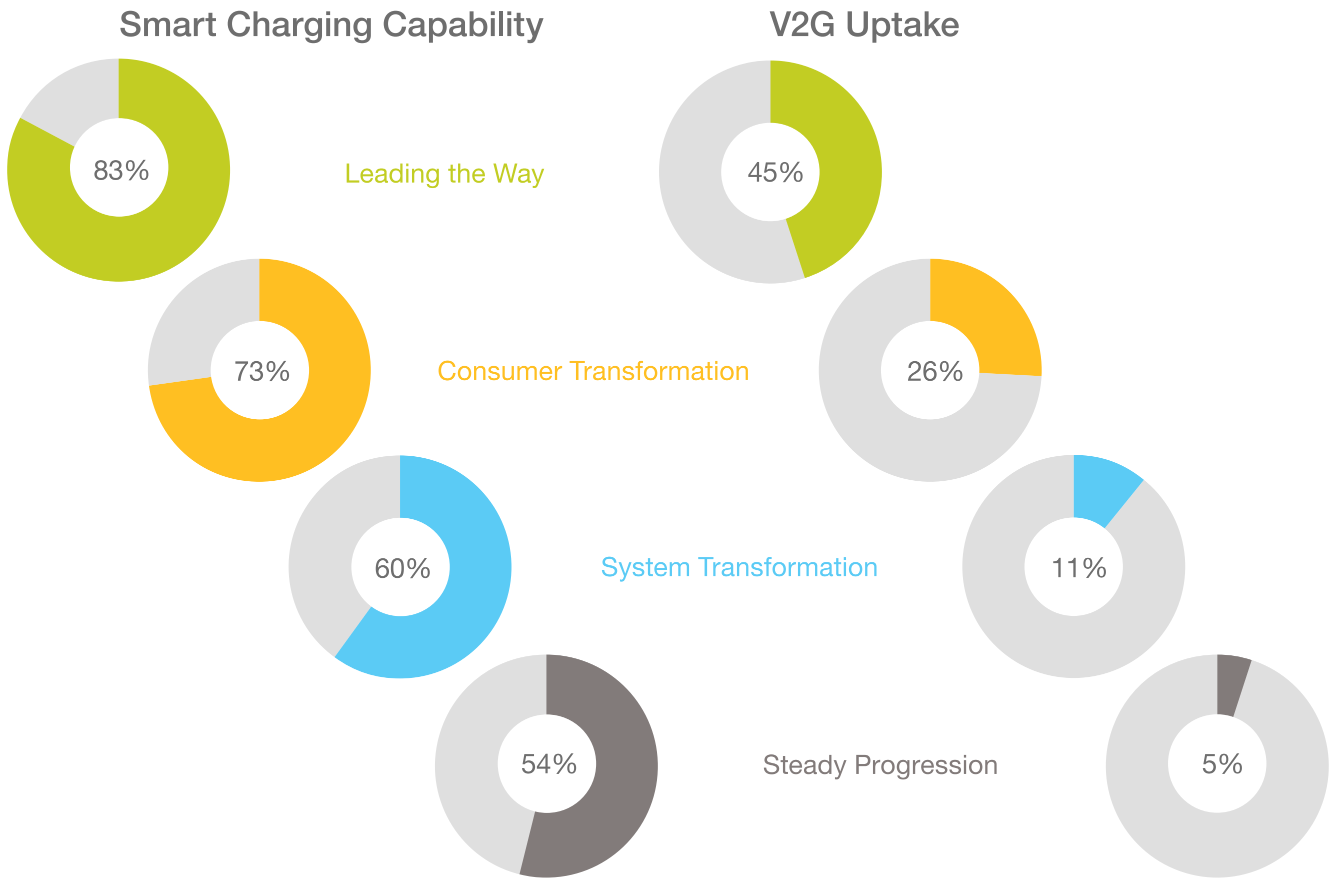
Smart charging

Owning an EV, as many people will in 2050, is not just about having a zero-emission vehicle; it will also play an important role in facilitating the wider decarbonisation of our energy system.

Today, most EV owners plug in their vehicles only when they need to charge, regardless of the time of day. In future, EV owners will be encouraged to keep their vehicles plugged in. A smart charging system will decide when is the best time to charge based on time of use tariffs designed to encourage charging when there is excess renewable energy and to avoid charging at times of peak demand. This will help network operators to manage electricity supply and maximise use of renewable resources.

Additionally, vehicle-to-grid (V2G) technology will enable the car to provide energy storage. This could store electricity in the home (for example, from solar panels), or even generate income for the owner, as the EV's battery is available to store excess renewable generation or to feed its charge back on to the local network during peak demand. As long as the car is plugged in, this resource can be remotely accessed, with little owner intervention required. In the case of AVs, their capacity for V2G could mean that they are directed to parts of the grid further away, to support a network fault. Of course, there will be occasions when the car needs to be charged at a certain time. But most people's car usage is fairly predictable and by ensuring that car charging infrastructure is available at places of work as well as home, V2G could reduce the running costs of the car and the network.

Figure CV.28: Engagement in smart charging and V2G in 2050



FES 2020 / Consumer view / Transport 85

System view

Introduction

The energy system must evolve while safely and reliably delivering low carbon energy to end consumers; when and where they need it to meet net zero. This will involve increasing scale, complexity and interdependency of energy conversions from one fuel to another. Flexibility will also become increasingly important to manage differences in when and where energy is produced and consumed.

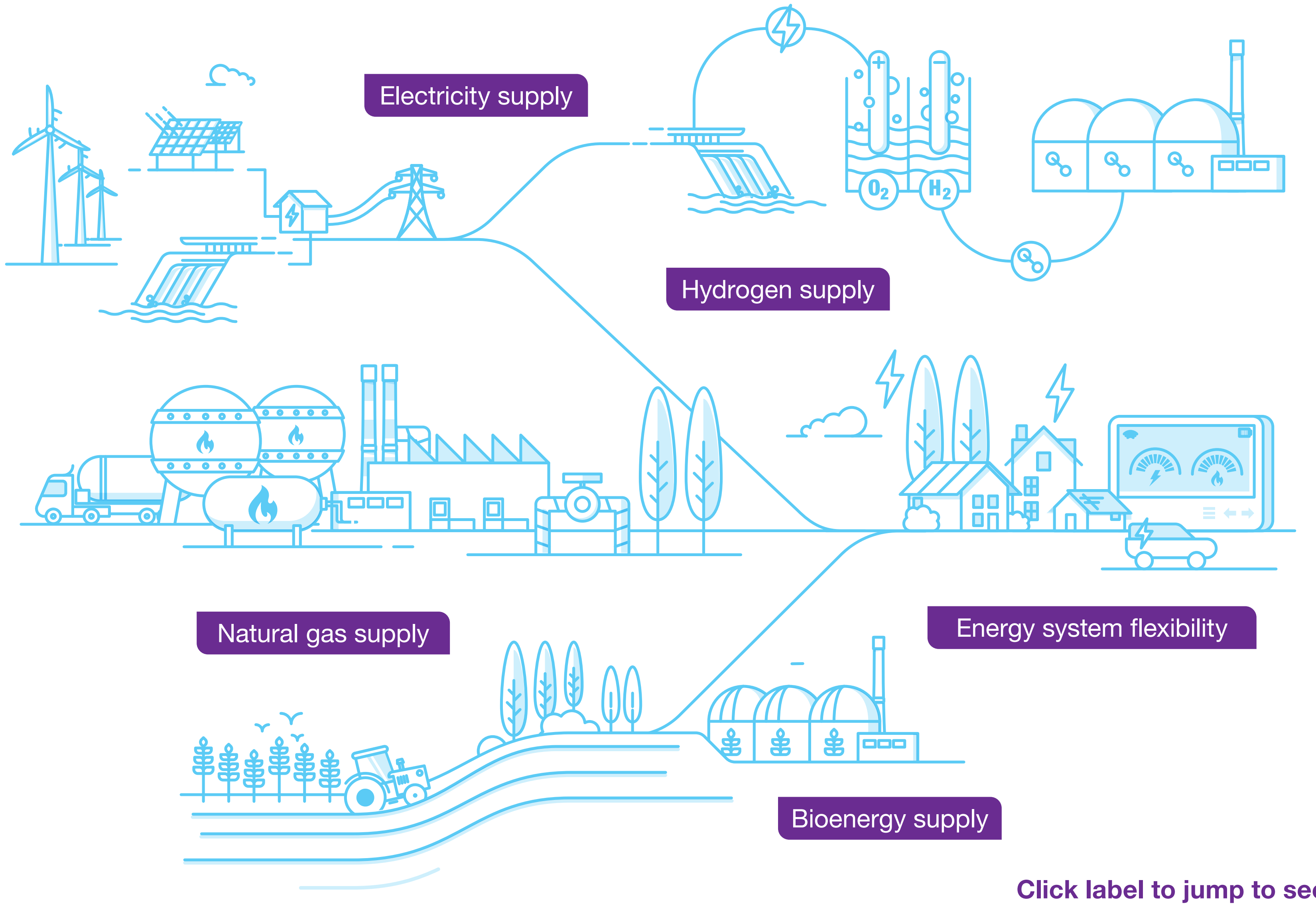
The System View chapter covers how energy is converted from primary fuels to meet consumer-level demand for decarbonised energy.

It looks at:

- Bioenergy supply;
- Natural gas supply;
- Hydrogen supply;
- Electricity supply; and
- Energy system flexibility.

As well as providing high-level context to energy flows across the scenarios in 2050, this introduction to the chapter also includes:

- how UK emissions are reduced between now and 2050;
- how FES ensures security of supply by meeting peak demands across the different scenarios.



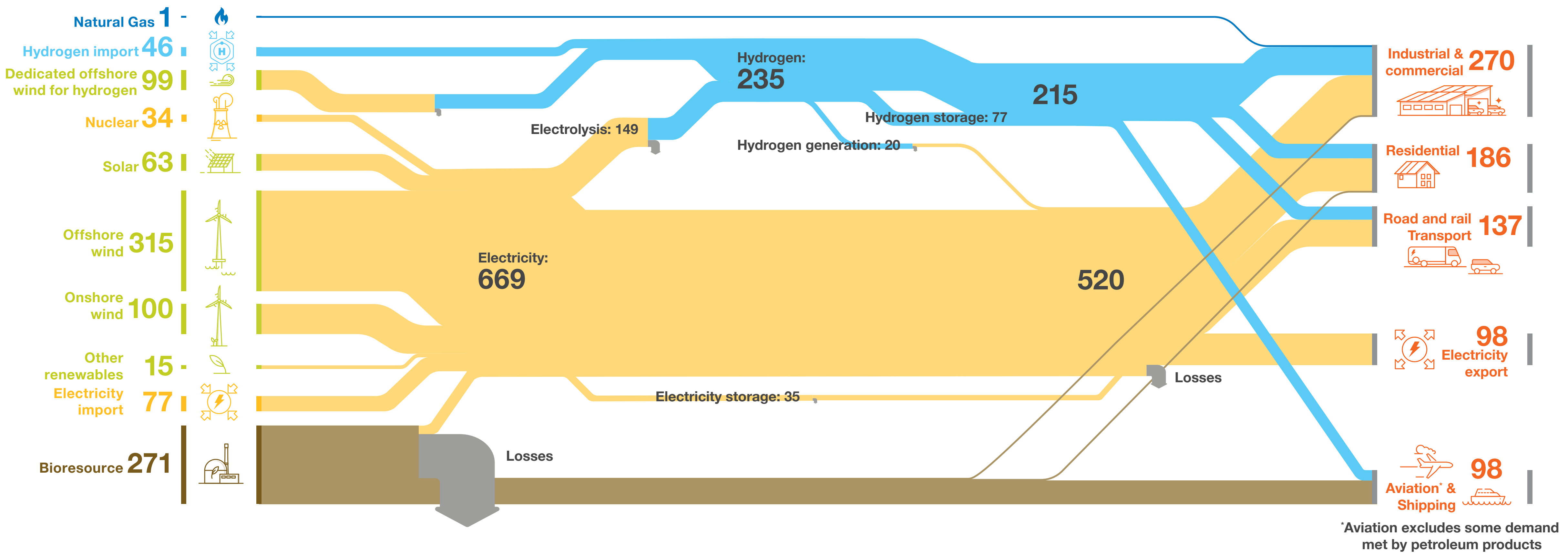
Click label to jump to section.

FES 2020 / System View / Introduction 87

What we've found

Consumer Transformation: energy demand and supply (TWh)

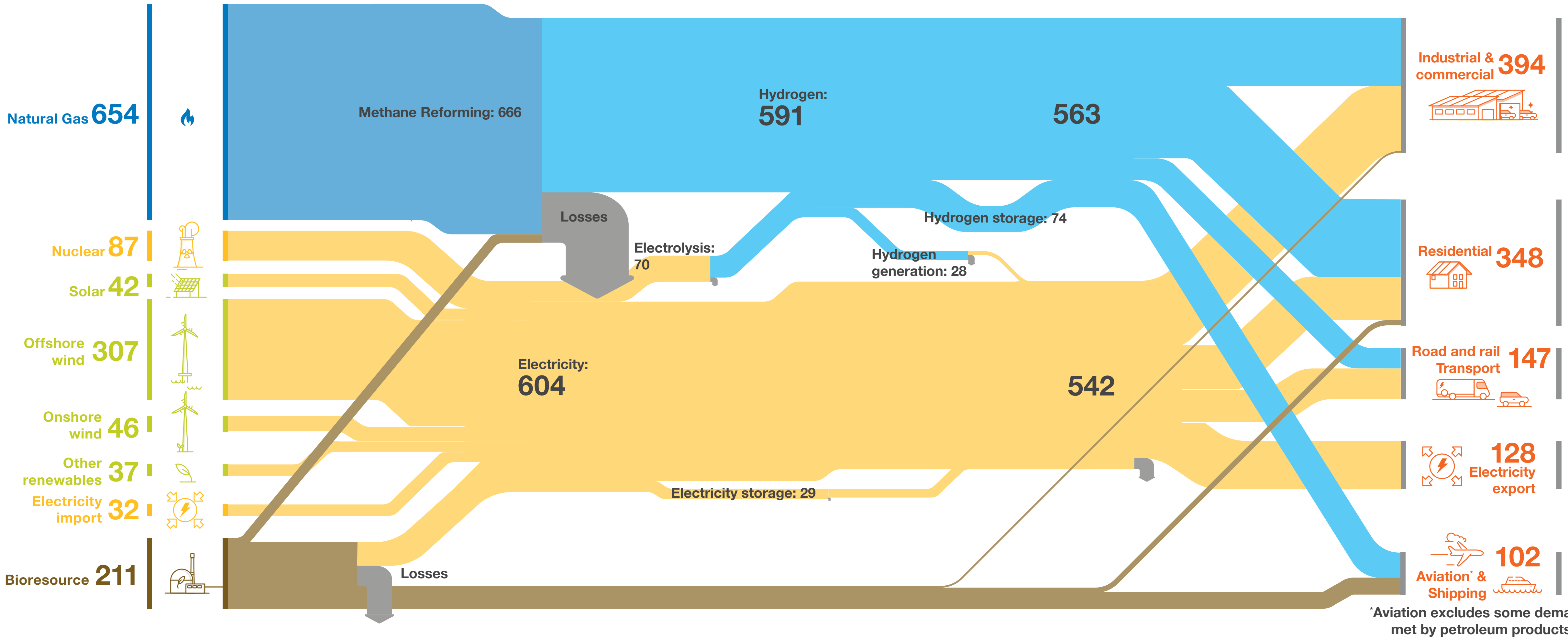
FES considers total energy supply annually across sources such as bioenergy, natural gas, and renewables. How this "primary" energy, which is often converted into electricity and hydrogen, meets consumer demand across the Industrial & Commercial, Residential and Transport sectors can be seen in the following energy flow diagrams.



What we've found

System Transformation: energy demand and supply (TWh)

FES considers total energy supply annually across sources such as bioenergy, natural gas, and renewables. How this "primary" energy, which is often converted into electricity and hydrogen, meets consumer demand across the Industrial & Commercial, Residential and Transport sectors can be seen in the following energy flow diagrams.



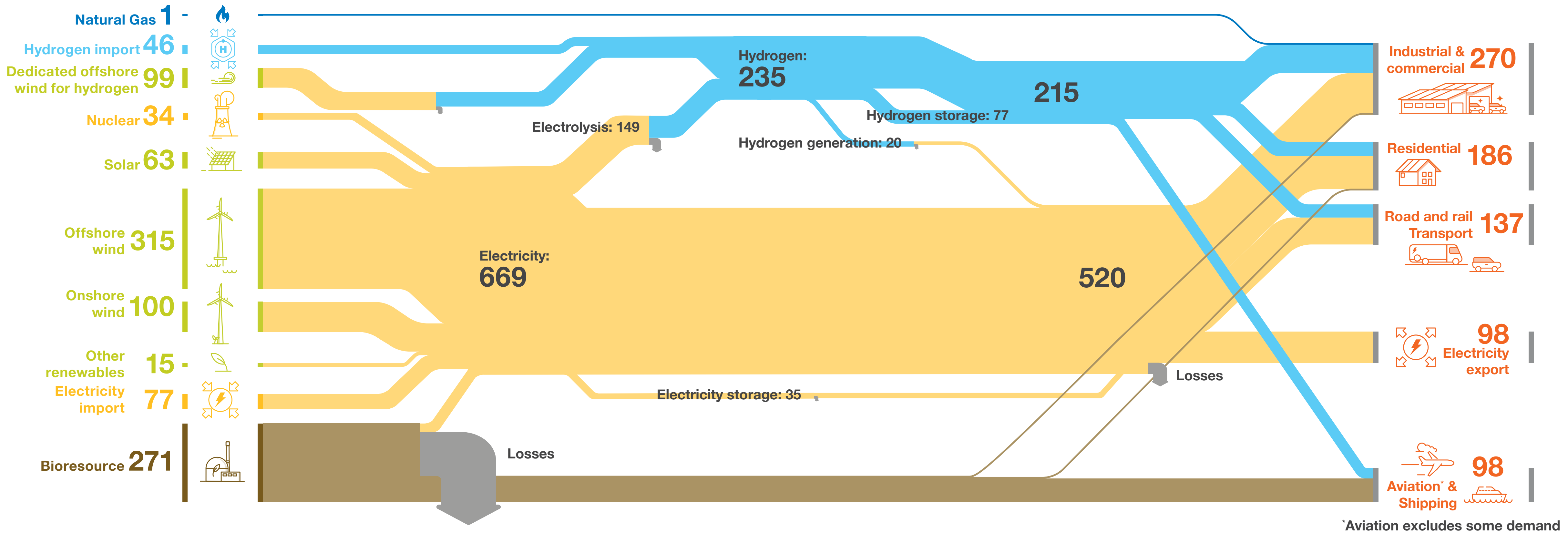
*Aviation excludes some demand met by petroleum products

FES 2020 / System View / Introduction 89

What we've found

Leading the Way: energy demand and supply (TWh)

FES considers total energy supply annually across sources such as bioenergy, natural gas, and renewables. How this "primary" energy, which is often converted into electricity and hydrogen, meets consumer demand across the Industrial & Commercial, Residential and Transport sectors can be seen in the following energy flow diagrams.



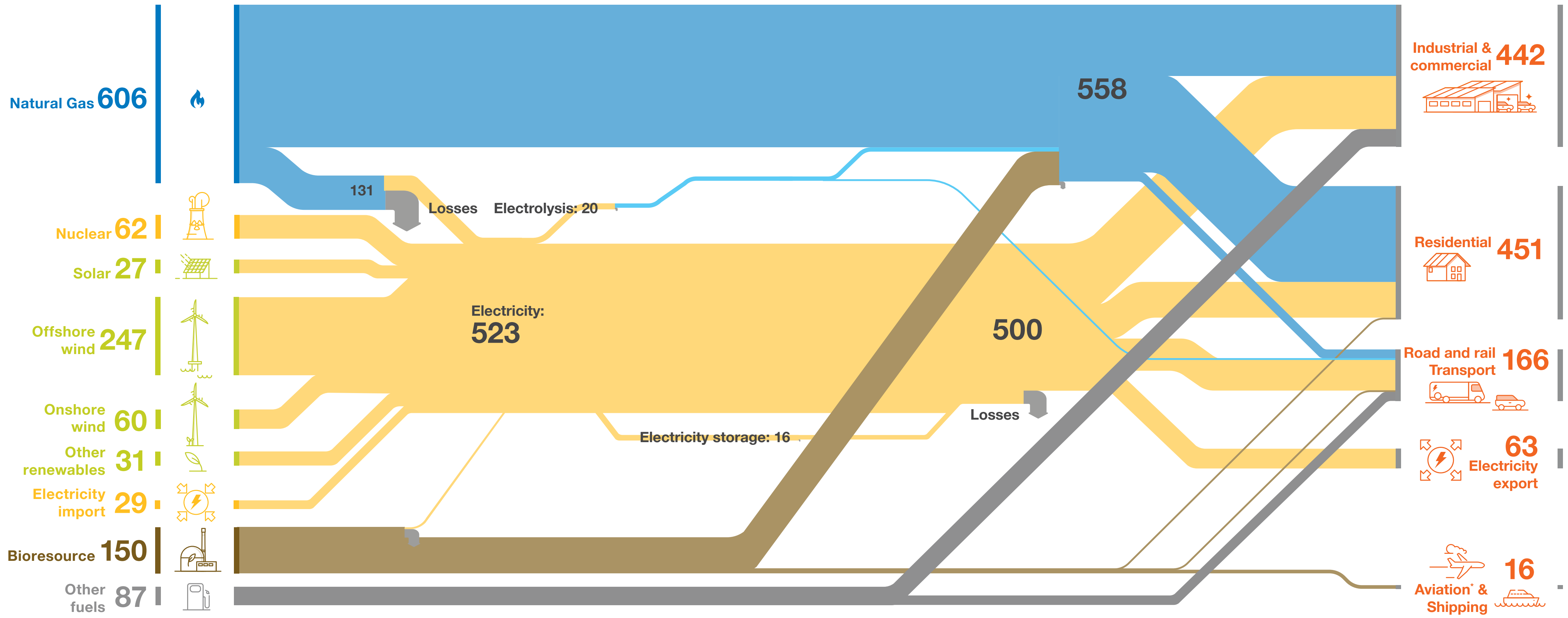
*Aviation excludes some demand met by petroleum products

FES 2020 / System View / Introduction 90

What we've found

Steady Progression: energy demand and supply (TWh)

FES considers total energy supply annually across sources such as bioenergy, natural gas, and renewables. How this "primary" energy, which is often converted into electricity and hydrogen, meets consumer demand across the Industrial & Commercial, Residential and Transport sectors can be seen in the following energy flow diagrams.



*Aviation excludes some demand met by petroleum products

FES 2020 / System View / Introduction 91

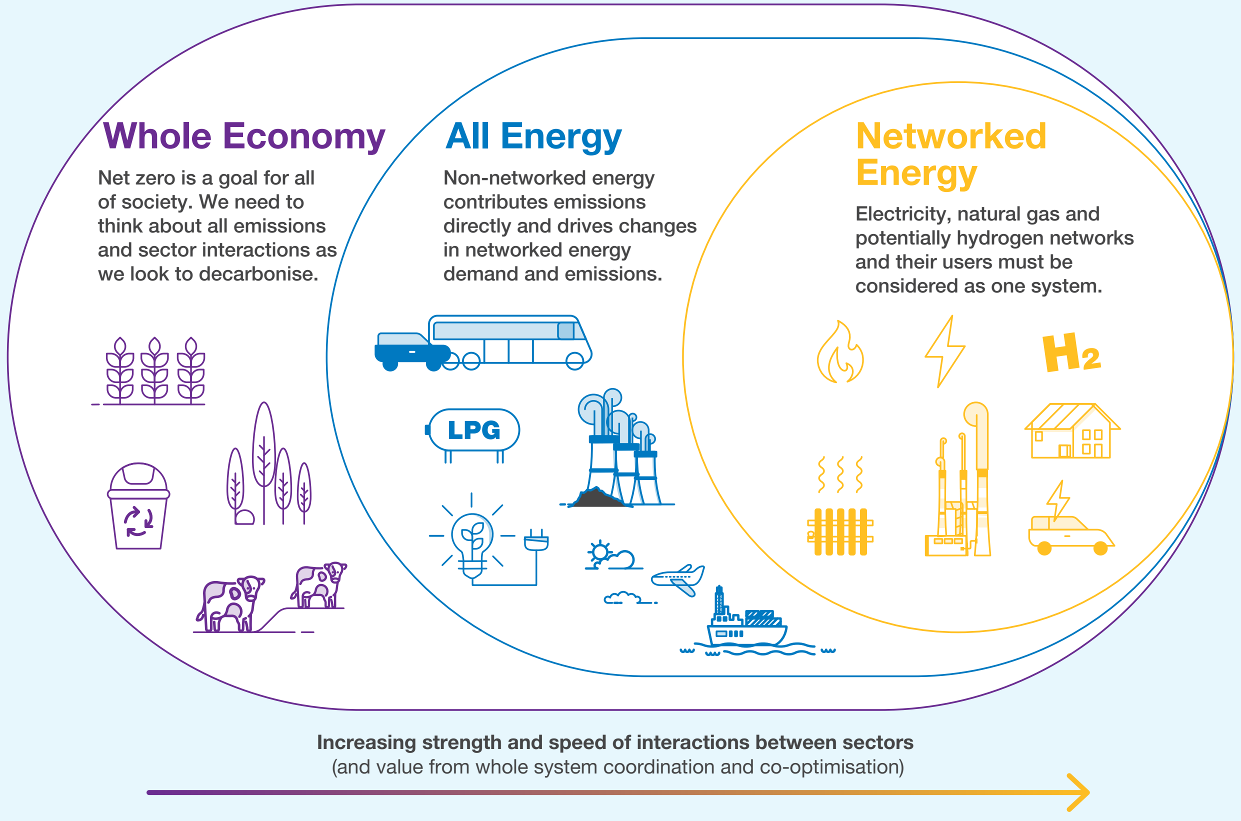
The importance of Whole System thinking for net zero

The legislated net zero target is for all of the UK[1]; so we must think across the whole economy rather than focusing only on individual sectors.

Even when focusing on energy use across the whole system, we find many important interactions. These can be considered at three different levels.

- **Networked energy** – by this we mean energy that is transported from where it is produced to where it is consumed using networks, such as electricity and gas, that interact strongly 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 impact on energy decarbonisation. This can be seen most clearly in the complex role of bioenergy and the corresponding land use implications but also includes how societal change impacts energy and emissions.

Figure SV.1:
Whole system interactions for net zero



Some interactions will play out in investment timescales, such as the transition of road or air transport from fossil fuels to zero carbon networked electricity or hydrogen.

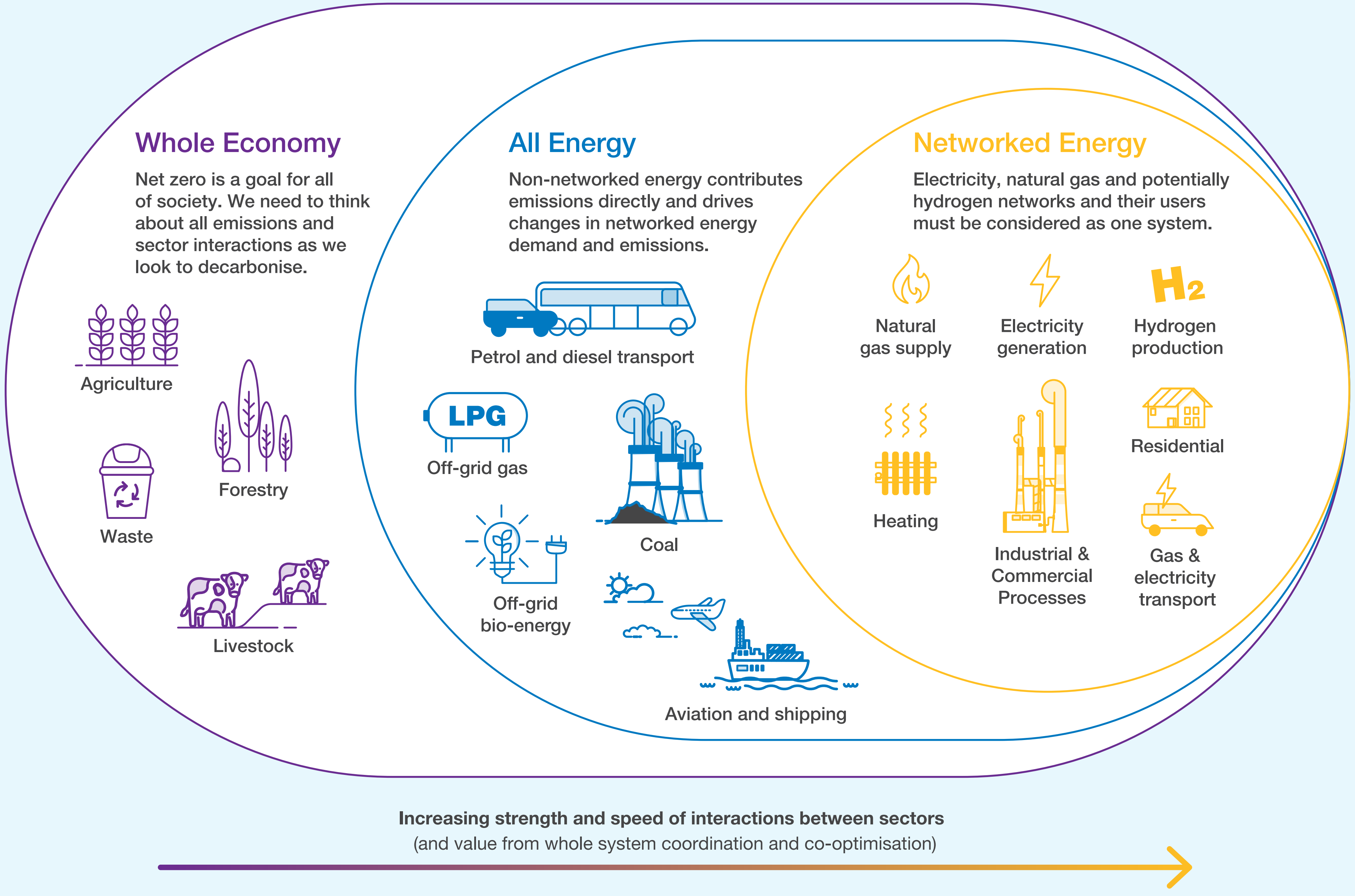
Other interactions will be seen operationally, such as changes in the amount of biomass, natural gas or hydrogen being used to generate electricity.

FES 2020 considers energy use in sectors that haven't been included in our analysis in previous years, such as aviation and shipping. We also consider emissions from non-energy sectors such as agriculture and "land use, land-use change, and forestry" (LULUCF). 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 CCC analysis and engagement with their experts.

1 While emissions are considered on a UK basis, energy demand and supply in FES analysis are always at a GB level (i.e. it doesn't include Northern Ireland).

FES 2020 / System View / Introduction 92

The importance of Whole System thinking for net zero



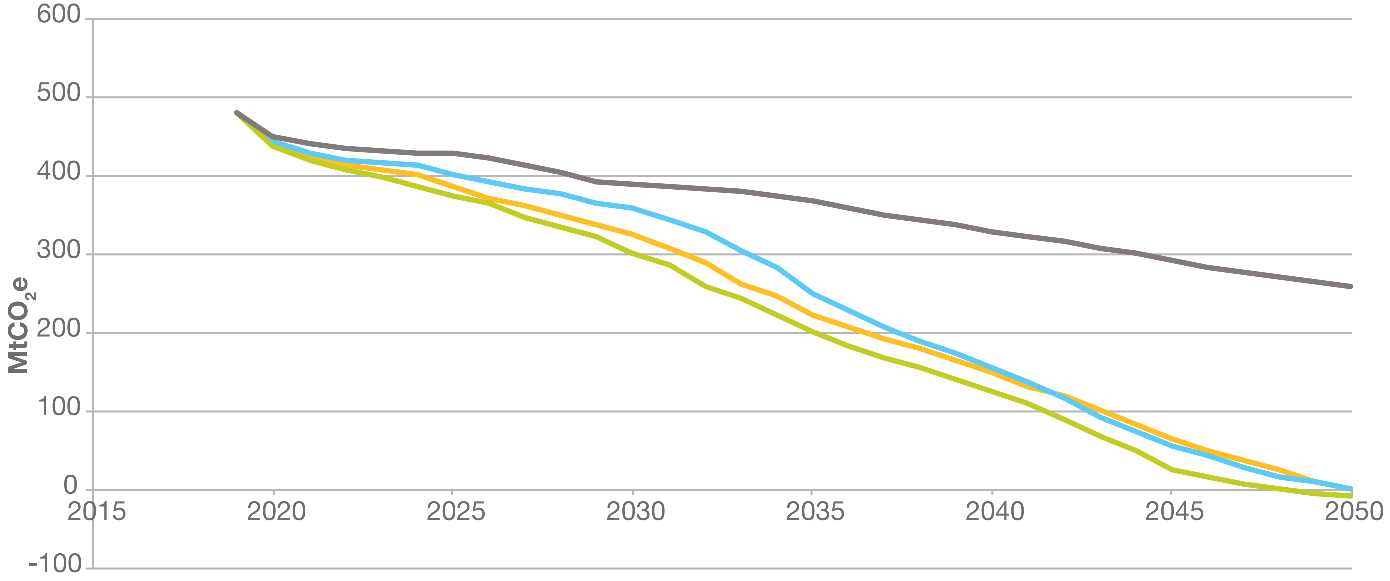
FES 2020 / System View / Introduction 93

Tracking the journey to net zero

UK greenhouse gas emissions in 2019 were 480 $MtCO_2e$. While this represents an improvement on 1990 levels, meeting the legislated target of net zero emissions by 2050 will be challenging. Emissions fell an average of 19 $MtCO_2e$ each year from 2008 to 2018 and must still fall an average of more than 15 $MtCO_2e$ each year from 2018 to 2050 to meet the net zero target.

As designed in the scenario framework, **Consumer Transformation** and **System Transformation** both hit the target of net zero emissions in 2050. **Leading the Way** achieves net zero slightly before this in 2048 whereas **Steady Progression** still emits 258 $MtCO_2e$ in 2050. This equates to a reduction of 68% compared to the level in 1990.

Figure SV.2: Total net greenhouse gas emissions



All Scenarios

The table shows the sectors that still emit in 2050 and the corresponding negative emissions that are required to achieve net zero. Alongside land use changes such as reforestation, most negative emissions are delivered by use of BECCS in the power sector although **System Transformation** also achieves some negative emissions from hydrogen creation using biomass gasification.

Figure SV.3: 2050 greenhouse gas emissions by category

$MtCO_2$ equivalent	2019	CT 2050	ST 2050	LW 2050	SP 2050
Heat for buildings	87	0	0	0	78
Electricity before BECCS	57	3	2	2	30
BECCS in power sector	0	-52	-49	-61	0
Industry	102	4	4	4	55
Road transport	113	0	0	0	16
Hydrogen production	0	0	-1	0	0
Other[2]	121	45	45	45	79
Total[3]	**480**	**0**	**0**	**-10**	**258**

Unlike the sensitivity analysis undertaken in FES 2019 which achieved 96% emissions reduction and relied on novel technologies to make up the remaining 4%, **Consumer Transformation**, **System Transformation** and **Leading the Way** all fully meet net zero emissions by 2050.

2 Other includes Agriculture and LULUCF, Waste, F-gases, Aviation and Shipping
3 Note that some of these figures do not add up exactly due to rounding

FES 2020 / System View / Introduction 94

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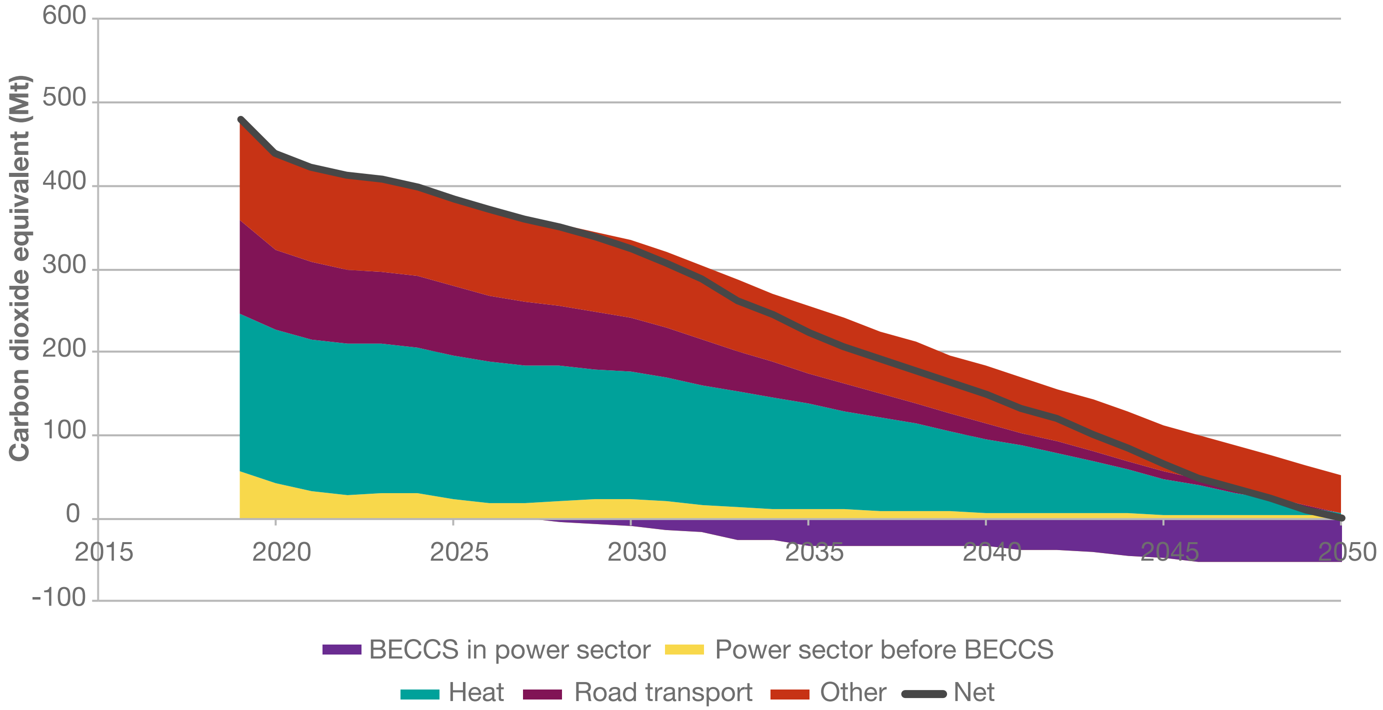
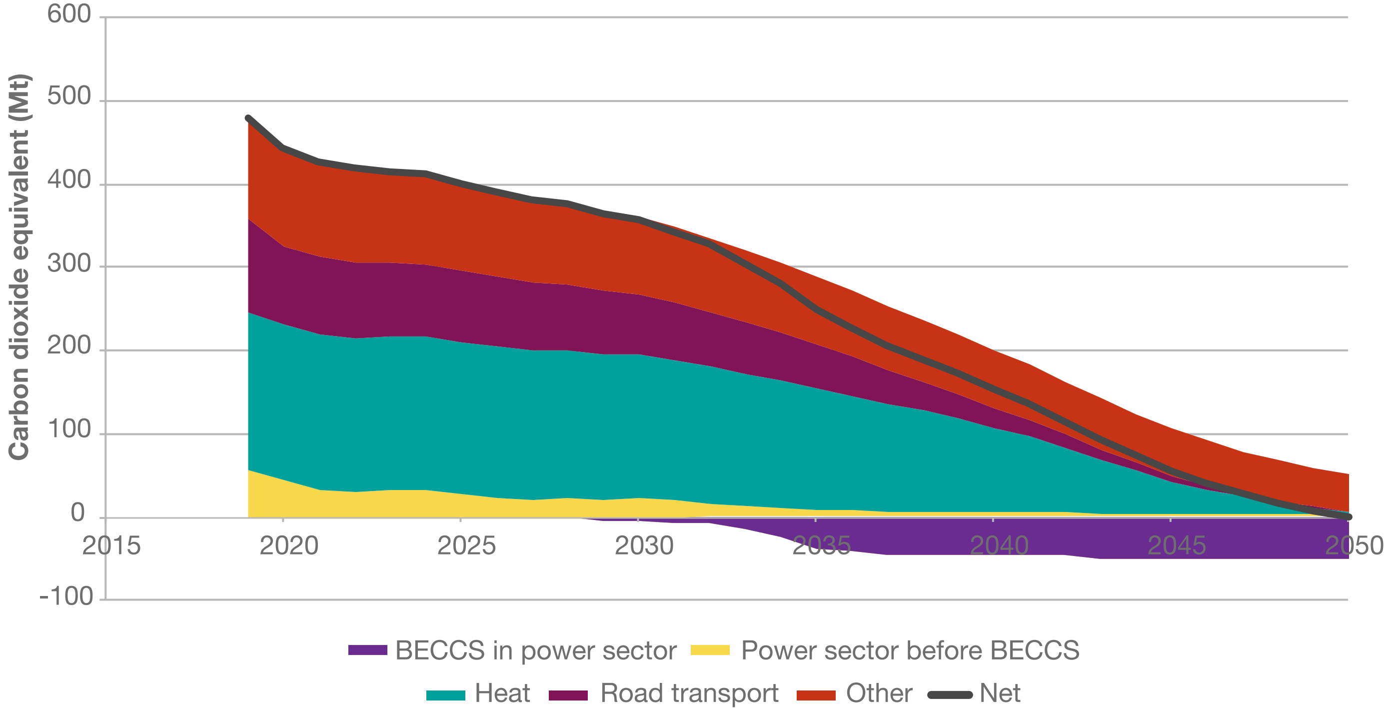
FES 2020 / System View / Introduction 95

Figure SV.2: Total net greenhouse gas emissions



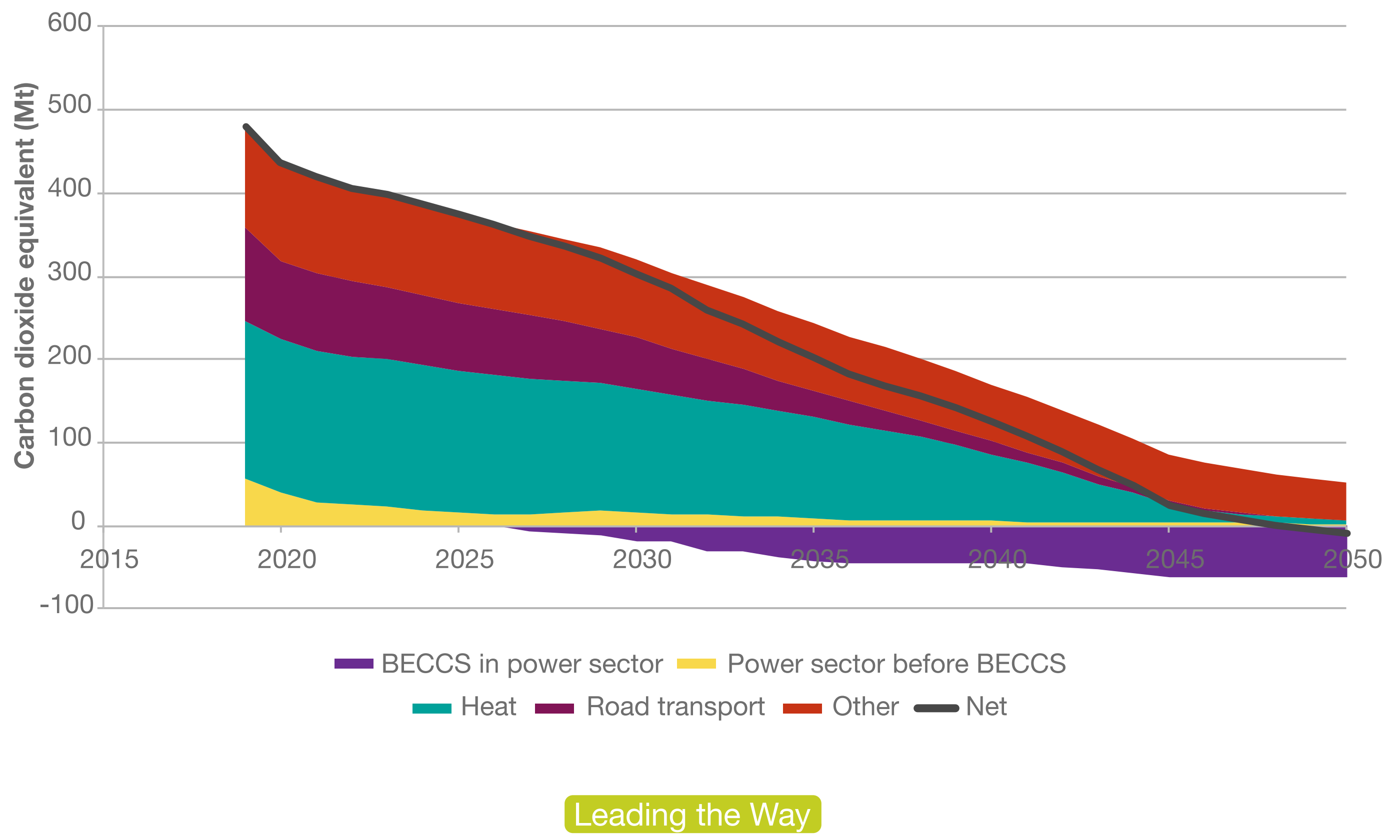
Consumer Transformation

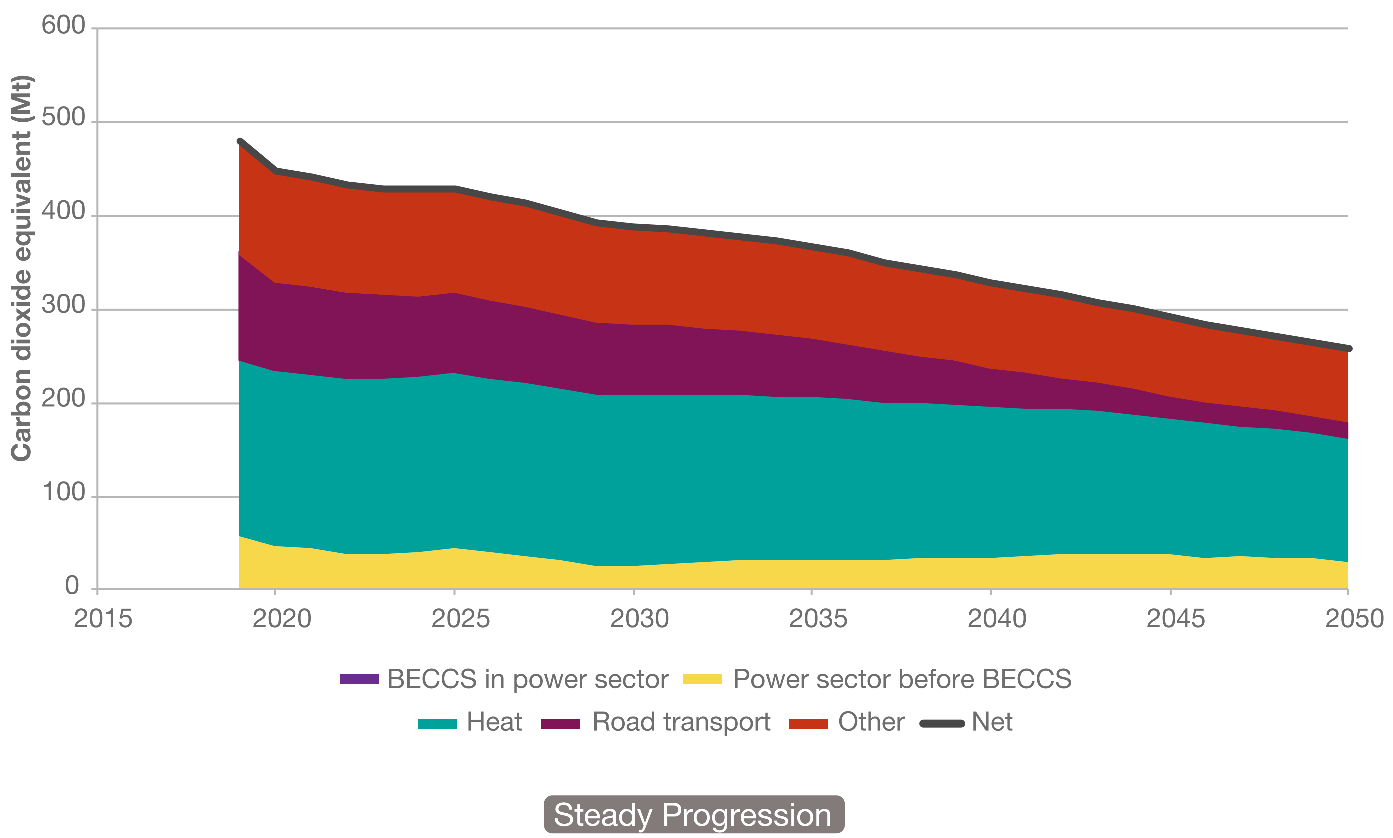


System Transformation

FES 2020 / System View / Introduction 96

Figure SV.2: Total net greenhouse gas emissions





FES 2020 / System View / Introduction 97

Security of supply

A key role of the energy system is to ensure security of supply. Our analysis assesses different security of supply metrics for electricity and natural gas.

- For electricity, a reliability standard set by the Secretary of State – currently three hours per year loss of load expectation (LOLE[4]) - is met for all years in each scenario.
- For natural gas, there is enough supply to meet the peak demand on a very cold day (a 1-in-20 peak winter day[5]) in all years and in each scenario.

In addition to the peak demands that are used in these security of supply metrics, energy flows are also analysed at daily and half-hourly granularity to consider energy balancing challenges and the need for whole system flexibility to manage them.

4 An approach used to describe electricity security of supply. For detailed definition, please refer to glossary.
5 Peak demand for gas is the level of demand that, in a long series of winters, with connected load held at levels appropriate to the winter in question, would be exceeded in one out of 20 winters, with each winter counted only once.

FES 2020 / System View / Introduction 98

Electricity peak demand

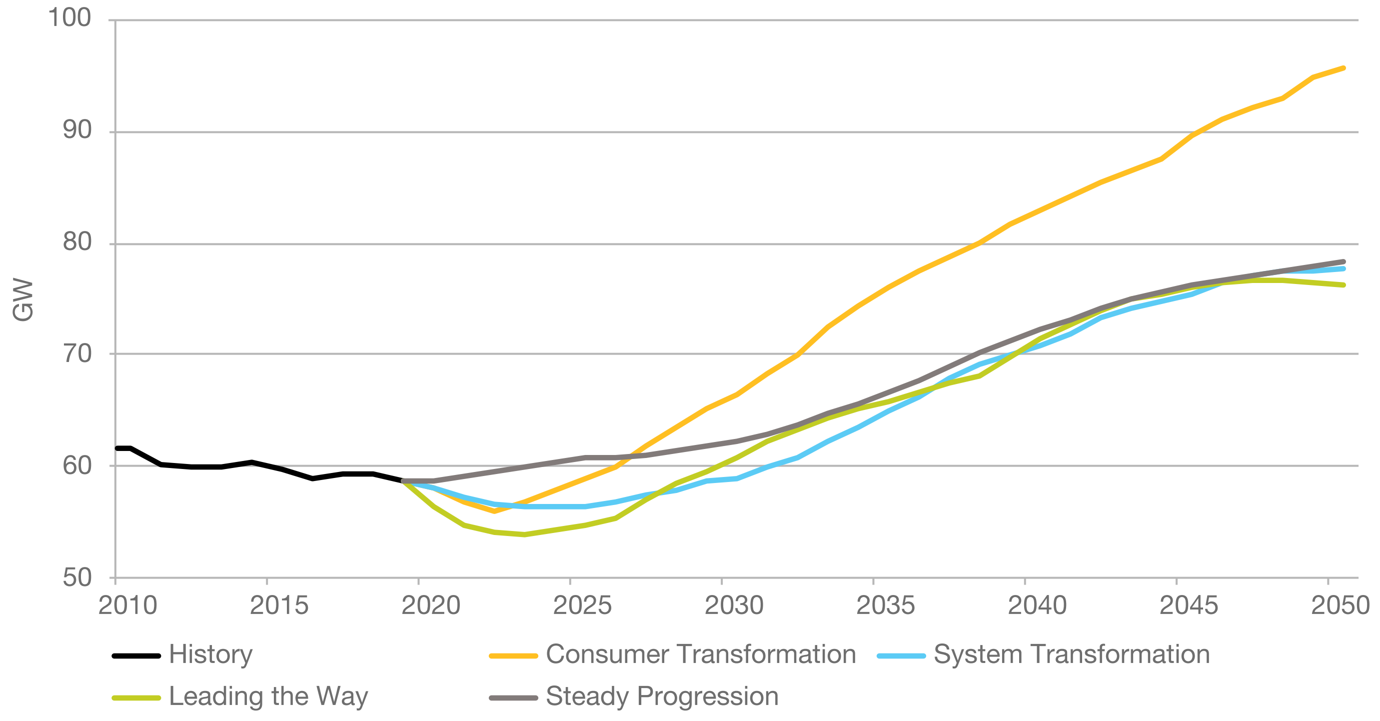
Historically, electricity peak demand across the electricity network at a GB-wide level[6] has always occurred at around 17:30 on weekday evenings. There is also a correlation with cold weather with the peak demand of the year tending to fall on cold weekdays - although this correlation is not as strong as for peak natural gas demand[7] for which residential heat is a larger proportion.

However, as demand becomes smarter and end consumers begin to increase their consumption at times of low prices caused by high renewable output on the energy system, it is possible that the consumption at these times of high renewable output could exceed the traditional peak demand. The emergence of electricity demand from electric vehicles and hydrogen electrolysers will significantly amplify this effect.

Conversely, when renewable output is low, flexible demand (e.g. EVs and electrolysers) will reduce their consumption and technologies like battery storage and vehicle to grid will discharge power back into the energy system.

The chart (right) shows the traditional peak demand that might be experienced on a cold winter's evening on a weekday. Each scenario has enough de-rated generation capacity to meet this demand and provide the required level of de-rated plant margin. Put simply, there is enough generation to meet demand.

Figure SV.4: Electricity peak demand (including losses)



6 At a more local level peak demands may fall at different times across the country (e.g. residential demand at street level tends to peak later in the day than I&C demand).
7 FES uses the Average Cold Spell (ACS) definition of electricity demand which is consistent with the treatment of demand in the electricity Capacity Mechanism. As more heat demand is electrified, it may be more appropriate to consider a more weather-related metric such as the gas 1-in-20 peak day demand.

De-rated generation capacity

De-rated generation capacity

De-rated generation capacity is when the installed capacity of generation is reduced to best reflect what is expected to be available in real time. The reduction is to account for unexpected outages or breakdowns and other restrictions to the generators which is based on historical performance.

For wind a metric called “Equivalent Firm Capacity” is applied which is an assessment of the entire wind fleet’s contribution to capacity adequacy. It represents how much of 100% available conventional plant could theoretically replace the entire wind fleet and leave the security of supply position unchanged.

Interconnectors are de-rated based on analysed flows under potential stress event conditions.

De-rating of generation in FES follows the same approach as is used in the Capacity Market and more information can be found in the Modelling Methods Document[8].

De-rated plant margin

De-rated plant margin

The de-rated plant margin is the sum of de-rated generation capacity declared as being available during the time of peak demand plus support from interconnection, minus the expected demand at that time and basic reserve requirement.

It can be presented as either an absolute GW value or a percentage of demand (demand plus reserve) and is explicitly linked to the Loss of Load Expectation (LOLE).

This de-rated plant margin is consistent with that used as part of the Capacity Market analysis and the Winter Outlook Report. See the Modelling Methods Document[8] for more details.

FES 2020 / System View / Introduction 100

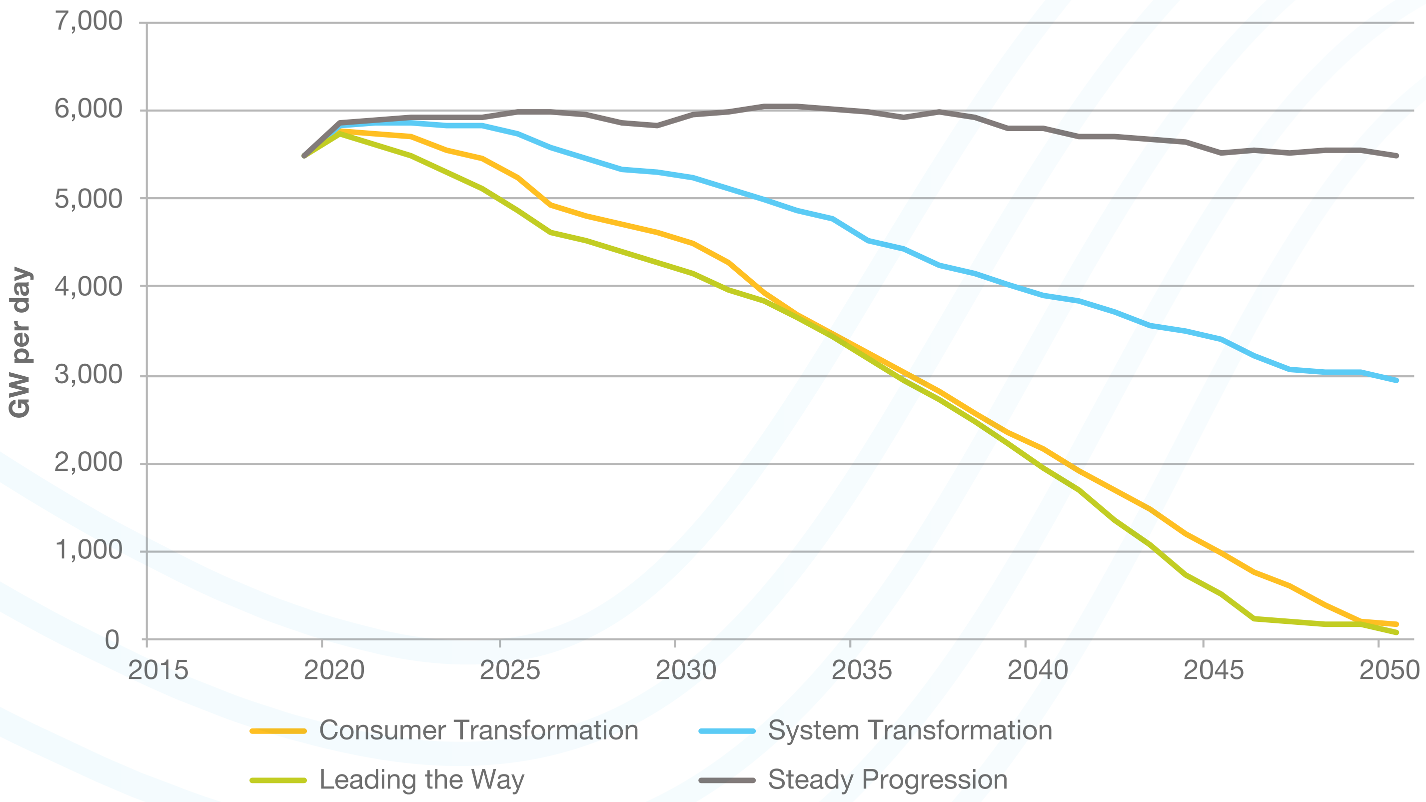
8 Modelling Methods Document - https://www.nationalgrideso.com/future-energy/future-energy-scenarios/fes-2020-documents

Natural gas peak demand

Trends in peak natural gas demand[9] generally mirror annual natural gas demand in each scenario as many of the factors which influence annual demand also influence peak demand, but the declines are not as rapid. For instance, if a property converts from a gas boiler to an electric heat pump, this will reduce both the annual and the peak demands. Similarly, energy efficiency measures impact peak demand, as well as annual demand, as a better insulated property would retain heat better during winter and require less gas in cold snaps.

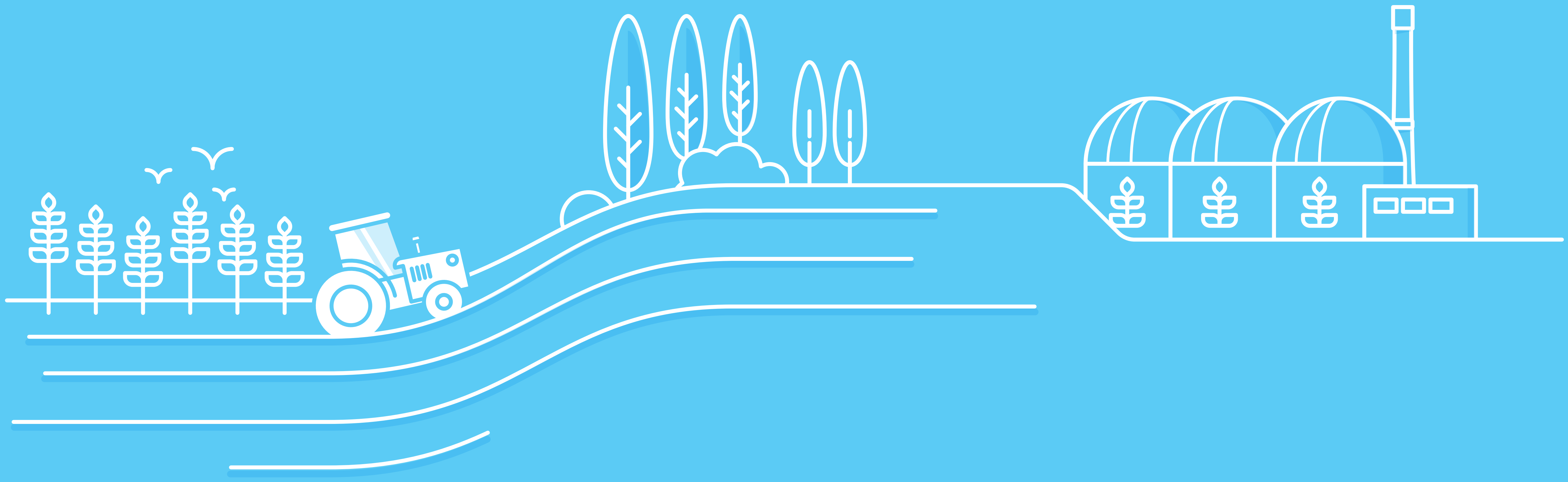
However, if properties move to hybrid heating systems, the annual demand for gas is likely to be reduced as the electric heat pump contributes a large share of the energy; but on a peak day, the gas boiler would fire up and peak demand could stay relatively high even as annual demand decreases.

Figure SV.5: Peak natural gas demand (1-in-20 day)



9 This is a 1-in-20 demand which means that statistically, in a long series of winters, it would be exceeded in one out of twenty winters.

Bioenergy Supply



Key insights

- Bioenergy has an important potential role in decarbonising our energy system and wider economy when combined with carbon capture, usage and storage (CCUS) to deliver negative emissions.
- A sustainable supply of feedstock for bioenergy is influenced by many factors, such as land use, waste management and competing demand from non-energy sectors like agriculture and construction.
- Meeting the net zero target in our scenarios depends on negative emissions to balance residual emissions from other non-energy sectors. Bioenergy with CCUS can deliver this but will rely on increased domestic production or imports of bioenergy feedstocks to achieve the scale needed.

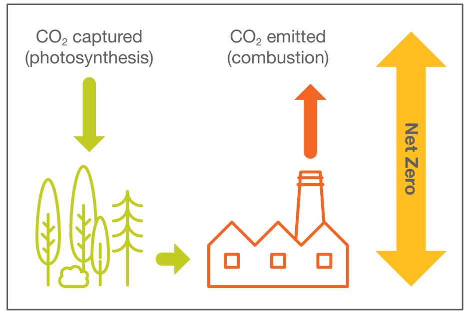
Bioenergy is produced when we use organic feedstocks like energy crops, forestry and agricultural waste and biological materials to produce energy. These feedstocks can be burned to produce heat or power, or processed to produce biogas or liquid biofuel. Plants and trees are part of the natural carbon cycle. They absorb carbon from the atmosphere as they grow, and release it when they are burned or decay. Bioenergy is therefore considered to have no net emissions. If we then combine bioenergy with carbon capture and storage (BECCS) it results in negative emissions.

FES 2020 / System View / Bioenergy supply 103

BECCS

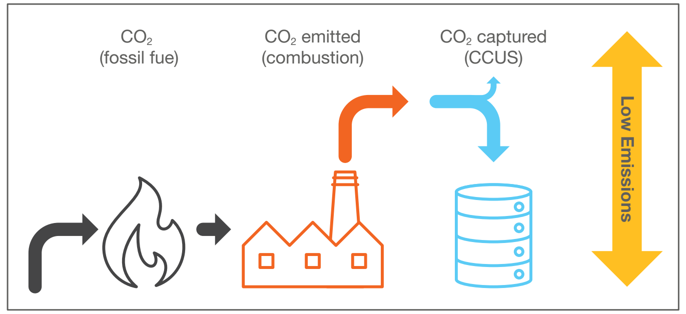
How does BECCS deliver negative emissions?

Coupling bioenergy with carbon capture and storage to capture the CO_2 produced on combustion means that the process, known as BECCS, delivers negative emissions. So how does this work?



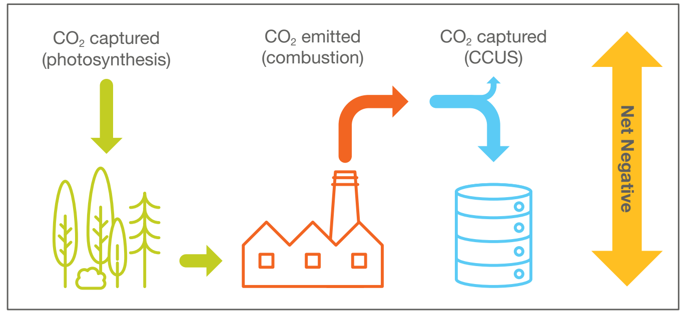
Switching fossil fuels for bioenergy

Trees naturally pull CO_2 out of the atmosphere (absorbing it during photosynthesis). This results in carbon being stored in forests, vegetation and in the soil. While the burning of fossil fuels releases carbon that has been 'trapped' underground for many millions of years; when we burn sustainably sourced wood or other bioenergy crops, the CO_2 they emit can be offset by the CO_2 they have absorbed over their life, resulting in net zero emissions.



Using Carbon Capture and Storage

Technology can capture CO_2 from fossil fuel combustion before it is released into the atmosphere but there is a certain level of CO_2 leakage. Capture rates are expected to range between 95 and 97 per cent across the FES 2020 scenarios. So this approach results in low, but not zero, emissions.



Combining the two for negative emissions

If we then combine CCUS with bioenergy, to trap and store recently absorbed CO_2, this will result in negative emissions. For example, generating electricity by burning organic matter (biomass) rather than coal or gas, with the resultant CO_2 emissions being captured will result in negative emissions. This process is known as BECCS (bioenergy with carbon capture and storage).

FES 2020 / System View / Bioenergy supply 104

Where we are now?

In the UK, bioenergy currently provides around seven per cent of total primary energy demand.

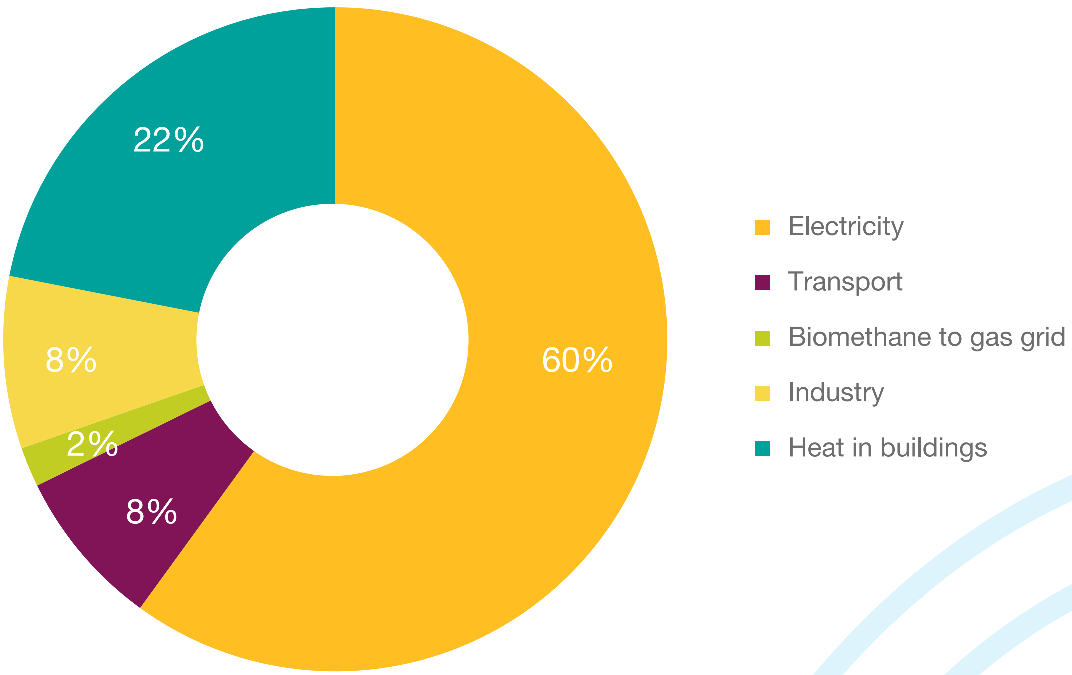
Bioenergy has a particularly valuable role in certain energy sectors which are difficult to decarbonise. Aviation requires high energy density fuel, and biofuels (such as bioethanol) are ideal. Other industries, for example cement, iron and steel, have high heat processes with very specific combustion characteristics. Blends of feedstock that include biomass can meet these energy needs. Because they are energy dense and easy to transport in compressed forms, biofuels can also provide zero-carbon heating for off-grid rural homes that are expensive to insulate and electrify.

Production of bioenergy has more than doubled in the past 10 years, mostly driven by policy initiatives:

- The Renewable Transport Fuel Obligation (RTFO) incentivising fuel blends that include bioethanol, biodiesel and biomethane;
- The Renewable Heat Incentive (RHI) supporting use of biomass boilers in around 13,000 UK homes and increasing levels of biomethane injection into the natural gas network;
- The Renewables Obligation (RO) and the Contracts for Difference (CfD) incentivising the use of biomass for electricity generation.

Whilst around a third comes from organic waste (solid waste incineration, anaerobic digestion of food and farm waste, landfill gas) the remainder relies on plant-based biomass products, and there is competition for these resources (or the land on which they grow) from the agriculture, farming and forestry sectors. So, in response to growing demand, there has been a rapid rise in imported biomass from around 11 TWh in 2008 to 40 TWh in 2017.

Figure SV.6: Bioenergy use in the UK in 2017 (based on primary energy required)[1]



1 Source: CCC - Biomass in a low carbon economy 2018

Where we are now?

Total primary energy demand

Primary energy demand

Primary energy demand in this context means the total input energy that is required to meet end consumer demand including:

- losses incurred during transportation (e.g. energy lost as heat during electricity transmission/distribution or leakage/venting of gas)
- conversion from, or processing of, primary energy (e.g. fossil fuels or renewables into secondary fuels such as electricity or hydrogen).

FES 2020 / System View / Bioenergy supply 106

What we've found

Our analysis explores how domestic production of bioenergy feedstocks could increase from today's levels, recognising the need for this to be sustainable across all sectors that use land (food, agriculture etc). Waste for use in bioenergy will continue to be available and imported feedstocks are critical for some net-zero pathways, recognising they must also come from sustainable sources.

We have considered low, medium and high levels of bioenergy feedstocks and applied them across our scenarios. The low case assumes limited UK policy support and poor global governance, leaving available supply largely the same as today. The medium case assumes UK policy support enables domestic production to increase. Strategically managed land use and waste products lead to around 220 TWh of bioresource, the majority domestically produced. In the high case scenario, there is a favourable global context for sustainable biomass production. The UK becomes an early mover in the developing global import market[2], resulting in access to around 275 TWh of bioresources (domestic and imported) by 2050.

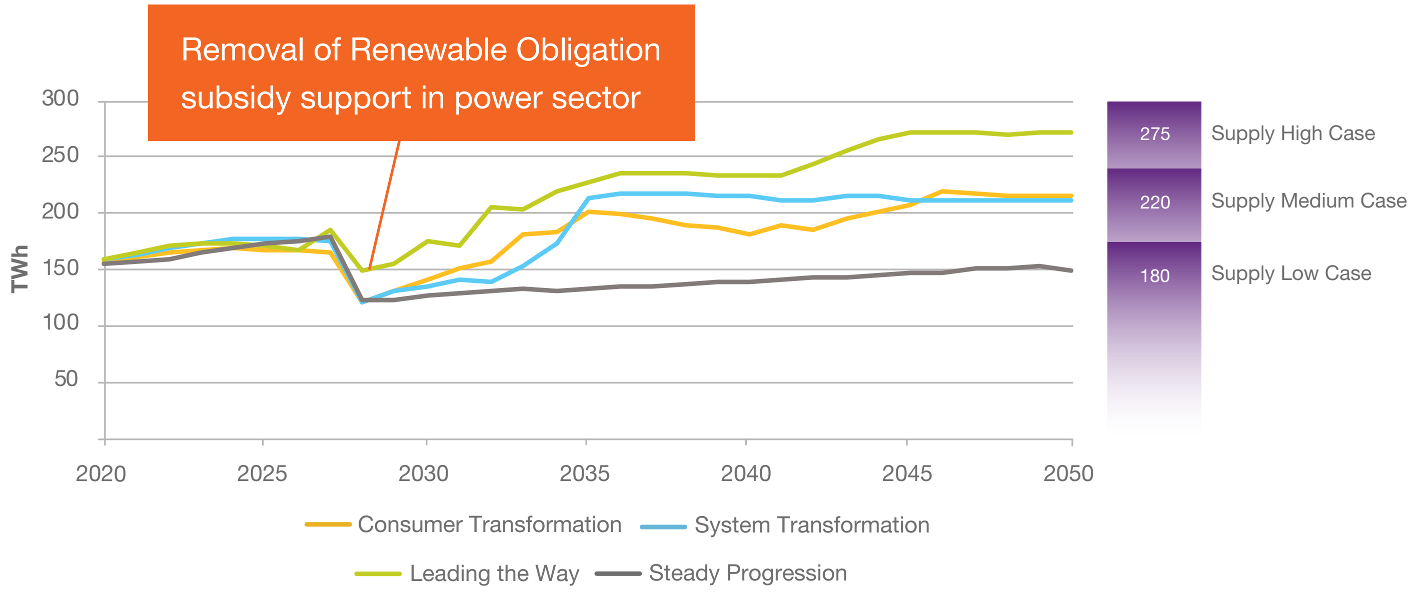
The decisions on how best to use the limited supplies of bioresource are complex and can span all sectors of the economy. For example, harvested timber could be used for bioenergy production, but also in place of cement, brick or steel for construction to provide a long-term store of carbon and displace emissions from the fossil-fuel intensive process for manufacturing those materials. Our analysis has identified 'best use' of this limited resource in the energy sector as:

1. Meeting end consumer demand where no alternative options for decarbonisation exist

2. BECCS for electricity generation to deliver negative emissions

3. Biomass gasification for hydrogen production (with CCUS) to deliver negative emissions

Figure SV.7: Bioresource use



2 In line with CCC analysis, we assume the UK would have access to an 'equal share' of the global sustainable biomass resource, based on the UK's projected share of global primary energy demand in 2050

FES 2020 / System View / Bioenergy supply 107

What we've found

Land use

How to best use our land for carbon reduction?

There are competing uses for land to consider when exploring how much feedstock that may be available for producing negative emissions from the energy sector.

- We can increase carbon removal by building up the number of forests across the UK (afforestation), or restocking existing forests (reforestation), as the forests remove carbon from the atmosphere as they grow.
- A form of charcoal called biochar can be added to soils to improve soil fertility and act as a stable long-term store of carbon. Biochar is produced by the thermal decomposition of biomass in the absence of oxygen.
- Silicate rocks naturally remove carbon from the air over geological timescales. This process can be speeded up by grinding up rocks (to vastly increase the exposed surface area) which can be dispersed over cropland. This is known as enhanced weathering.
- When wood is used for construction instead of cement or steel, it effectively stores away carbon. The subsequent forest regrowth can then sequester additional carbon.
- Peat is one of the largest and most efficient land-based stores of carbon. Peat is partially decomposed plant material which forms when plant material is deposited in an oxygen-poor environment. Protecting and restoring peatlands is a clear option for carbon storage.
- We can increase the amount of carbon stored in soils through improved agricultural practice. This is known as soil carbon sequestration.

FES 2020 / System View / Bioenergy supply 108

What we've found

bioenergy

Spotlight

What do we mean by 'bioenergy'?

Bioenergy is energy produced from organic matter. This may either be from agricultural crops grown specifically for that purpose or forestry residues, or from the waste products of various sectors. Whilst there are many different ways of producing bioenergy, not all organic matter can be used in each production process. Many forms of bioenergy also have very specific uses. The table right explores the various elements of that value chain.

The bioenergy value chain

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

FES 2020 / System View / Bioenergy supply 109

What we've found

imported feedstocks

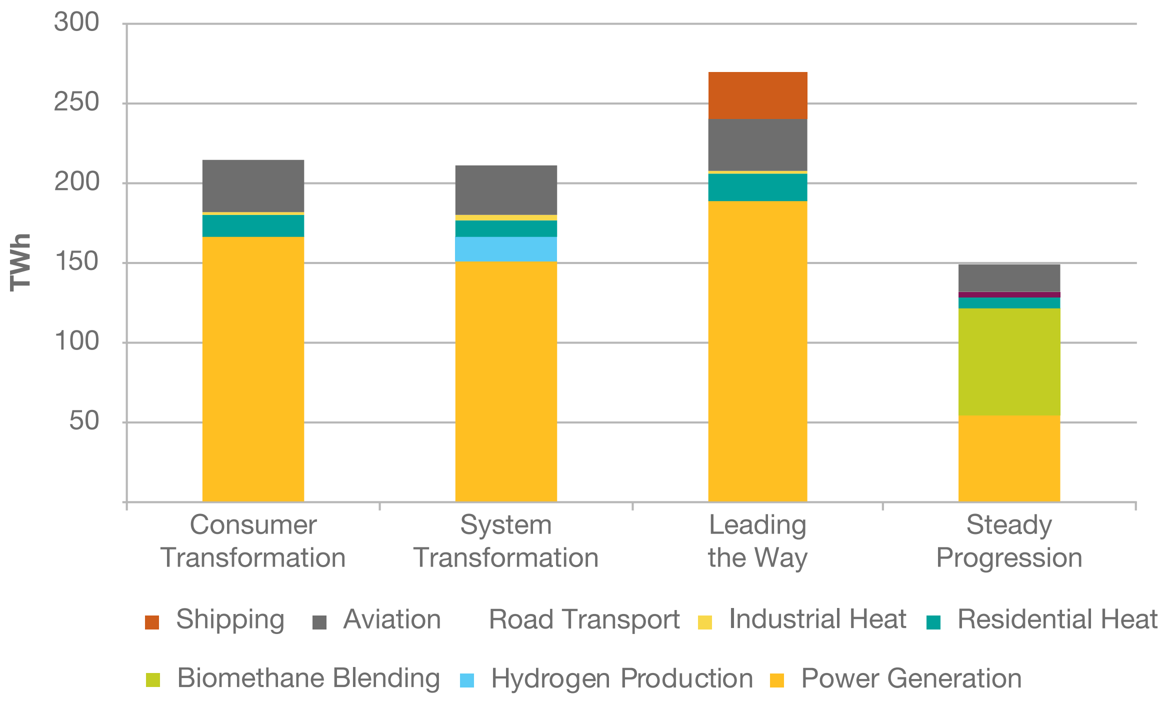
Uncertainty around biomass imports

Probably the greatest uncertainty around the amount of future biomass is whether a global market could develop. We have already seen countries with smaller populations and large amounts of land exporting biomass such as wood pellets to the UK. In addition, the UK has excellent potential for future carbon storage – for instance in depleted North Sea gas fields - which many other countries do not have. With the right incentives, a market could develop where countries export biomass to the UK for use in negative carbon processes

FES 2020 / System View / Bioenergy supply 110

What we've found

Figure SV.8: 2050 bioenergy demand



For assumptions on non-networked energy use, such as aviation and shipping, we have drawn on modelling from the CCC, tested against expert views from a range of stakeholders. We assume the aviation sector will depend on bioenergy in all scenarios as there are currently limited alternatives for emissions reduction.

Shipping is assumed to prioritise hydrogen (converted to ammonia) over bioenergy, unless there is enough available taking into account other priorities.

In **Consumer Transformation**, the primary use of biomass is for generating electricity (BECCS) with the removal of 52 $MtCO_2e$ from the atmosphere. Biomass boilers are used in some off-grid homes and bio-LPG may supplement heat pumps on particularly cold days. Industries that are difficult to electrify rely on bioenergy more in this scenario as there is less hydrogen available.

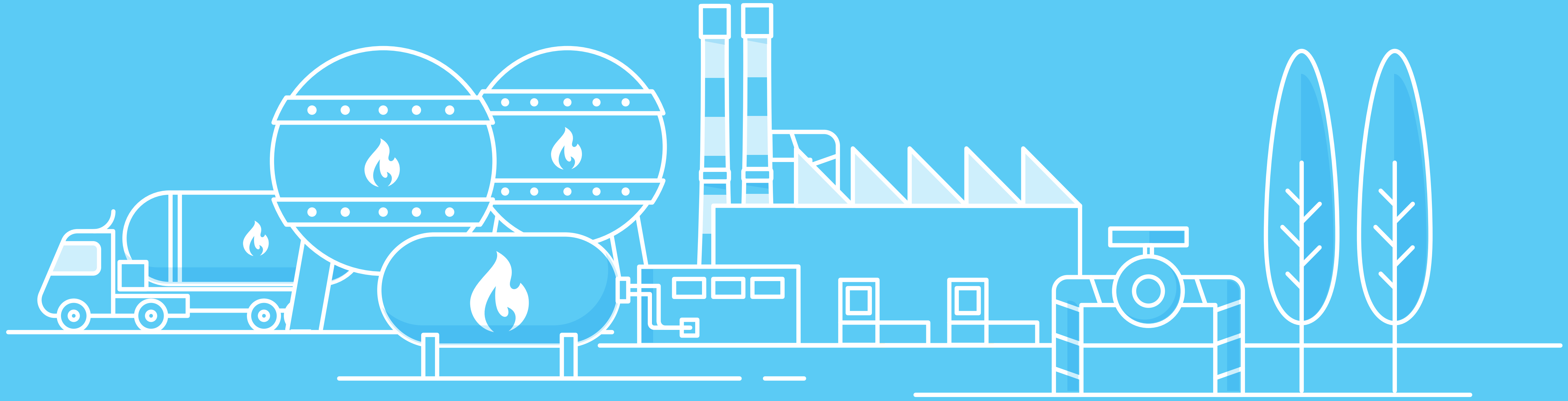
In **System Transformation**, just 7% of bioenergy feedstocks are used to directly meet end consumer demand. This includes delivering heat via local heat networks using biomass CHPs and decarbonising some industrial processes. In this scenario, biomass delivers negative emissions through production of hydrogen and industrial heat as well as electricity (all paired with carbon capture technology) resulting in 55 $MtCO_2e$ of negative emissions to offset other sectors.

Leading the Way includes the most BECCS for electricity generation (189 TWh by 2050), reflecting the increased availability of biomass from the growing import market. Use of BECCS ramps up earlier in this scenario, from 2027, due to faster deployment of commercial CCUS. Biofuels are used in shipping as well as aviation, supported by the growing global market.

In **Steady Progression**, use of bioenergy reduces from today's levels as many of the incentives are removed. Specific demands from transport and residential sectors, whilst important, are low in scale. Bioenergy continues to be injected into the natural gas grid. As there is no CCUS, no negative emissions are delivered by BECCS. Instead, bioresources are used to generate carbon-neutral electricity in dedicated biomass plant and in combined heat and power (CHP) units.

FES 2020 / System View / Bioenergy supply 111

Natural gas supply



Key insights

- Natural gas supply levels stay broadly similar to today in **System Transformation** and **Steady Progression** and fall away significantly in **Consumer Transformation** and **Leading the Way**.
- Shale gas is not present in the net zero scenarios due mainly to reduced support from government and consumers.
- To meet net zero, bioresources are required for negative emissions and in hard-to-decarbonise sectors; this limits the amount of green gas available for injection into the grid.
- Imports provide 98% of natural gas supply in **System Transformation** as the UK Continental Shelf (UKCS) declines and there are no contributions from shale or green gas.

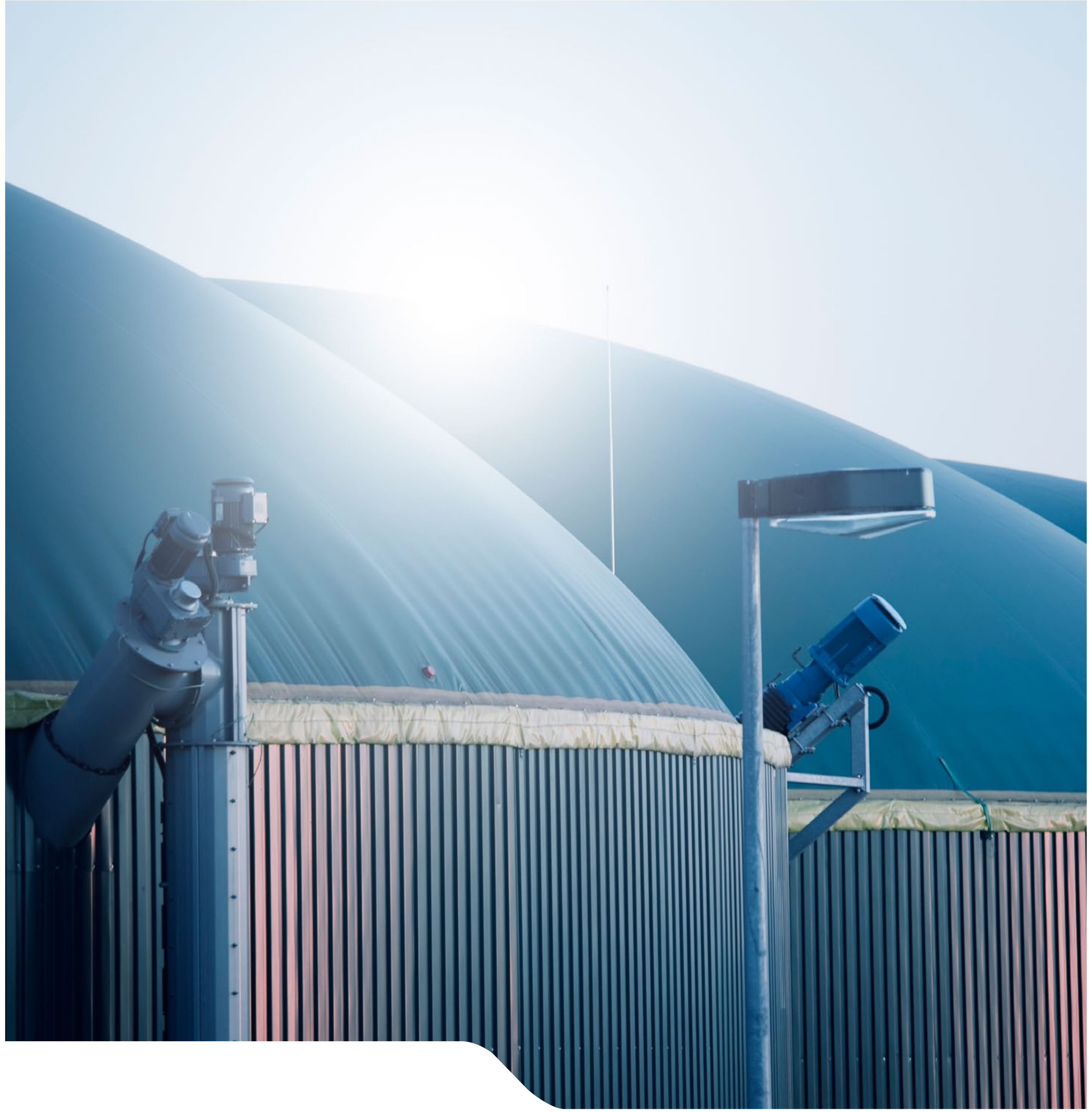
Green gas

This is used in our scenarios to refer to both biomethane and bioSNG.

In comparison to fuels like coal and diesel, natural gas emits less CO_2 for a given amount of energy. Natural gas remained an important part of the energy mix under the previous 2050 target (i.e. 80% reduction in greenhouse gas emissions based on 1990 levels), but cannot be burned unabated in net zero scenarios. Instead, conversion to blue hydrogen or use alongside CCUS will be needed if it is to have a role in net zero and this will require significant development.

Blue hydrogen

Blue hydrogen is created via methane reforming using natural gas as an input plus CCUS.



FES 2020 / System View / Natural gas supply 113

Where are we now?

Natural gas supplied over 80bcm of energy in GB in 2019[1]. This is equivalent to around 900 TWh and was from a variety of sources. This diversity is an important element in security of supply as it reduces reliance on a single source.

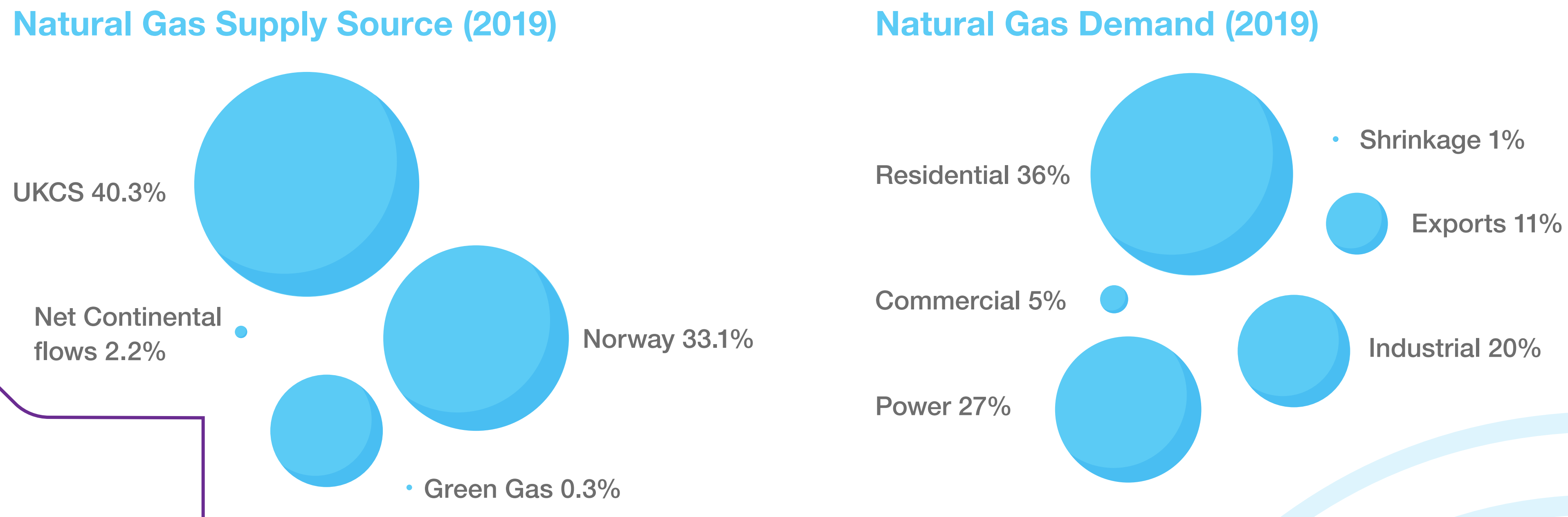
This natural gas met a direct consumer demand of 551 TWh with the difference reflecting conversion to other energy forms such as electricity as well as shrinkage through the system.

Shrinkage

This describes losses of gas from the system. It includes:

- Compressor fuel usage (i.e. the energy used to run the compressors needed to manage gas pressure on the system);
- Calorific value shrinkage (i.e. gas which cannot be billed to consumers);
- Unaccounted for gas (i.e. the remaining unallocated gas after taking into account all measured inputs and outputs from the system). More information can be found on the National Grid Gas website[2].

Figure SV.9: Current GB demand and supply for natural gas



1 This includes net storage
2 National Grid Gas website - https://www.nationalgrid.com/uk/gas-transmission/about-us/system-operator-incentives/nts-shrinkage

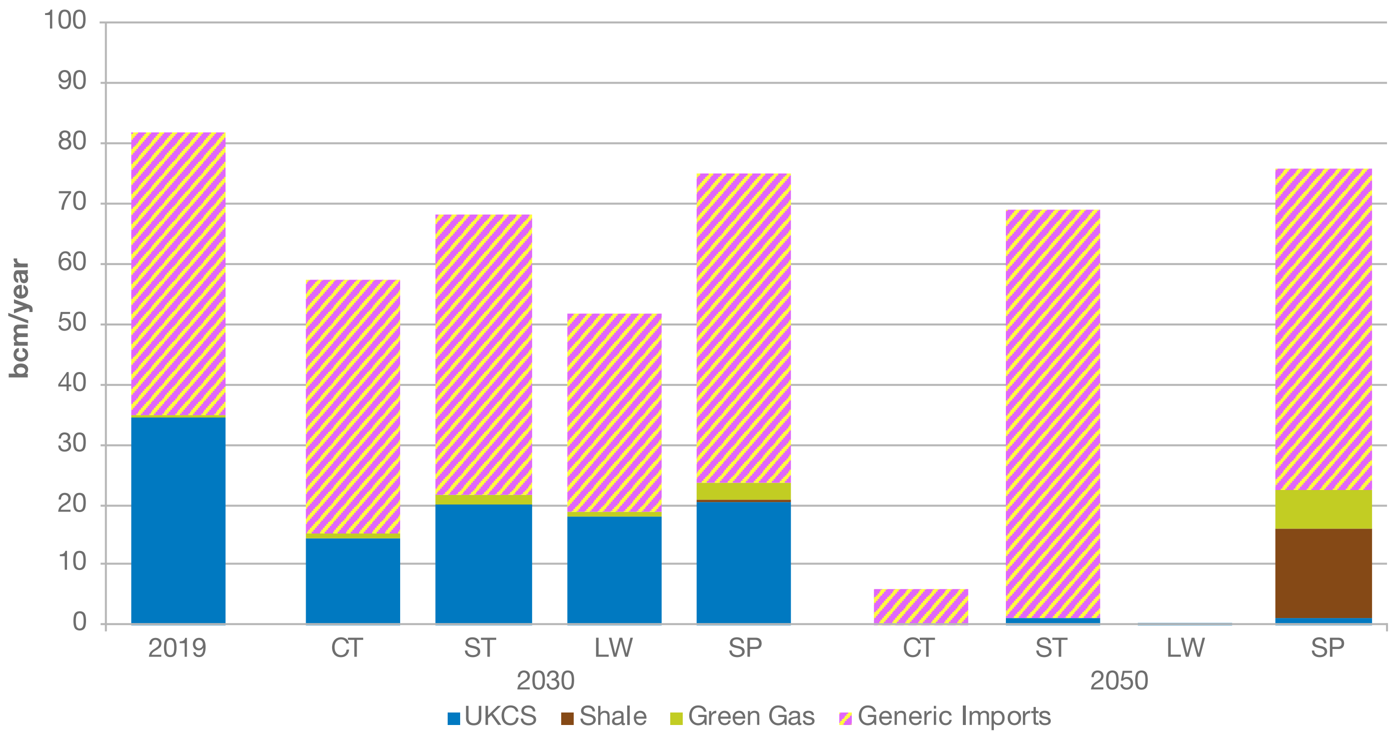
What we've found

Uses of Natural Gas

As explored in the Consumer View chapter, natural gas demand varies significantly across the scenarios.

- High levels of electrification in **Consumer Transformation** combined with the majority of hydrogen being produced by electrolysis mean that demand for natural gas reduces steadily each year from 2020 to 2050.
- **Leading the Way** has an even swifter reduction in natural gas use and all hydrogen is produced from electrolysis.
- Although demand for natural gas at end consumer level is replaced by hydrogen in **System Transformation**, hydrogen is produced from natural gas which causes demand to remain high out to 2050.
- Demand for natural gas in **Steady Progression** remains constant out to 2050.

Figure SV.10: Summary of natural gas supply across all scenarios



FES 2020 / System View / Natural gas supply 115

What we've found

Natural Gas Supply

Our scenarios explore the variety of natural gas supplies into GB between now and 2050. Several elements of the supply mix are consistent across the scenarios:

While there are similarities between **System Transformation** and **Steady Progression** (where demand for natural gas is high) and between **Consumer Transformation** and **Leading the Way** (where it is low), differences between these scenarios remain and can be seen in charts on the next page.

FES 2020 / System View / Natural gas supply 116

What we've found

Imports

Over the next few years the LNG market is expected to rebalance as global demand increases. However new liquification projects could bring a 'second wave' of new supply to the market. Global LNG price influences flows across the interconnectors with continental Europe. In the longer term, other markets may transition to hydrogen from natural gas.

Green gas

In the short term, production of green gas is expected to grow. The proposed introduction of the Green Gas Levy from the recent budget could support this. However, the increasing value of bioresources for negative emissions, and for meeting demand that is hard to decarbonise, mean there is limited availability for green gas in the long term.

Shale

There is currently a moratorium on shale and recent statements from government suggest this is unlikely to be lifted. The lack of government support and low public acceptability mean that it only appears in **Steady Progression**.

Norway

Supply from Norway is traditionally more flexible than UKCS and greater reserves mean it is expected to produce natural gas for considerably longer.

UKCS

Production is expected to tail off out to 2050 as fields continue to deplete. However, attempts to push back the decline mean the initial reduction in output is gradual.

FES 2020 / System View / Natural gas supply 117

Figure SV.11:
Annual gas supply in Consumer Transformation

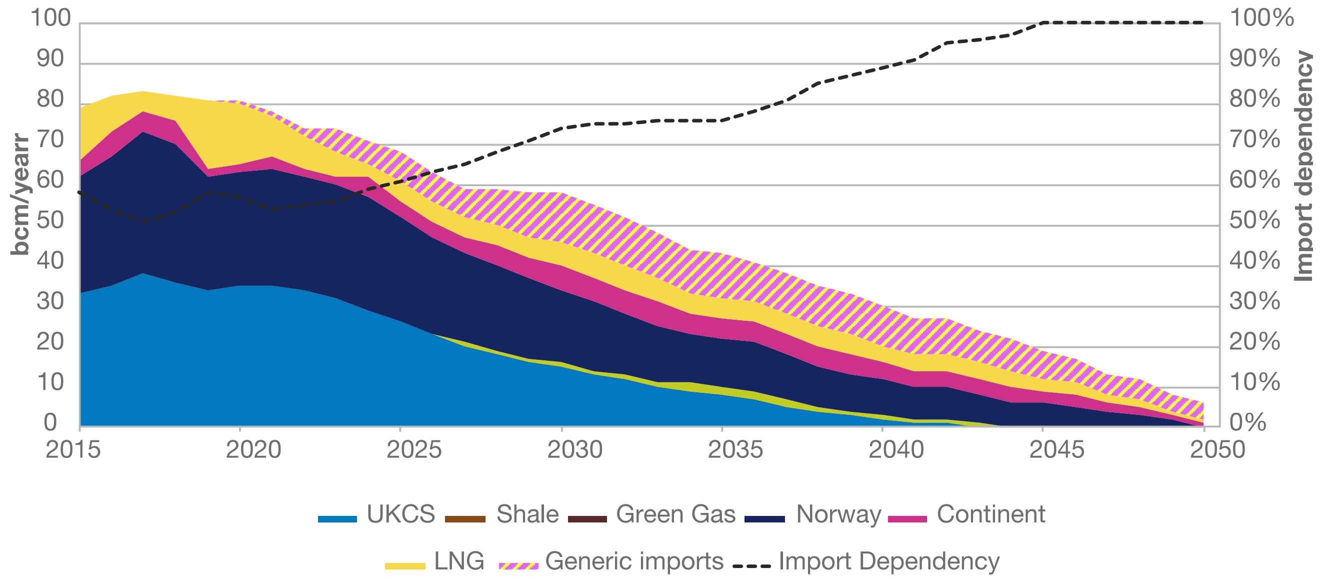
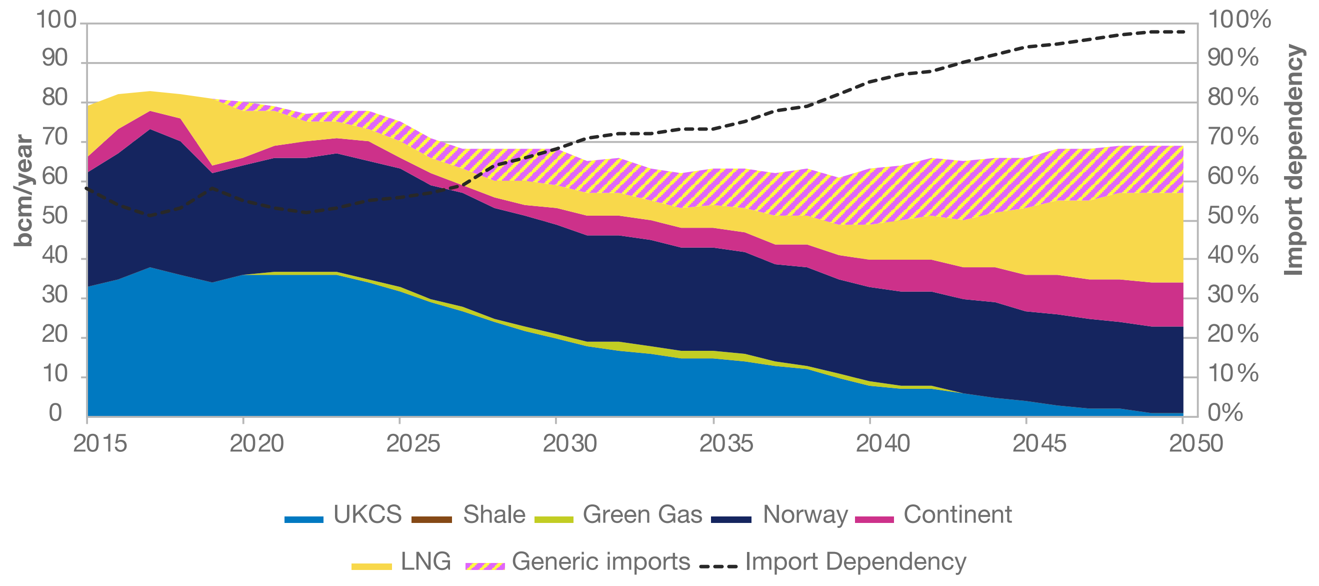


Figure SV.12:
Annual gas supply in System Transformation



- Demand for natural gas reduces steadily due to high levels of electrification and increasing hydrogen demand being mostly met by electrolysis.
- This necessitates more flexible supply and so UKCS production ends by 2045 with demand then completely met by imports.
- By 2050, the remaining demand (e.g. from industrial clusters with CCUS and for the dedicated methane reformers in the shipping sector) is fully met by LNG imports and from the continent.
- Green gas supplies are provided by decentralised sources in the 2030s but decline from the 2040s as demand for bioenergy increases in other sectors.
- Demand for natural gas reduces slightly and then increases in the 2040s as decarbonisation relies heavily on hydrogen produced by methane reformation.
- Green gas is displaced over time as hydrogen production increases.
- While import dependency is very high in 2050, a diverse supply mix helps ensure resilience. This mix does not include shale gas.

FES 2020 / System View / Natural gas supply 118

Figure SV.13:
Annual gas supply in **Leading the Way**

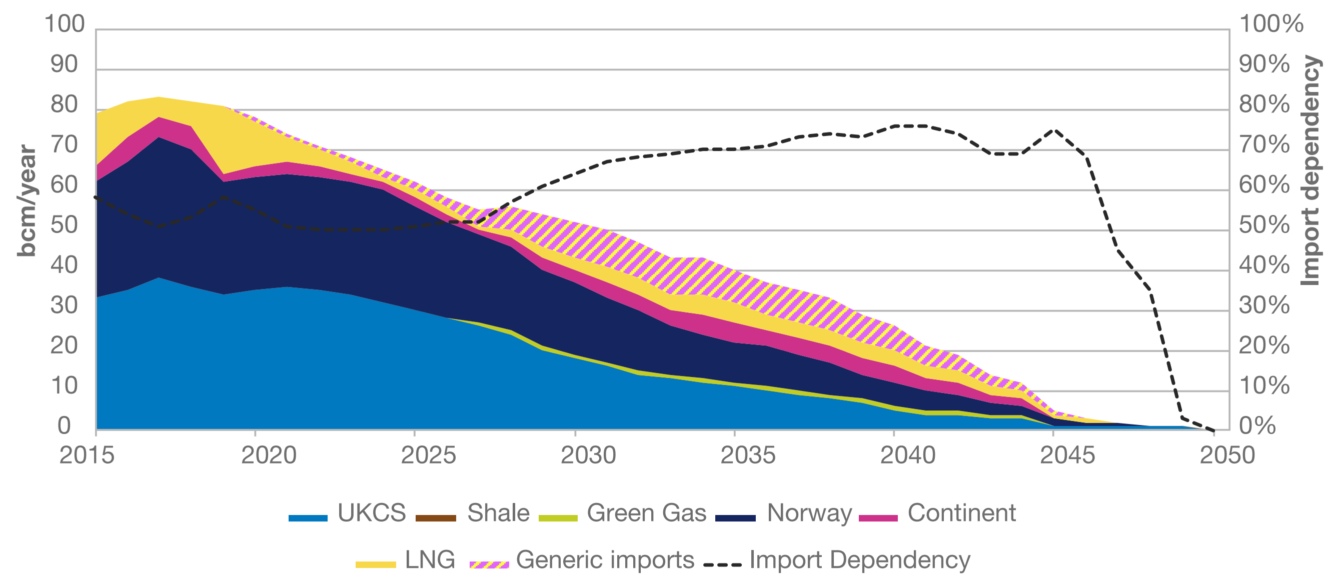
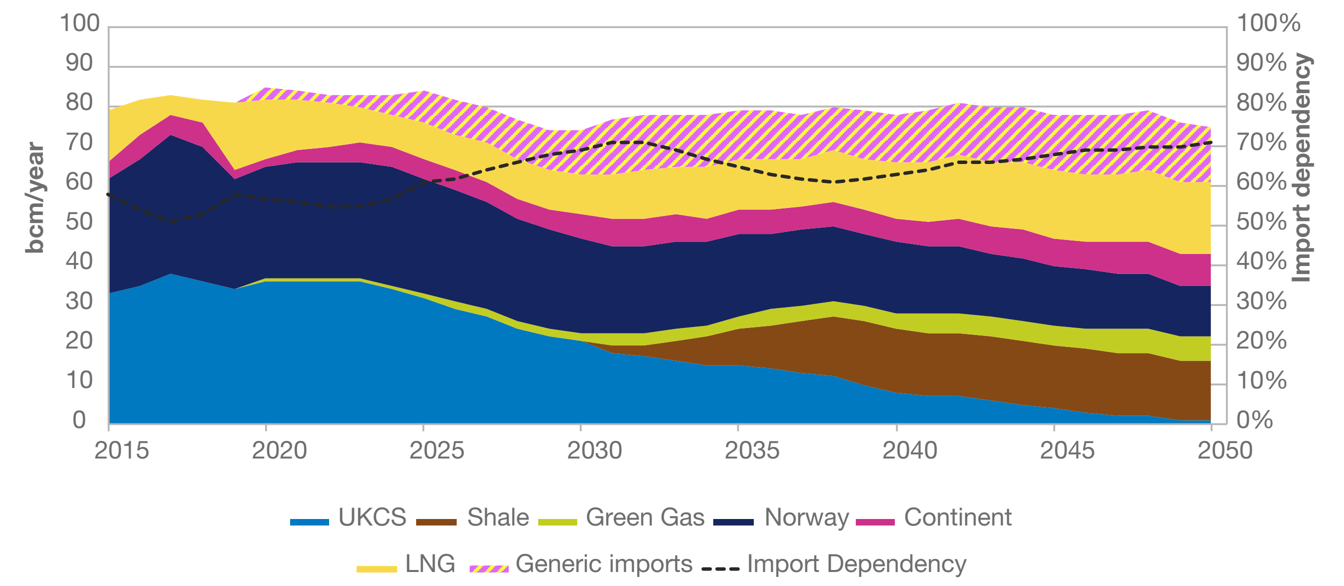


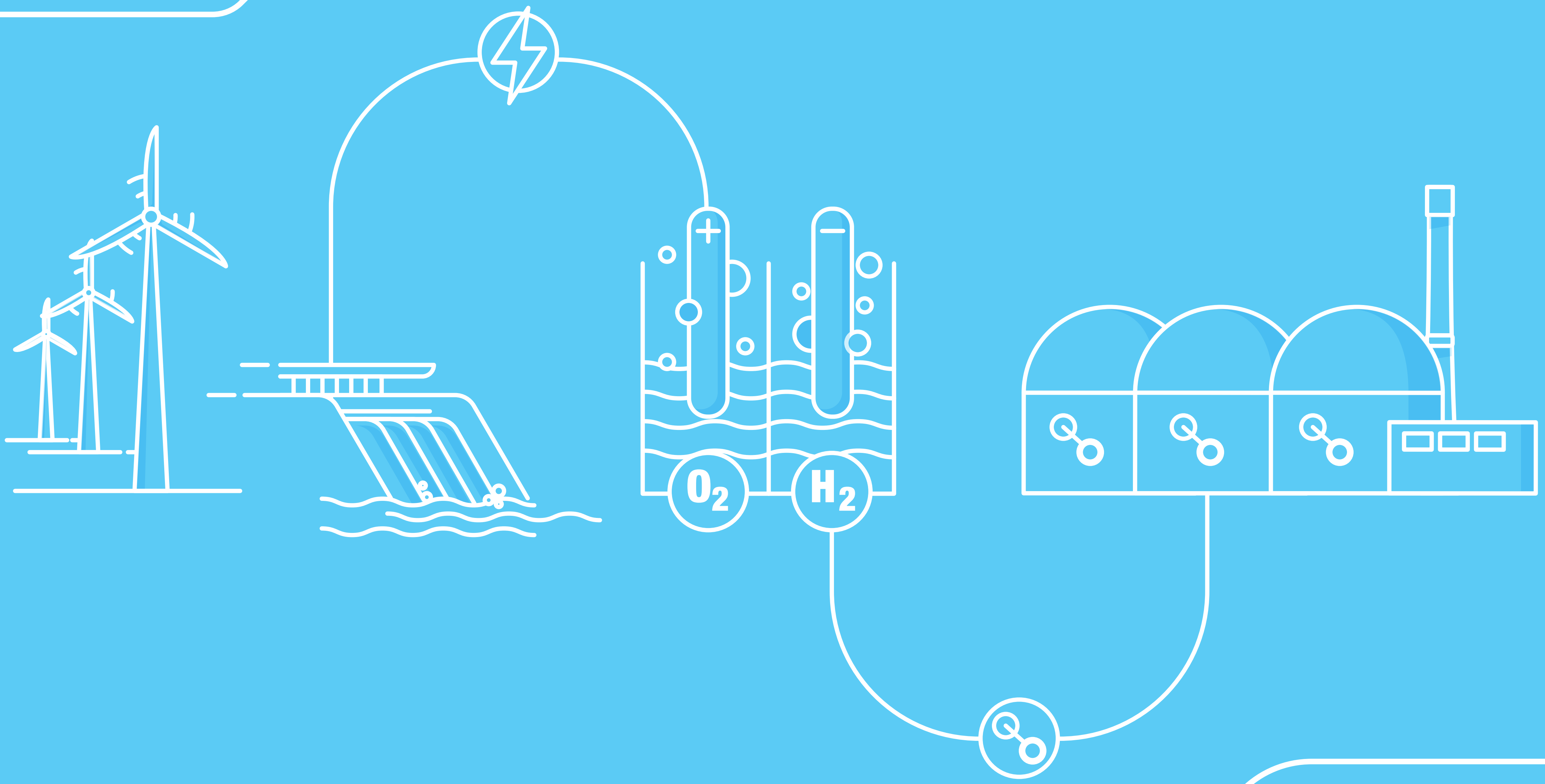
Figure SV.14:
Annual gas supply in **Steady Progression**



- Lowest demand for natural gas across the scenarios due to earlier decarbonisation and higher levels of hydrogen from electrolysis.
- UKCS still producing at very low levels until 2050.
- LNG and continental natural gas imports decline by late 2040s to be replaced by hydrogen imports.
- There is low import dependency for natural gas supply. For hydrogen, imports make up 20% of total supply in 2050.
- Highest demand for natural gas across the scenarios due to continued reliance on gas for heating across residential, industrial and commercial sectors.
- UKCS is still producing in 2050 and use of green gas means import dependency is less than in **Consumer Transformation** and **System Transformation**.
- Including indigenous shale gas in this scenario reduces import dependency from 90% to 70%. In addition, when looking at the full emissions cycle, it may be more carbon intensive overall for the natural gas to be shipped into the country in liquefied form rather than extracted domestically.

FES 2020 / System View / Natural gas supply 119

Hydrogen Supply



Key insights

- At least 190 TWh of energy for hydrogen production is required in all net zero scenarios.
- Hydrogen plays an important and complementary role in a highly-electrified world by enabling storage of the large volume of energy required for seasonal flexibility.
- Hydrogen production through electrolysis can facilitate increased market penetration of wind and solar generation without adding to peak electricity demand at times of low supply due to its reliance on low electricity prices.
- The initial development of hydrogen production is likely to be in regional clusters. This will drive geographic differences in energy use, which could remain local or could scale up to widespread change across the UK.

Hydrogen has great potential to provide zero or low carbon energy to help the UK achieve net zero by 2050. But before UK consumers can really tap into hydrogen's potential to decarbonise heating and transport, the challenges of zero carbon production and transportation at scale must be met.

FES 2020 / System View / Hydrogen supply 121

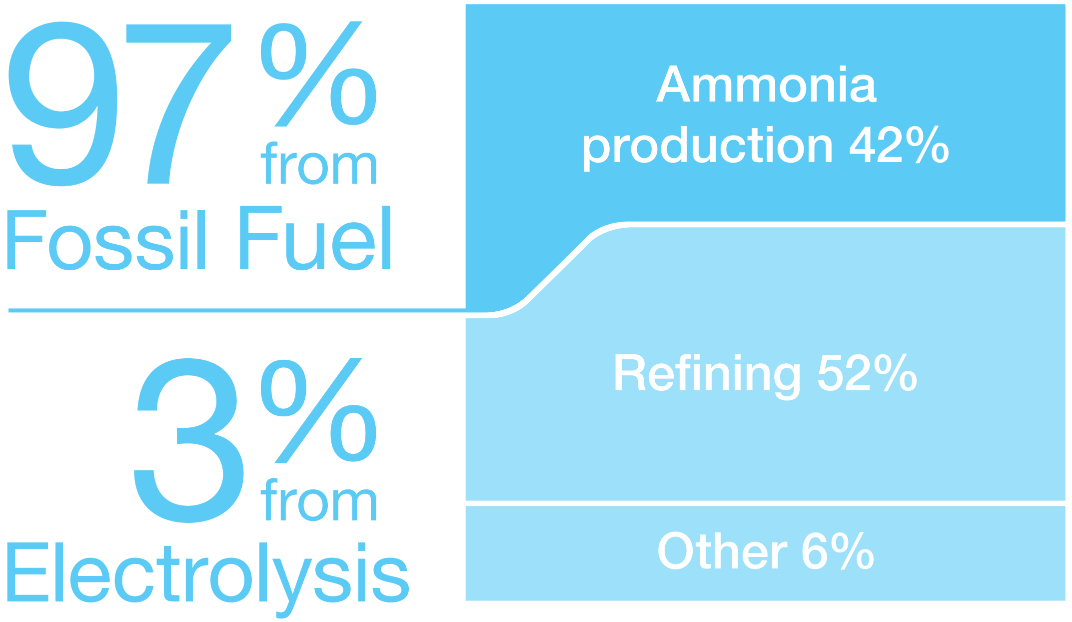
FES 2020 / System View / Hydrogen supply 122

Where are we now?

The production of hydrogen at scale is not a new process. Each year, around 50 Mt hydrogen (or 2,000 TWh of energy equivalent) is produced globally, of which around 0.7 Mt is both produced and consumed in the UK. There are various methods of producing hydrogen, but currently almost all UK hydrogen production uses methane reforming without CCUS, which has a carbon footprint of 10-12 $kgCO_2e$ per kg of hydrogen.

Currently, hydrogen is mostly used as a feedstock for industrial processes, for example in oil refining and the production of ammonia for fertilisers. Most consumption occurs near the point of production, but it is typically converted into ammonia for transportation since ammonia stores almost twice as much energy per unit as liquid hydrogen.

Figure SV.15: Current production and use globally[1]



1 Source: International Energy Agency

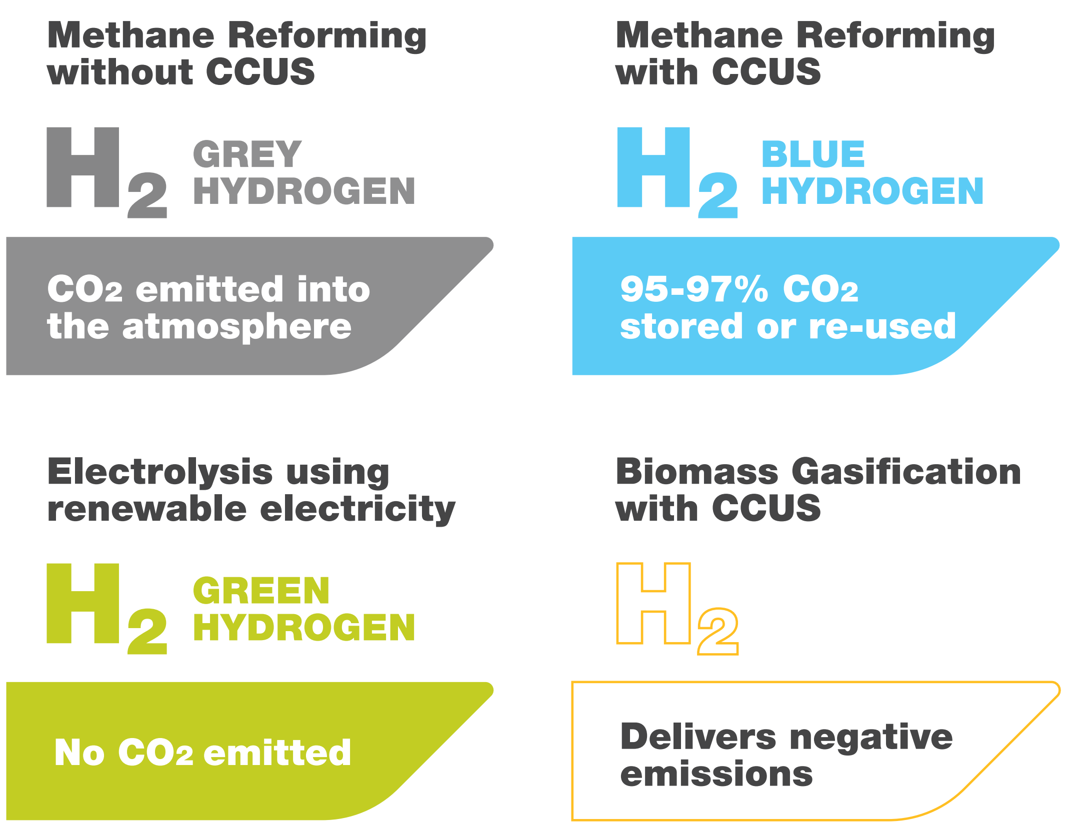
Where are we now?

Hydrogen produces no carbon emissions at the point of combustion, opening a number of opportunities for its role in the decarbonisation of the energy system. But there are challenges for the supply, storage and transportation of hydrogen to the point of combustion:

- Hydrogen is extremely scarce in our atmosphere, which means it must be separated from other substances such as methane or water.
- The energy density of hydrogen has transportation and storage implications. Although when compressed hydrogen has a much higher energy density than batteries used to store electricity, it is less energy dense by volume than other fuels used today such as natural gas.
- Not all hydrogen production methods[2] are zero carbon. Some will rely on carbon capture, or being offset against negative emissions, to deliver a net zero outcome.

These challenges and alternative methods mean there is uncertainty around the future pathways for a hydrogen economy. Publicly funded innovation projects have been initiated to 'make a case for hydrogen' across the UK. These include the £33 million Low Carbon Hydrogen Supply competition and the UK Hydrogen for Heating Project[3]. These projects will evaluate the relative costs, efficiency and deployment challenges of the various production methods. They will also explore barriers to entry into the energy market and other important aspects such as safety.

Figure SV.16: Different types of hydrogen production



2 Categorising hydrogen production types as colours is not specific to FES and is used across the energy industry (e.g. https://www.worldenergy.org/publications/entry/innovation-insights-brief-new-hydrogen-economy-hype-or-hope)
3 For more information see https://www.gov.uk/government/publications/hydrogen-supply-competition and https://www.gov.uk/government/publications/hydrogen-for-heating-project

FES 2020 / System View / Hydrogen supply 123

What we've found

Uses of Hydrogen

As explored in the Consumer View chapter, hydrogen could be the solution to many of the hardest parts of the transition to net zero.

This includes demands such as:

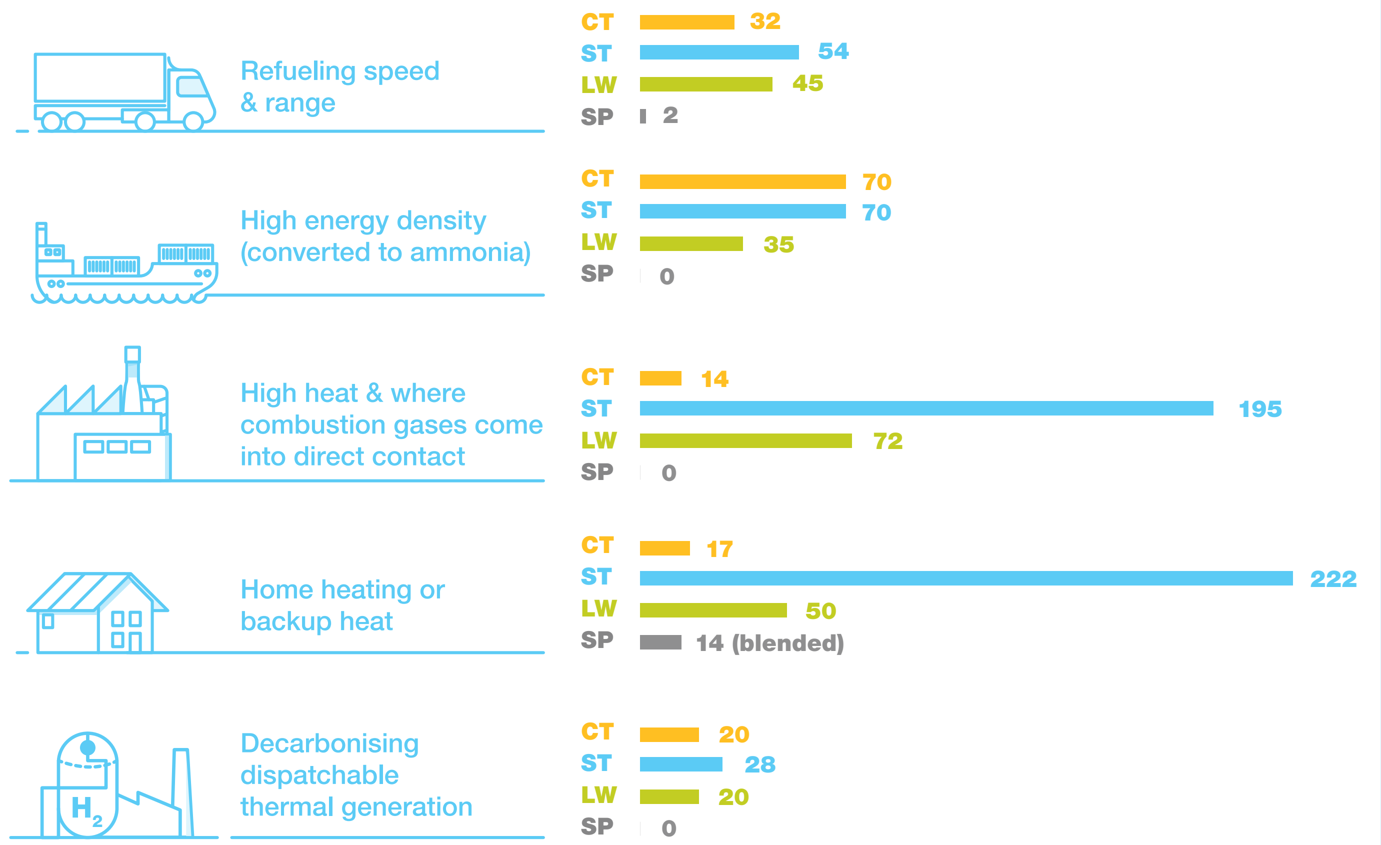
- Transport where greater ranges, as well as weight and volume considerations, mean that high energy density of fuel is essential (e.g. HGVs and shipping);
- Industrial sectors that are difficult to electrify due to a requirement for high grade heat or chemical considerations (glass, steel, ceramics);
- Heating solutions that minimise change to homes or behaviours (e.g. homes unsuitable for heat pumps without significant insulation).

Across our scenarios, hydrogen also helps manage electricity system balancing challenges (covered in more detail in our section on Flexibility *(See page 169)*). For example:

- Providing additional energy storage during the summer when demand is lower than renewable output and all electrical forms of storage (e.g. batteries) are full;
- Providing a decarbonised form of dispatchable generation to use this stored energy to help meet winter heat and electricity demands, in periods when renewables (wind and sun) are scarce and interconnector imports are constrained.

In the scenarios with lower societal change, fewer end consumers electrify their energy needs (which requires investments such as even higher levels of home insulation, installation of heat pumps, technology replacement for industrial fuel switching) and there is a much greater need for hydrogen to help them decarbonise. Particularly when used for heating, hydrogen provides a broadly similar consumer experience to natural gas.

2050 Hydrogen demand (TWh)



System Transformation is the scenario with the highest demand for hydrogen, seeing large-scale rollout to homes and businesses as well as being used in transport and industry. In **Consumer Transformation**, hydrogen demand for end consumption that cannot be easily be electrified is centred around industrial clusters and transportation hubs. **Leading the Way** explores a scenario where engaged end consumers seek the fastest route to decarbonisation, resulting in more early adopters of hydrogen being located closest to where it can either be rolled-out most quickly or be cost-effectively produced. In **Steady Progression**, current policy incentives are not renewed and the only real areas for growth in hydrogen use are for long range vehicles and some blending into the natural gas network.

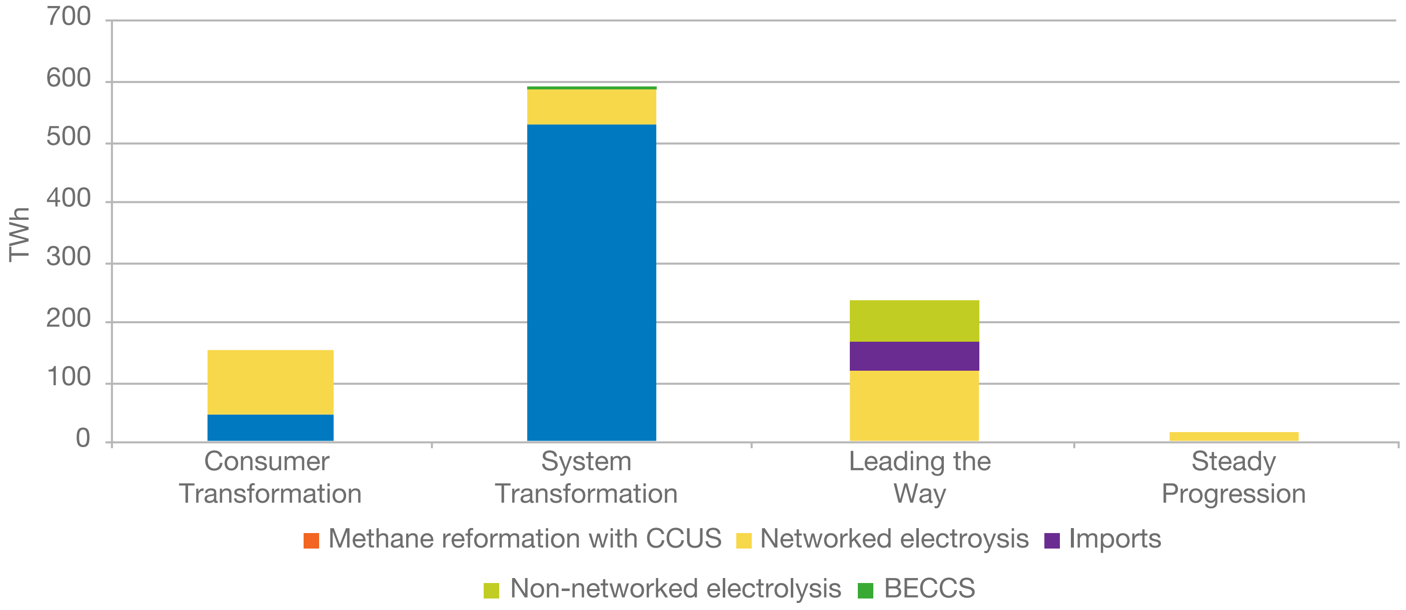
FES 2020 / System View / Hydrogen supply 124

Hydrogen Supply

Our scenarios explore the uncertainty in both the methods and scale of hydrogen production.

In a net zero world, hydrogen can no longer be produced using methane reforming unless the associated carbon emissions are captured and stored, and hydrogen production via electrolysis must use renewable electricity. Hydrogen production can also deliver negative emissions if produced using biomass gasification and emissions are captured.

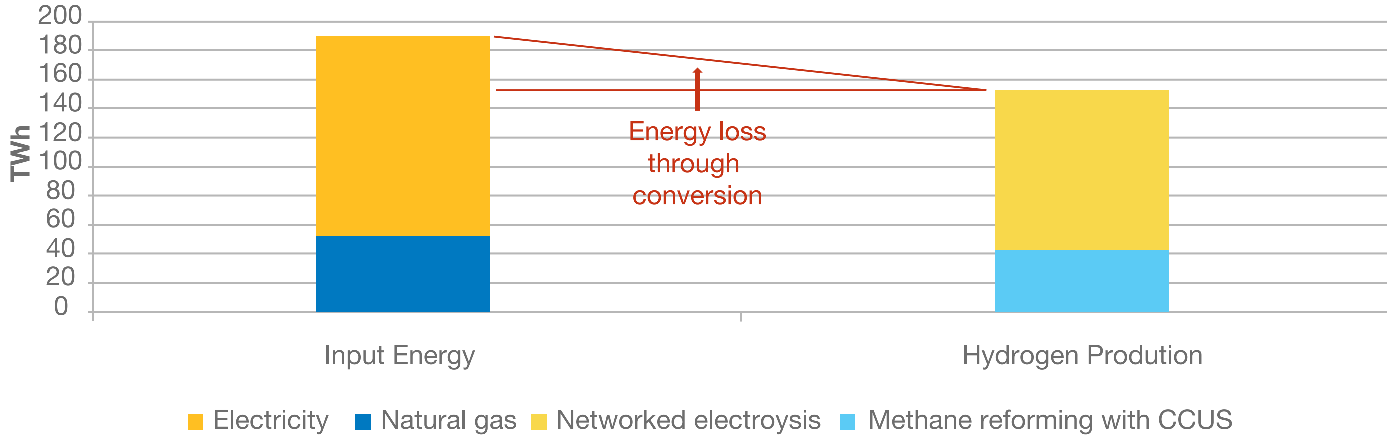
Figure SV.17: 2050 Hydrogen Supply



The production of hydrogen involves efficiency losses.

For example, by 2050 in **System Transformation** producing 591 TWh of hydrogen will require 736 TWh of input energy. Current efficiency rates are around 73% for methane reforming and 70% for electrolysis. Our models assume this will improve to around 80% for both technologies by 2050. Biomass gasification is less efficient, with current rates at around 50% in 2030 increasing to 54% by 2050.

Figure SV.18: Hydrogen conversion efficiency in **Consumer Transformation**



FES 2020 / System View / Hydrogen supply 125

Hydrogen Supply

Figure SV.17: Electricity demand for hydrogen production

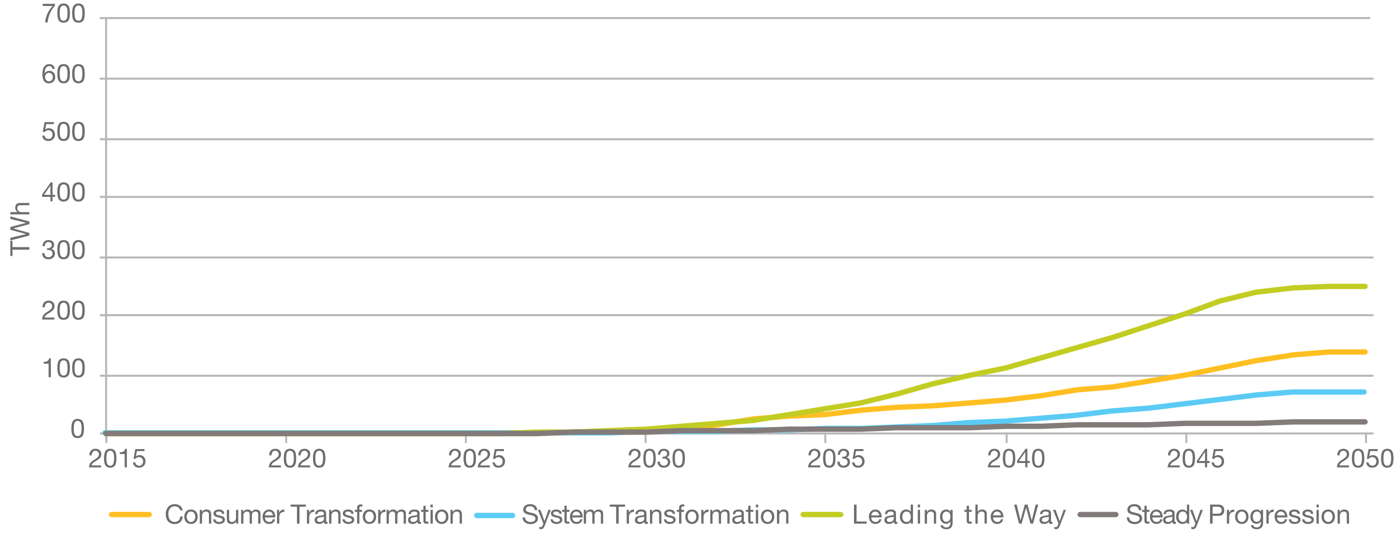


Figure SV.18: Hydrogen conversion efficiency in System Transformation

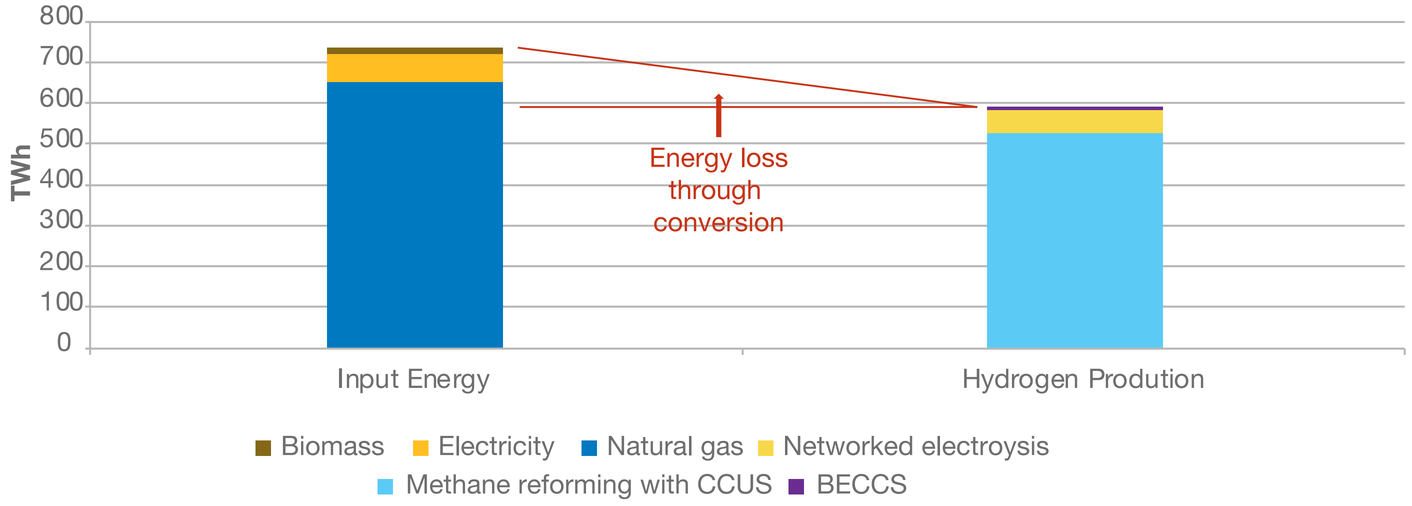


Figure SV.17: Natural gas demand for hydrogen production

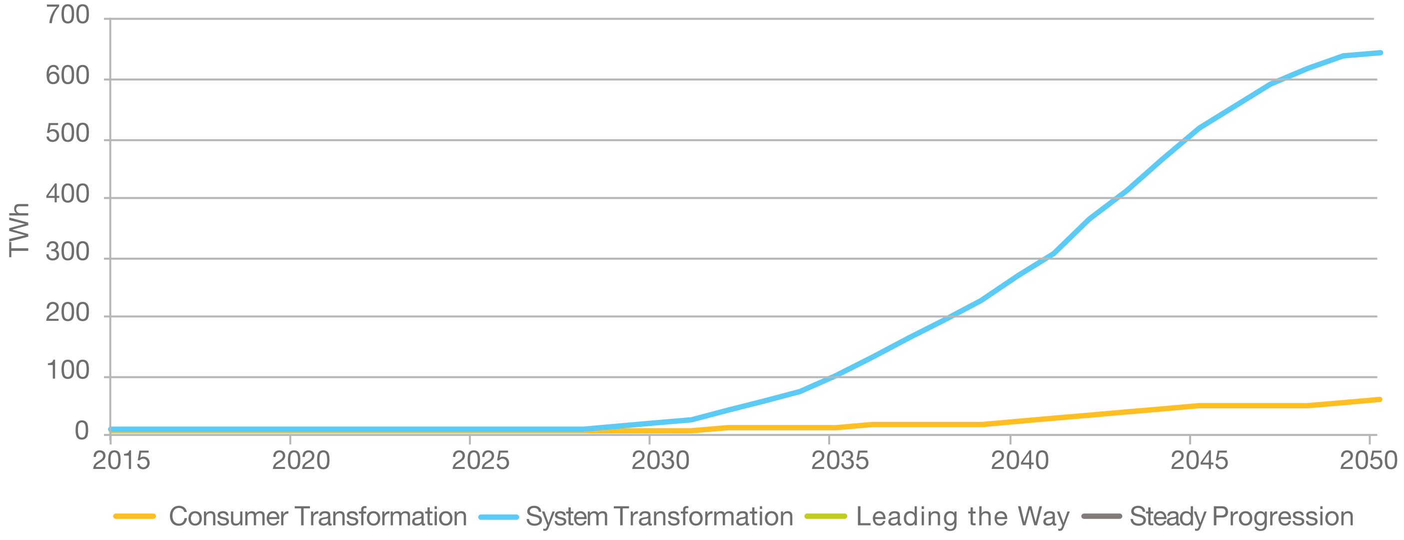
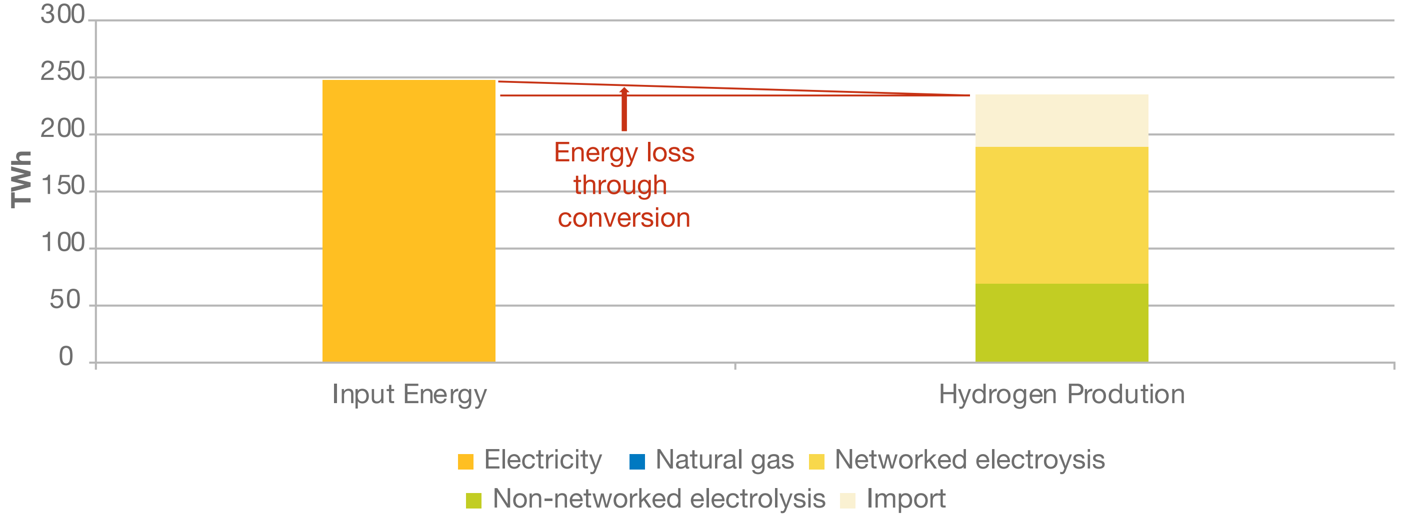


Figure SV.18: Hydrogen conversion efficiency in Leading the Way



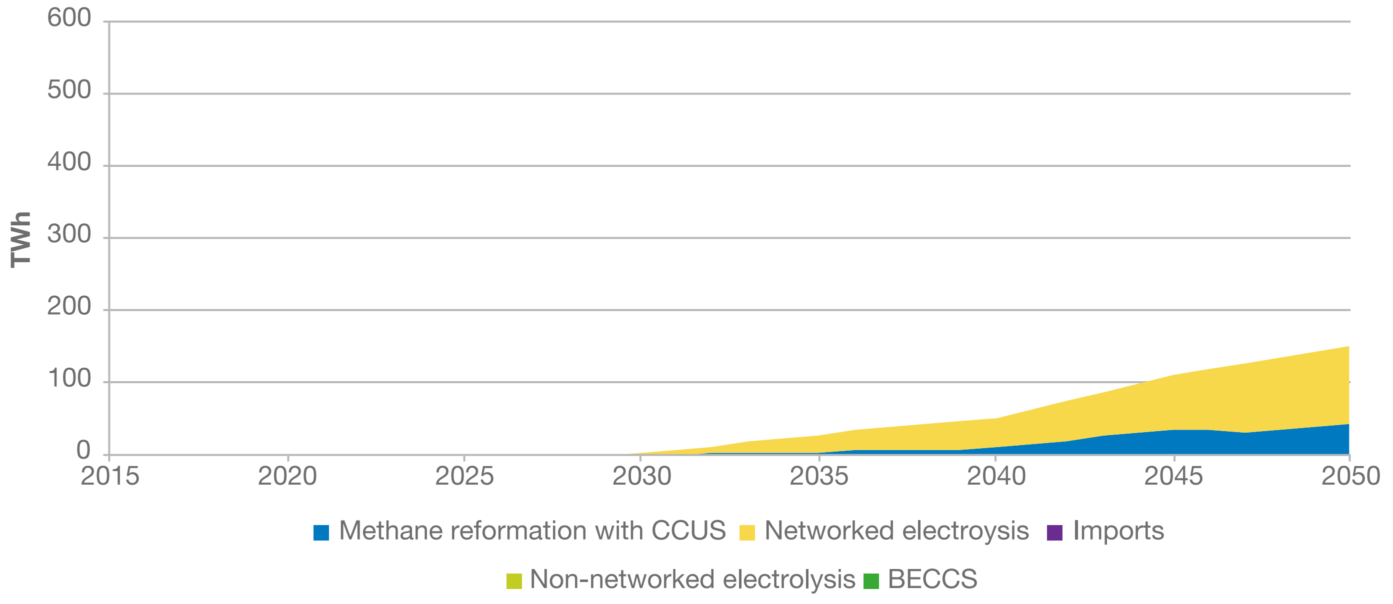
Consumer Transformation

In comparison to other net zero scenarios, **Consumer Transformation** has a much lower demand for hydrogen, almost half of which is for shipping. The developing needs of this sector will be met by dedicated methane reformers located near sources of natural gas.

All other hydrogen demand is met by zero carbon production, using renewable electricity to produce hydrogen via electrolysis (green hydrogen). Hydrogen is valued for its ability to support the high flexibility needs of the electricity system in this scenario. Electrolysis is likely to be deployed close to use but will be connected to the electricity network (Networked electrolysis). This avoids the costs of transporting pressurised or liquefied hydrogen but may require some investment in the local electricity network.

For green hydrogen to take a significant market share, the technology must be able to scale up economically. Research suggests green hydrogen is most likely to achieve commercial viability when it can use low-cost surplus renewable electricity. We have based our assumptions on current projections that indicate it could achieve cost parity with blue hydrogen around the mid-2030s. By 2050, we anticipate that around 70% of hydrogen production can make use of curtailed generation.

Figure SV.19: Consumer Transformation hydrogen supply

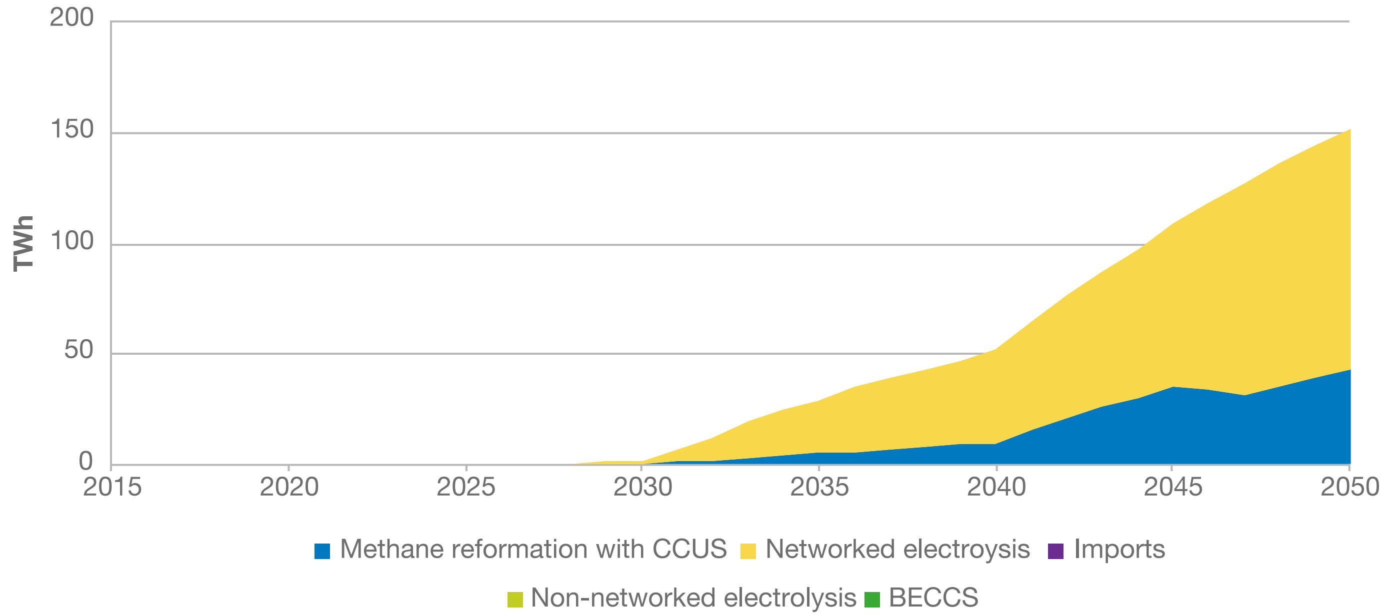


Scaled view

FES 2020 / System View / Hydrogen supply 127

Hydrogen Supply

Figure SV.19: Consumer Transformation hydrogen supply



Non-scaled view

FES 2020 / System View / Hydrogen supply 128

Hydrogen Supply

System Transformation

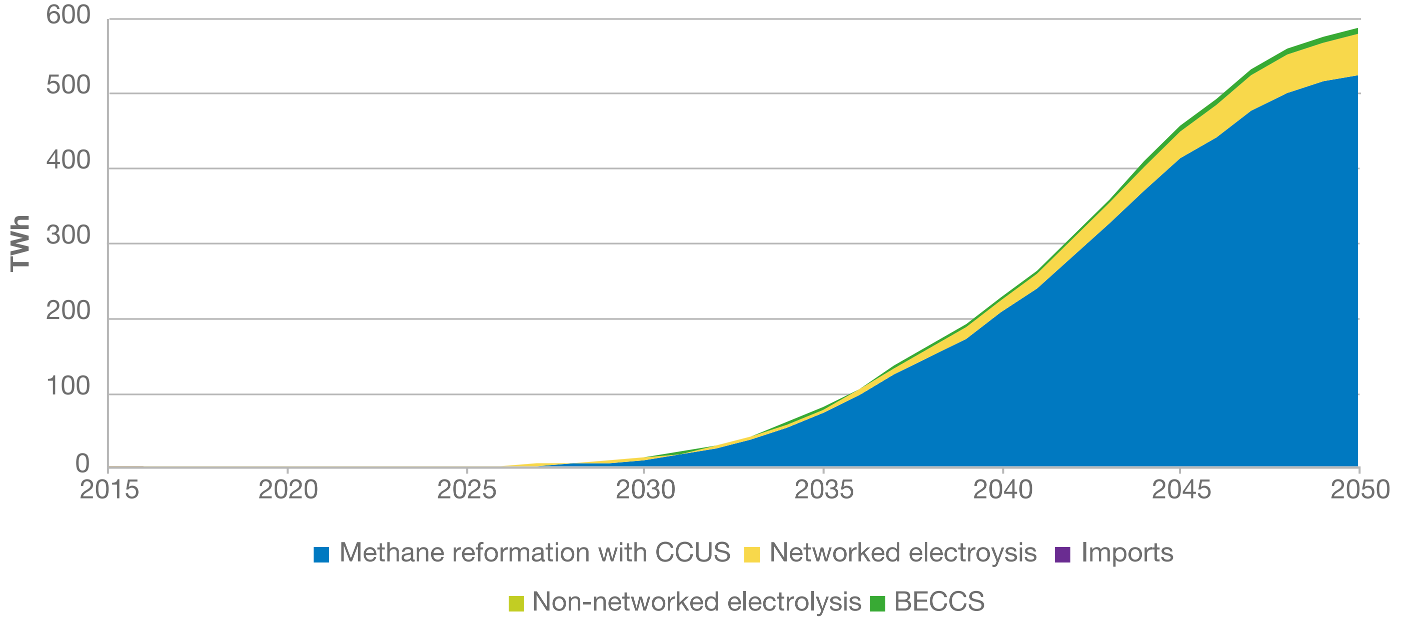
System Transformation assumes strong government support and clear strategy for a hydrogen economy. Most production is via methane reforming with CCUS (blue hydrogen) to meet the steady minimum demand of this high hydrogen scenario. Production will initially develop in industrial clusters from the late 2020s, ramping up in the early 2030s. CCUS is anticipated to have some carbon leakage and we assume a 97% capture rate by 2050. Locating production alongside coastal industries means the carbon can be piped out to sea and stored in disused gas fields. In this scenario hydrogen networks are the most cost-effective method of transporting hydrogen to end users. This will result in the transition of the natural gas networks to hydrogen, or development of new hydrogen pipelines. The rollout of hydrogen to residential and commercial properties is coordinated to minimise the impact of decarbonisation on end consumers. Readily available networked hydrogen also meets the needs of dispatchable generation, replacing natural gas in peaking plant to provide flexibility in balancing intermittent generation.

Since hydrogen is meeting heating needs, there will be a seasonal variation in demand. There is storage in the hydrogen networks to support daily variability, but additional storage will be needed for more seasonal variations since methane reformation and CCUS processes ideally operate at high load factors. Salt cavern storage historically used for natural gas, is used for hydrogen.

Large scale deployment of blue hydrogen limits investment in technology for electrolysis, which remains more expensive unless using low-cost electricity. In this scenario, hydrogen produced via electrolysis is used in the transport sector due to its purity and this production is sited near to the demand to both minimise hydrogen transportation costs and maximise access to surplus low-cost electricity.

Some hydrogen is produced via biomass gasification. As this lower electricity demand scenario uses less BECCS for electricity generation, there is enough biomass to deliver negative emissions from hydrogen production as well as use in BECCS for electricity generation. This will remove 4.74 $MtCO_2e$ from the atmosphere, more than mitigating the carbon losses from CCUS used to produce blue hydrogen.

Figure SV.20: System Transformation hydrogen supply



Storage

Storing hydrogen

One of the advantages of transporting hydrogen through pipelines is that the pipelines themselves provide relatively low cost storage. This will be very 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 does not increase over time, but there may be some limitations on the rate of import/exports due to impacts on the geology. 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.

Purity

Hydrogen purity

Sometimes the choice of production method for hydrogen is influenced by the demand it is meeting. For example, we note that hydrogen for use in transport needs to be a much higher level of purity than typically required for heating or some industrial processes. Methane reforming does not currently produce hydrogen at sufficient purity for transport needs. Additional purification steps can be added but these come at additional cost.

FES 2020 / System View / Hydrogen supply 130

Hydrogen Supply

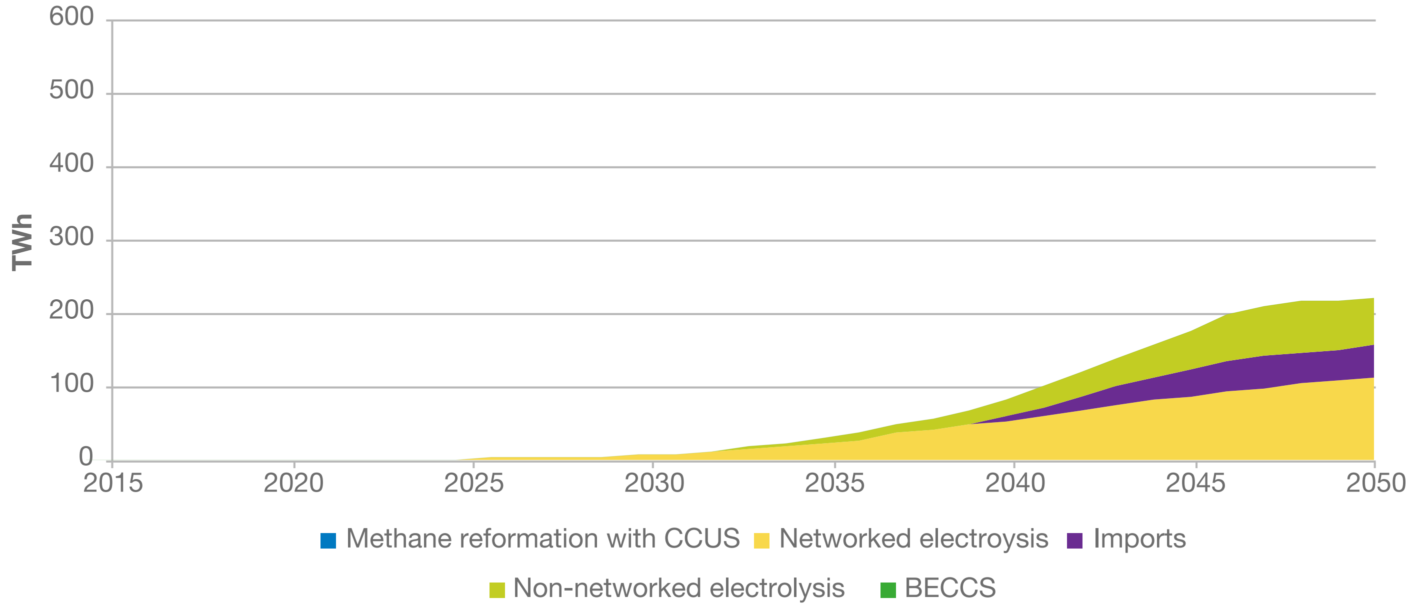
Leading the Way

To meet net zero earlier than 2050, **Leading the Way** requires accelerated decarbonisation of certain sectors through early deployment of electrolysis across the UK. It assumes that global innovation and investment in electrolysis drives down costs, with commercialisation at scale from the early 2030s. An import market for green hydrogen begins to develop from the early 2040s to support the growing demand for hydrogen in the UK.

Dedicated offshore wind coupled with electrolysis in deep-water sites use floating platforms to access high levels of reliable wind. Piping hydrogen to the UK shore is assumed to be more cost effective than extending the electricity network over these longer distances (i.e. these sites are connected to the hydrogen network but are non-networked from an electricity perspective), although some additional energy needs such as desalination of the water supply will affect efficiency rates. As growth in hydrogen demand begins to level off in the late 2040s, there are opportunities to export excess hydrogen to Europe.

In this scenario, there are hydrogen networks to transport the offshore hydrogen from coast to end consumer. Onshore electrolysis can be located close to generation and connected to the hydrogen network, minimising investment in the electricity network being driven by hydrogen production.

Figure SV.21: Leading the Way hydrogen supply

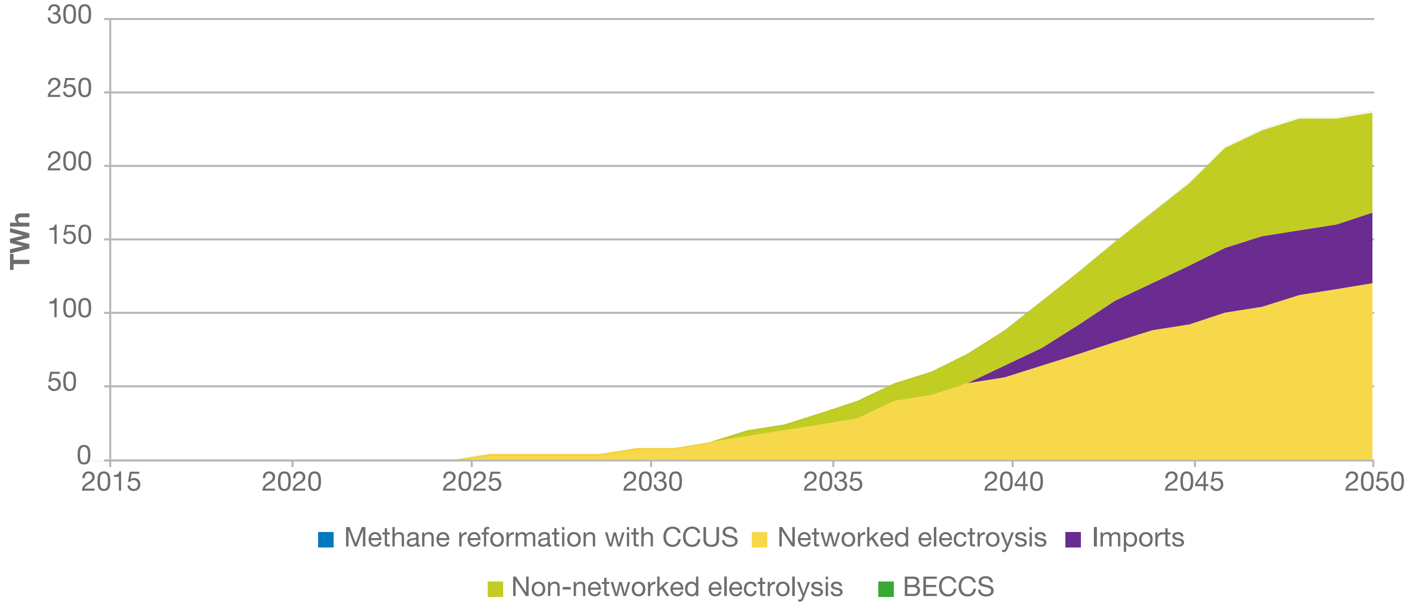


Scaled view

FES 2020 / System View / Hydrogen supply 131

Hydrogen Supply

Figure SV.21: Leading the Way hydrogen supply



Non-scaled view

FES 2020 / System View / Hydrogen supply 132

Electrolysis in deep-water sites

Deep Water sites – Dolphyn project:

Environmental Resources Management (ERM) has developed a design for Dolphyn (Deepwater Offshore Local Production of HYdrogeN) to produce green hydrogen at scale from offshore floating wind. Earlier this year, the UK government allocated £3.12m for the second phase of this programme, initially established under the BEIS Energy Innovation Programme.

The concept involves floating semi-submersible wind turbines integrated with electrolysis and desalination facilities. The electrolysers will split desalinated seawater into hydrogen and oxygen, with the hydrogen being piped ashore. The use of floating turbines will give access to the most favourable UK offshore wind resources in deep water several hundred kilometres from land.

The initial stage will involve a 2MW prototype, aimed to begin operations off the coast of Scotland in 2024, with a 10MW full scale pre-commercial facility three years later. This could produce up to 800 tonnes of hydrogen per year - enough to heat around 2,500 homes, fuel up to 240 buses or run 8 to 12 trains.

Over the long term the project aims to roll out 400 turbines in the 2030s, with a capacity of 4GW and producing over 320,000 tonnes of hydrogen per year - enough to heat 1.5 million UK homes.

Desalination

Water for electrolysis and desalination:

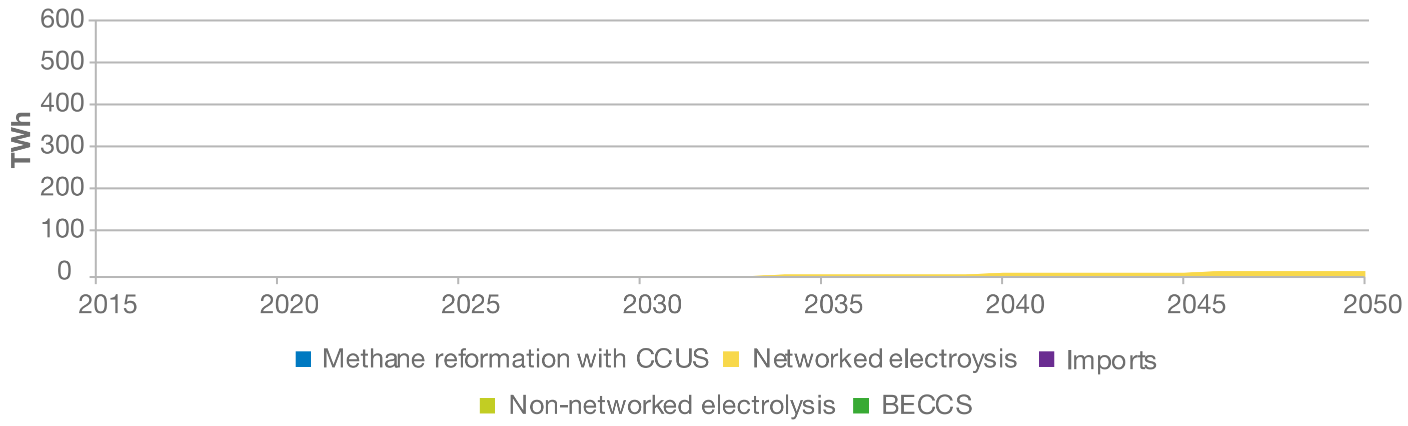
Where electrolysis takes place offshore, we have assumed that it would not make sense to pipe fresh water from the mainland so instead propose that some input energy is required to power co-located desalinisation equipment. This reduces the conversion efficiency of the process in energy terms which is reflected in our analysis where we have assumed a 70% efficiency.

FES 2020 / System View / Hydrogen supply 133

Steady Progression

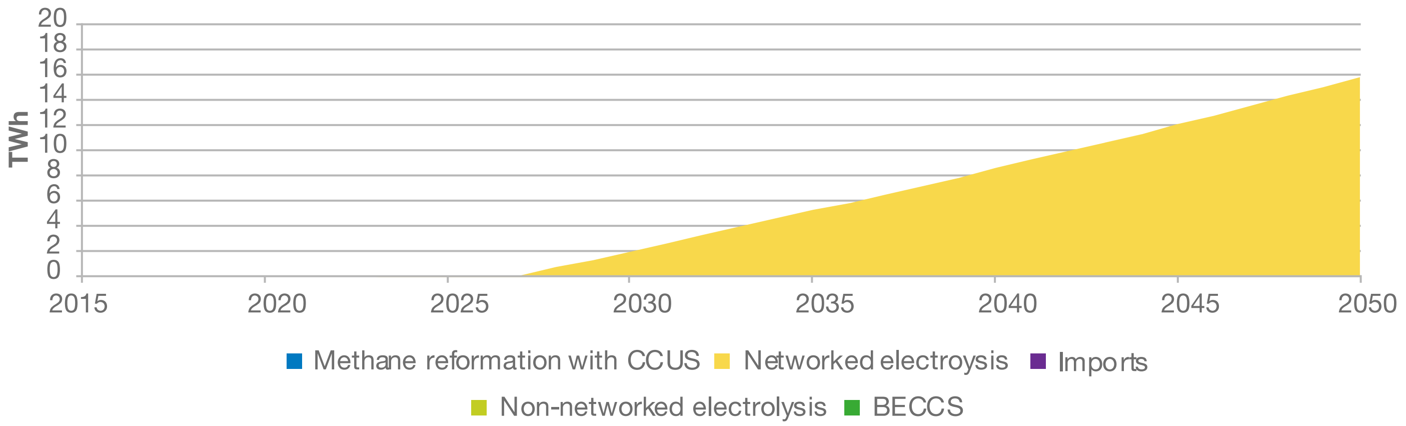
In **Steady Progression**, CCUS is not deployed at scale. Hydrogen is produced via electrolysis, which is located near wind or solar farms to make maximum economic use of curtailed generation. It is then transported in compressed form via tankers to hubs for use by heavy goods vehicles and transport fleets or injected into the natural gas network to support the decarbonisation of connected gas users.

Figure SV.22: Steady Progression hydrogen supply



Scaled view

Figure SV.22: Steady Progression hydrogen supply



Non-scaled view

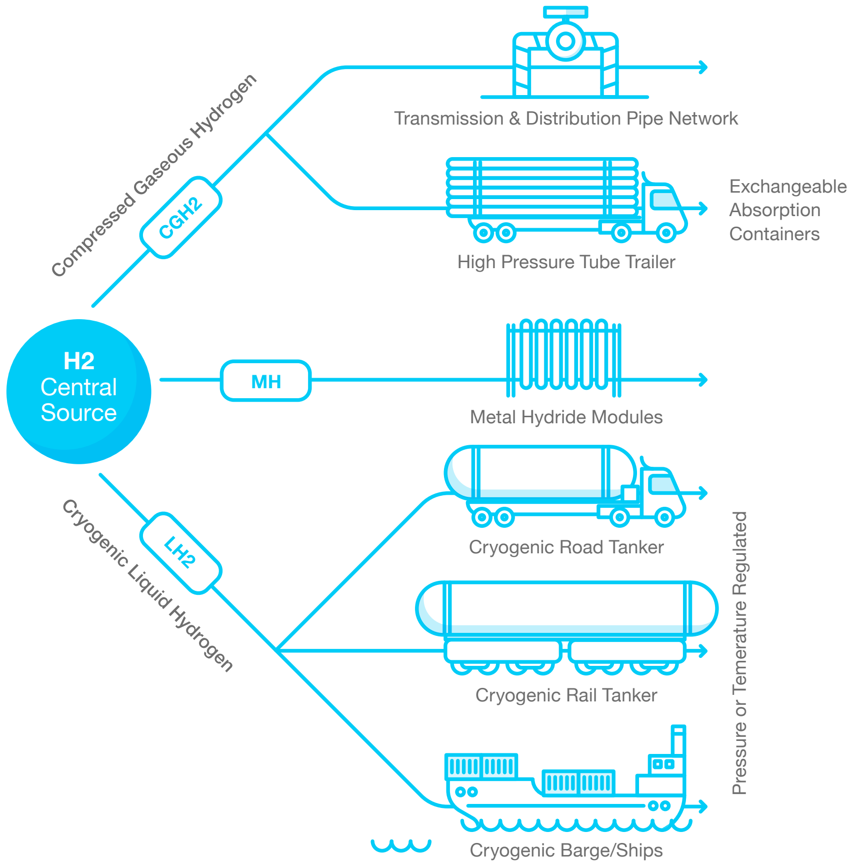
FES 2020 / System View / Hydrogen supply 134

Transported

Transporting hydrogen

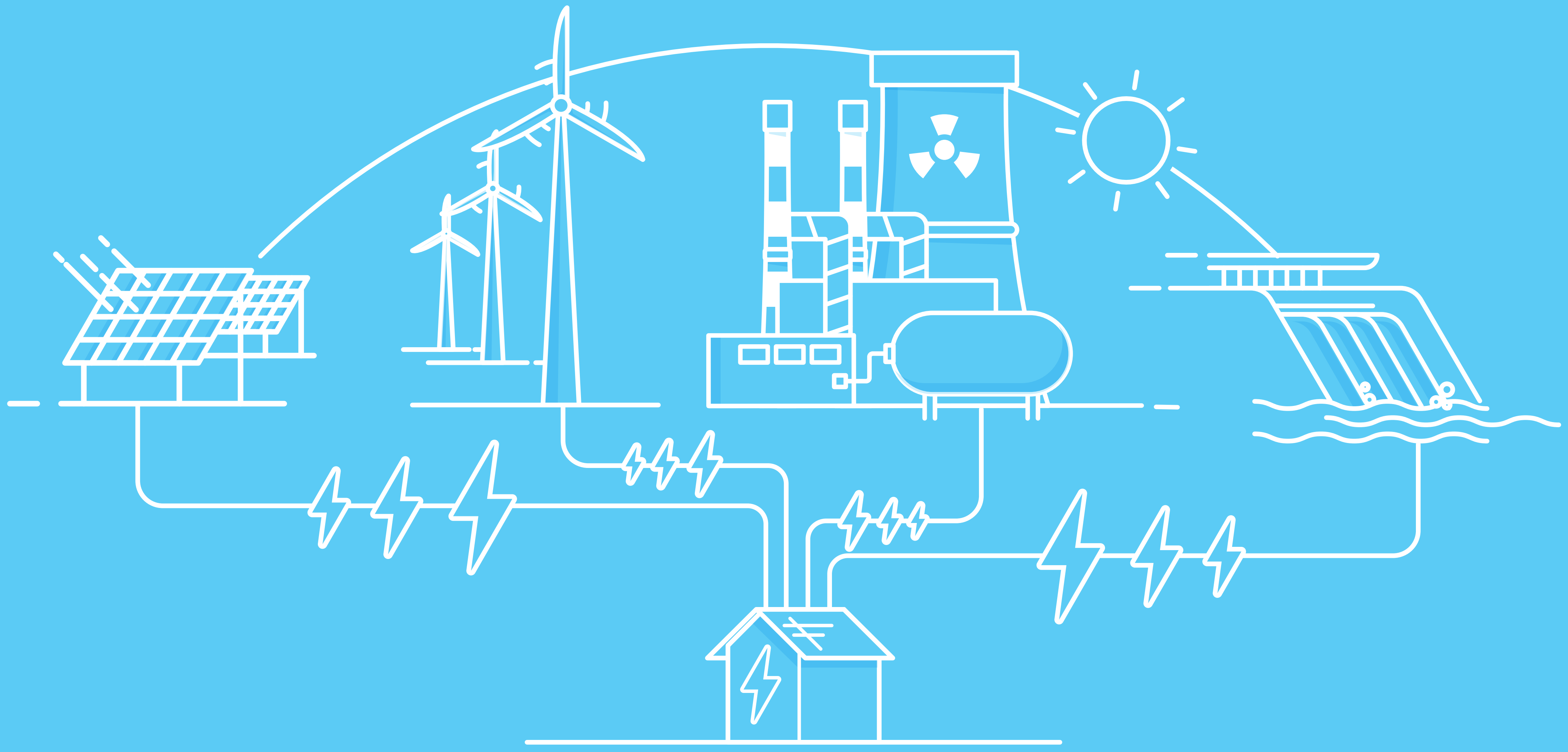
What options for transporting hydrogen exist other than a pipeline network? Hydrogen can be liquefied to be transported at volume and unpressurised, but this must be done at extremely low temperatures (-253degC) which adds to the energy use and cost. Alternatively, hydrogen can be reacted with nitrogen, producing ammonia. Ammonia can be transported as a liquid below -33degC, or at high pressure and is less costly to transport than liquefied hydrogen. This works well when shipping is the preferred method of transport.

Other developing processes include use of Liquid Organic Hydrogen Carriers (LOHC) which offer a way that hydrogen can be transported at ambient temperature and pressure. The hydrogen can be extracted after transportation and the carrier re-used.



FES 2020 / System View / Hydrogen supply 135

Electricity Supply



Key insights

- Net zero will require significantly higher levels of electricity generation; in 2050 **Consumer Transformation** has 2.8 times more capacity than today.
- Bioenergy with carbon capture and storage (BECCS) is included in all net zero scenarios, with up to 9.6 GW installed by 2050 in **Leading the Way**. This provides the negative emissions needed to reach net zero across the whole economy.
- In 2050, four technologies produce over 90% of electricity generation in net zero scenarios: wind, solar, nuclear and BECCS.

To meet the net zero target, we must decarbonise the power sector; electrification of demand for heat and transport only decarbonises these sectors if the electricity is decarbonised. This means there can be no fossil fuel electricity generation without carbon capture and storage in a net zero world.

Growth in renewable generation over the past decade has led to a significant fall in the carbon intensity of GB electricity supplies, down 53% from 529g CO_2/kWh in 2013 to 215g CO_2/kWh in 2019[1]. This trend is likely to continue as renewable technologies continue to become cheaper and more investment is made. The last year has seen further milestones in low carbon generation, with records set for renewable generation output, minimum carbon intensity and coal-free periods. To meet the 2050 net zero target, full elimination of carbon emissions from this sector will need to be accelerated.

Between now and 2050

In all scenarios:

1. Annual electricity demands increase significantly due to combinations of electric vehicles, heat pumps and electrolysis. This means significantly more capacity is required to meet these demands.
2. The increase in renewable generation with relatively low annual load factors compared to fossil fuels means significantly more capacity is required to meet demand.
3. The weather dependence of renewable generation means that much larger amounts of flexibility are required.
4. Large generation connected to the transmission network is increasingly complemented by small decentralised generation connected to distribution networks, reaching up to 42% of GB capacity by 2050.

In net zero scenarios:

1. There won't be any unabated fossil fuel generation in 2050.
2. The power sector delivers negative emissions to offset residual emissions in other sectors.

1 National Grid Carbon Intensity data, 2020, carbonintensity.org.uk

FES 2020 / System View / Electricity supply 137

Load factors

Load Factor

The load factor or capacity factor of a technology refers to the electricity generated as a proportion of the maximum potential generation. Variable renewable technologies typically have a substantially lower maximum potential load factor than fossil fuel generation due to the nature of the resources they are harnessing; for example, solar PV generation is limited by hours of daylight.

Average UK load factors over the last five years range from 11% for Solar PV, 27% for onshore wind and 39% for offshore wind, through to 77% for plant biomass combustion and 74% for nuclear generation. Load factors for gas CCGTs have fallen from 65% between 2000 and 2010 to 38% from 2011 to 2018. (BEIS Energy Trends September 2019, Digest of UK Energy Statistics 2019). This means generating an equivalent amount of energy to that coming from fossil fuel generators running as base load requires significantly higher installed renewable capacity.

Larger wind turbines, particularly offshore, have higher load factors with those built in recent years getting up to 50%. Seasonal load factors for wind are typically higher in winter than summer due to higher average wind speeds.

FES 2020 / System View / Electricity supply 138

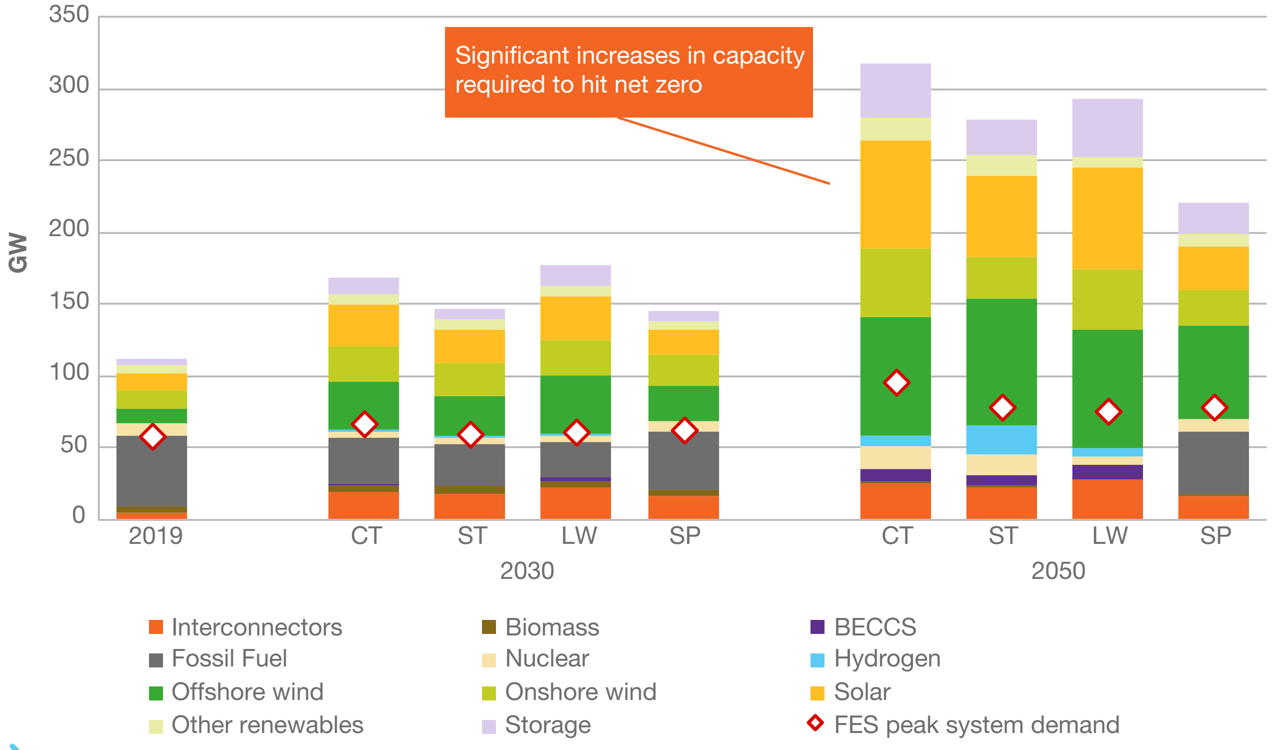
Electricity supply capacity

Overall capacity grows in all scenarios and increases most in the more electrified world of **Consumer Transformation**, which in 2050 has 2.8 times the total generation capacity of today. The proportion of renewable generation rises in all scenarios, including **Steady Progression**, as the reduced cost of wind and solar and increases in electricity demand lead to increased use of these technologies.

We assume that measures continue to be in place to ensure sufficient generation capacity to achieve the security of supply standard of no greater than a 3-hour loss of load expectation in all scenarios.

The lower load factors of renewable generation compared to current fossil fuel generation, combined with increased demands, lead to an increase in total electricity generation capacity in all scenarios. The changes in electricity supplied, capacity and load factors for different types of generation are shown in Figure SV.24. This is explored in more detail in the flexibility section *(See page 169)*.

Figure SV.23: Installed electricity generation capacity, plus storage and interconnection (no vehicle-to-grid or non-networked offshore wind)



Cost of wind and solar

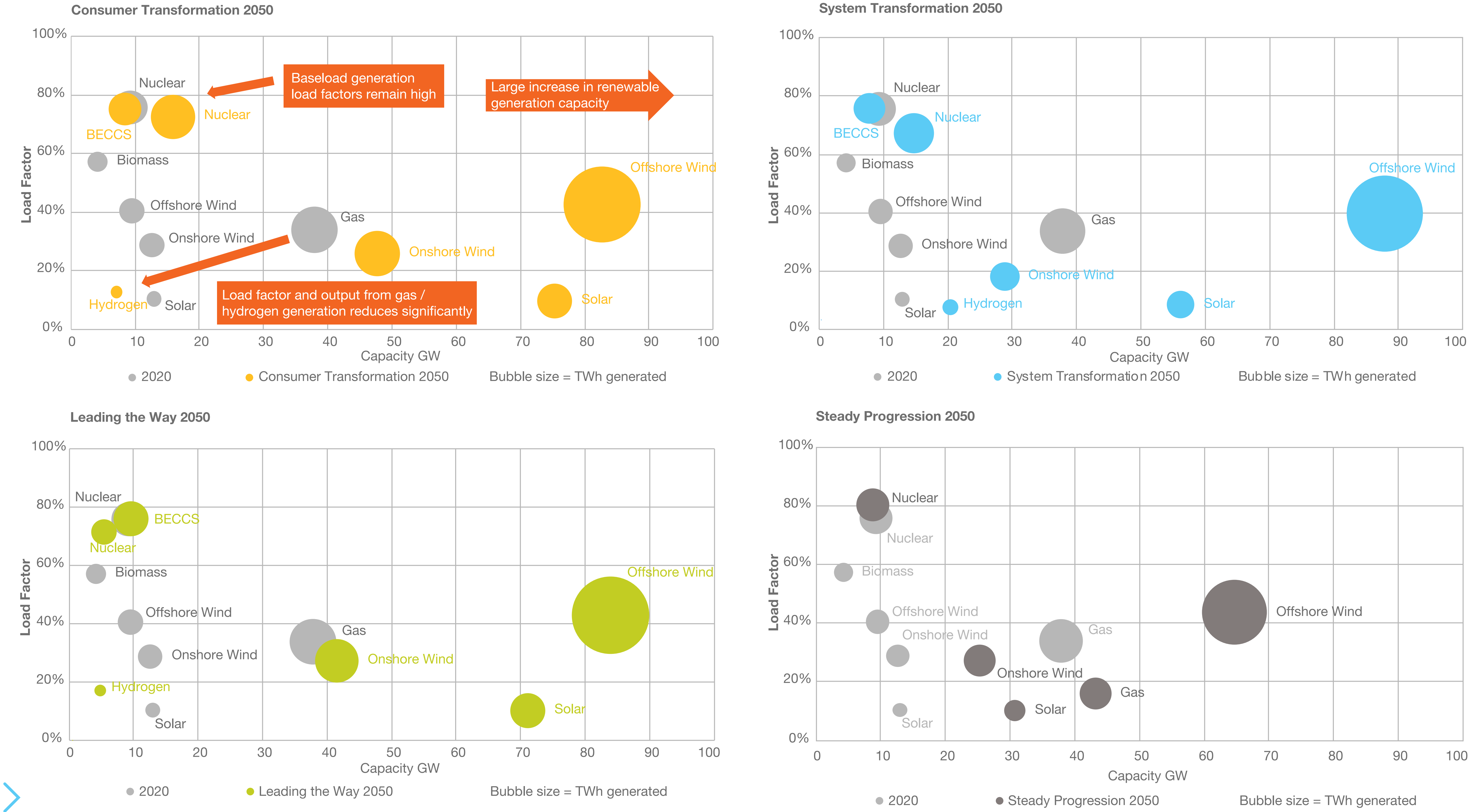
Historic wind and solar cost reductions

Strike prices for Contracts for Difference (CfD) for new offshore wind projects have fallen from £114/MWh in 2015 to below £40/MWh in 2019 (BEIS CfD Allocations Round 1 and Round 3 results).

Global weighted average levelised cost of electricity (LCOE) of solar PV has fallen 77% between 2010 and 2018 to $0.085/kWh (IRENA (2019), Renewable Power Generation Costs in 2018).

FES 2020 / System View / Electricity supply 139

Figure SV.24: Load factors



FES 2020 / System View / Electricity supply 140

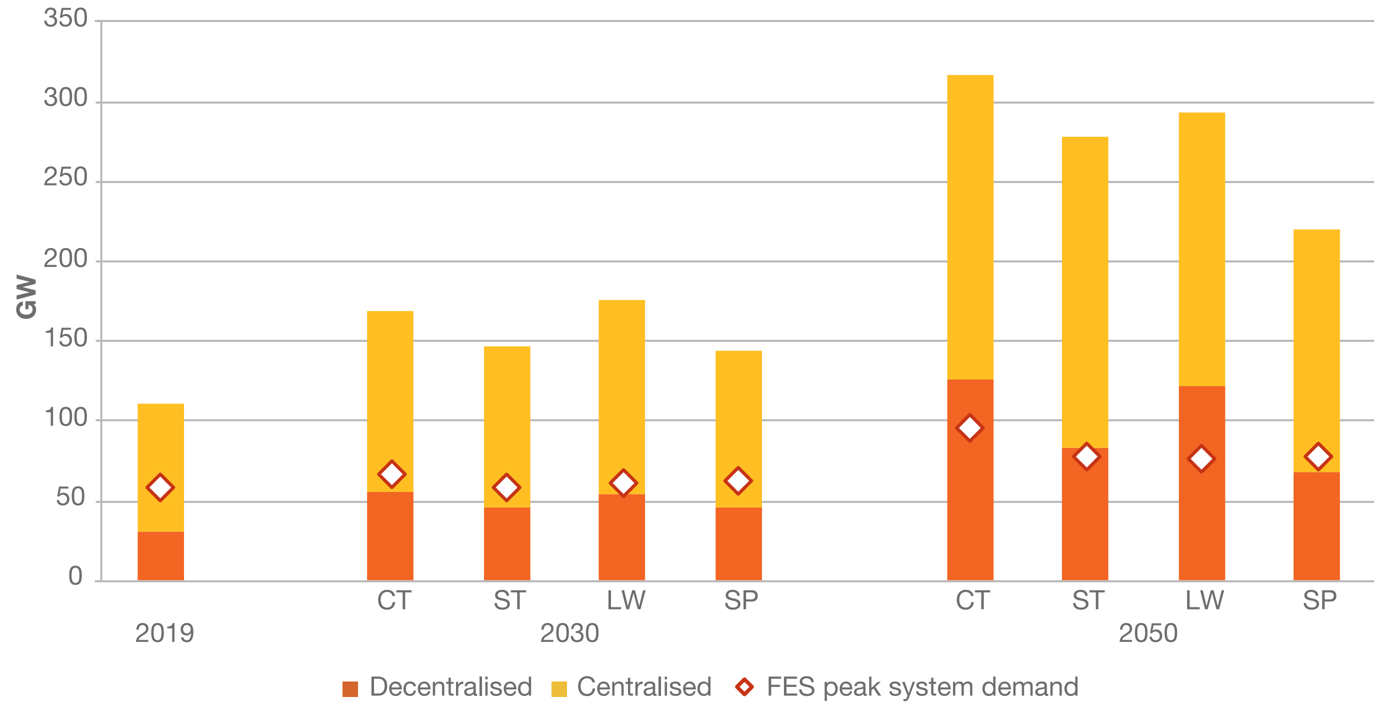
Decentralisation

All scenarios show higher levels of decarbonisation and decentralisation compared with today.

By 2050 up to around 42% of generation capacity could be decentralised, meaning it is connected to the distribution networks. High levels of capacity are required to meet annual demand and transmission-connected offshore wind has the largest increase in all scenarios. The increase in offshore wind tends to limit the maximum contribution of decentralised generation as a proportion of electricity production.

By 2050 the level of decentralisation in all scenarios suggests the role of the transmission system may often be to transport electricity from one distribution network to another, rather than delivering from transmission connected generation to distribution networks.

Figure SV.25: Connection location of installed generation capacities and peak demand (excluding vehicle-to-grid)



FES 2020 / System View / Electricity supply 141

Decentralisation

Decentralisation

Decentralisation refers to how close the production and management of energy is to the end consumer. High levels of decentralisation mean closer links between sources of energy supply and demand via local networks, with consumers being more active in managing their energy needs.

In a decentralised world, more small-scale energy supplies connect to the distribution networks, including renewables and small-scale green gas. On a yet smaller-scale, consumers use technology to manage their own electricity needs in a more localised manner.

FES 2020 / System View / Electricity supply 142

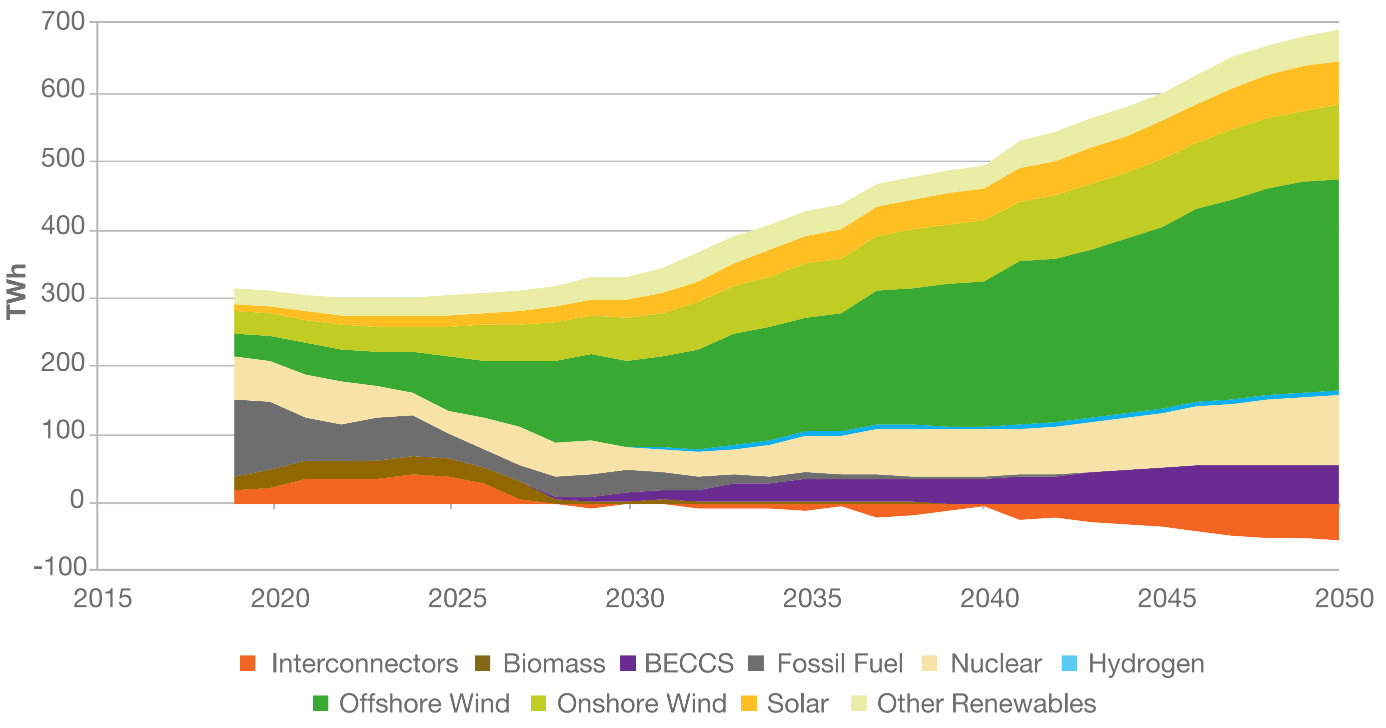
Electricity supply output

In the net zero scenarios in 2050 most electricity generated comes from four technology types: wind, solar, nuclear and BECCS. In **Steady Progression** wind is also the largest source of generation with nuclear, solar, and natural gas also making significant contributions.

Consumer Transformation has the highest levels of demand electrification in 2050 and hence the highest electricity supply with 691 TWh generated domestically, while **Steady Progression** has the lowest supply level of 494 TWh.

Overall hydrogen generation output is low in all net zero scenarios as it is operated with low annual load factors as a flexible source of supply to meet peak demands. Biomass generation output declines to low levels in all scenarios by 2030 as bioresources are prioritised for other sectors. In the net zero scenarios this is replaced by BECCS for negative emissions. Most electricity generation in the *Other Renewables* category comes from marine, hydroelectric and energy from waste generation; this contributes the most to overall supply in **Consumer Transformation** and **System Transformation**.

Figure SV.26: Electricity output by technology (excluding non-networked offshore wind)

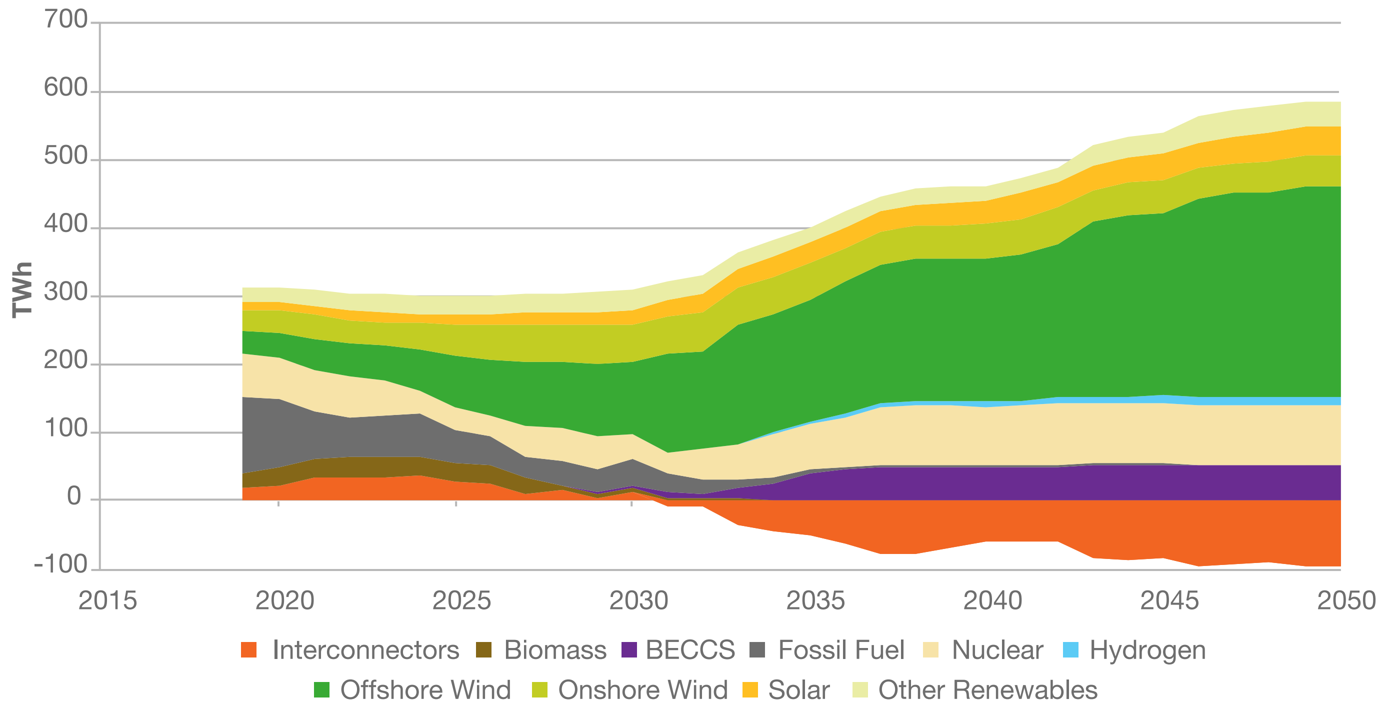


Consumer Transformation

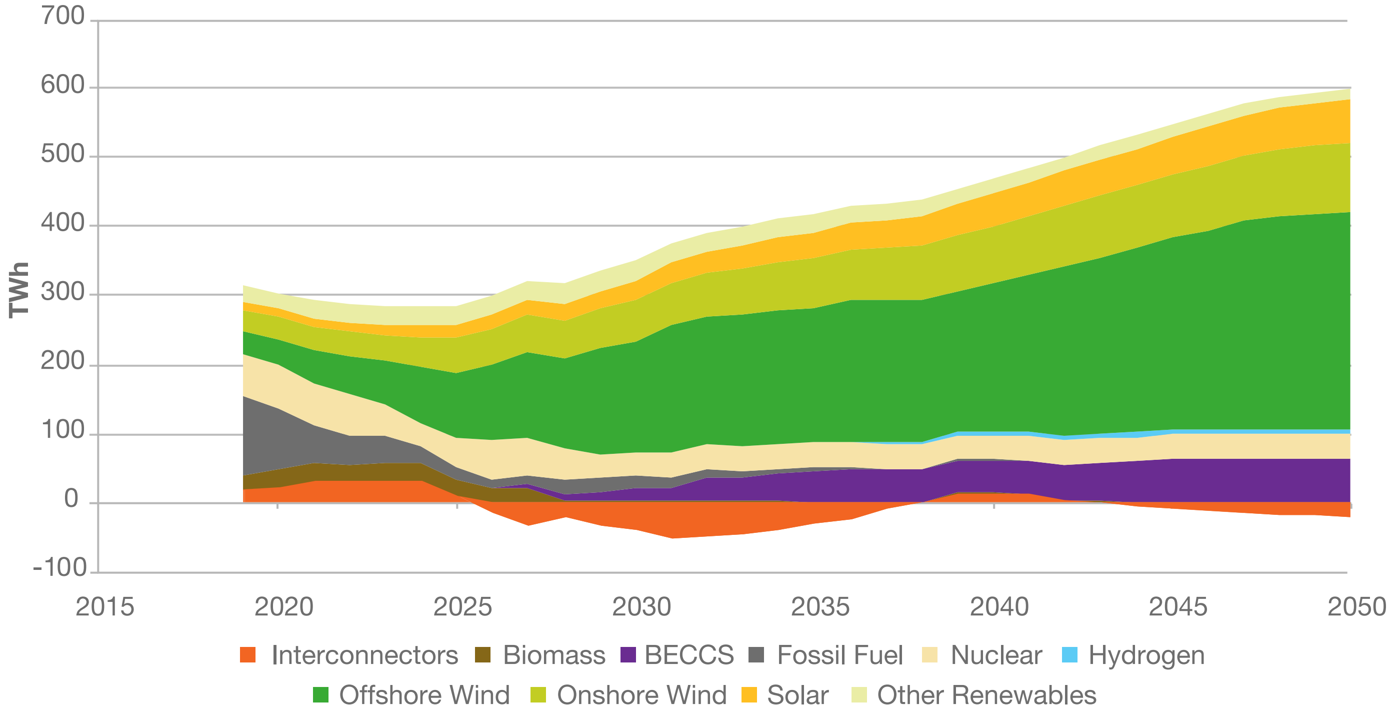
FES 2020 / System View / Electricity supply 143

Electricity supply output

Figure SV.26: Electricity output by technology (excluding non-networked offshore wind)



System Transformation

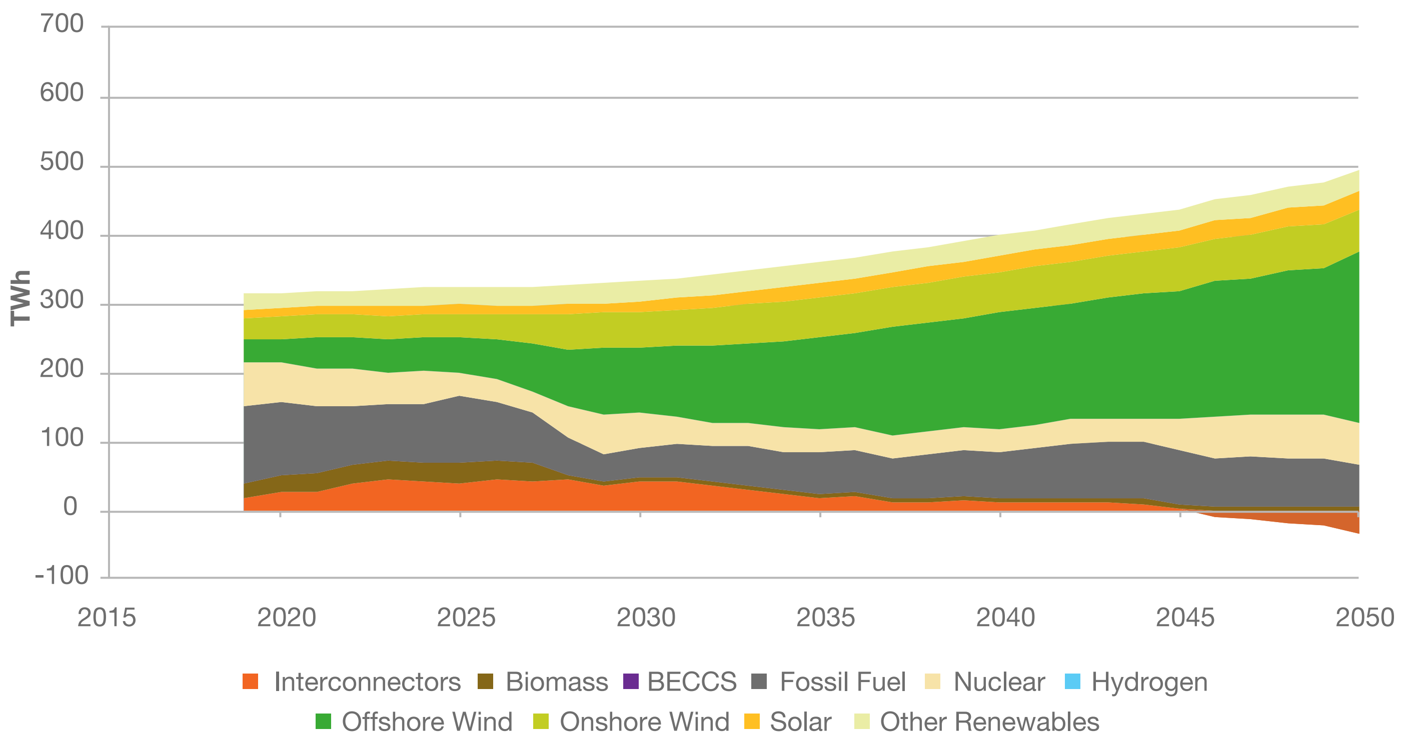


Leading the Way

FES 2020 / System View / Electricity supply 144

Electricity supply output

Figure SV.26: Electricity output by technology (excluding non-networked offshore wind)



Steady Progression

FES 2020 / System View / Electricity supply 145

In **Steady Progression** the largest increase in generated electricity between today and 2050 comes from offshore wind, which sees the biggest growth in capacity. There is a continuing role for unabated gas generation to flexibly support renewables and meet peak demand out to 2050.

In the net zero scenarios new sources of flexibility beyond generation become more important to meet peak demand. If there is too much renewable generation compared to demand such as on windy, sunny summer days, this excess is met by flexible demand from demand side response (DSR) or electrolysis to produce hydrogen, used to charge electricity storage or is exported. This and other balancing issues are explored in more detail in the flexibility section *(See page 169)*.

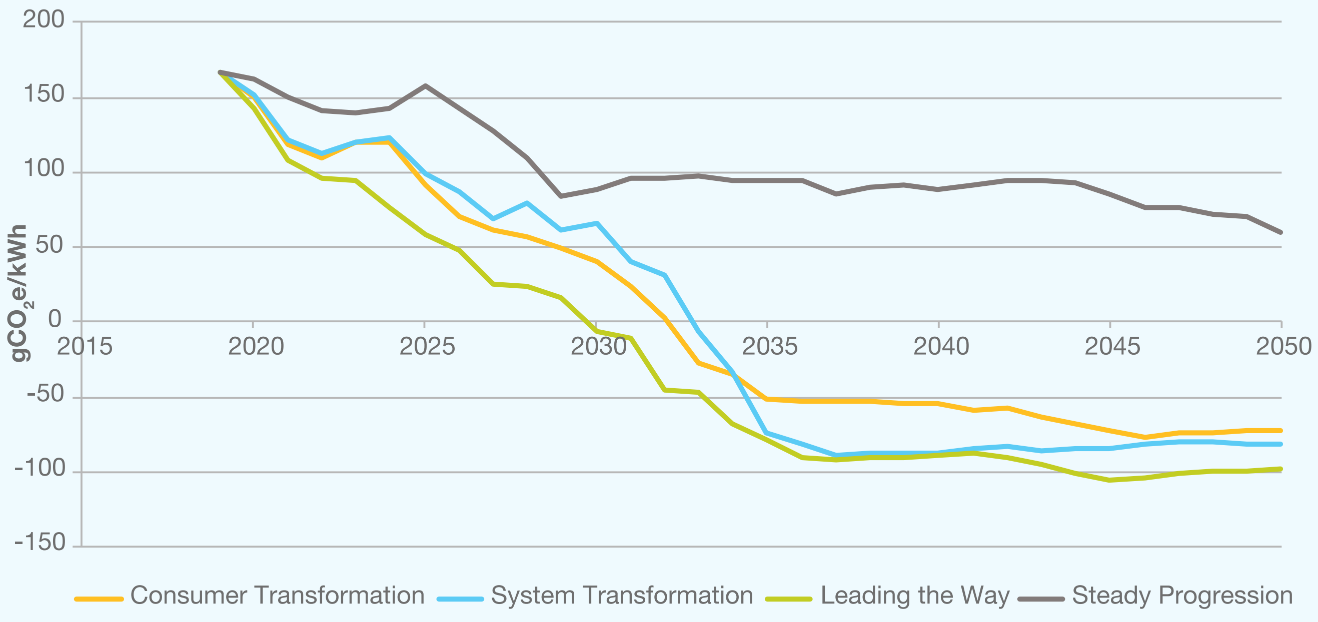
Currently interconnector operation predominantly imports electricity from continental Europe. In all scenarios total volumes of electricity traded across the interconnectors in both directions increases as renewable generation increases in GB and Europe, and GB becomes a net exporter of electricity by 2050. We have assumed that the UK will continue to have access to European electricity markets for wholesale electricity with a broadly similar mechanism and costs as we do today. Exported electricity is greatest in **System Transformation** which relies most heavily on interconnectors as a source of flexibility to help balance the high levels of variable renewable generation and has lower levels of electrolysis than the other net zero scenarios. This is discussed in more detail in the flexibility section.

More detailed output data by technology for all scenarios can be found in the Data Workbook.

Power sector carbon emissions

Carbon emissions from the power sector continue to fall in all scenarios, with **Leading the Way** becoming net negative by 2030; other net zero scenarios achieve this by the mid-2030s. **Steady Progression** does not reach net negative emissions due to the continued presence of fossil fuels in the generation mix and the absence of CCUS.

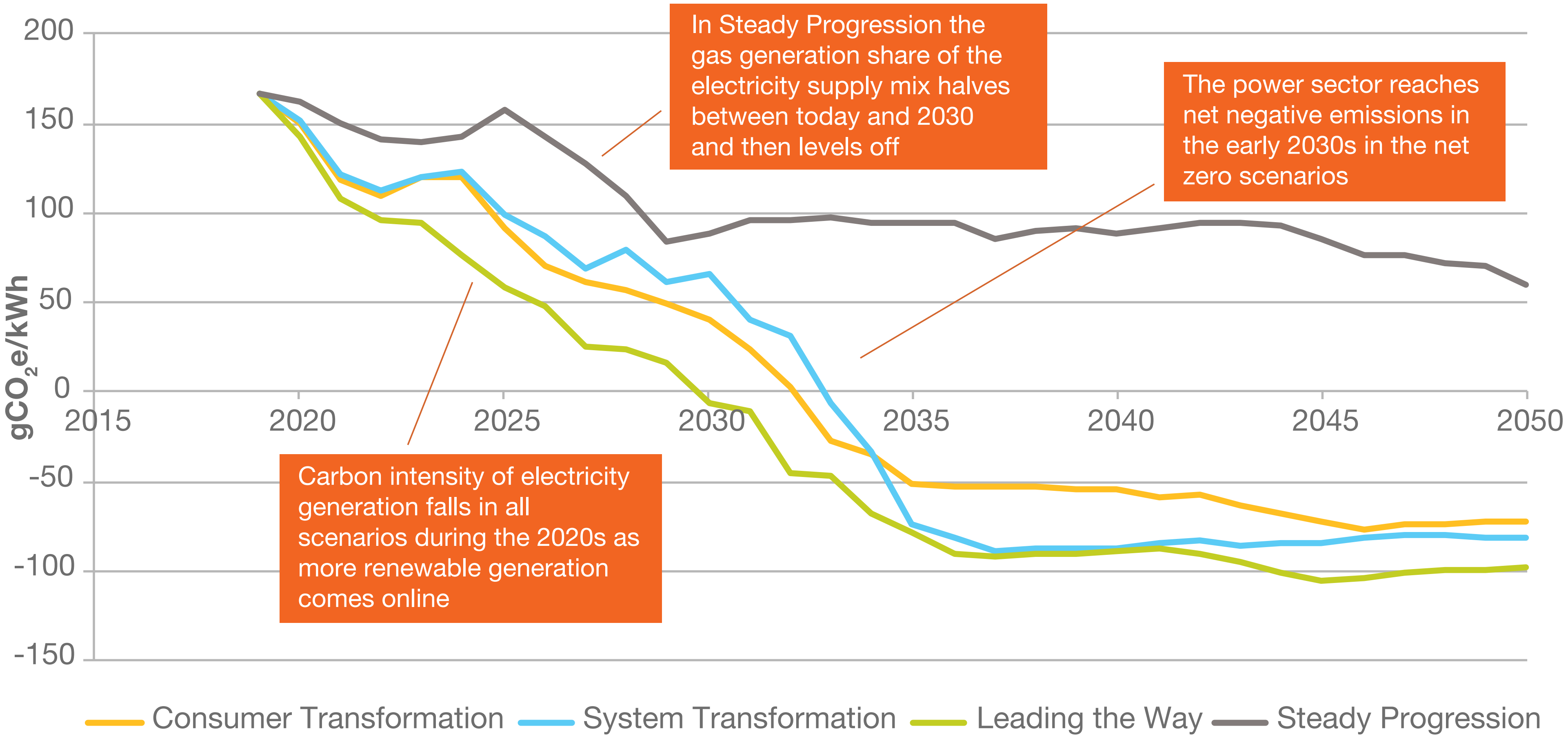
Figure SV.27: Power sector carbon intensity[2]



2 Grid connected generation only

Power sector carbon emissions

Figure SV.27: Power sector carbon intensity[2]



2 Grid connected generation only

FES 2020 / System View / Electricity supply 147

Renewables

Key insights

- Strong policy support for continued growth of wind and solar drives decarbonisation and sees increases in our projections for the growth of renewable generation.

- Offshore wind continues to dominate renewable generation capacity. **Leading the Way** reaches 42 GW by 2030, while **Consumer Transformation** delivers the Sector Deal target of 30 GW by 2030 and **System Transformation** falls just short.

- Solar capacity projections have increased significantly since last year's scenarios, supported by growth in flexible electricity demand for electrolysis.

Renewed government support for some renewable technologies has driven our expectation of higher growth in renewable generation to a level which will be necessary to meet net zero. The more established technologies of solar and wind dominate compared to smaller contributions from other technologies such as wave, tidal and hydro generation.

Solar

The closure of subsidy schemes for solar PV has led to growth slowing over the last few years after a decade of rapid growth. The Smart Export Guarantee came into force in 2020 requiring energy suppliers to pay small-scale low carbon generators for electricity exported to the grid, which we expect to support growth at present levels. We expect continued slow growth in the short term, but cost reductions, the renewed eligibility of solar PV for Contracts for Difference support, and co-location with storage should boost solar growth in the late 2020s.

Our projections see significantly higher levels of solar generation post-2035 than in FES 2019, as increased electricity demand in a net zero world leads to greater demand for renewable generation. Solar is increasingly supported by co-location with energy storage or hydrogen production to provide an additional revenue stream, particularly in **Leading the Way**, as increasing solar leads to falling daytime power prices in summer.

Figure SV.28: Solar capacity by scenario

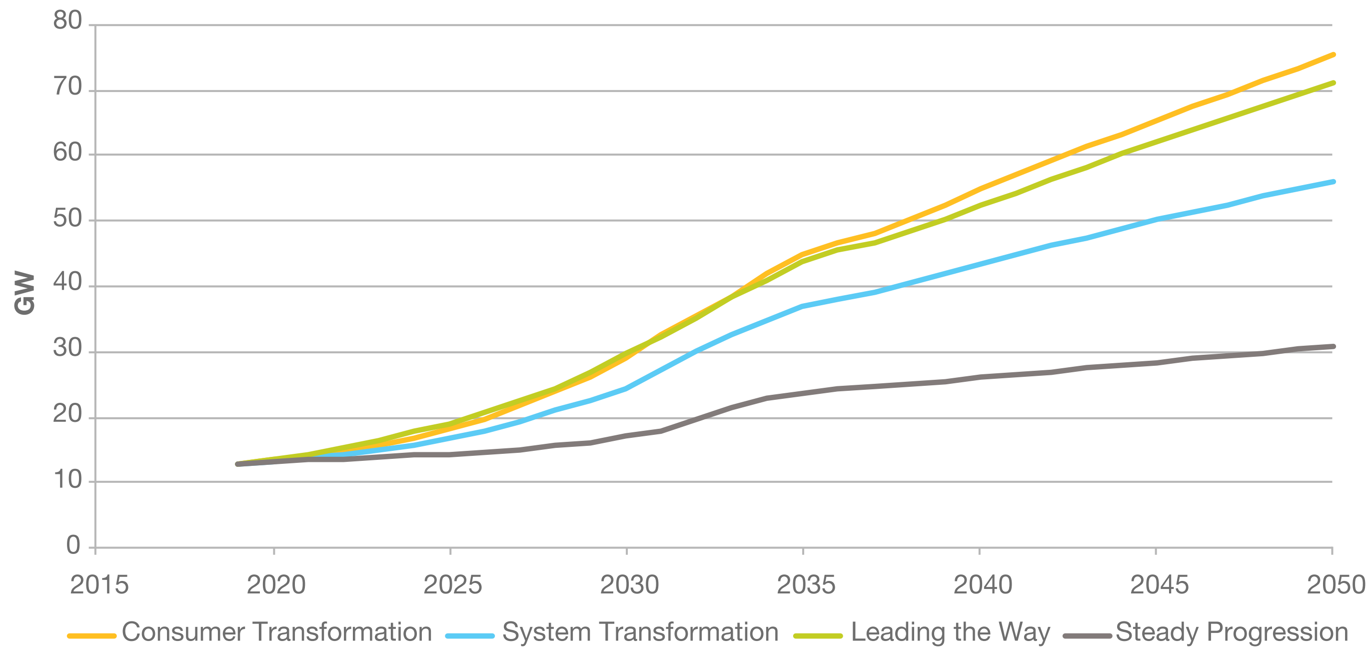
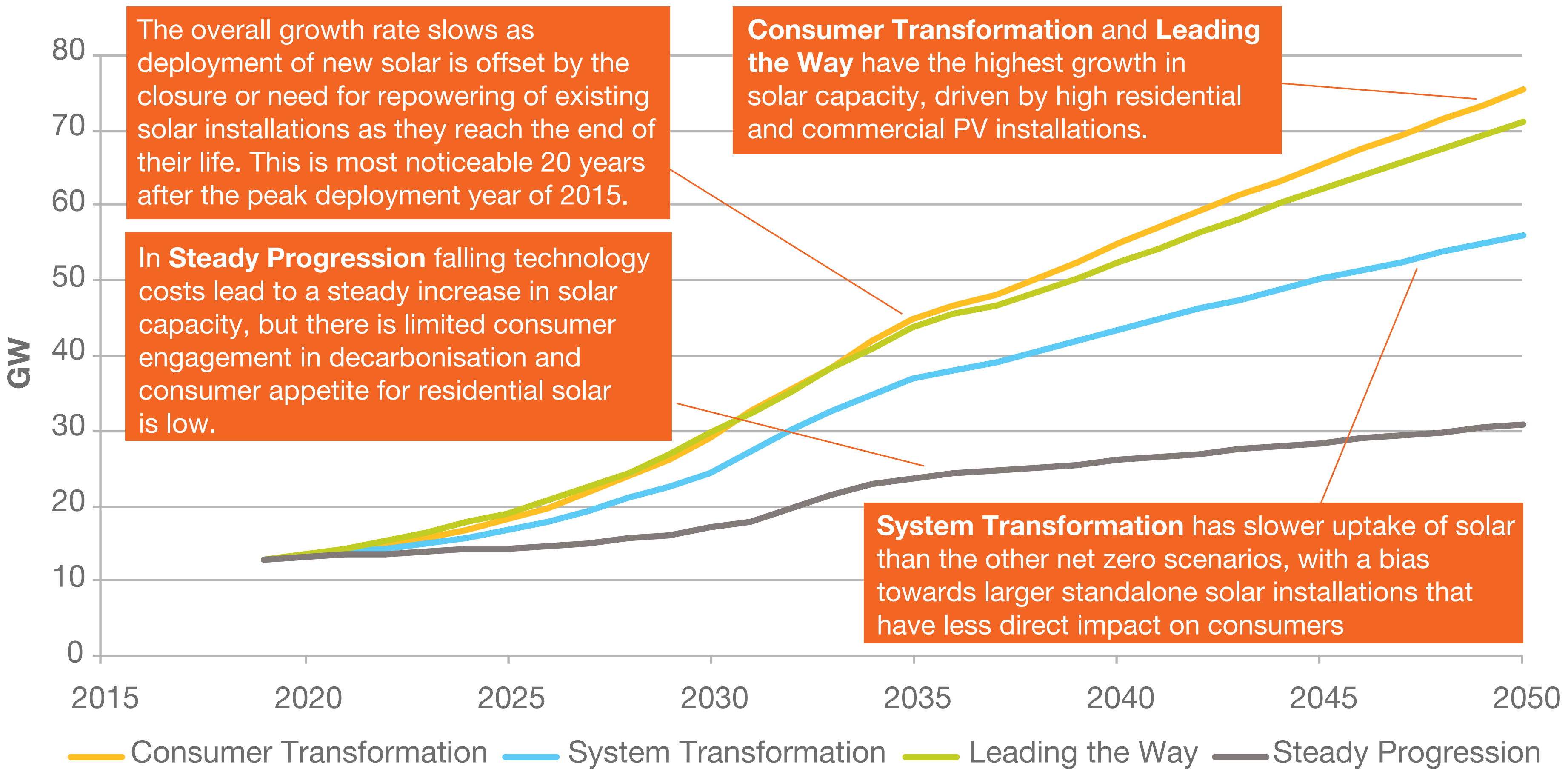


Figure SV.28: Solar capacity by scenario



FES 2020 / System View / Electricity supply 150

Wind

Total wind capacity increases in all scenarios, mainly driven by growth in offshore wind. Falling costs, technology development and political support have led us to forecast higher growth than in FES 2019.

Scenarios with higher societal change have higher levels of onshore wind, although growth is more limited than offshore wind due to land restrictions and stricter planning regulations. Most onshore wind growth in these scenarios is assumed to be distribution-connected in future, although there is some growth in transmission-level onshore wind, particularly in Scotland, with more in **System Transformation**.

We expect high levels of growth in offshore wind in all scenarios. The 2019 Conservative election manifesto set out an ambition for 40 GW of offshore wind by 2030, building on the March 2019 Sector Deal that committed to 30 GW by the same date. The Sector Deal target is achieved in **Consumer Transformation**, while **System Transformation** falls just short. **Leading the Way** achieves the higher ambition, with 42 GW of offshore wind installed by 2030. Meeting the 40 GW target will require rapid scaling up of the offshore wind supply chain and further government policy support. Figure SV.29 shows the pipeline of offshore wind projects to 2030 and their categorisations in the development process.

Figure SV.29: Potential offshore wind projects by scenario

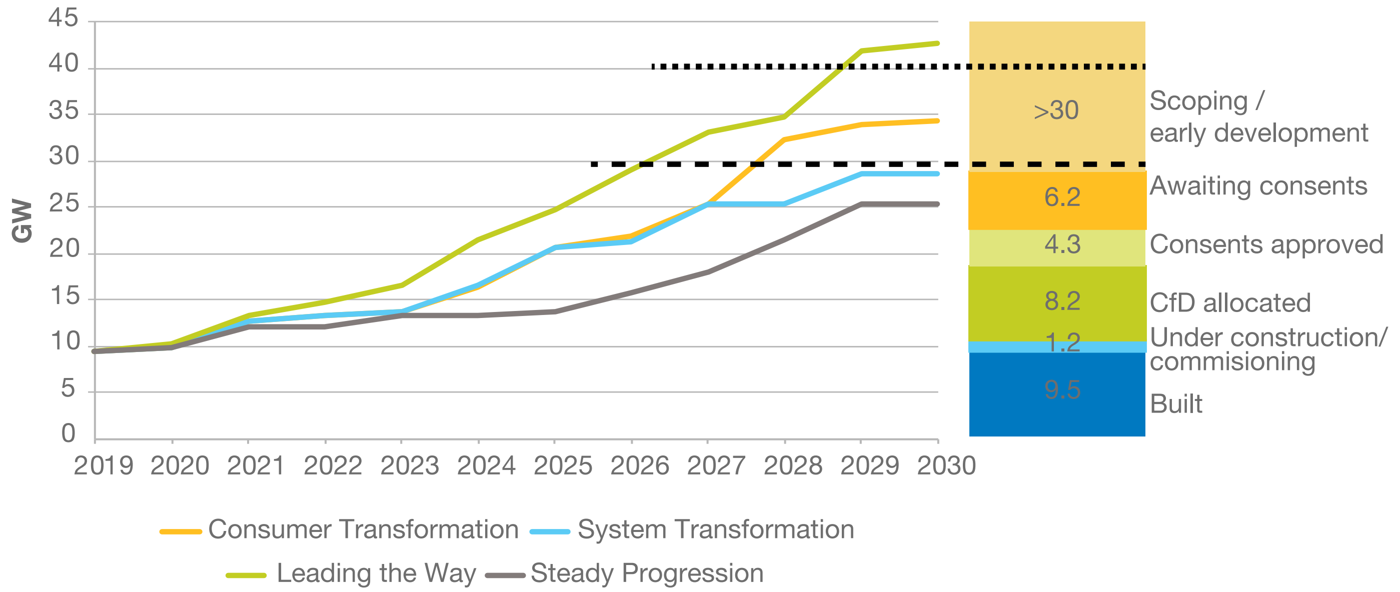


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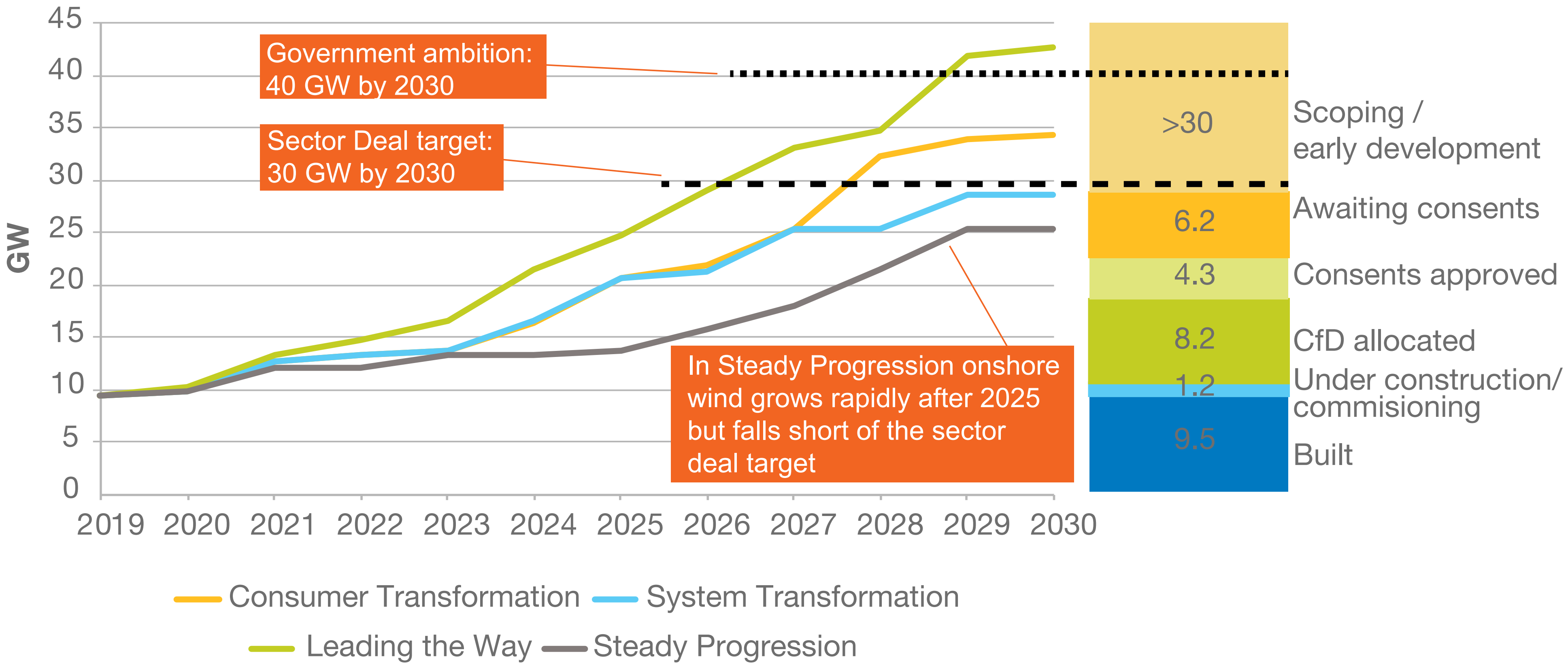
Figure SV.29: Potential offshore wind projects by scenario



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FES 2020 / System View / Electricity supply 152

Transmission-level

Transmission level generation

Generation above certain thresholds is connected to the transmission network rather than the distribution network, although these thresholds differ between England and Scotland. While the transmission network in England and Wales is typically operated at 275kV or 400kV, in Scotland lower voltages are also considered as transmission. This difference means that a greater share of onshore generation is transmission-connected rather than distribution-connected in Scotland compared to the rest of Great Britain.

Sector Deal

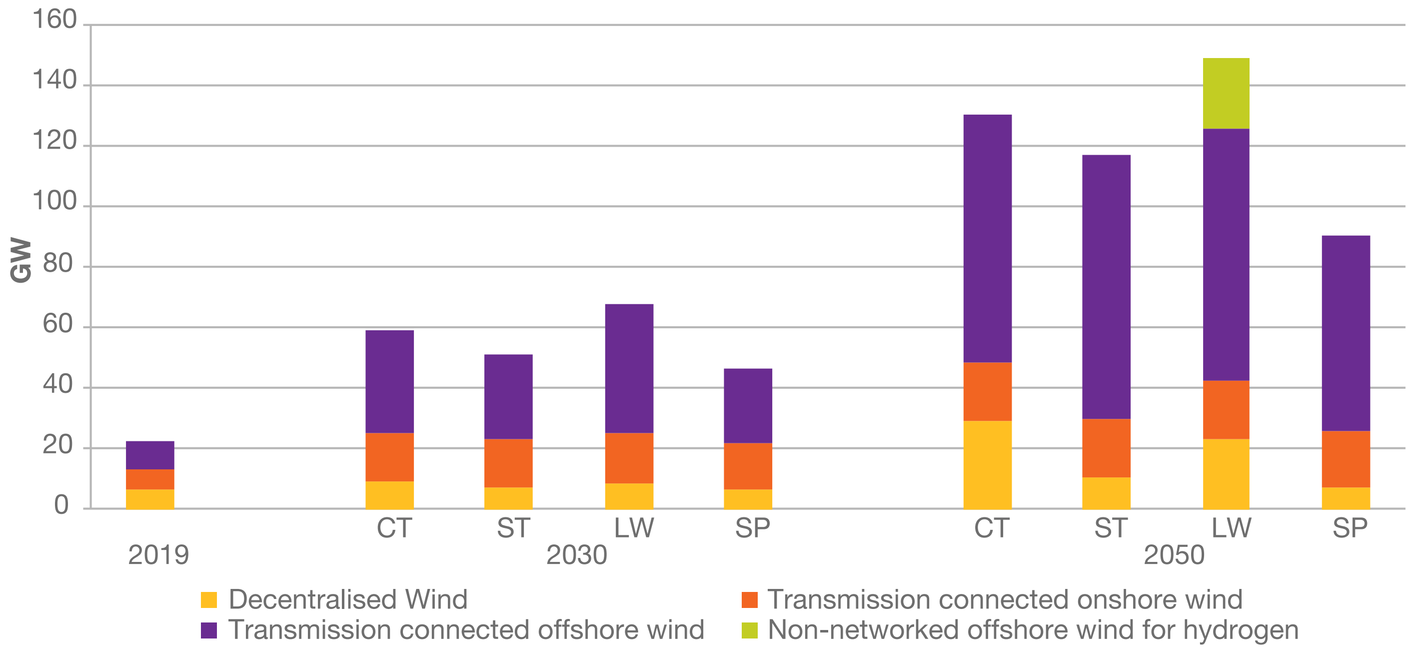
Offshore wind Sector Deal

The Sector Deal is a partnership between the government and the offshore wind sector to support continued growth of offshore wind technologies.

FES 2020 / System View / Electricity supply 153

In **Leading the Way**, we also see some non-networked offshore wind generation. This is co-located with electrolysis and the hydrogen produced is piped to shore. As this generation is not used to meet electricity demand it has not been included in Figure SV.23 showing total capacity of networked generation; however it is included in Figure SV.30 to allow comparison of dedicated capacity for hydrogen production against networked wind capacity. Sources of hydrogen production are explored in more detail here *(See page 120)*.

Figure SV.30: Wind capacity by scenario (including non-networked offshore wind)



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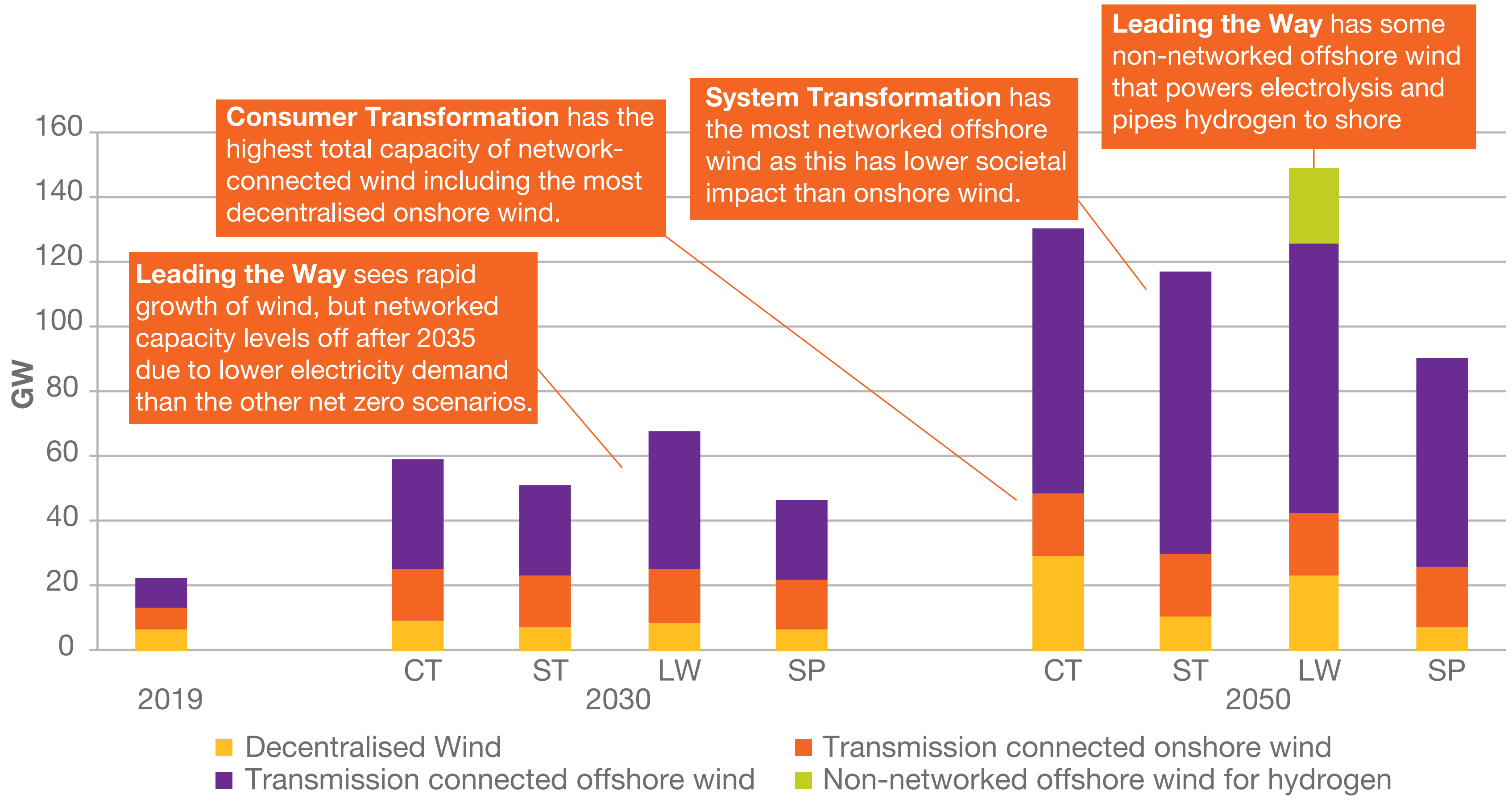
FES 2020 / System View / Electricity supply 154

Figure SV.30: Wind capacity by scenario (including non-networked offshore wind)



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FES 2020 / System View / Electricity supply 155

Other renewables

Other renewable technologies, such as hydroelectric, marine and geothermal generation are also included in FES 2020.

System Transformation and **Consumer Transformation** have high levels of tidal generation capacity, with up to 10 GW installed by 2050. Hydroelectric and geothermal generation see more growth in the higher societal change scenarios than in **System Transformation**, but overall growth is low as they are limited by the available geography.

Energy from waste generation declines in the net zero scenarios as more environmentally conscious consumers adapt to low waste living, with levels of waste reduction increasing with the level of societal change. In **Steady Progression** generation from waste remains similar to today, due to the continued availability of waste as a fuel source.

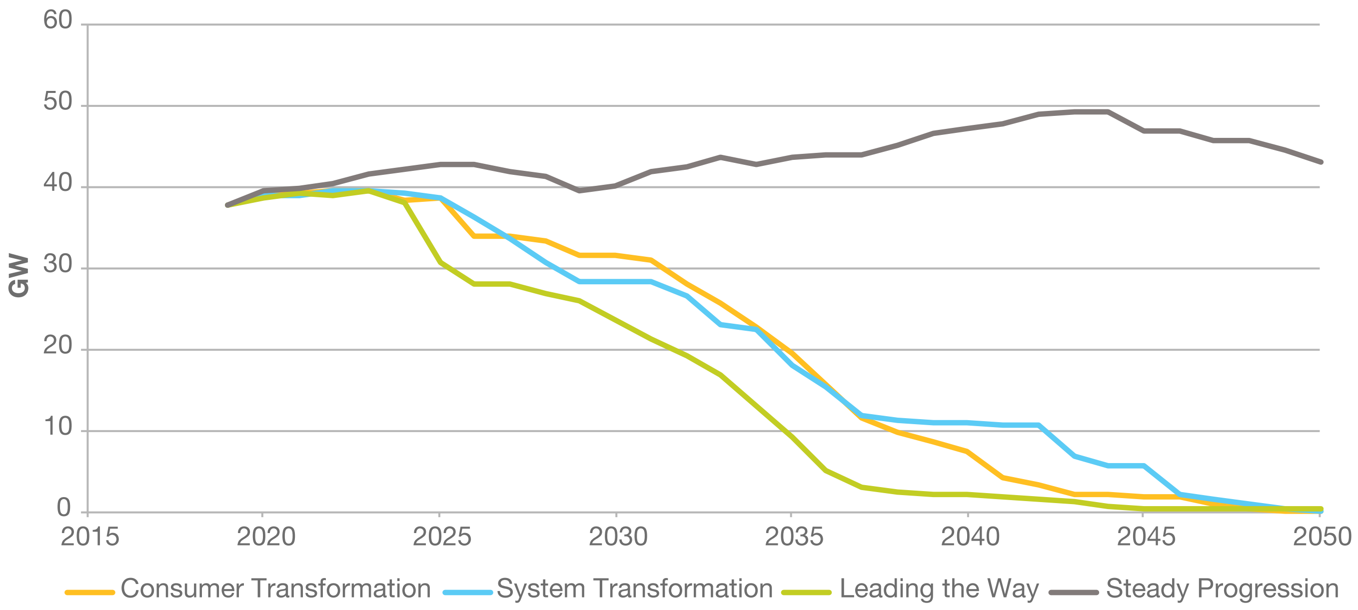
Details of all renewable generation technologies modelled can be found in the Data Workbook.

FES 2020 / System View / Electricity supply 156

Fossil fuel generation

Gas generation capacity falls in the net zero scenarios although it will continue to provide short-term flexibility and back-up generation for renewables into the 2030s. To meet net zero there can be no unabated fossil fuel generation by 2050. In **System Transformation** we see some interim use of gas generation with CCUS in the 2030s before this is displaced by hydrogen generation. Gas capacity remains high in **Steady Progression** at similar levels to today, although its role changes to provide more flexibility rather than as a primary source of electricity generation. The economics of gas plant will be increasingly reliant on their ability to provide network services and flexibility in all scenarios.

Figure SV.31: Total natural gas-fired generation capacity including gas CCUS



Annotations off

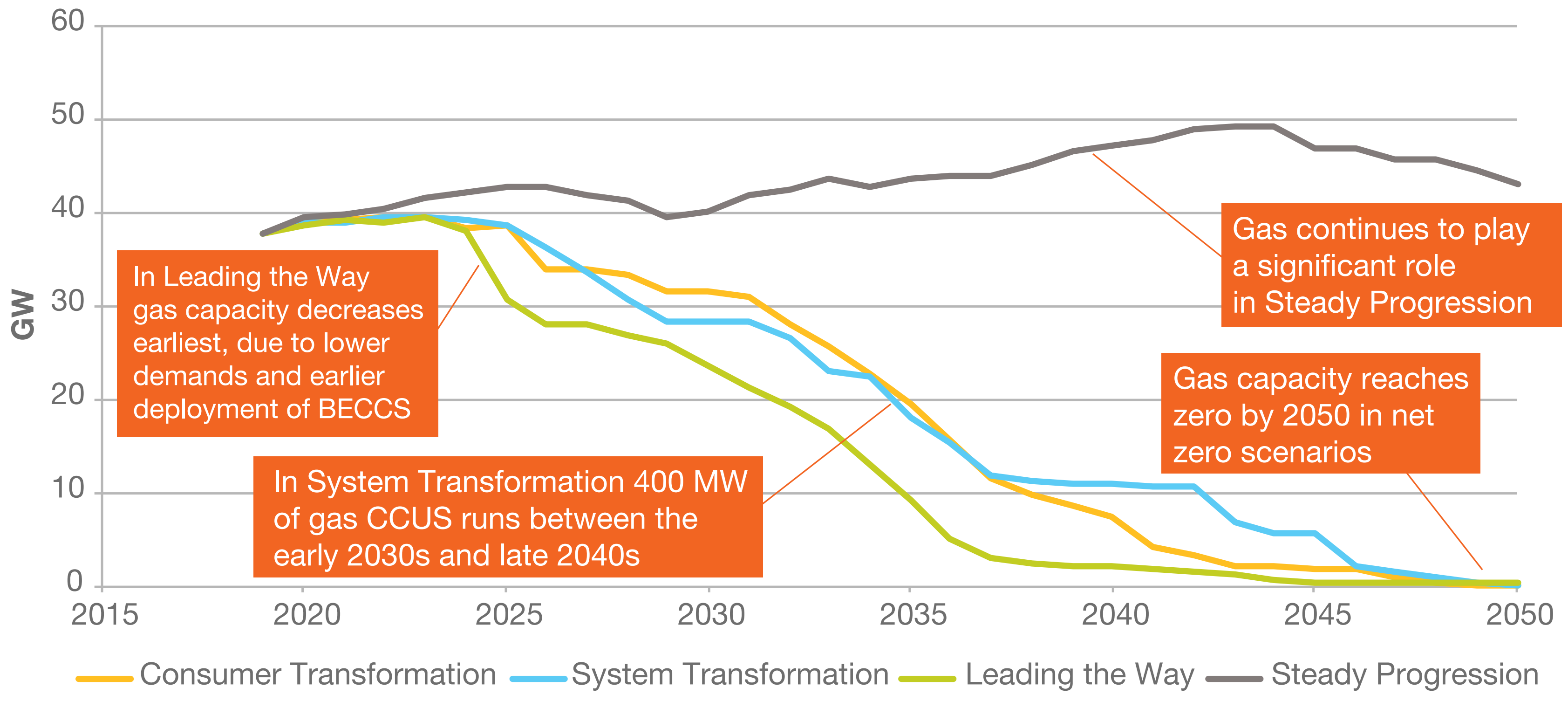
Changes to electricity network charging, including in the Targeted Charging Review weaken the economics of distribution-connected generation including diesel engines and, combined with the decarbonisation agenda, lead to a rapid reduction in all scenarios with all plant closed by the early 2030s. Replacement of diesel with gas reciprocating engines leads to an increase in distribution connected gas generation in all scenarios. In the net zero scenarios this starts to decline after 2030 to reach zero in the 2040s, while in **Steady Progression** installed capacity increases to over 10 GW by 2030. Gas CHP capacity also declines in the net zero scenarios; as the carbon intensity of electricity generation continues to fall, the value of gas CHPs in reducing carbon emissions reduces. These plants are replaced by a mixture of bio-fuelled CHP, hydrogen CHP and electrically sourced heat.

Coal generation has been declining rapidly and the past year has seen records broken repeatedly for the longest period without any coal-fired generation. All coal plants are assumed to close by 2025, in line with the Government's commitment to phasing out unabated coal generation. Additional short-term uncertainty around the Capacity Market could lead to even earlier closures. In the net zero scenarios the last coal plant closes after the winter of 2023/24, while in **Steady Progression** this occurs a year later.

FES 2020 / System View / Electricity supply 157

Fossil fuel generation

Figure SV.31: Total natural gas-fired generation capacity including gas CCUS



Annotations on

FES 2020 / System View / Electricity supply 158

Targeted Charging Review

Targeted Charging Review

The Targeted Charging Review (TCR) examined the 'residual charges' which recover the fixed costs of providing pylons and cables, and the differences in charges faced by smaller distributed generators and larger generators to remove market distortions. Ofgem concluded that residual charges should be levied as fixed charges for all households and businesses rather than charged on usage at times of peak demand.

FES 2020 / System View / Electricity supply 159

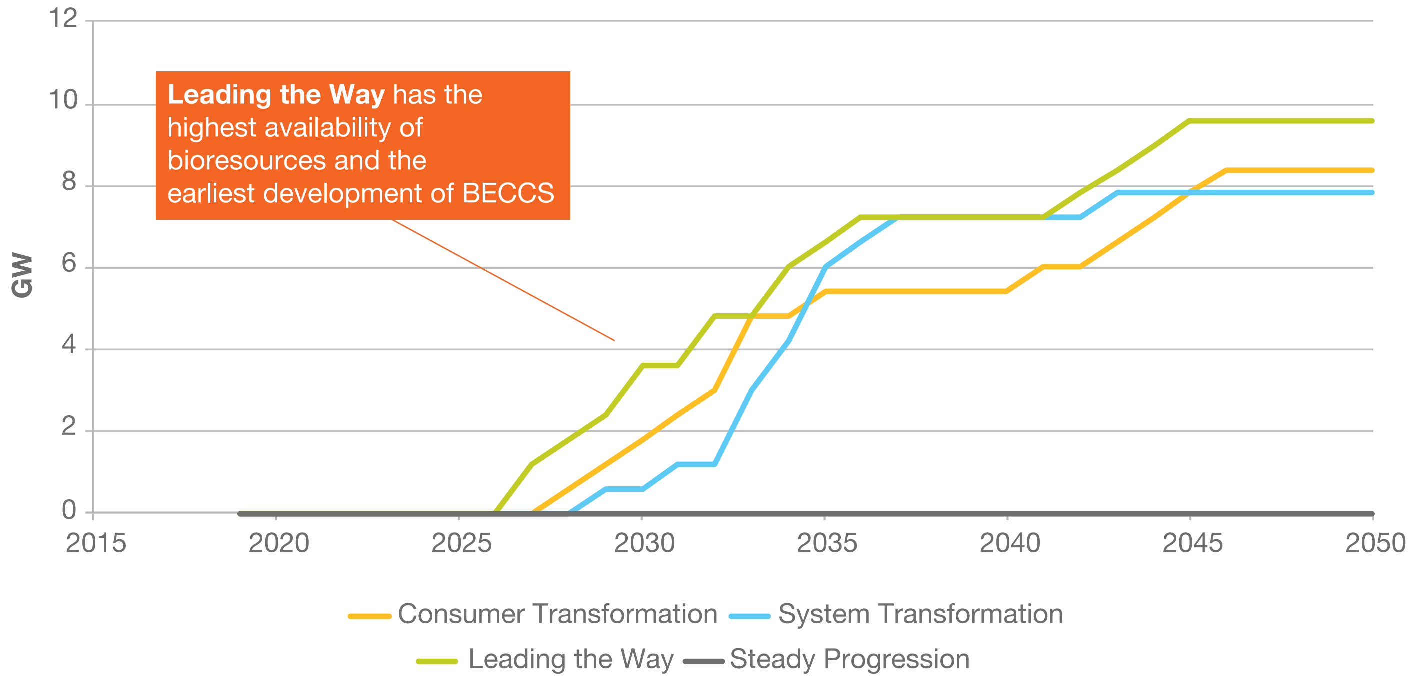
Bioenergy and bioenergy with carbon capture and storage (BECCS)

Biomass generation has increased in recent years, with the conversion of older coal plants to burn biomass instead. This is classed as carbon neutral, so adding carbon capture and storage allows the plant to reach negative emissions as discussed in the bioenergy section *(See page 102)*. We assume these plants will operate mostly as baseload generation to maximise the negative emissions from BECCS driven by high carbon pricing.

In July 2019, the government published a consultation on future CCUS business models in different sectors[3] as part of their CCUS Action Plan to enable the UK's first CCUS facility to be commissioned from the mid-2020s. Our net zero scenarios then see CCUS deployed at scale from the late 2020s.

The net zero scenarios develop BECCS projects by the late 2020s and see a rapid increase in capacity in the 2030s. In all scenarios there continues to be some biomass without CCUS but this is minimal in the net zero scenarios as bioresources are prioritised for the sectors that are hardest to decarbonise or for negative emissions.

Figure SV.32: BECCS electricity generation capacity



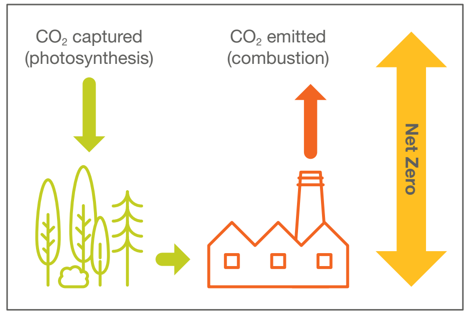
3 https://www.gov.uk/government/consultations/carbon-capture-usage-and-storage-ccus-business-models

FES 2020 / System View / Electricity supply 160

BECCS

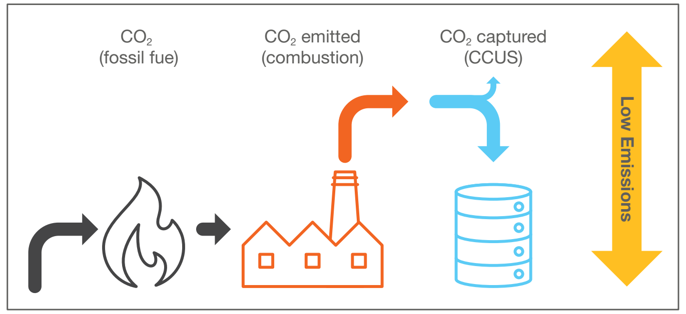
How does BECCS deliver negative emissions?

Coupling bioenergy with carbon capture and storage to capture the CO_2 produced on combustion means that the process, known as BECCS, delivers negative emissions. So how does this work?



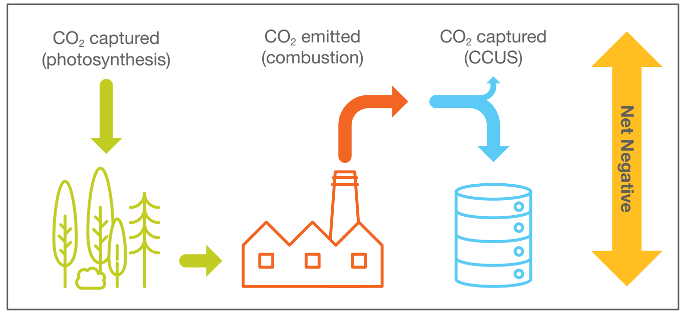
Switching fossil fuels for bioenergy

Trees naturally pull CO_2 out of the atmosphere (absorbing it during photosynthesis). This results in carbon being stored in forests, vegetation and in the soil. While the burning of fossil fuels releases carbon that has been ‘trapped’ underground for many millions of years; when we burn sustainably sourced wood or other bioenergy crops, the CO_2 they emit can be offset by the CO_2 they have absorbed over their life, resulting in net zero emissions.



Using Carbon Capture and Storage

Technology can capture CO_2 from fossil fuel combustion before it is released into the atmosphere but there is a certain level of CO_2 leakage. Capture rates are expected to range between 95 and 97 per cent across the FES 2020 scenarios. So this approach results in low, but not zero, emissions.



Combining the two for negative emissions

If we then combine CCUS with bioenergy, to trap and store recently absorbed CO_2, this will result in negative emissions. For example, generating electricity by burning organic matter (biomass) rather than coal or gas, with the resultant CO_2 emissions being captured will result in negative emissions. This process is known as BECCS (bioenergy with carbon capture and storage).

FES 2020 / System View / Electricity supply 161

Nuclear

We see a reduction of nuclear capacity in the 2020s in all four scenarios as stations reach the end of their life and only one new station comes online by 2030.

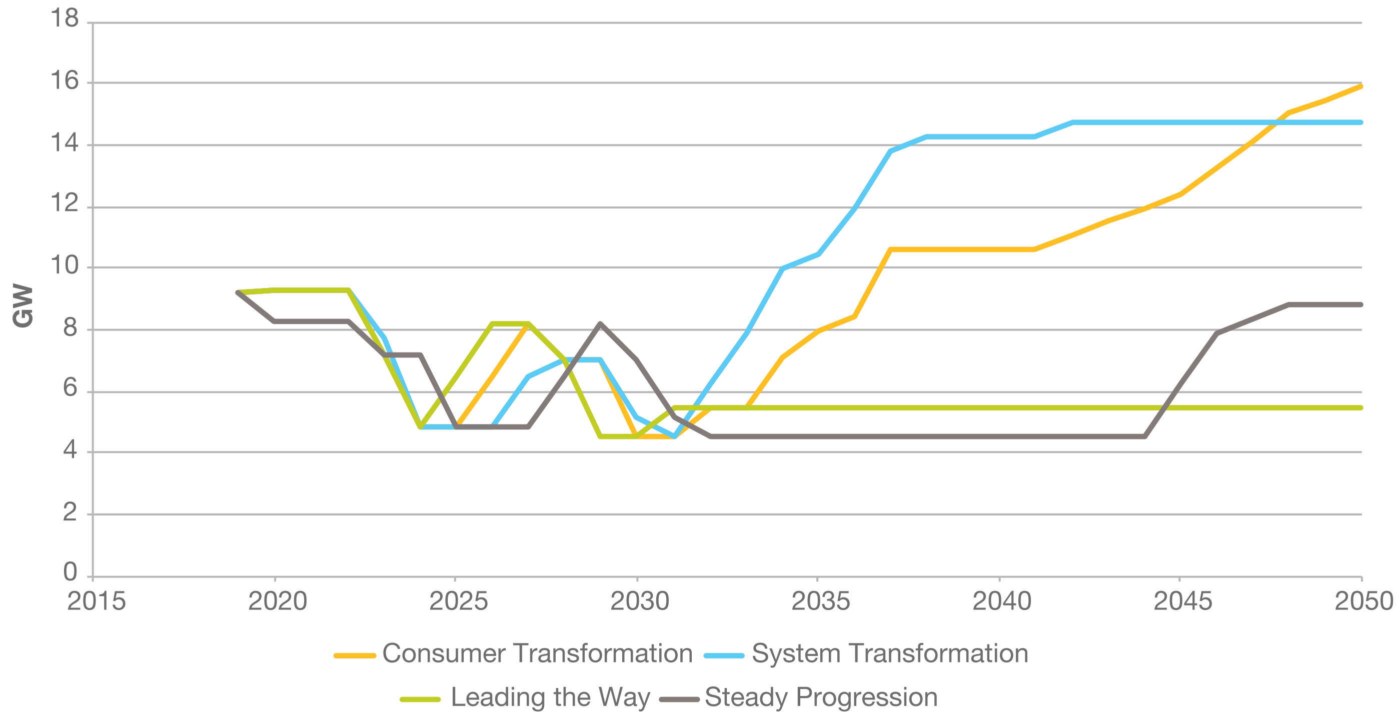
New nuclear capacity is delivered from the early 2030s to meet energy demands in **Consumer Transformation** and **System Transformation**.

Today's nuclear power sector mostly consists of reactors due to reach end of life in the 2020s. This leads to a reduction in nuclear capacity, with Hinkley Point C the only new project coming online by 2030 in all scenarios.

In **System Transformation** the ambition to decarbonise with more centralised technologies leads to a focus on large-scale nuclear generation, while in **Consumer Transformation**, despite the focus on decentralised generation, we still see nuclear as transmission connected, but with greater uptake of small modular reactors.

Steady Progression and **Leading the Way** have low levels of nuclear capacity. In **Leading the Way** there is a mix of technologies to decarbonise, including development of small modular reactors in 2031. Despite this, rapid deployment of renewable and BECCS generation, combined with lower electricity demands than the other net zero scenarios, reduces the need for new nuclear. In **Steady Progression** there is some ambition to develop new nuclear projects; however the first new project after 2030 doesn't come online until the 2040s.

Figure SV.33: Installed nuclear capacity



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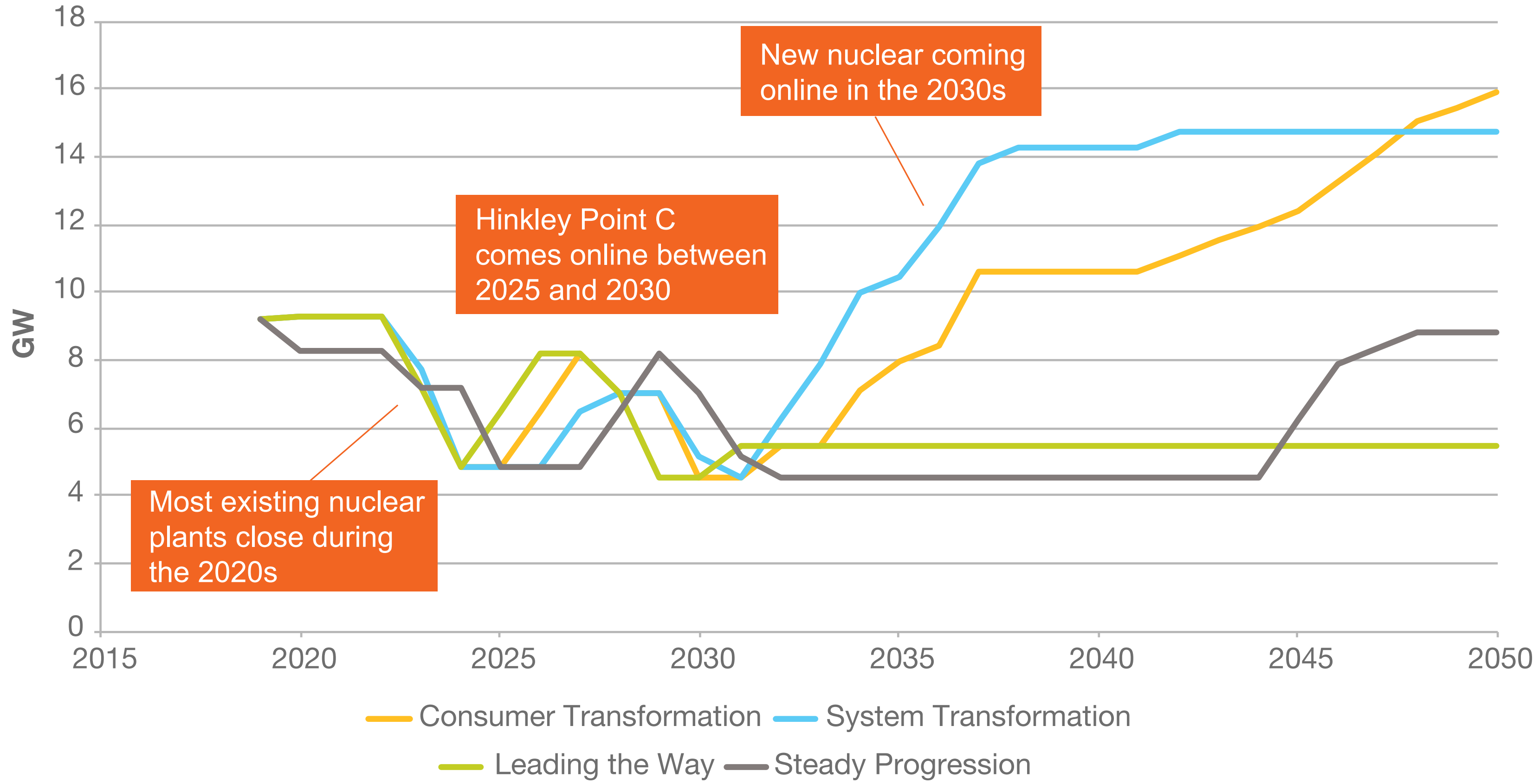
FES 2020 / System View / Electricity supply 162

Figure SV.33: Installed nuclear capacity



Annotations on

FES 2020 / System View / Electricity supply 163

Small modular reactors

Small modular reactors

Small modular reactors offer an alternative approach to nuclear power generation. These are modelled as smaller in capacity than traditional nuclear plant, around 500MW, compared to 1-3 GW for existing plants. They could be delivered by a range of designs, though none is yet operational. Multiple units are assumed to be located together on existing sites of nuclear generation and connected to the transmission system.

FES 2020 / System View / Electricity supply 164

Hydrogen generation

Hydrogen generation will play an important role on the electricity system in the net zero scenarios.

While it is unlikely to be a major contributor to total annual electricity production, its role as a source of zero carbon flexibility and peaking plant will be particularly important in the net zero scenarios. Our scenarios consider hydrogen combined cycle turbines to be a more economic option for this role than gas with CCUS. The up-front capital cost of gas CCGTs with CCUS is higher than that of a hydrogen CCGT, while a high carbon price combined with residual carbon emissions after CCUS makes gas very expensive to run even for limited hours.

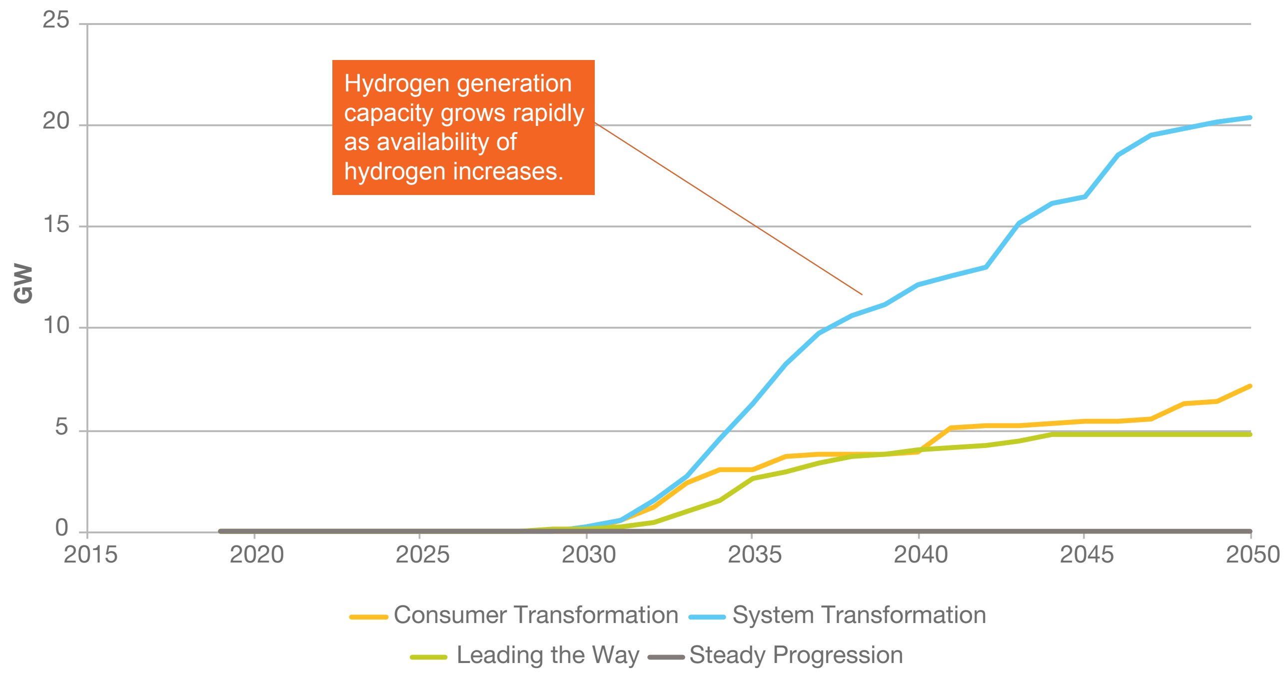
In **Steady Progression**, continued use of gas, and lower availability of hydrogen means no take-up of hydrogen generation. In the net zero scenarios we see hydrogen introduced from the early 2030s primarily as peaking plant to provide flexibility in an electricity supply sector dominated by renewable generation. The overall efficiency of converting electricity to hydrogen with electrolysis and then converting it back to electricity will be low.

Therefore, it does not make a significant contribution to annual demand in any scenario. However, its flexibility, even from small annual volumes, can be very valuable.

In **System Transformation** the transmission and distribution gas networks are converted to deliver hydrogen which makes hydrogen generation an attractive option. It has up to four times the level of hydrogen generation than the other net zero scenarios, so less flexibility is provided by storage and interconnectors. In this scenario distribution-connected gas reciprocating engines are replaced with hydrogen engines as their local gas networks are converted to deliver hydrogen, while some gas CHP is converted to hydrogen CHP.

Leading the Way and **Consumer Transformation** have lower volumes of hydrogen, but have high flexibility needs, so hydrogen generation as peaking plant is still an attractive option. We assume hydrogen plants could be connected to the transmission or distribution networks and expect the highest growth in locations where gas networks convert to hydrogen. In **Consumer Transformation** this is only in limited, favourable locations for connecting to hydrogen production and storage.

Figure SV.34: Installed hydrogen generation capacity



FES 2020 / System View / Electricity supply 165

Electricity interconnector capacity

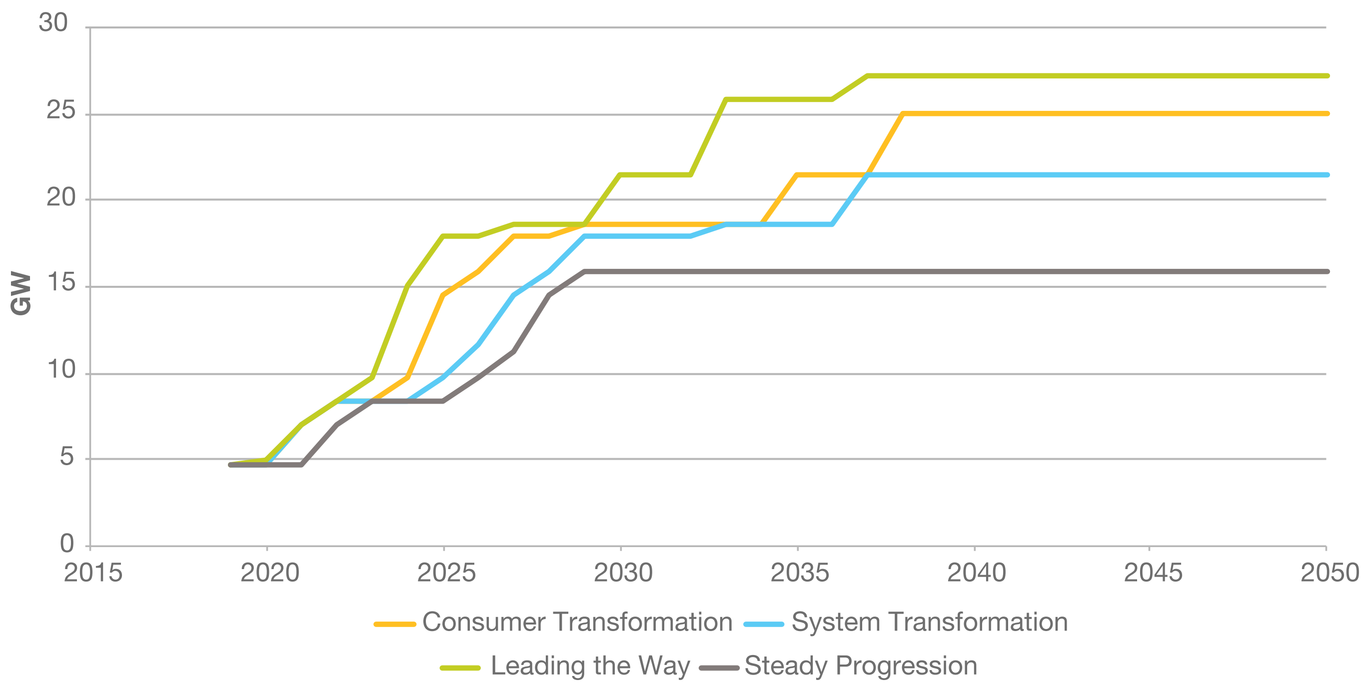
The outlook for interconnector capacity growth remains strong, with Capacity Market agreements providing greater short-term certainty of new projects connecting over the next few years.

Interconnector capacity grows in all scenarios, driven by a strong pipeline of projects and regulatory approval through the cap and floor regime, with all scenarios seeing increases through the 2020s. This includes new connections to countries including France, Denmark, Ireland, Norway, Belgium and the Netherlands.

Figure SV.35 shows how interconnector capacities are higher in the scenarios with greater levels of societal change, as high levels of intermittent generation favour more flexible sources such as interconnection. Interconnectors play an increasingly important role providing flexibility in the net zero scenarios; this is discussed in more detail in the flexibility section *(See page 169)*.

Our scenarios assume continued cooperation on trade of electricity after the UK's exit from the European Union. We assume that a negotiated deal closely replicates current arrangements for capacity allocation and use of the interconnectors. We assume that the GB carbon price, which is currently a combination of the EU Emissions Trading Scheme (ETS) and the GB Carbon Price Support (CPS), continues on a similar trajectory to the EU ETS.

Figure SV.35: Installed interconnector capacity



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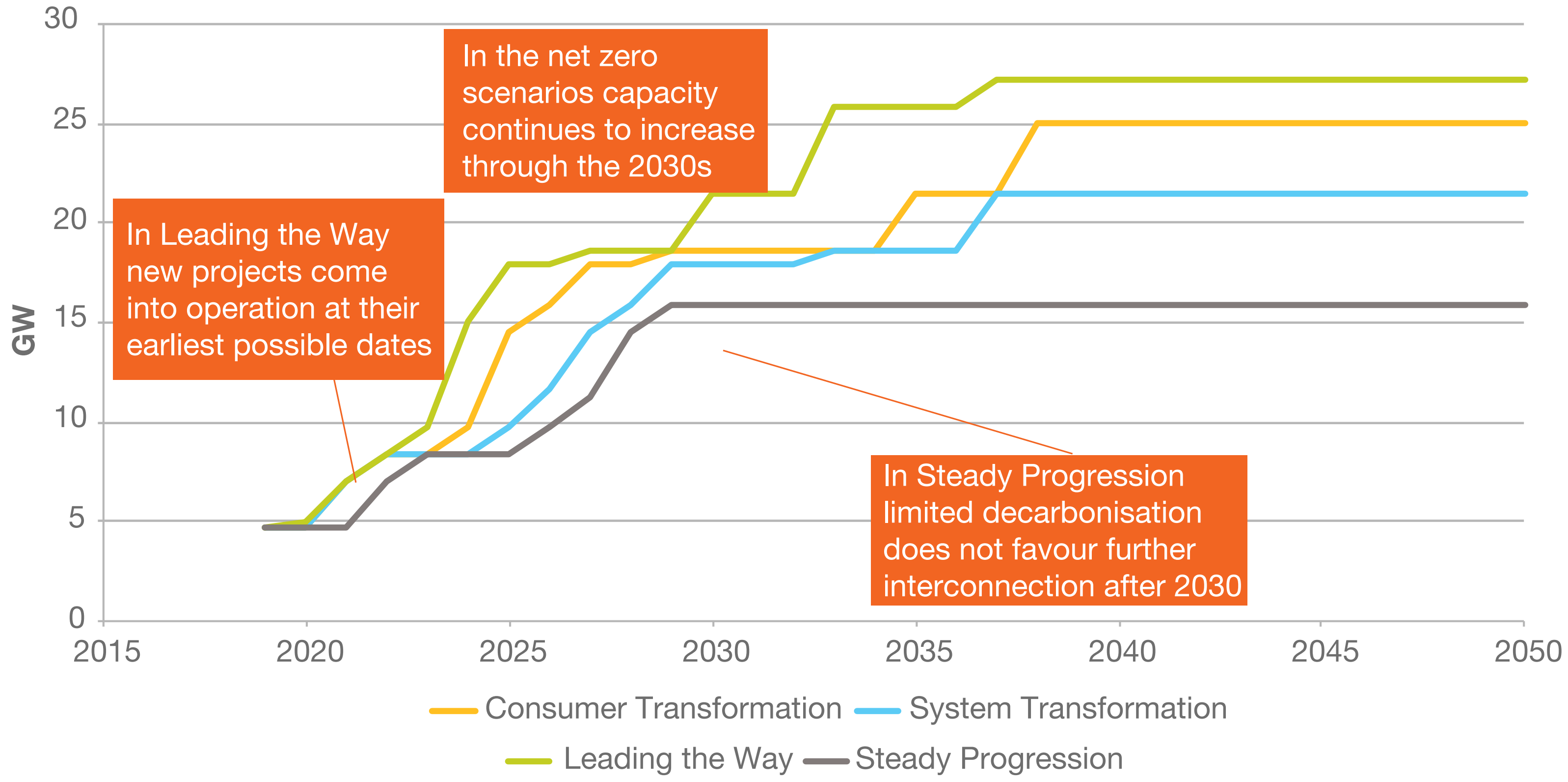
FES 2020 / System View / Electricity supply 166

Figure SV.35: Installed interconnector capacity



Annotations on

FES 2020 / System View / Electricity supply 167

Electricity Storage

The electricity storage sector is changing rapidly, with further growth seen over the last year.

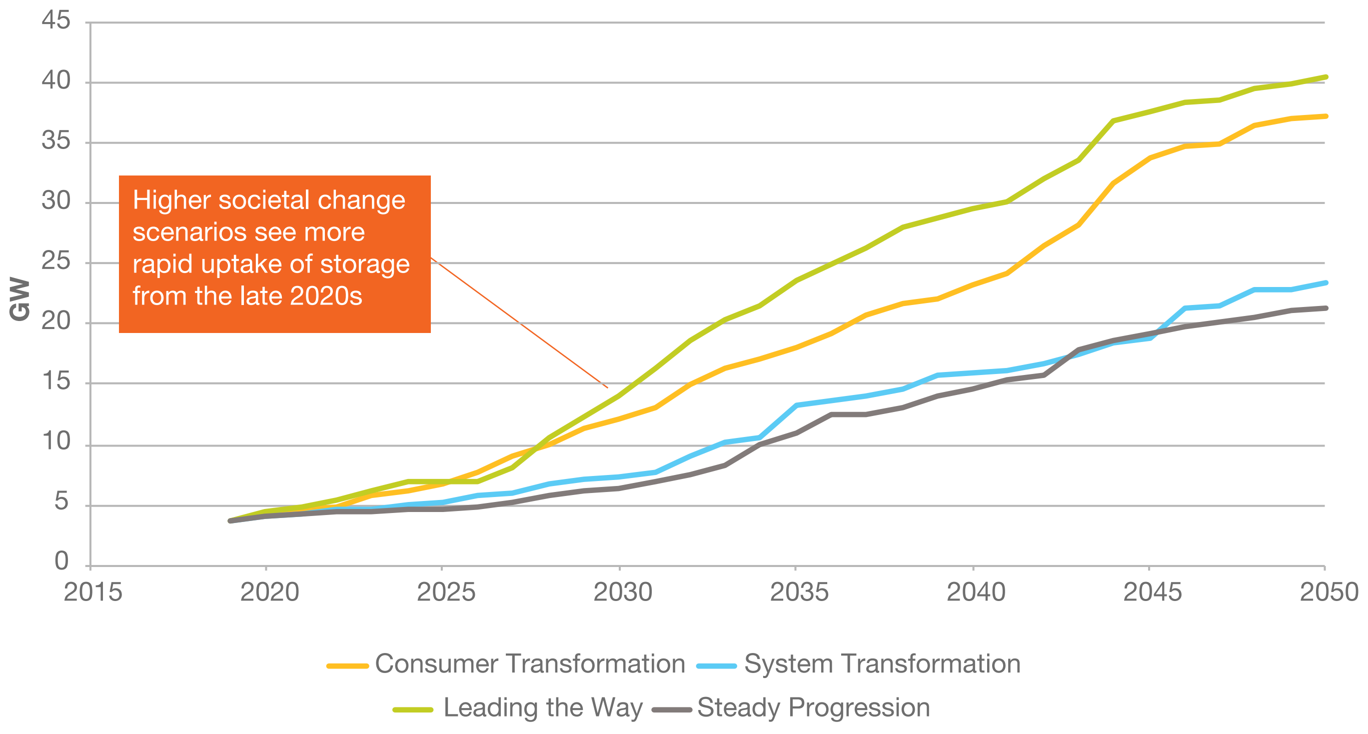
This section considers total electricity storage capacity from technologies including batteries, liquid and compressed air and pumped hydro. We do not examine the operation of EV batteries and non-electrical storage such as hydrogen and heat here, these are discussed in more detail in the flexibility section *(See page 169)*.

Growth of storage over the last year has slowed; however there is still a strong pipeline of new projects. The past year has seen 164 MW of new storage capacity, predominantly battery storage, with most connected to the distribution network. Electricity storage is often co-located with wind or solar generation, supporting the business case with a range of revenue streams, including price arbitrage, the balancing market and providing services to the grid.

Electricity storage increases in all scenarios as costs fall and renewable generation increases. Larger, longer duration storage will be needed to support decarbonisation in the net zero scenarios, however **System Transformation** sees less electricity storage than the other net zero scenarios, particularly for long durations, due to high use of hydrogen as a flexible energy source in many areas of the economy.

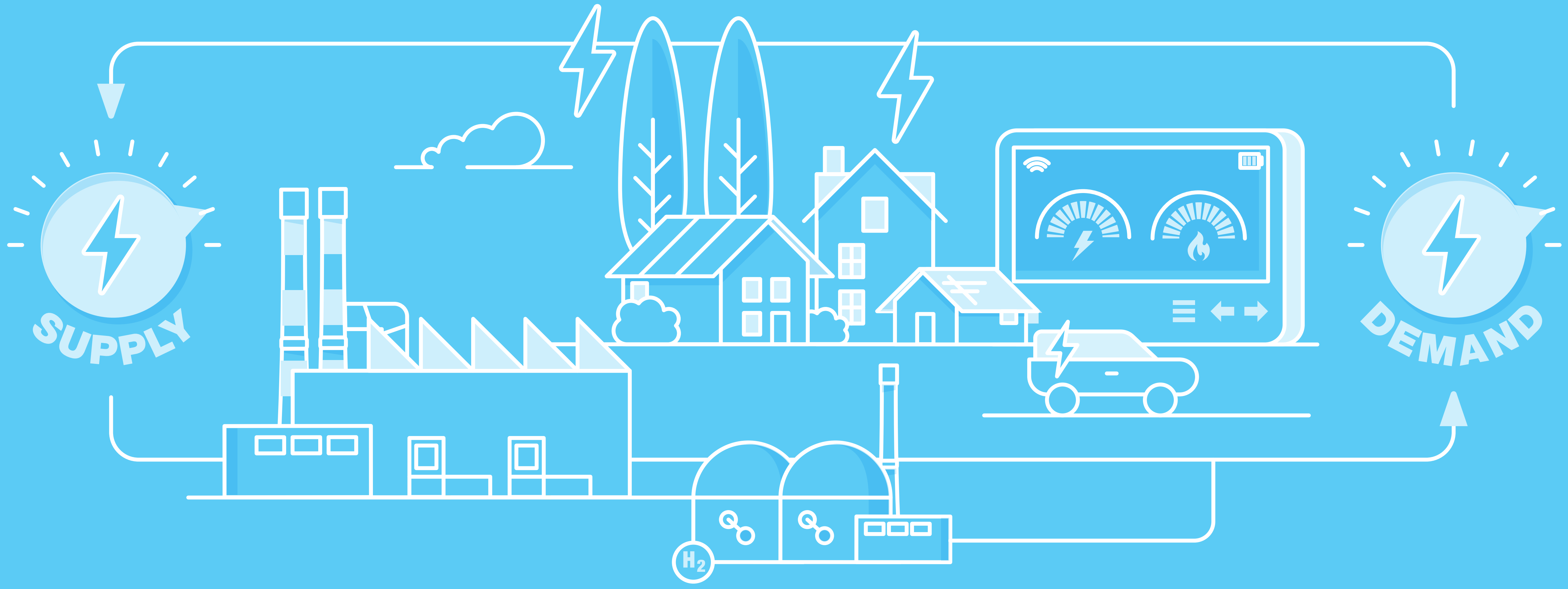
Batteries make up most of the network-connected capacity, however these typically have lower storage volumes, so large-scale technologies such as pumped hydro and compressed air provide more of the total volume of stored energy. Energy storage volumes are discussed in the flexibility section *(See page 169)*.

Figure SV.36: Installed electricity storage capacity[4]



4 Excluding vehicle-to-grid

Energy system flexibility



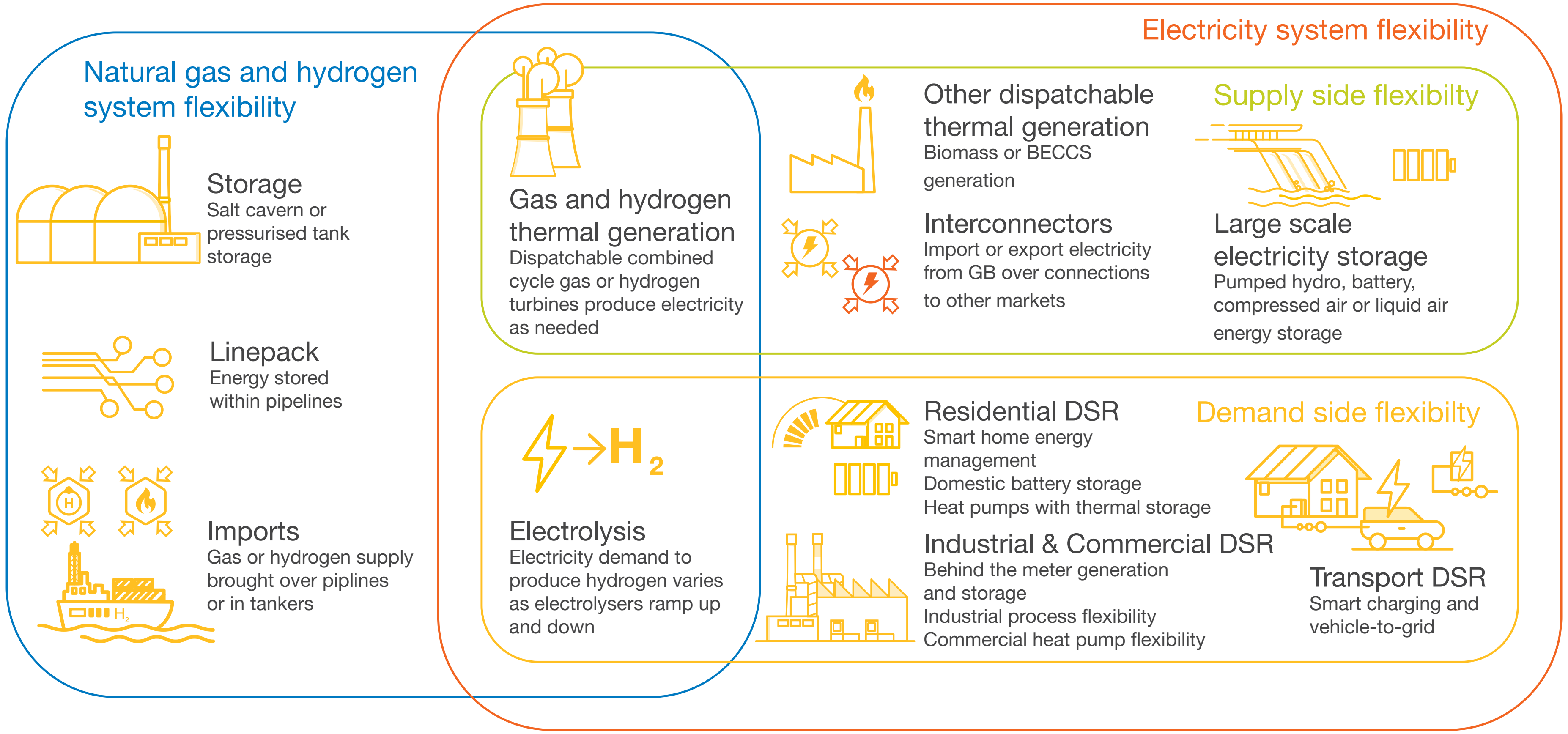
Energy system flexibility

Energy systems need to continuously match supply to demand; we call this energy balancing. Energy system flexibility is the ability to adjust supply and demand to achieve that balance. It also allows us to keep the flows of energy through the networks within safe limits[1].

To meet net zero carbon emissions, system flexibility will become more important in all areas as society reduces reliance on fossil fuels which can be stored and increases reliance on weather-driven energy sources.

This section considers how flexibility will help to deliver for consumers across the whole energy system, and then in more detail for specific elements of the electricity system.

A more detailed overview of energy system flexibility and why it's important can be found here.



1 FES analysis assumes no network constraints. The network impacts of these flows are analysed in other ESO and industry publications.

FES 2020 / System View / Energy system flexibility 170

Whole system flexibility

Key insights

- Hydrogen plays a key role in all net zero scenarios to meet interseasonal demands and provide whole-system flexibility.
- Net zero scenarios all require at least 15 TWh of hydrogen storage by 2050.
- **System Transformation** has the highest level of interaction between the gas and electricity networks of the net zero scenarios, through repurposing the gas network to carry hydrogen.

Whole system flexibility refers to when energy demand and supply need to be managed across fuels, and includes:

- the interactions between natural gas and electricity systems that we see today (through gas-fired generation);
- the delivery of heat to consumers through a combination of electricity, natural gas, and hydrogen;
- the conversion to, and storage of, energy as hydrogen so that it can be used in the future.

Interactions between different networked energy systems become increasingly important as the country moves towards net zero. Natural gas today, and hydrogen in the future, can provide an economical large-scale store of energy to help meet total energy demands and support the electricity system to meet future much higher electricity demands. Further information on gas- and hydrogen-fired generation can be found here *(See page 189)*.

The seasonal nature of heat demand, which is currently met primarily by the gas network, creates further challenges in a net zero world in which no unabated fossil fuel combustion is allowed. While today summer gas and electricity demands are similar, during the heating season hourly gas demands from the gas distribution networks can be over four times greater than national electricity demands. This highlights the importance of the gas network in meeting seasonal heat demand today, and the challenge of meeting net zero by electrifying other sectors.

In the net zero scenarios in 2050 whole-system flexibility is provided primarily through converting energy between hydrogen and electricity, and by storing energy as hydrogen. While conversion efficiency[2] should be considered, this form of flexibility has implications for existing and future infrastructure.

[2]Producing hydrogen through electrolysis offers demand side flexibility and burning it in turbines offers supply side flexibility to the electricity system. If the hydrogen is not used for heat or transport, it can be compressed and stored, in potentially very large volumes, for hours or months. While this allows energy generated in windy weeks to be used in calm weeks, 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.

FES 2020 / System View / Energy system flexibility 171

Whole system flexibility

Reaching net zero will mean phasing out unabated natural gas use and increasing use of hydrogen in our energy system, which creates an opportunity to transition existing natural gas infrastructure such as networks and storage facilities to handle hydrogen. This transition has implications for whole system flexibility:

- Hydrogen has a lower energy density than natural gas, potentially reducing the energy held in linepack storage inherent in the system, and in network-connected storage.
- Hydrogen production may have different profiles to that of natural gas and this may drive a need for increased storage infrastructure. Hydrogen production from methane reformation will be most efficient at constant levels, but this would need to be cost-optimised with storage and demand flexibility in meeting demand.
- Hydrogen production from electrolysis will be influenced by weather patterns, renewable electricity supply, and electricity prices. Renewable generation surpluses can occur throughout the year, while hydrogen demand is higher in winter, creating a need for long-term storage to store this energy for when it is needed.
- Interconnection and imports reduce the need for storage. In **Leading the Way** we expect to have hydrogen imports to GB as other markets also develop significant production of hydrogen. This could be through converted gas interconnectors, new offshore hybrid wind and electrolysis hubs or shipping to converted LNG terminals. The development of an international hydrogen market for import and export is highly uncertain at this stage.

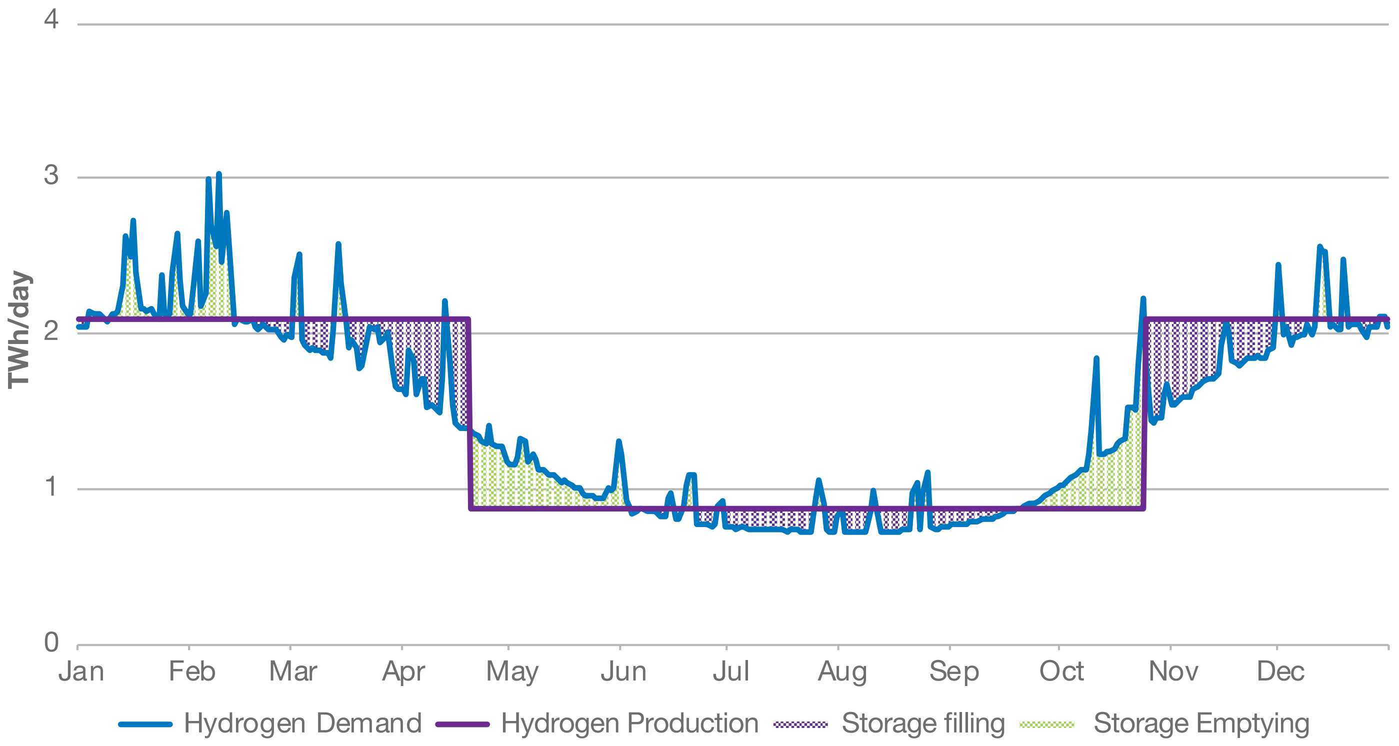
Linepack Storage

This is the 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'.

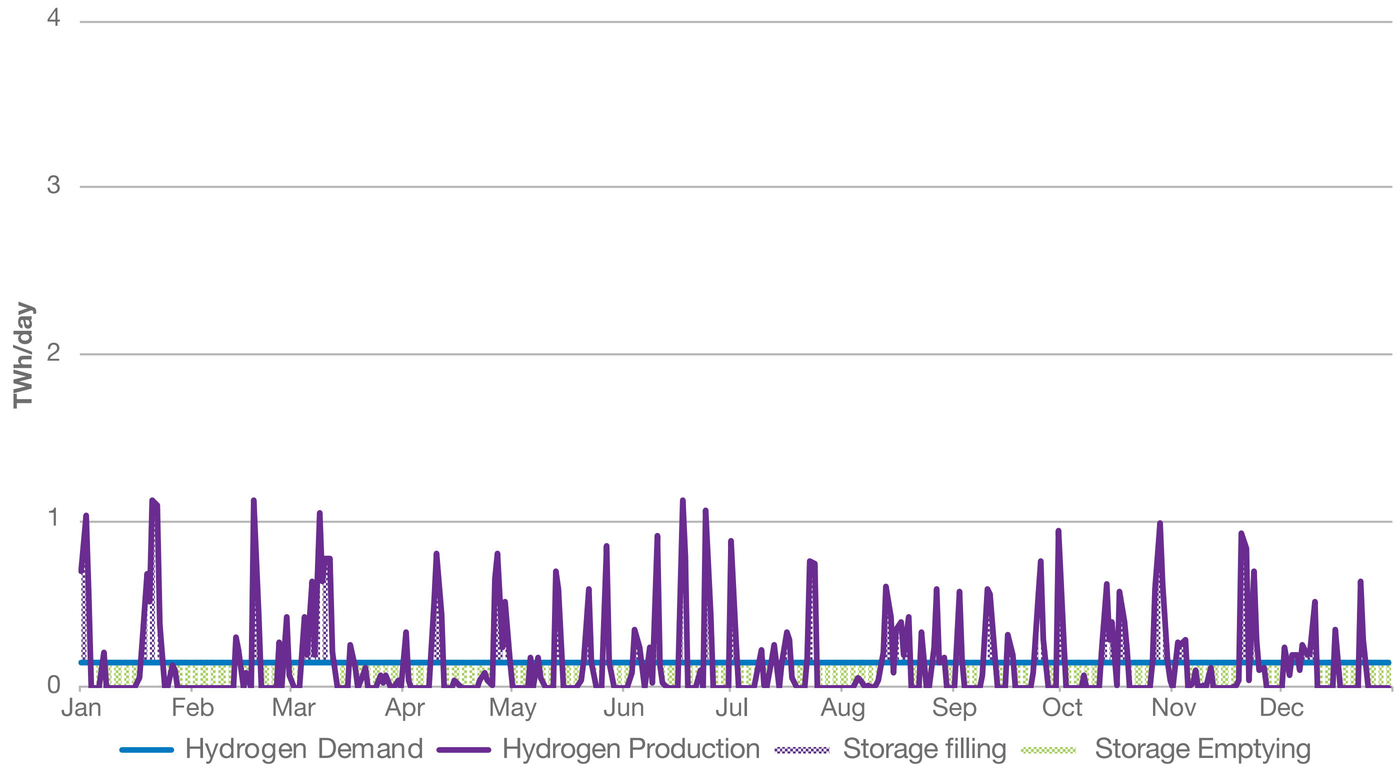
Throughout the gas day, supply and demand are rarely in balance. If demand exceeds supply, levels of linepack in the national transmission system (NTS) will decrease along with system pressures. The opposite is true when supply exceeds demand.

FES 2020 / System View / Energy system flexibility 172

Figure SV.37: Hydrogen daily demand and supply in 2050



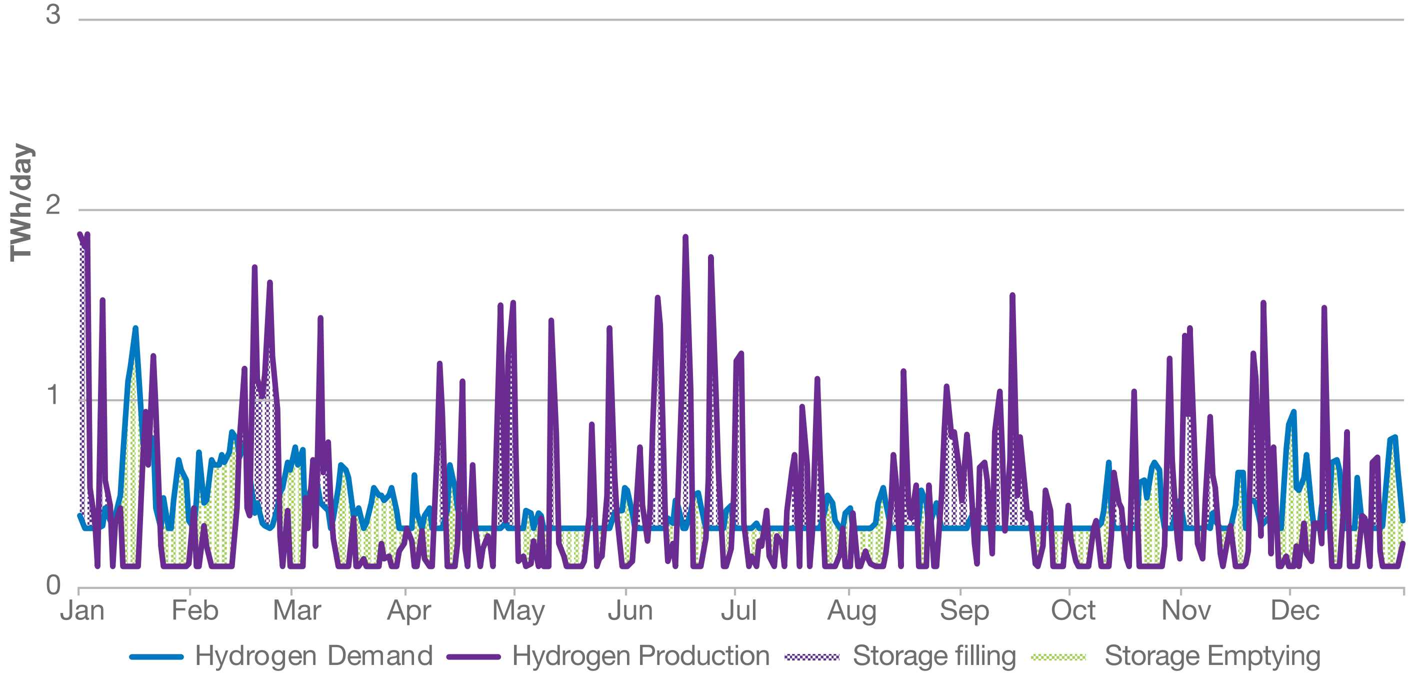
System Transformation - Methane Reforming



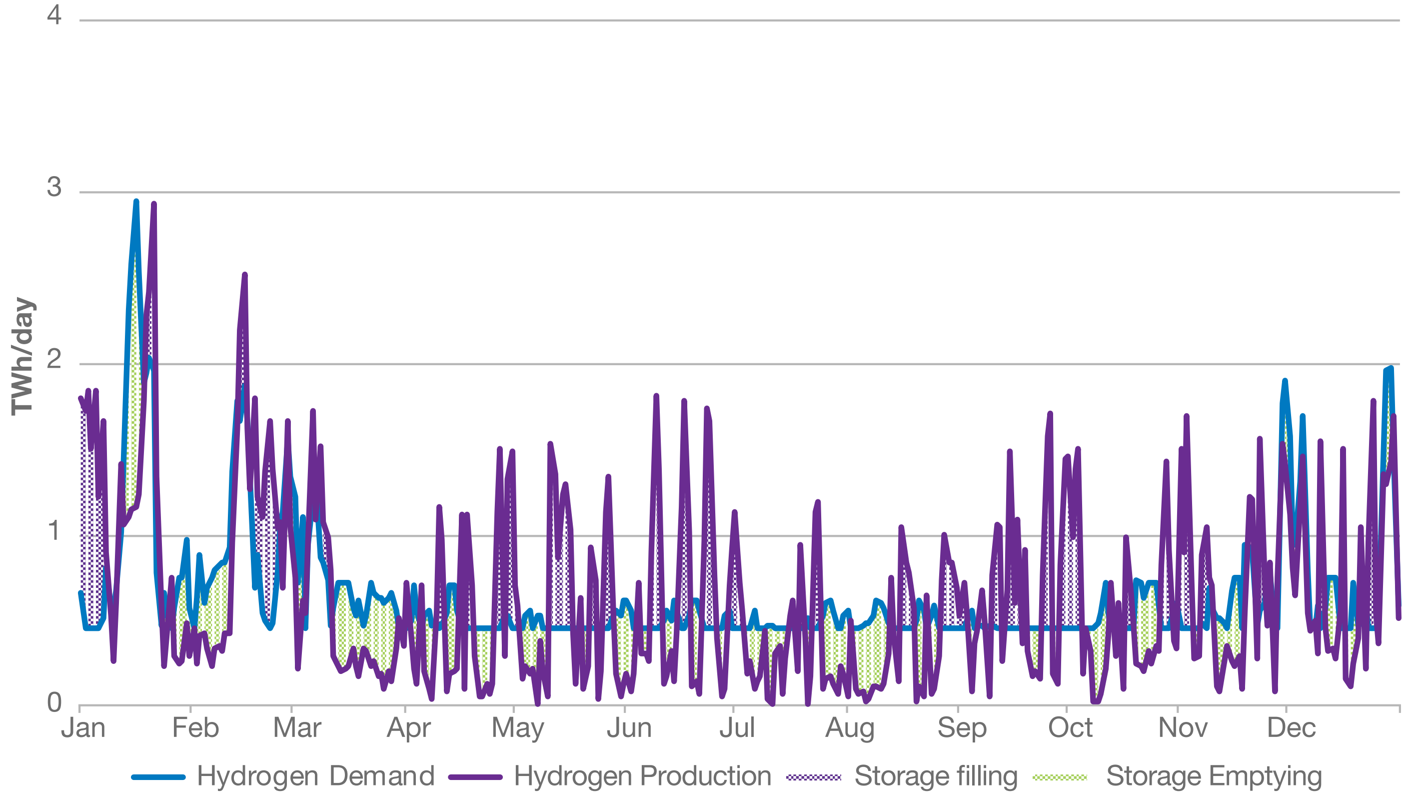
System Transformation - Electrolysis

FES 2020 / System View / Energy system flexibility 173

Figure SV.37: Hydrogen daily demand and supply in 2050



Consumer Transformation



Leading the Way

Whole system flexibility

In **Leading the Way** we see additional hydrogen coming ashore from both dedicated offshore wind sites co-located with electrolysis, and also some hydrogen imports. Offshore electrolysis fluctuates through the year according to wind generation availability, while hydrogen imports mainly during winter can help balance the system and reduce the need for hydrogen storage.

Total hydrogen storage requirements in all three net zero scenarios reach at least 15 TWh. The lower energy density of hydrogen compared to methane means that despite this requirement being similar to energy stored in gas storage today it may require larger storage volumes.

In **System Transformation** separate storage is needed for hydrogen produced from methane reformation and hydrogen from electrolysis. Hydrogen from electrolysis has higher purity and is used solely for transport in this scenario. This is assumed to be stored in pressurised tanks, while the hydrogen produced from methane reformation is stored in salt caverns.

In **Leading the Way** and **Consumer Transformation** long-term hydrogen storage is assumed to be primarily in salt caverns.

Methane reformation production is assumed to operate at full capacity from November through to April and at half capacity from May to October. This allows scheduled maintenance to be carried out in the summer and reduces the requirement for interseasonal storage.

In **System Transformation**, changes in the volume of hydrogen stored are driven by the difference between methane reformation production levels and demand. We see total levels of stored hydrogen fall over the winter before rising in the spring when supply exceeds demand. Hydrogen storage requirement for electrolysis only is low.

In **Consumer Transformation** we see total hydrogen stored fall over the winter to lows in spring, and then slowly climb to a peak in early autumn while supply exceeds demand, before falling again. **Leading the Way** has the lowest total hydrogen storage requirement due to the flexibility provided by hydrogen imports.

Storing hydrogen

One of the advantages of transporting hydrogen through pipelines is that the pipelines themselves provide relatively low cost storage. This will be very 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 does not increase over time, but there may be some limitations on the rate of import/exports due to impacts on the geology. 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.

Hydrogen purity

Sometimes the choice of production method for hydrogen is influenced by the demand it is meeting. For example, we note that hydrogen for use in transport needs to be a much higher level of purity than typically required for heating or some industrial processes. Methane reforming does not currently produce hydrogen at sufficient purity for transport needs. Additional purification steps can be added but these come at additional cost.

FES 2020 / System View / Energy system flexibility 175

Figure SV.38: Hydrogen in storage in 2050

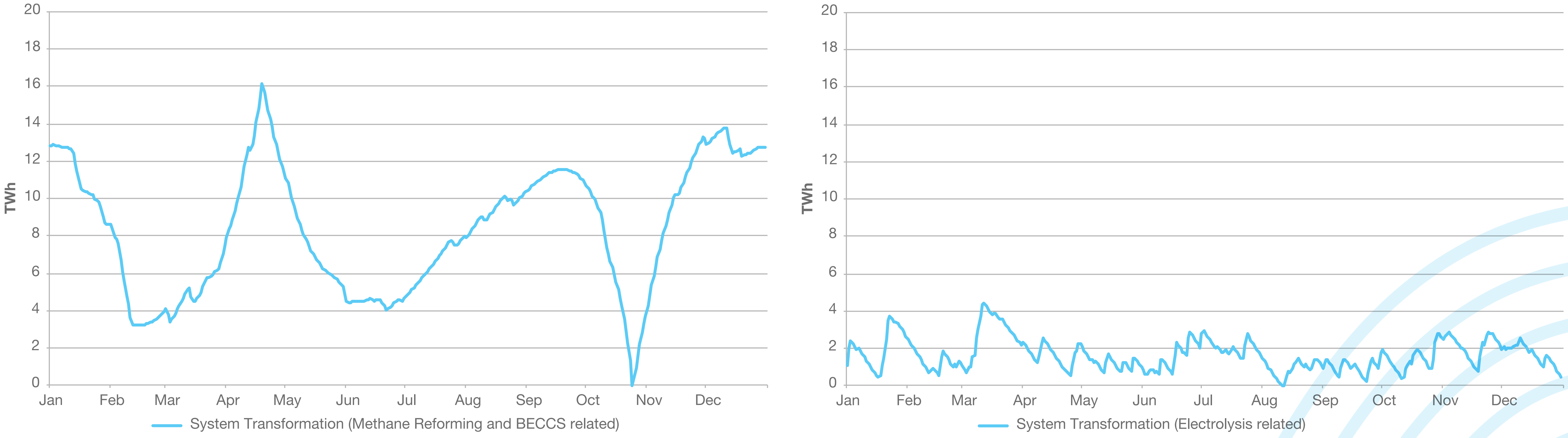


Figure SV.38: Hydrogen in storage in 2050

FES 2020 / System View / Energy system flexibility 177

Electricity system flexibility

Key insights

- Accommodating high levels of renewable generation and electrification requires a significant increase in flexibility over short and medium timescales from minutes to weeks.
- The high societal change scenarios of **Leading the Way** and **Consumer Transformation** have the highest levels of consumer engagement in flexibility with high levels of demand side response, domestic storage and vehicle-to-grid.
- Frequent oversupply of electricity generation will require an increase in flexible demand to avoid generation being curtailed.

Different sources of electricity flexibility can perform different roles in the energy system, and each have different limiting factors.

Demand side flexibility will become increasingly important, particularly in scenarios with higher levels of electrification and societal change (explored in the Consumer View chapter). A wide variety of technologies and markets can help consumers to change how and when they use electricity, and to be incentivised to do so.

Supply side flexibility is predominantly provided by dispatchable thermal generation such as natural gas, biomass, and hydrogen fuelled generators. Generation provides a smaller proportion of total system flexibility in the net zero scenarios as variable renewable generation becomes the dominant source of electricity, while in **Steady Progression** gas-fired generation continues to play a major role in providing flexibility to the system.

Electricity storage can respond to market signals quickly and can be utilised in many different locations, sizes, and use cases. However, it is limited in the duration it can produce its maximum output for by the capacity of energy in the battery or volume of water in the reservoir.

Interconnector flows are subject to market conditions, while demand side response may only be available at certain times. This is discussed in more detail in the following section.

Levels of electricity flexibility increase slowly between now and 2030 in all scenarios, as increases in interconnection, electricity storage and demand side response (DSR) are offset by reduced dispatchable thermal generation capacity. Between 2030 and 2040 as renewable generation dominates, further flexibility is needed to balance a net-negative carbon emission electricity system in the net zero scenarios.

FES 2020 / System View / Energy system flexibility 178

Demand side electricity flexibility

Demand side flexibility can be provided from any of the industrial and commercial, residential, or transport sectors, and each will have different characteristics and abilities to respond.

The impact of any individual action is low; however aggregating large numbers of simultaneous consumer responses can have a significant impact. This needs to be coordinated and this is generally achieved by offering an incentive to individual participants to provide flexibility, or to use a portfolio of DSR technologies and generation to deliver contracted flexibility. Different types of DSR may compete against each other in future. Our scenarios show the range of outcomes for the take-up of different types of DSR; however future cost reductions that impact certain types of DSR more than others may change their market shares.

Growth in technologies like domestic battery storage, electric vehicles and smart home energy management systems will allow residential demand to become more flexible and demand profiles to respond to price signals and align with variable generation patterns. In **System Transformation** there is a lower need for demand side flexibility due to:

- lower levels of electrification;
- non-electrical flexibility offered by the conversion of the gas network to run on hydrogen; and
- higher levels of dispatchable thermal generation.

FES 2020 / System View / Energy system flexibility 179

Demand side electricity flexibility

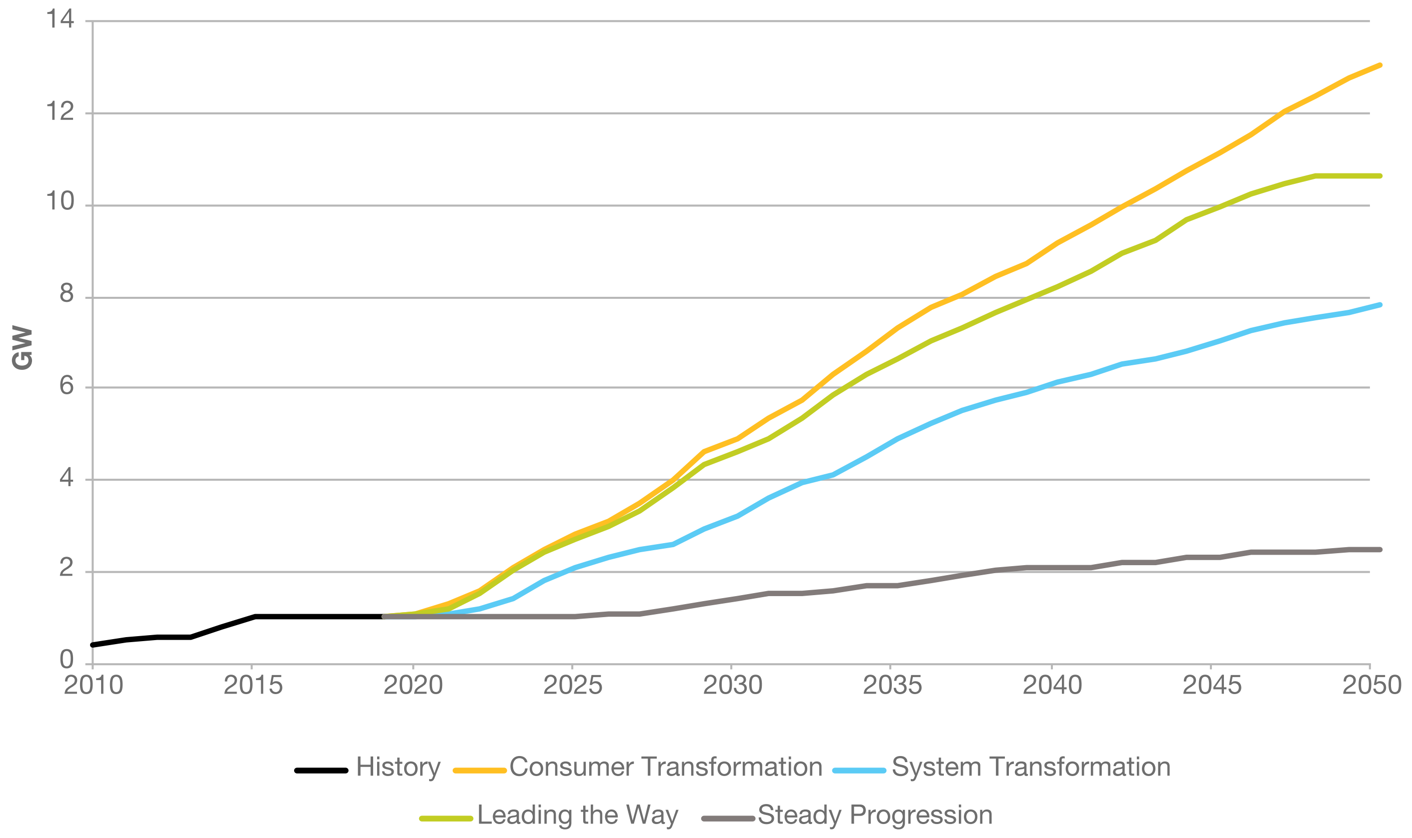
Industrial and Commercial demand side response (DSR)

In FES we define I&C DSR as the turning up or down, or off or on, of electricity consumption in response to external signals. In our scenarios we model end-use demand. If a consumer chooses not to reduce their demand, but instead switches to an alternative energy source such as an onsite diesel generator or batteries, this is captured in other areas of the analysis (for example, distributed generation and storage). To avoid double counting, this is not included in our definition of I&C DSR.

In all scenarios we see DSR potential grow. As the market for flexibility increases it becomes more valuable; with much faster increases in the net zero scenarios as the market develops faster and uptake of smart technology increases. In the scenarios with higher levels of societal change the markets to reward demand side flexibility develop even more quickly, and businesses see greater incentives to vary their demand.

Greater uptake of heat pumps leads to a big increase in total flexibility from I&C sites, with the highest flexibility seen in **Consumer Transformation** which has the highest electrification of heat. DSR from workplace vehicle charging is covered later in the transport flexibility section.

Figure SV.39: Total pure Industrial and Commercial Demand Side Response



FES 2020 / System View / Energy system flexibility 180

Demand side electricity flexibility

Figure SV.39: Demand Side Response from Industrial & Commercial Processes

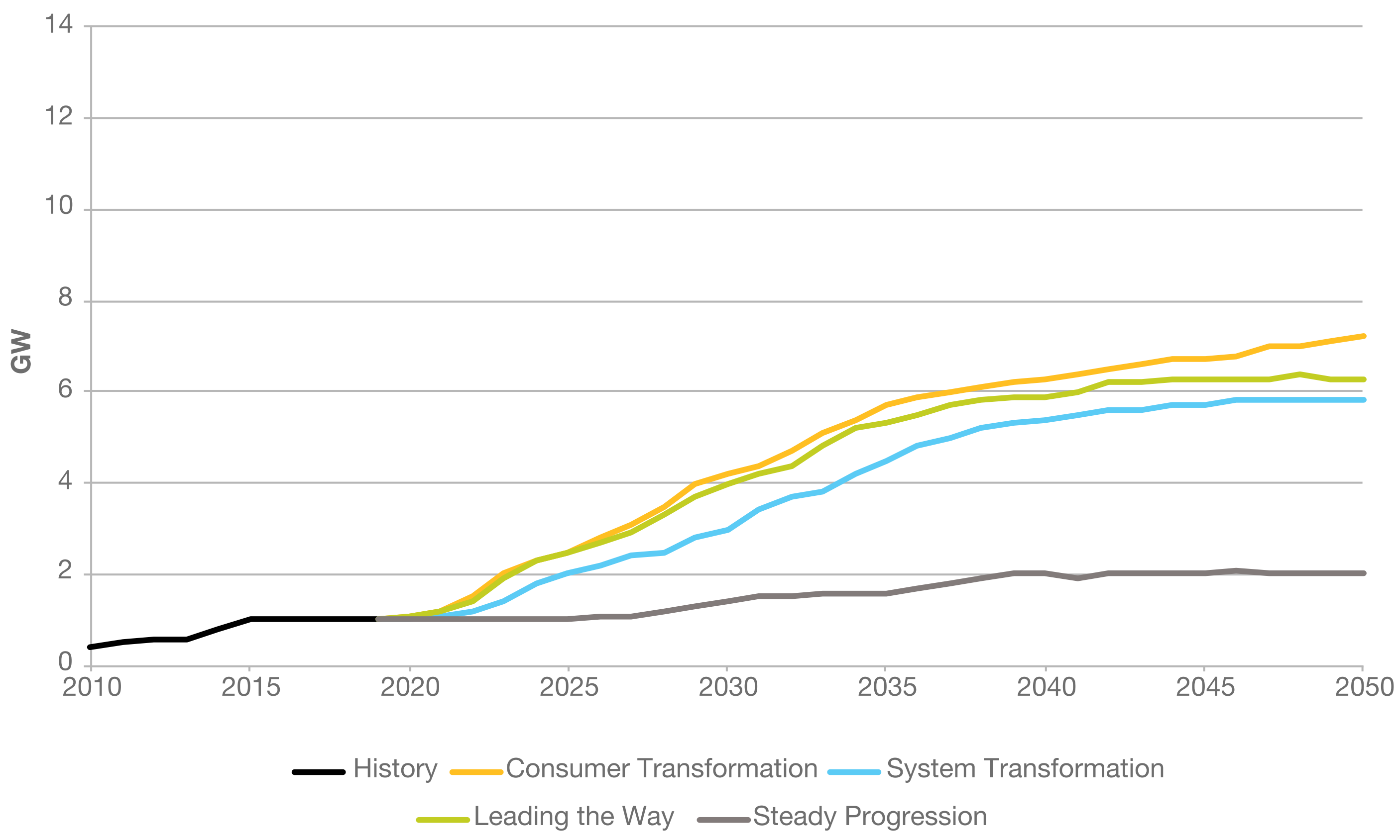
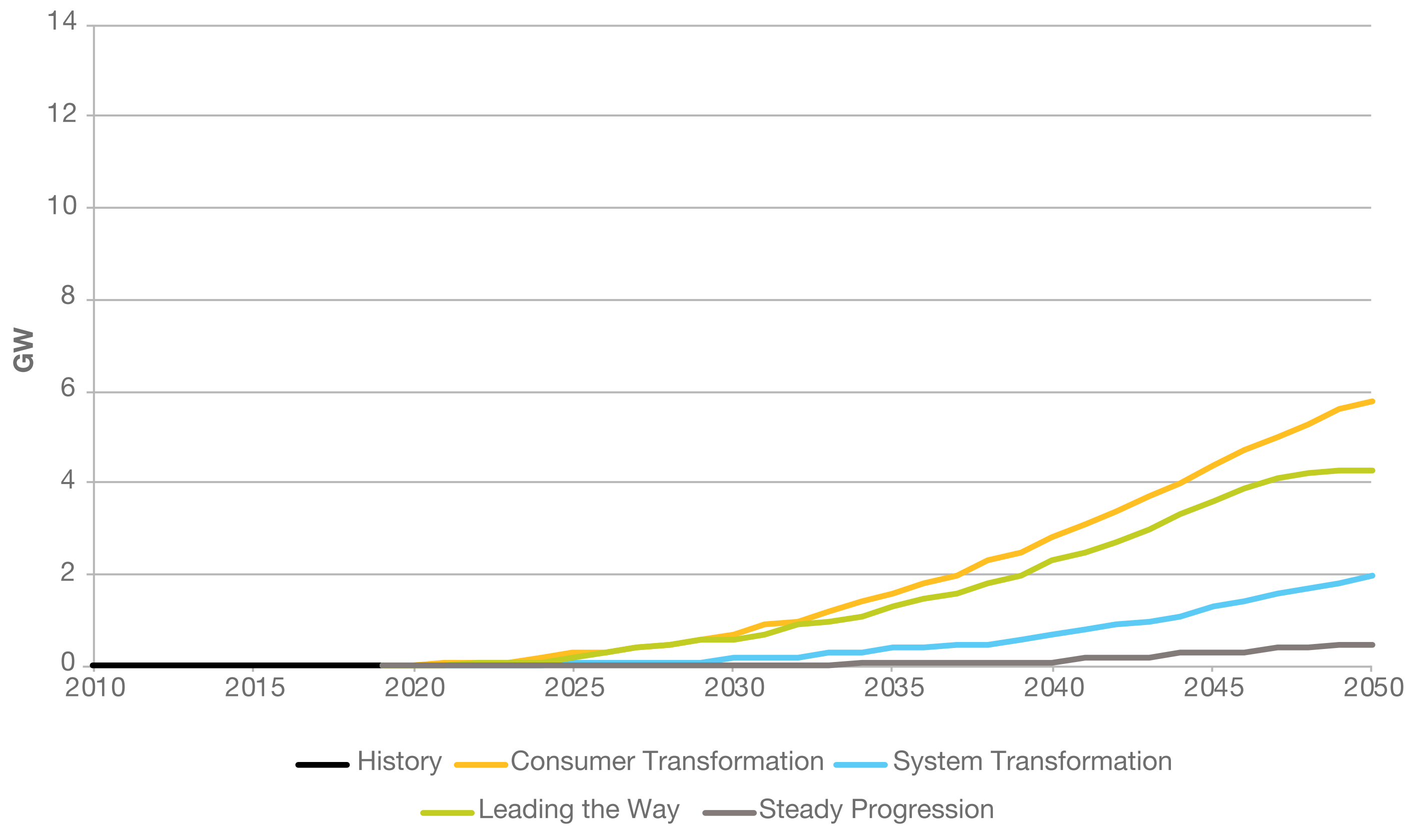


Figure SV.39: DSR from Commercial Heat Pumps



FES 2020 / System View / Energy system flexibility 181

Demand side electricity flexibility

Residential electricity flexibility

Current levels of residential flexibility are low, as consumers have neither the technology nor the incentive to shift their demands aside from in some specific cases such as households with solar panels and battery storage, or who are on an Economy 7 tariff.

However, we expect consumers in the future to shift to electricity tariffs with pricing that can vary through the day, rather than flat rate tariffs, facilitated by the roll-out of smart meters across the UK. We also assume electric vehicle and heat pump ownership will lead to greater adoption of time of use tariffs (TOUTs) and demand side response growth within the residential sector, as these are large energy loads which offer the greatest benefits to consumers who adopt a variable tariff.

Each scenario assumes a different level of lag between the adoption of these technologies and the switch to a time of use tariff, with consumers in **Leading the Way** switching immediately, while those in **Steady Progression** with lower levels of engagement can take up to three years longer. These assumptions lead to a slower adoption of TOUTs than projected in FES 2019's high uptake Community Renewables scenario.

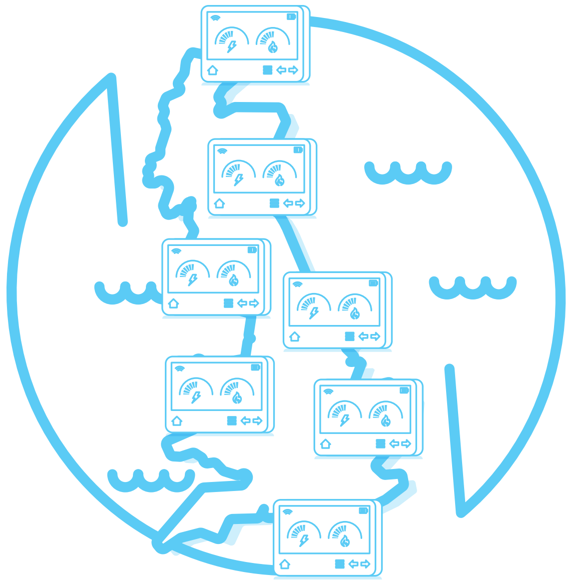
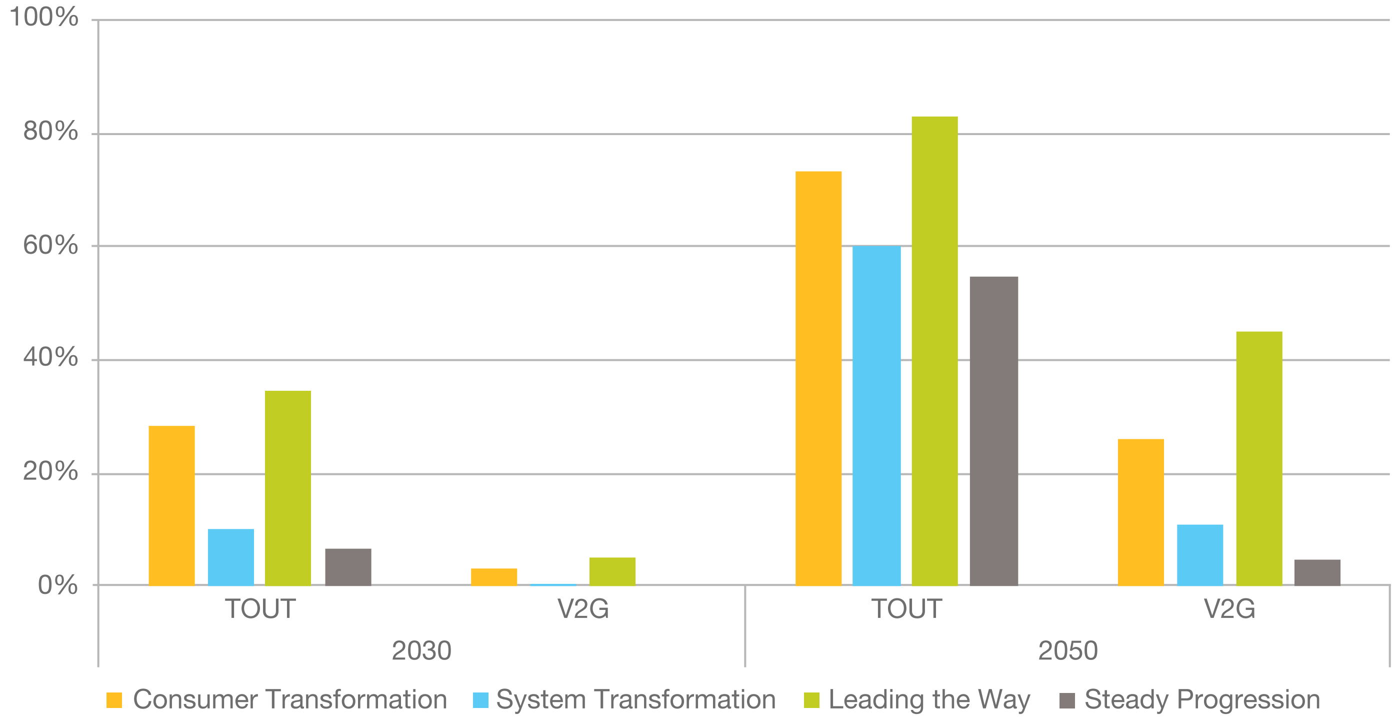


Figure SV.40: Adoption levels of time of use tariffs and vehicle-to-grid (V2G)



Once consumers have TOUTs other forms of flexibility will become more appealing, with increased take-up of smart appliances. Load shifting from appliances is low in the 2020s when this would need to be scheduled manually. However we expect white goods like dishwashers, washing machines and refrigerators which can respond automatically to price signals to add greater demand side response potential as smart appliances become more widely available in the 2030s. Smart appliances could shift up to 11.4% (or 1.5 GW) of peak appliances and lighting electricity demand in **Leading the Way** by 2050. This is equivalent to a third of the installed capacity of hydrogen generation. The impact of electric vehicle smart charging and vehicle-to-grid is discussed later in the transport flexibility section.

FES 2020 / System View / Energy system flexibility 182

Demand side electricity flexibility

Residential thermal flexibility

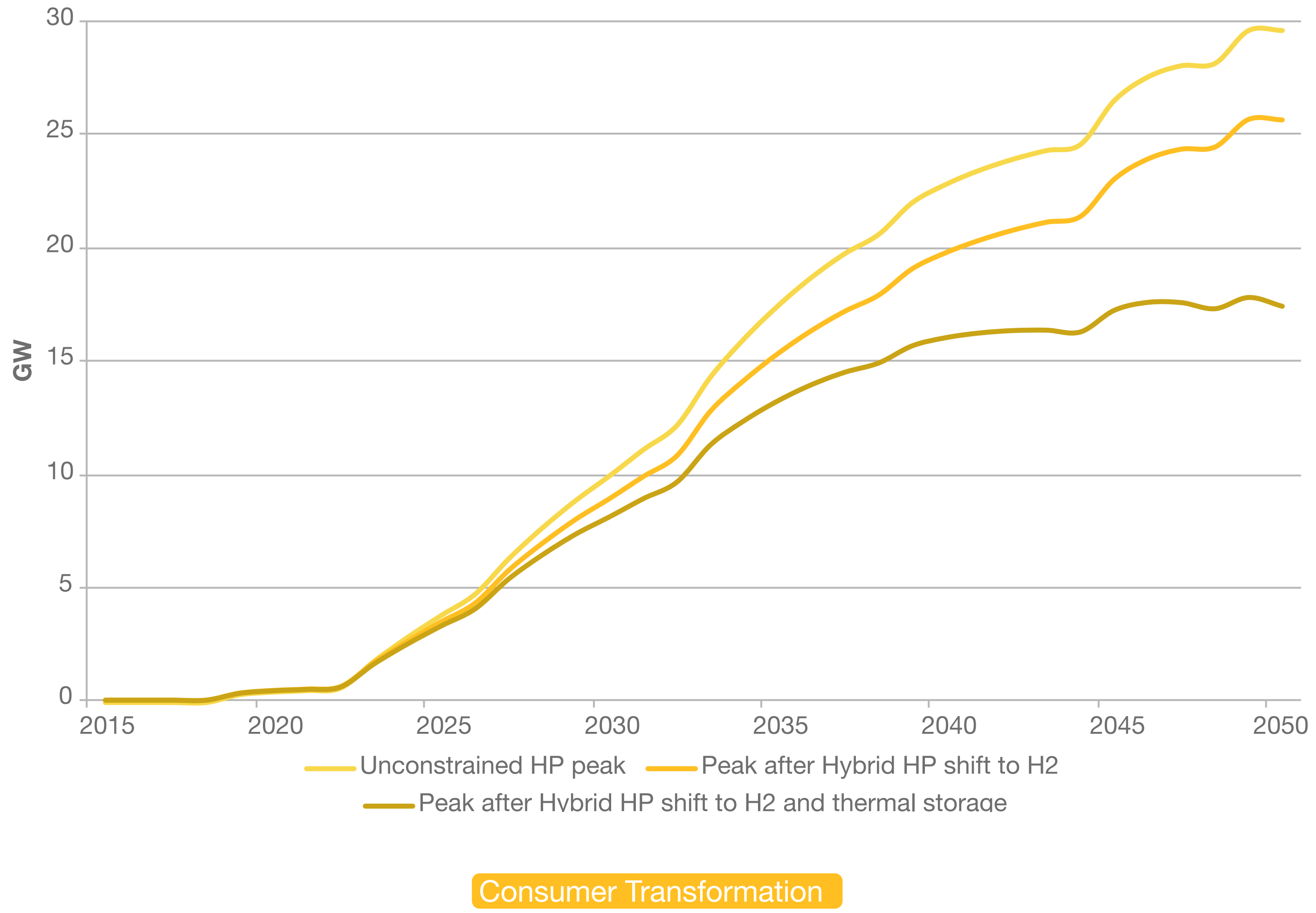
The residential heating technology mix shifts dramatically in all net zero scenarios, leading to significant changes in domestic energy consumption. Winter evenings, when heat demands are likely to be highest, overlap with electricity system demand peaks meaning flexibility becomes more important. Improved levels of domestic insulation in the net zero scenarios help bring down peak and overall demands.

In **Consumer Transformation** and **Leading the Way**, high levels of heat pump adoption increase peak demand, with flexibility playing an important role in managing this. In **System Transformation** the widespread use of hydrogen boilers allows hydrogen storage and the continued use of the gas network to provide thermal flexibility, while **Steady Progression** relies on the continued use of domestic gas boilers and the gas network to meet flexibility demands in this area.

A key assumption in our net zero scenario is the use of thermal storage alongside heat pumps to contribute to space heating at peak times. This can be hot water tanks or new forms of storage such as phase change materials and is sized to meet demand at peak times. Properties with hybrid heat pumps are also assumed to be able to run on hydrogen – **Leading the Way** has high levels of hybrid heat pump boilers, and so also sees reduced peak demands.

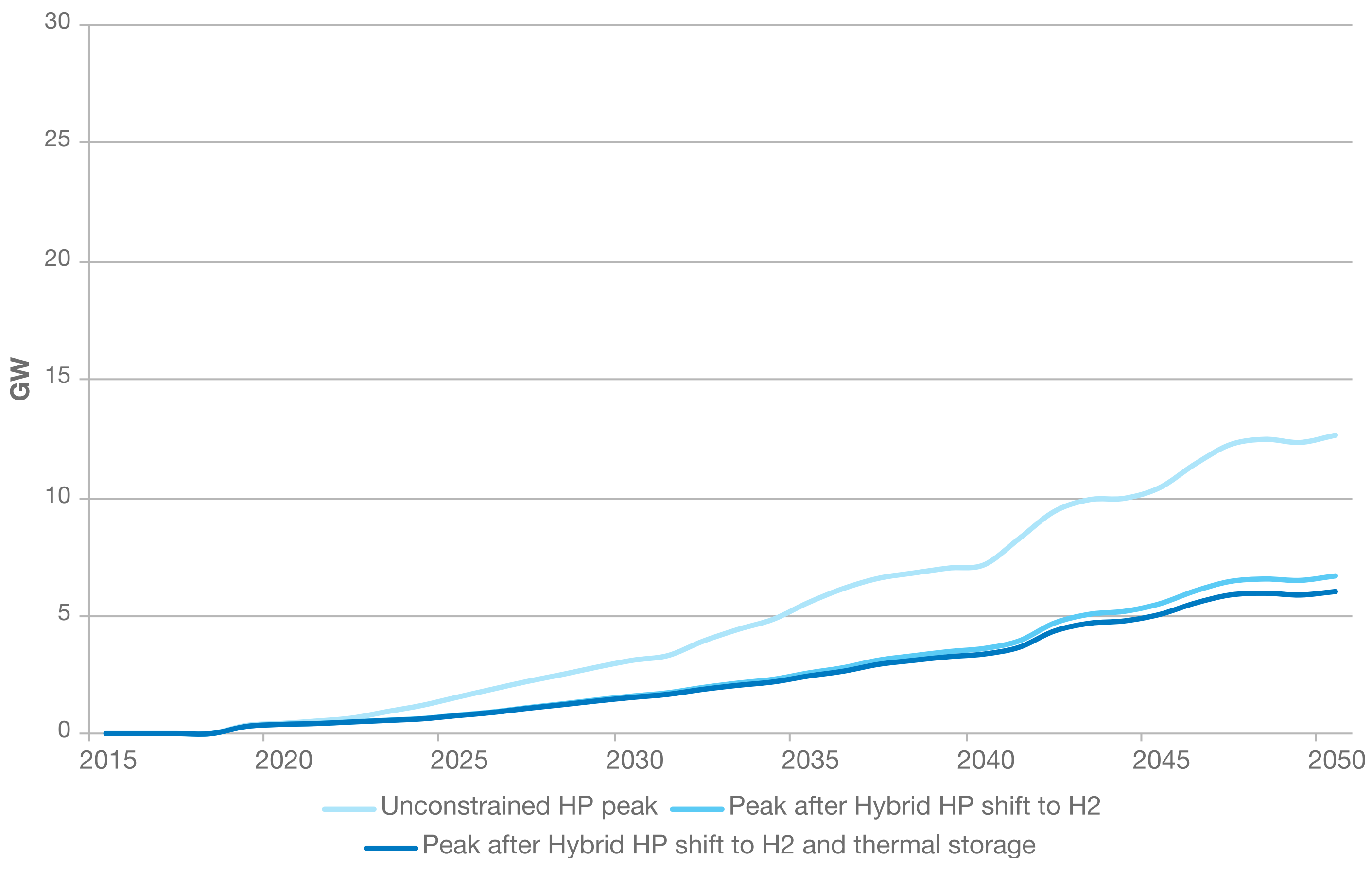
The high societal change scenarios see a growth in residential storage alongside the rise in heat pumps, with 40% of properties with heat pumps also having thermal storage installed by 2050. In the lower societal change scenarios, the market for residential thermal storage does not develop in the same way due to lack of consumer appetite. Thermal storage reduces total heat pump peak demands by up to one third in 2050.

Figure SV.41: Residential winter peak electricity demand for heating and flexibility from heat pumps and hybrid heat pumps

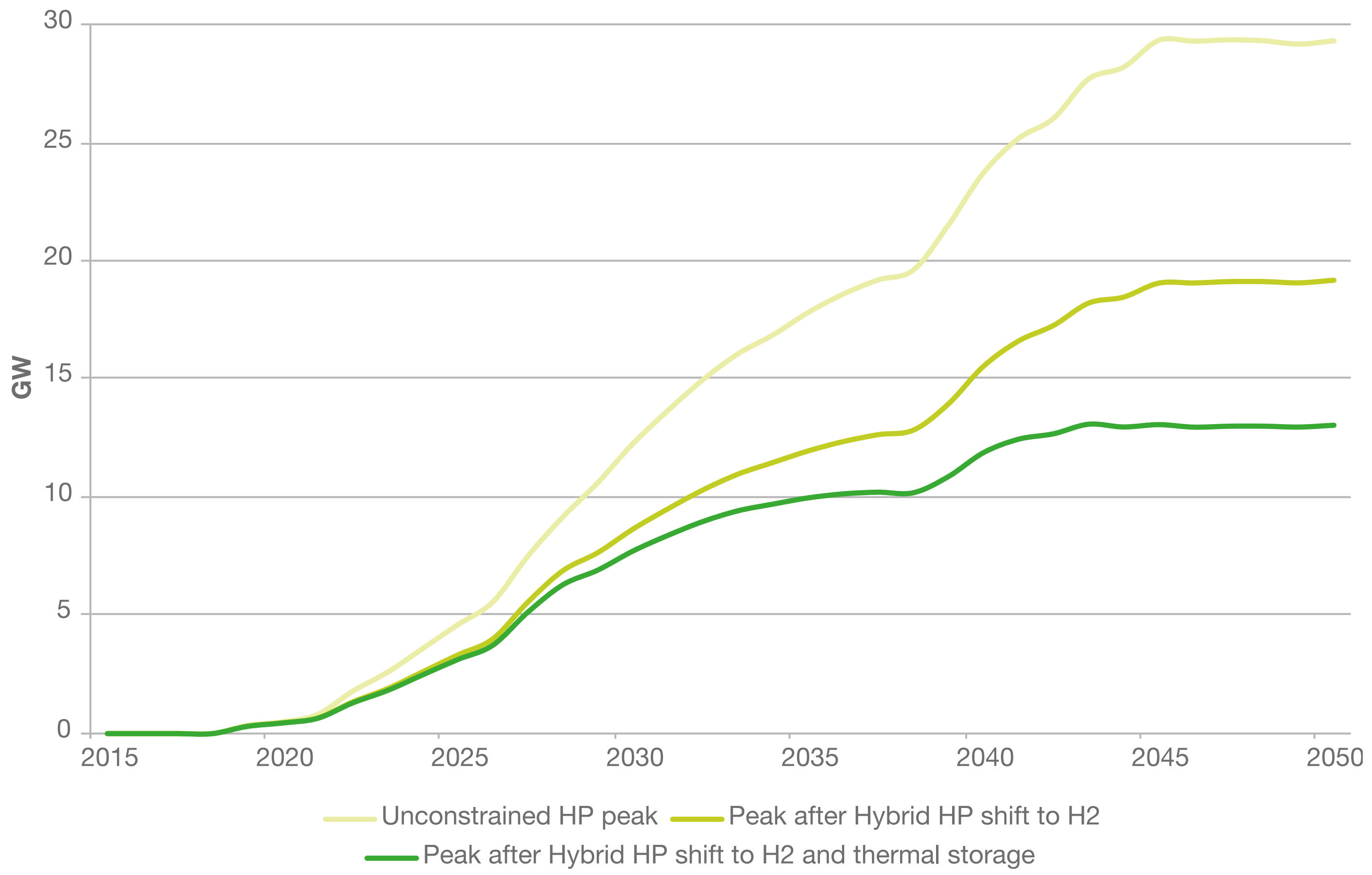


Demand side electricity flexibility

Figure SV.41: Residential winter peak electricity demand for heating and flexibility from heat pumps and hybrid heat pumps



System Transformation

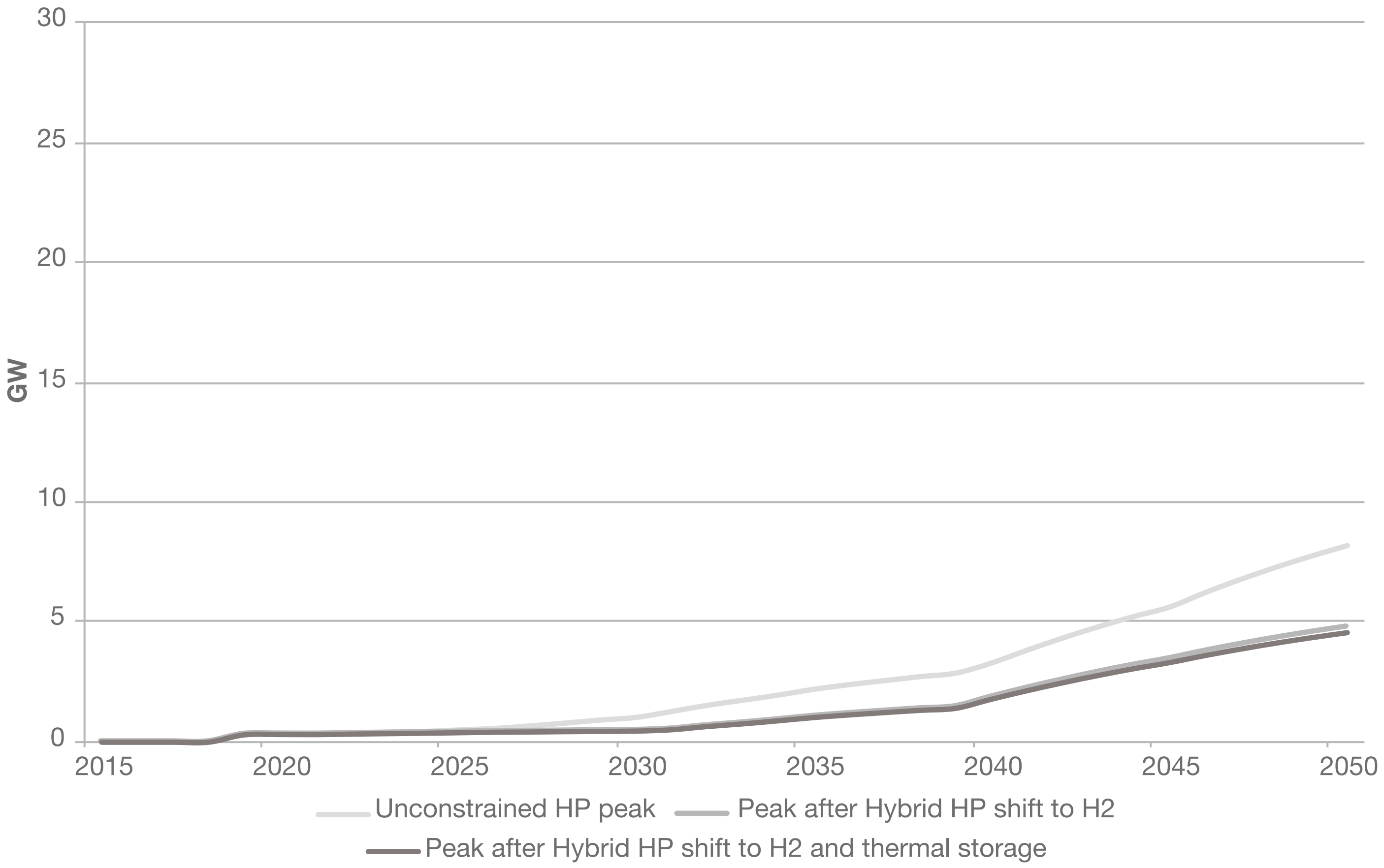


Leading the Way

FES 2020 / System View / Energy system flexibility 184

Demand side electricity flexibility

Figure SV.41: Residential winter peak electricity demand for heating and flexibility from heat pumps and hybrid heat pumps



Steady Progression

FES 2020 / System View / Energy system flexibility 185

Demand side electricity flexibility

Transport flexibility

We expect electric vehicles to have a significant impact on home energy use as consumers charge electric vehicles, as discussed in the Consumer View chapter. Smart charging can enable consumers to benefit from lower costs while also reducing the network impact by shifting charging away from times of system peak demand. Consumers with smart meters can access tariffs that change depending on wholesale electricity prices, and as the smart meter roll-out continues these will be available to increasing numbers of households. Automated smart charging will also be valuable to respond to dynamic price signals to help use energy when renewable generation exceeds conventional demand.

There are high levels of confidence in both the automotive and energy industries around smart charging; all scenarios see this increasing, with over 50% of households smart charging in all scenarios in 2050. High levels of smart charging uptake lead to a big impact on residential peak demand from electric vehicles, with additional demand after smart charging limited to under 6 GW in all scenarios.

There is a wide range of outcomes for vehicle-to-grid technology across our scenarios as this is an area with a high level of uncertainty. In the high societal change scenarios over a quarter of households make their vehicles available for V2G. Of participating households, only 50% of vehicles are assumed to be available at peak times to feed power back to the grid. This leads to high levels of net export of power to the grid at peak times from these households. In the net zero scenarios the levels of V2G export in 2050 offset the peak demands after smart charging leading to a net-negative effect on EV demand at peak.

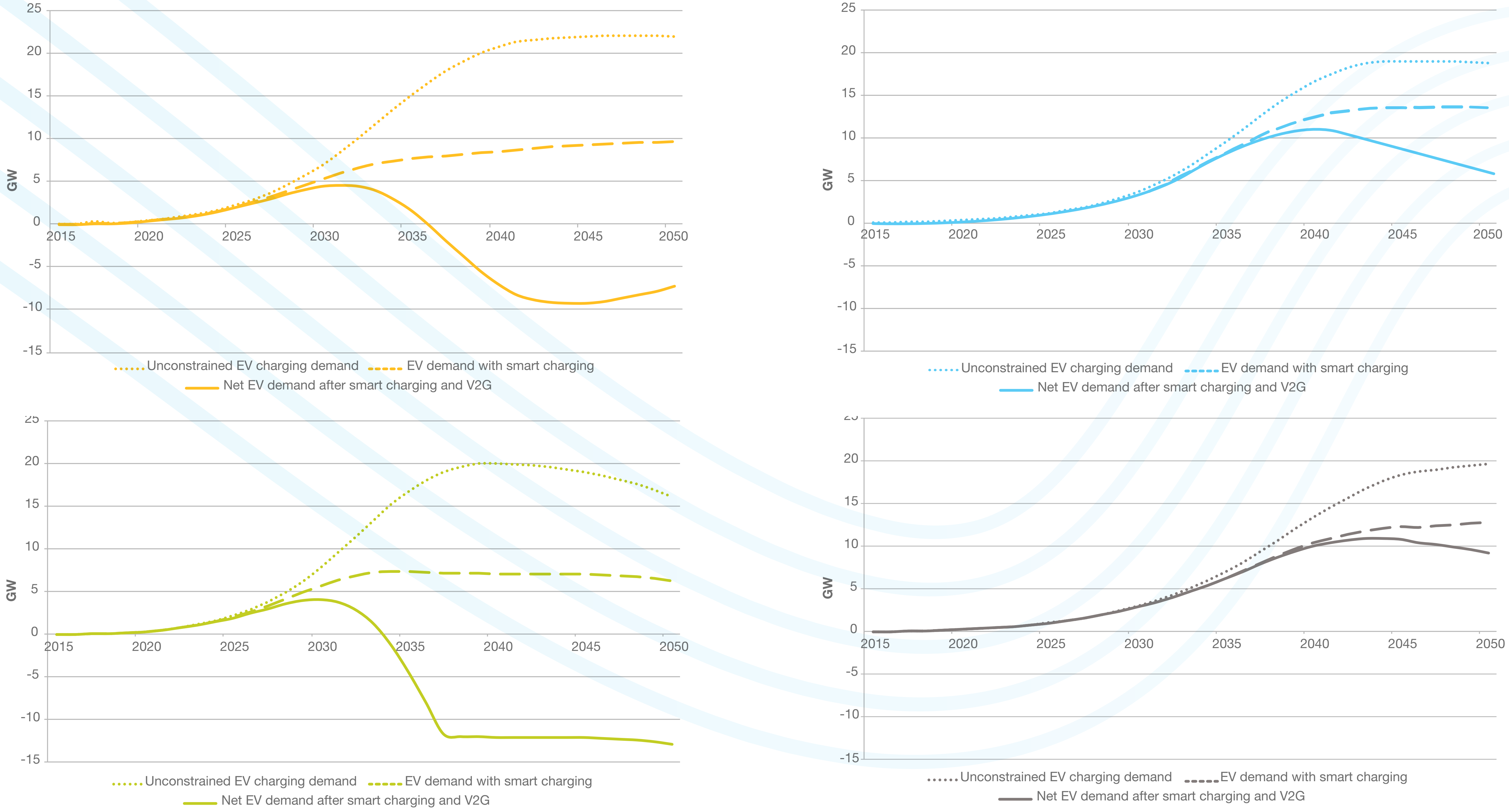
After 2045 in the high societal change scenarios we see the availability of V2G at peak times level off or start to fall due to the rising impact of autonomous vehicles.

These are more likely to be on the roads between 4pm and 8pm than privately owned vehicles and unavailable to provide V2G services at these times. Highly-engaged consumers who engage in V2G are also those mostly likely to be interested in autonomous vehicles, and so this limits the future growth of V2G.

In **System Transformation** and **Steady Progression** there is a steady increase in V2G activity after 2035, however it does not become widespread, limiting the overall contribution to peak management from the technology as it is outcompeted by other forms of flexibility.

FES 2020 / System View / Energy system flexibility 186

Figure SV.42: Electric vehicle charging behaviour at ACS[2] winter peak system demand



2 FES uses the Average Cold Spell (ACS) definition of electricity demand which is consistent with the treatment of demand in the electricity Capacity Mechanism.

FES 2020 / System View / Energy system flexibility 187

Demand side electricity flexibility

Electrolysis flexibility

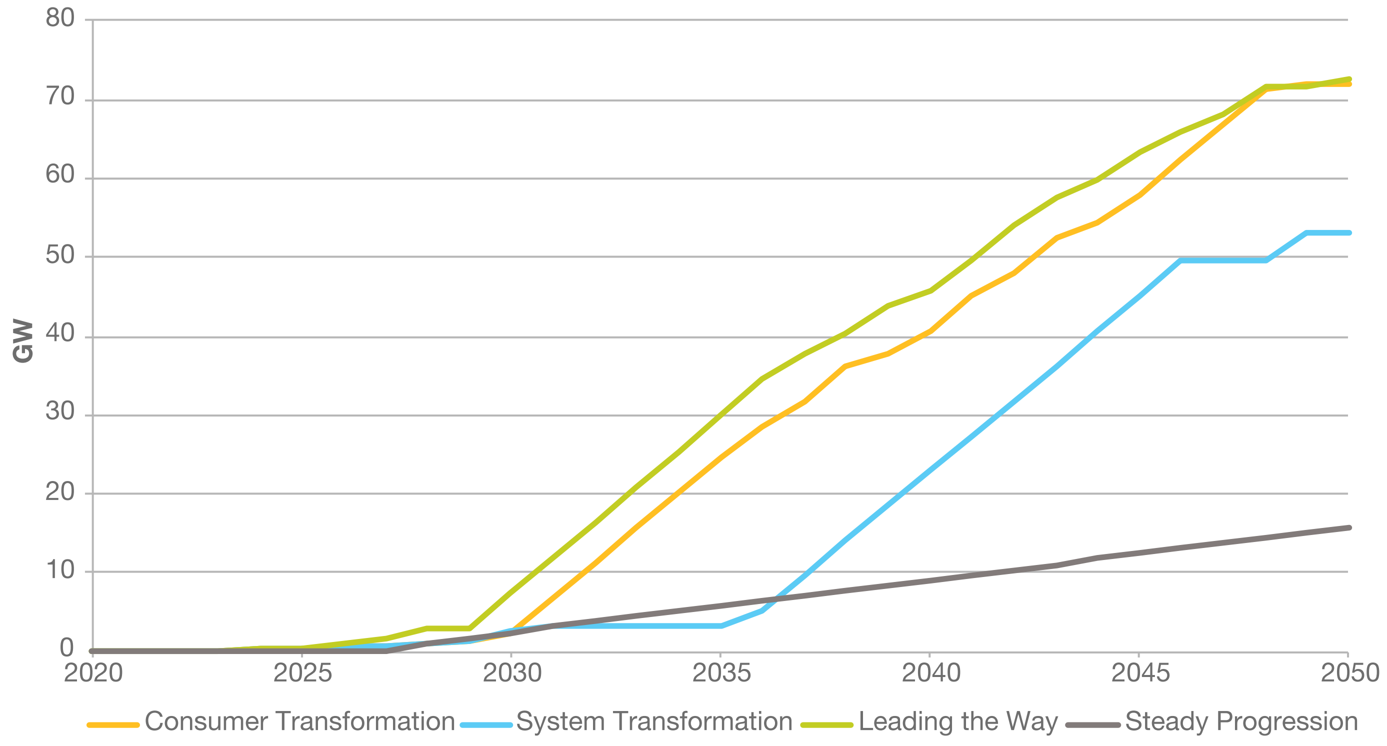
In the net zero scenarios hydrogen becomes increasingly important as an energy carrier. In **Leading the Way** and **Consumer Transformation**, hydrogen production is predominantly from electrolysis. This is a large electricity load which, importantly, can operate flexibly.

While electrolysis contributes to total annual demand, we assume that it won't increase peak demand. The economics of green hydrogen production rely on low electricity prices and so electrolysis is assumed not to run at ACS winter peak[2] times when electricity prices are typically high.

We assume electrolysis will be primarily driven by the availability of renewable generation and largely use renewable electricity that would otherwise have been curtailed, helping to match demand to generation.

This leads to relatively low annual load factors for hydrogen production from electrolysis. In the net zero scenarios in 2050 they produce between 15% and 24% of the hydrogen expected at full capacity all year round. The hydrogen can then be stored and used when required to meet end-use demand such as heating or to provide further system flexibility by powering hydrogen turbines to generate electricity.

Figure SV.43: Installed onshore network-connected electrolysis capacity by scenario



2 FES uses the Average Cold Spell (ACS) definition of electricity demand which is consistent with the treatment of demand in the electricity Capacity Mechanism.

Dispatchable thermal generation

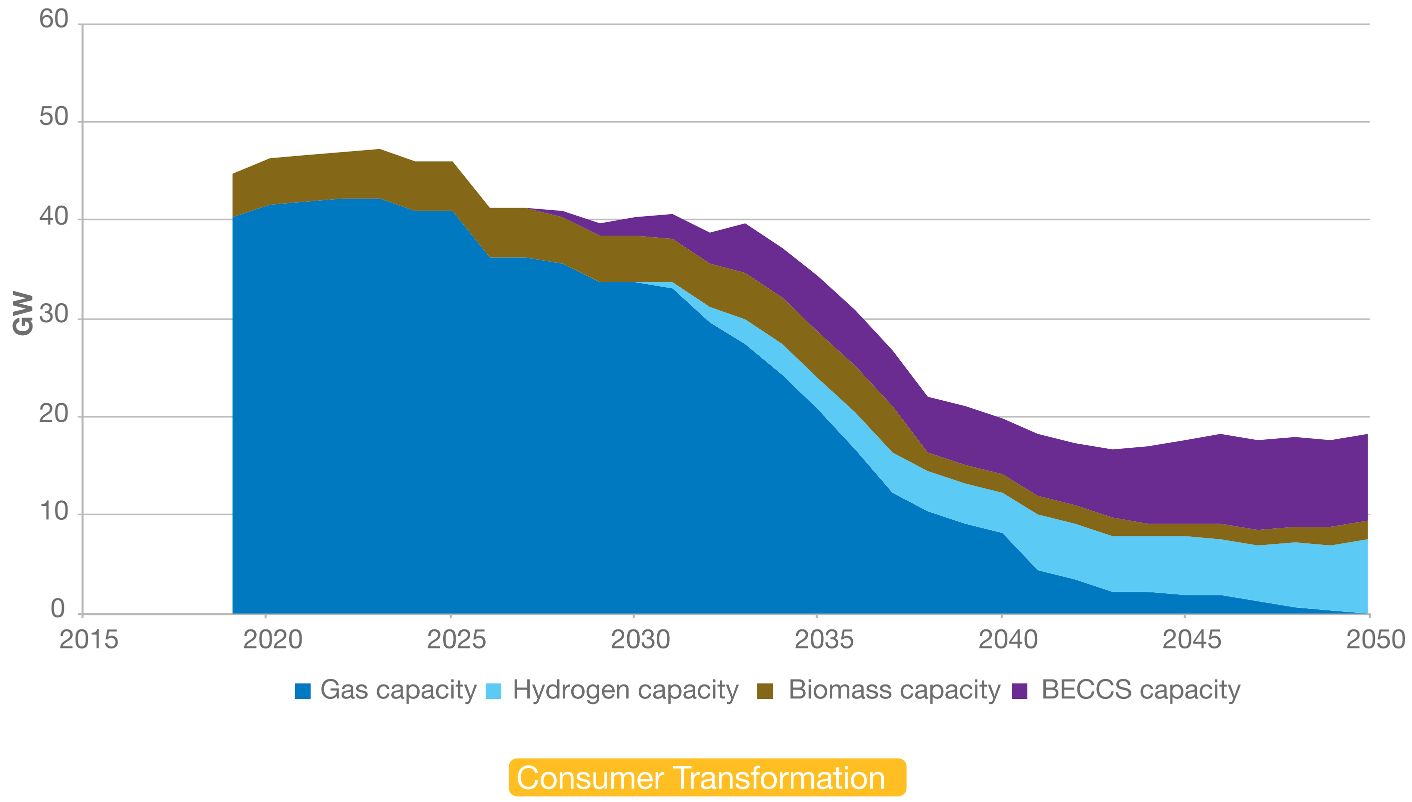
Dispatchable thermal generation uses a temperature difference produced by burning fuel to provide electricity and can be turned up and down in response to market signals. The main source today is from natural gas generation, which is shifting increasingly towards being a provider of flexibility rather than one of baseload generation. This is seen in gas generation having made up 47% of GB electricity supply in 2010 and 36% in 2018. By 2030 output from gas generation provides no more than 13% of electricity generated in the net zero scenarios. In all scenarios the primary role of gas generation is to provide flexibility and backing up variable generation output from renewables. Between 2025 and 2035 annual running hours become very low in the net zero scenarios.

Increases in the availability of hydrogen in the net zero scenarios after 2030 lead to hydrogen generation being preferred to gas with CCUS to provide flexibility, as the lower capital costs make hydrogen plant more economic when annual running hours are low. **System Transformation** has 20 GW of hydrogen plant in 2050, while **Consumer Transformation** and **Leading the Way** have 25-35% of this, with greater levels of flexibility provided by other sources. In **Steady Progression** continued use of unabated gas generation means there is no electricity produced from the limited amounts of available hydrogen.

Biomass generation is another form of dispatchable thermal generation. This will operate differently to BECCS which, while able to provide flexibility, will likely be run as baseload generation to maximise negative emissions, driven by high carbon pricing. In the net zero scenarios large-scale standalone biomass generation is converted to BECCS in the 2030s; however distributed biomass generation continue to operate flexibly.

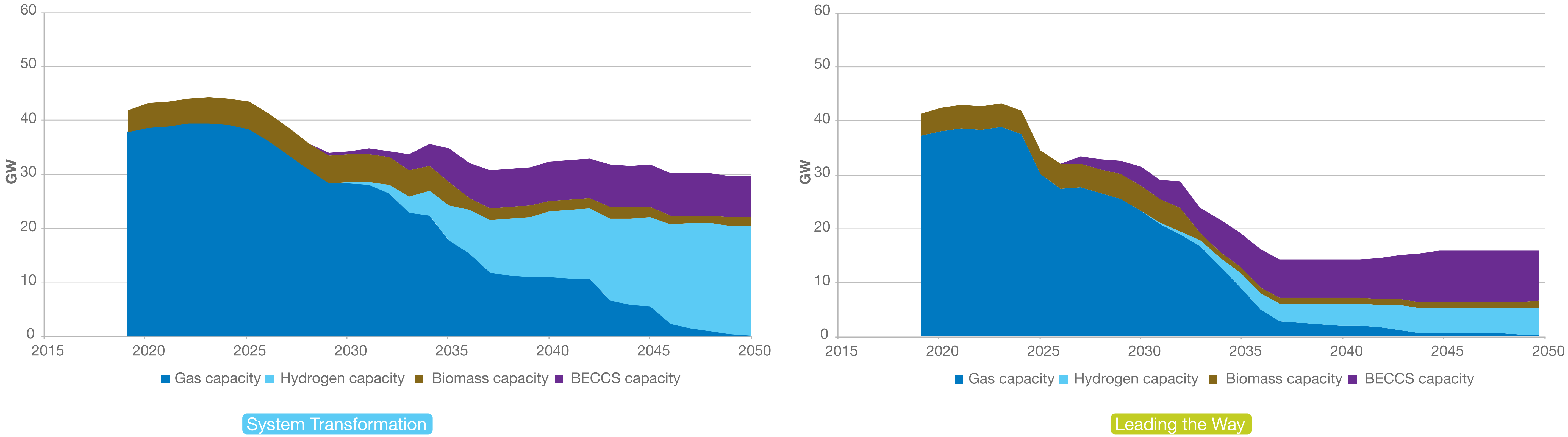
We assume a combination of policy and market change to support the required level of investment in flexible generation capacity with low annual running hours.

Figure SV.44: Installed capacity of dispatchable thermal generation



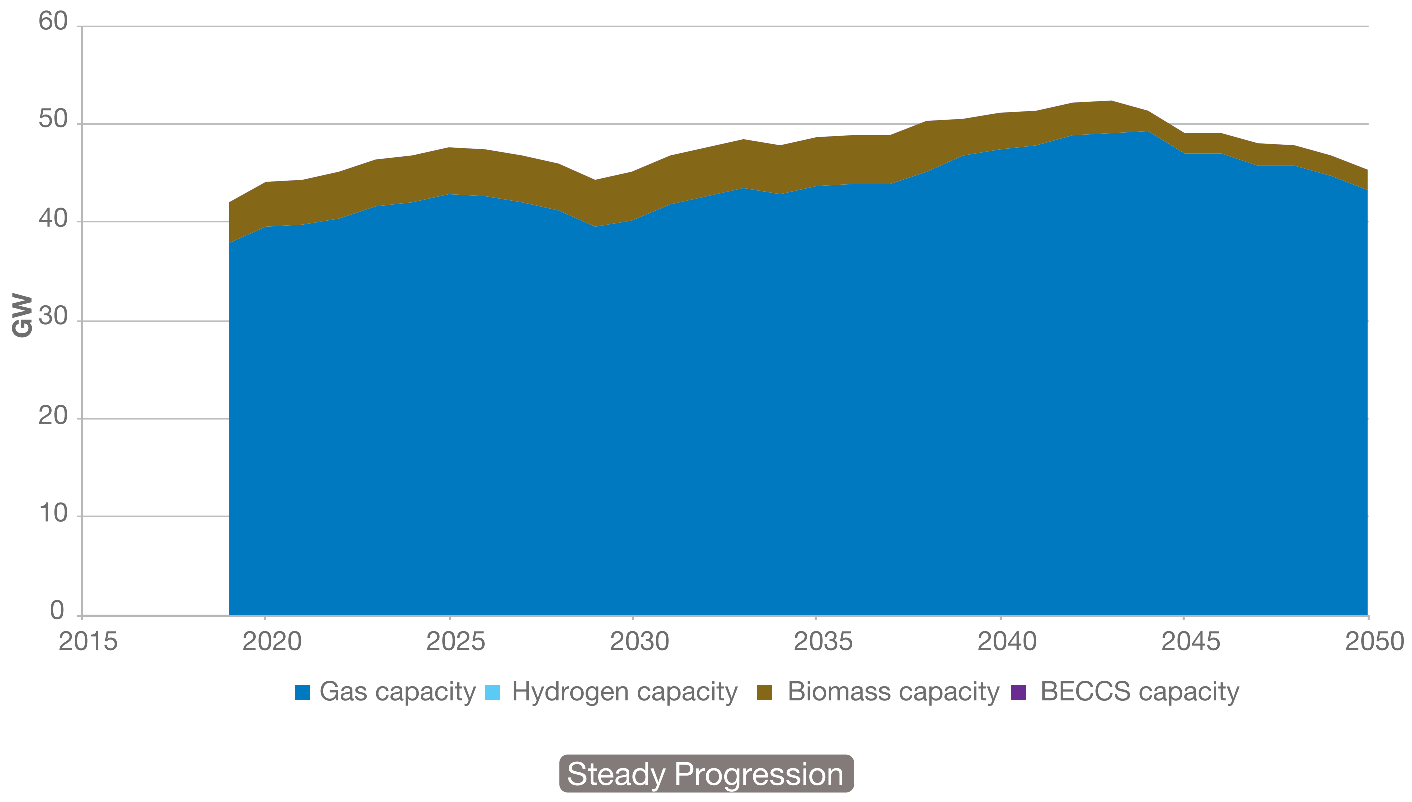
Supply side electricity flexibility

Figure SV.44: Installed capacity of dispatchable thermal generation



FES 2020 / System View / Energy system flexibility 190

Figure SV.44: Installed capacity of dispatchable thermal generation



FES 2020 / System View / Energy system flexibility 191

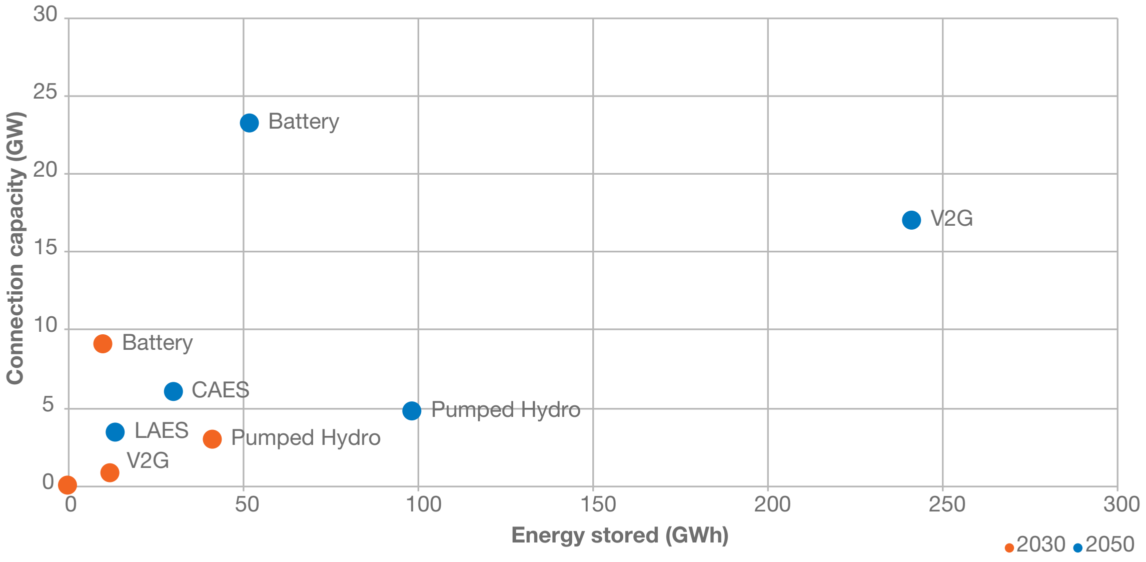
Supply side electricity flexibility

Large scale electricity storage

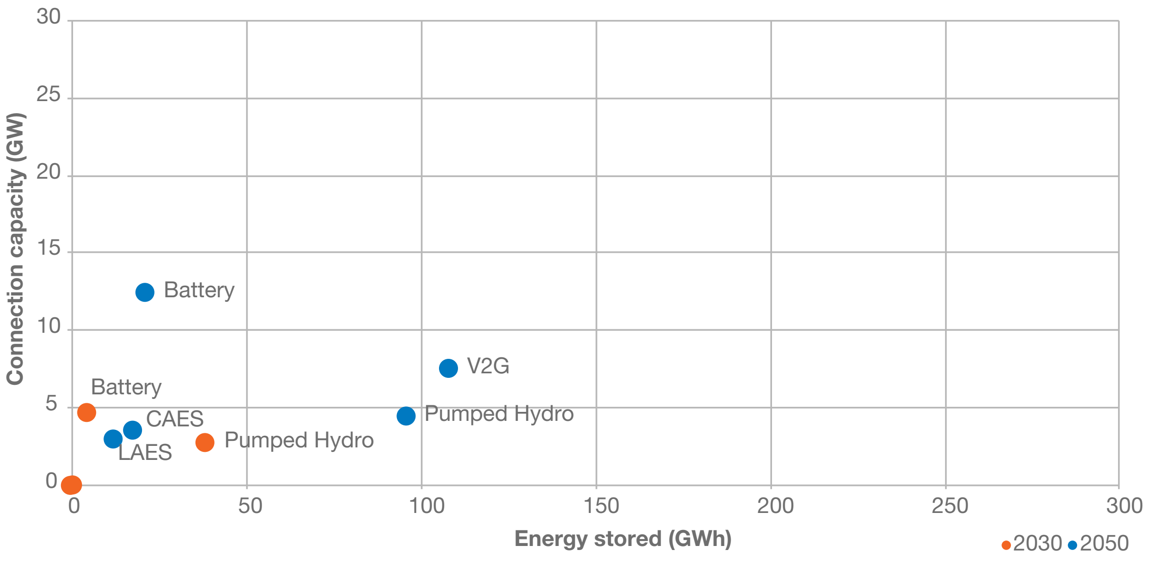
We expect significant growth in electricity storage to support the decarbonisation of the power system. Electricity storage includes pumped hydro, large-scale, residential and industrial behind-the-meter batteries, and compressed and liquid air projects. There is a wide range of uncertainty in development of vehicle-to-grid (V2G) technology, but it would require only a small proportion of vehicle owners to engage in order to have a significant impact on the system.

When considering the contribution of storage to flexibility on the system it is important to understand the total energy stored and the length of time it could discharge at full output. While batteries now have the same connection capacity as Cruachan and Ffestiniog pumped storage facilities, they can store only 1/20th of the energy. It will be necessary to develop large-scale storage with longer durations to support the decarbonisation of the power system.

Figure SV.45: Varying power and energy outputs of electricity storage types in 2030 and 2050[3]



Consumer Transformation



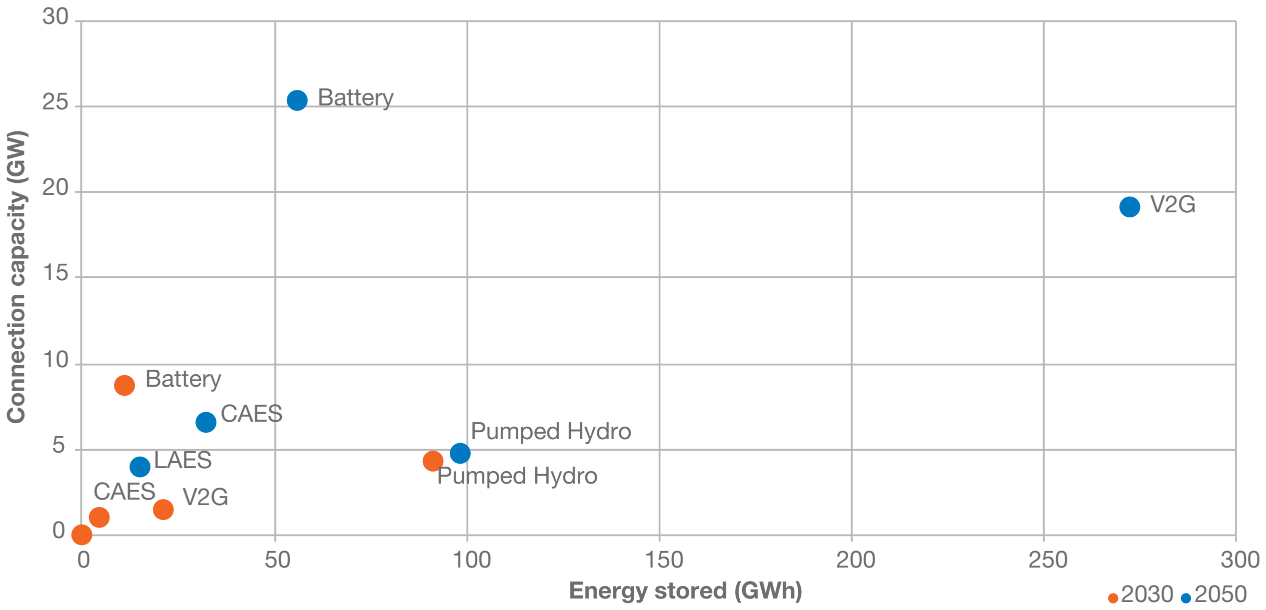
System Transformation

3 Vehicle-to-grid capacity represents availability at peak (5-6pm), while the energy stored assumes 50 kWh of useable battery storage per vehicle in 2050.

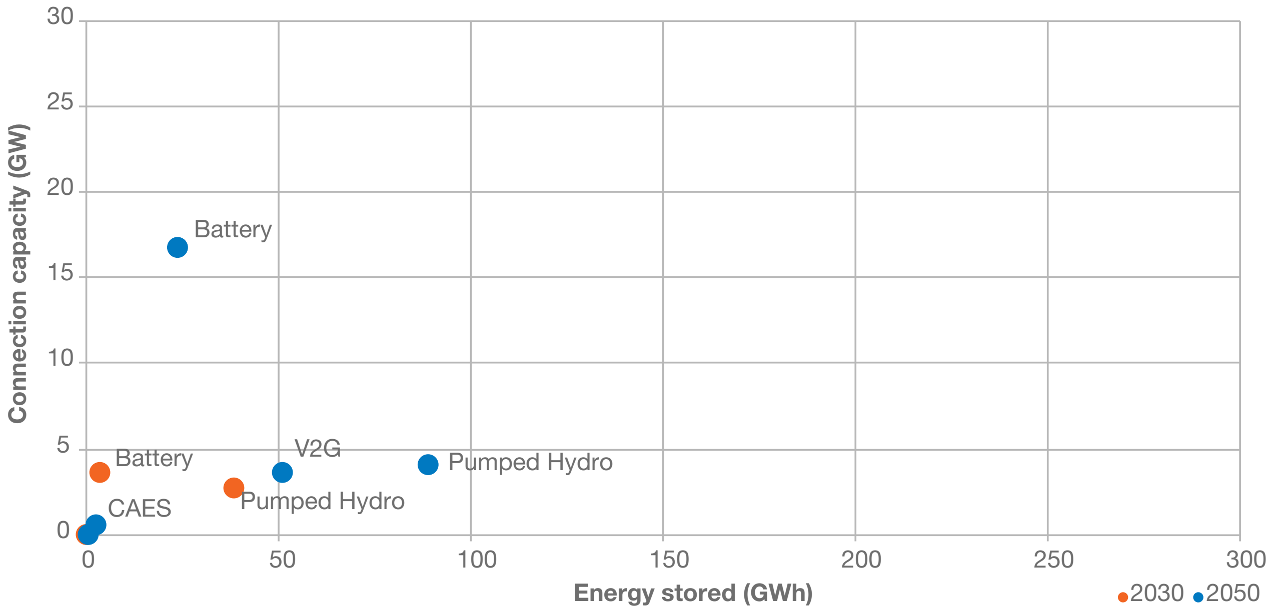
FES 2020 / System View / Energy system flexibility 192

Supply side electricity flexibility

Figure SV.45: Varying power and energy outputs of electricity storage types in 2030 and 2050[3]



Leading the Way



Steady Progression

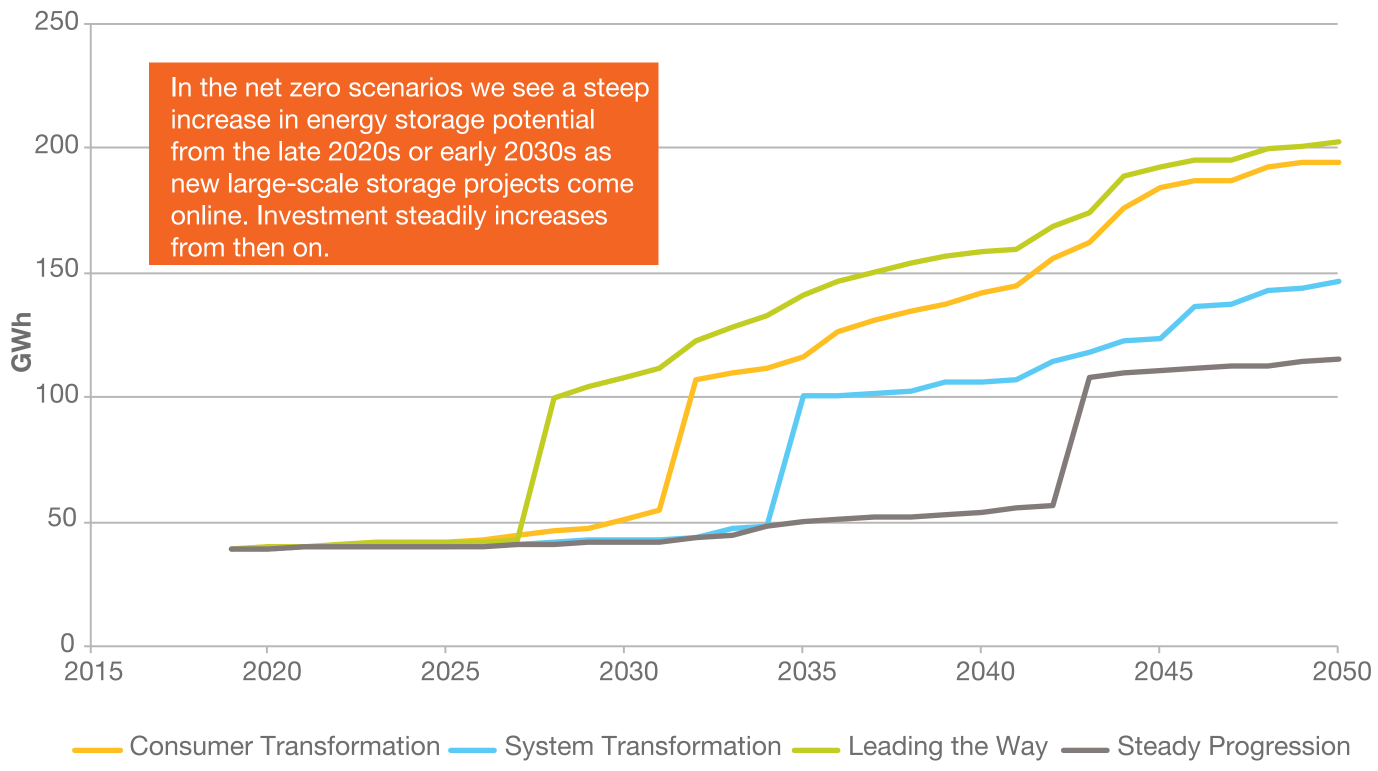
3 Vehicle-to-grid capacity represents availability at peak (5-6pm), while the energy stored assumes 50 kWh of useable battery storage per vehicle in 2050.

FES 2020 / System View / Energy system flexibility 193

Supply side electricity flexibility

Types of storage with different durations are used in varying ways. For example, short duration storage can meet short periods of peak demand, excess supply or provide grid stability services. Longer duration storage can balance the system over longer periods of high or low renewable generation. Very long term or interseasonal storage using other technologies such as hydrogen are discussed in the whole-system flexibility section.

Figure SV.46: Total electrical energy storage (excluding vehicle-to-grid)



FES 2020 / System View / Energy system flexibility 194

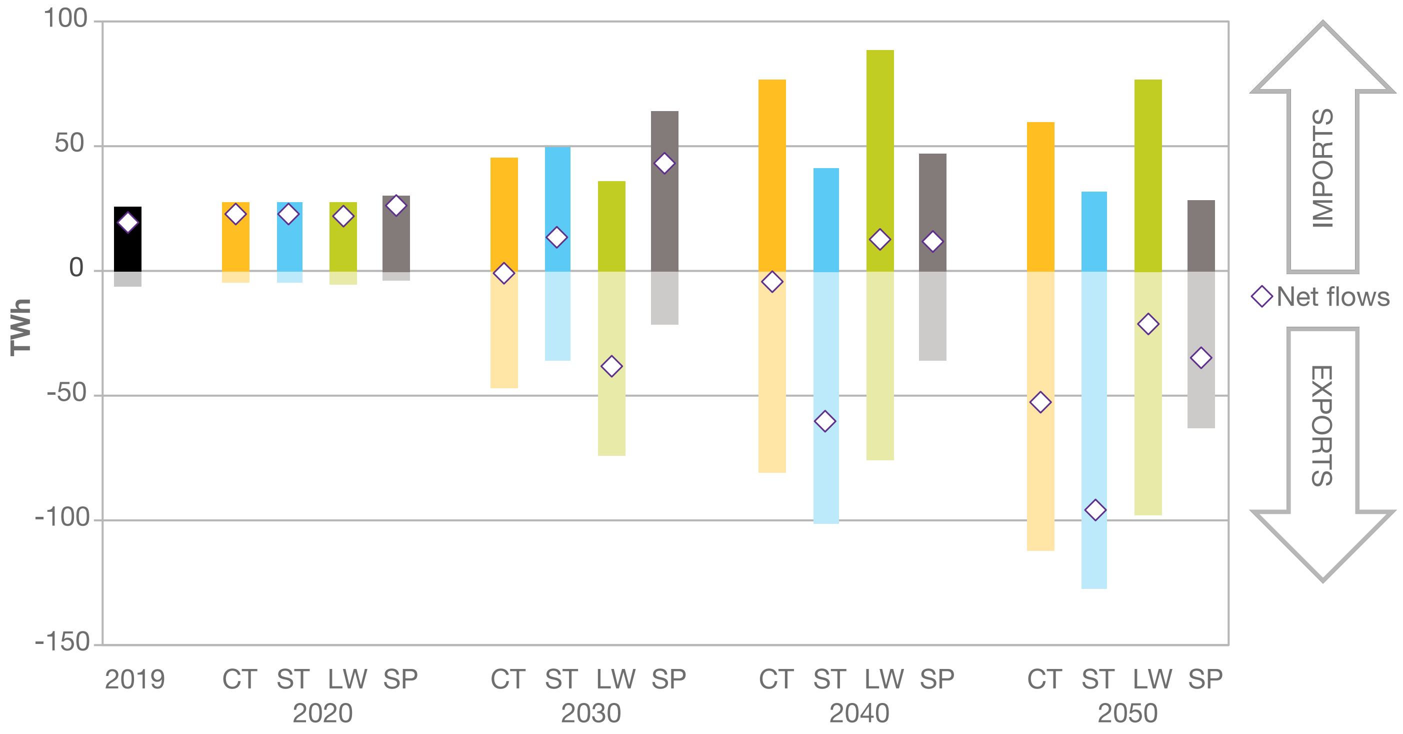
Electricity Interconnectors

Interconnector capacity is projected to increase in all scenarios as discussed in the electricity supply section, reaching 16-21 GW by 2030. With their flexibility, interconnectors will become increasingly important as renewable energy increases. Interconnector flows operate on a market basis, with energy typically sold from the higher-priced market to the lower-priced market. Across our scenarios we model price differentials between GB and European markets and flex carbon prices which help drive trading activity. This can also provide the flexibility to help meet demand on particularly cold winter days.

For most of the 2020s we project GB to import more electricity than it exports in all scenarios, driven by prevailing market conditions, however we expect the proportion of electricity imported to fall over time, particularly in the net zero scenarios. In **Leading the Way** high levels of renewable generation lead to the highest levels of total interconnector flows, reaching a net export by 2026.

In the net zero scenarios flows become more variable, with increased interconnector capacities transporting large volumes of electricity in both directions. As renewable generation capacities increase across GB and Europe, interconnectors help balance supply and demand with flows responding to price differences between countries that are increasingly driven by variable renewable generation output. **Steady Progression** net imports slowly decline from the 2030s, reaching net export by 2046. **System Transformation** relies the most heavily on exporting electricity over interconnectors due to high levels of renewable generation and lower levels of other sources of flexibility, particularly electrolysis, to absorb this generation; in 2050 net export is 16% of generated electricity.

Figure SV.47: Interconnector imports and exports

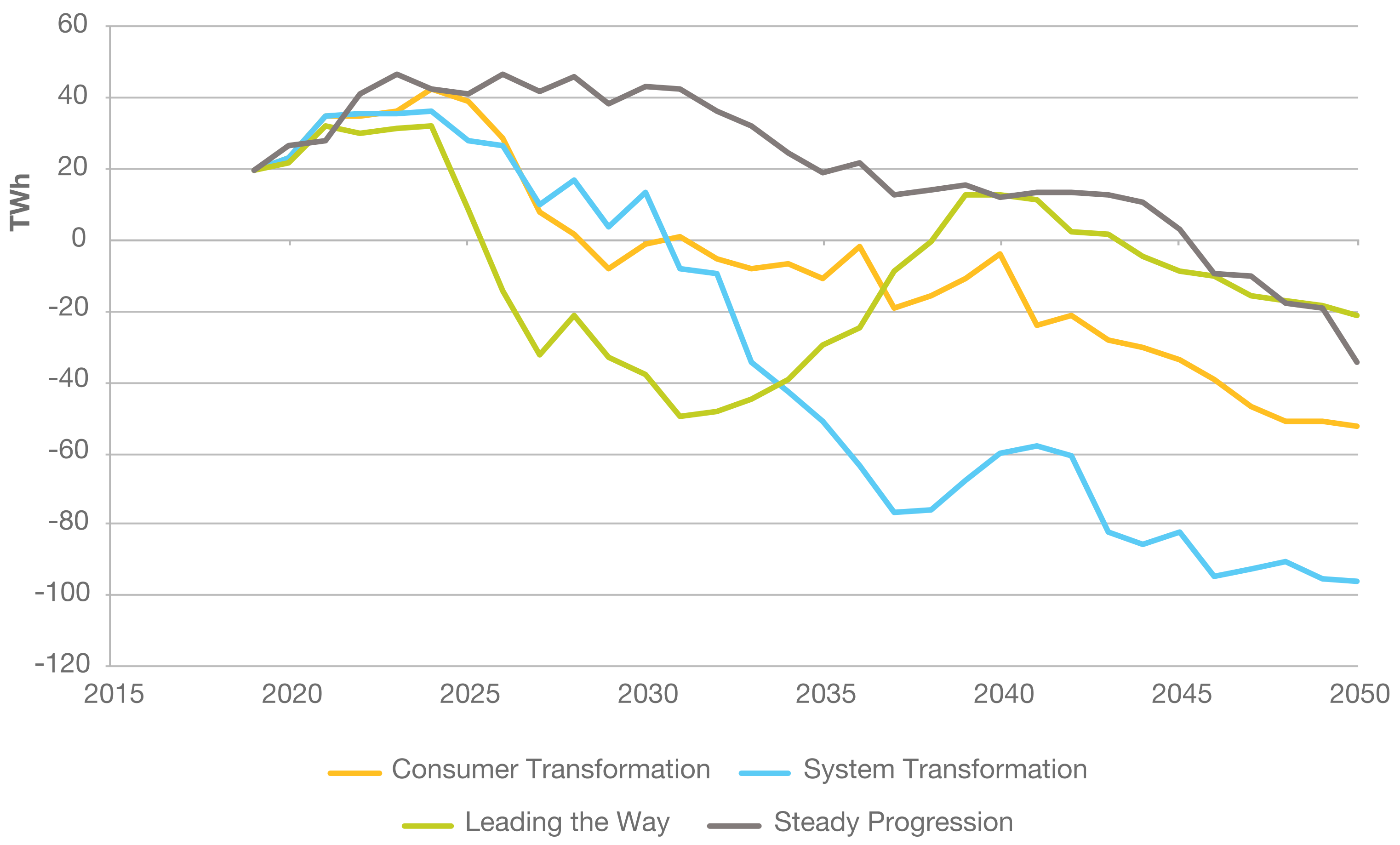


After 2030, increases in interconnector capacity are assumed to be delivered through the development of offshore hubs which include renewable generation and connection to two or more electricity markets. This combination will potentially add more flexibility than a standard interconnector.

FES 2020 / System View / Energy system flexibility 195

Supply side electricity flexibility

Figure SV.47: Interconnector net annual flows



FES 2020 / System View / Energy system flexibility 196

Interconnector flows at peak

Contribution at peak will continue to be driven by price differentials between connected electricity markets. Variation in renewable generation output, plant availability or demand will affect prices on each side of the interconnector, which will respond by moving power from cheaper to more expensive markets.

At peak times we expect GB to continue to be a net importer of electricity in most scenarios. The highest peak flows are seen in **Leading the Way** and **Consumer Transformation** which have the highest interconnector capacities. Expected flows at peak could vary considerably from period to period, and this does not necessarily mean every peak period will see the same pattern of flows.

FES 2020 / System View / Energy system flexibility 197

Glossary

Air Source Heat Pump (ASHP)
Heat pump which absorbs heat from the outside air. This heat can then be used to produce hot water or space heating.

Ancillary Services
Services procured by the ESO to support operation of the electricity system.

Arbitrage
In an energy context, this usually refers to the practice of buying energy when the price is low, storing this energy and then selling it when the price has risen.

Autonomous Vehicle (AV)
A vehicle, which is able to drive without human involvement.

Baseload Generation
An electricity generator that tends to operate at constant output for 24 hours a day throughout the year.

Battery Electric Vehicle (BEV)
A vehicle, which uses a battery as its sole means of propulsion and is recharged by plugging in to the electricity network.

Billion Cubic Metres (bcm)
A unit of volume, used in the gas industry. 1 bcm = 1,000,000,000 cubic metres. For gas, in GB, a good guide for converting from energy in watt hours to gas volume in cubic metres is to divide by 11.

Bioenergy
Energy produced from bioresources.

Bioenergy with Carbon Capture and Storage (BECCS)
The coupling of bioenergy with carbon capture and storage to capture the CO_2 produced during combustion. This process delivers negative emissions.

Biogas
A naturally occurring gas that is produced from organic material and has similar characteristics to natural gas. We use biogas to refer to gas that is not of pipeline quality.

Biomass
Plant or animal material used for energy production, heat production or in various industrial processes as a raw material.

Biomass Gasification
A process that generates hydrogen from biomass. When combined with CCUS technology this can produce hydrogen while also delivering negative emissions.

Biomethane
Biogas that has been further processed to make it suitable for injection into gas transmission or distribution networks.

Bioresources
Organic feedstocks like energy crops, forestry and agricultural waste and biological materials that can be used to produce energy.

Blended Gas
Gas supplied to homes and businesses, which contains hydrogen and/or biomethane blended in with natural gas.

Blue Hydrogen
Hydrogen created via methane reforming using natural gas as an input, plus CCUS.

Carbon Capture, Usage and Storage (CCUS)
A process by which the CO_2 produced in the combustion of fossil fuels is captured and transported to a storage location and isolated from the atmosphere. Capture of CO_2 can be applied to large emission sources like power plants used for electricity generation, production of hydrogen from methane reforming and industrial processes. The CO_2 is then compressed and transported for long-term storage in geological formations or for use in industrial processes.

FES 2020 / Glossary 198

Cap and Floor
This is a form of revenue regulation applied to electricity interconnectors in GB. Where interconnector revenue falls within a specified range it can be retained by the interconnector operator. Any revenue over and above the top of this range (cap) is returned to customers and any if revenue is below the bottom of the range (floor) it is supplemented from customers.

Capacity
The power output of an electricity generation technology - usually measured in Watts (or kW, MW or GW).

Capacity Market (CM)
The Capacity Market is designed to ensure security of electricity supply. This is achieved by providing a payment for reliable sources of capacity, alongside their electricity revenues, ensuring they deliver energy when needed.

Carbon Dioxide (CO_2)
The main greenhouse gas. The vast majority of CO_2 emissions come from the burning of fossil fuels.

Carbon Footprint
The amount of carbon dioxide released into the atmosphere as a result of the activities of a particular individual, organisation or community.

Carbon Intensity
A way of examining how CO_2 is emitted in different processes. Usually expressed as the amount of CO_2 emitted per km travelled, per unit of heat created or per kWh of electricity produced.

Carbon Neutral
When applied to bioenergy, indicates that the carbon dioxide given off from combustion is offset by carbon dioxide absorbed during the plant matter's lifetime.

Carbon Price Floor (CPF)
A UK Government policy which sets a target for the minimum price of carbon that is applied to carbon polluters to encourage low carbon investment. It consists of the EU ETS allowance price and the Carbon Price Support (CPS).

Carbon Price Support (CPS)
The CPS is effectively a carbon tax that tops up the EU ETS allowance prices, as projected by the Government, to the UK Carbon Price Floor target.

Carbon Pricing
Applying a cost to the emission of each tonne of carbon dioxide.

Clean Growth Strategy 2030
The government's comprehensive set of policies and proposals that aim to accelerate the pace of clean growth by delivering increased economic growth and decreased emissions.

Combined Cycle Gas Turbines (CCGT)
A power station that uses the combustion of natural gas or liquid fuel to drive a gas turbine generator to produce electricity. The exhaust gas from this process is used to produce steam in a heat recovery boiler. This steam then drives a steam turbine generator to generate more electricity.

Combined Heat and Power (CHP)
A system where both heat and electricity are generated simultaneously as part of one process. Covers a range of technologies that achieve this.

Contract for Difference (CfD)
A contract between the Low Carbon Contracts Company (LCCC) and a low carbon electricity generator, designed to reduce its exposure to volatile wholesale prices.

Data Centres
High electricity demand sites where computing and networking equipment is concentrated to store and process digital data for online services.

Decarbonisation
The process of removing carbon emissions (e.g. generated by burning fossil fuels) from our economic and social activities.

Decentralised Generation
Electricity generation that is connected to power networks below the high voltage transmission system. Includes distributed generation and onsite generation.

Demand Side Flexibility
The ability of energy users to adjust demand in response to market signals.

Demand Side Response (DSR)
A deliberate change to a consumer's natural pattern of metered electricity or gas consumption, brought about by a signal from another party.

FES 2020 / Glossary 199

De-rated Generation Capacity
When a reduction factor is applied to the installed capacity of generation to best reflect what is expected to be available in real time.

De-rated Plant Margin
The sum of de-rated generation capacity declared as being available during times of peak demand plus support from interconnection minus expected demand at that time and basic reserve requirement.

Dispatchable Generation
Generation that can be modulated up and down as required.

District Heating
A community based heating solution, which uses a single central hub to heat water, which is then pumped around a number of different homes and buildings.

Electric Vehicle (EV)
A vehicle driven by an electric motor. It can either be driven solely off a battery, as part of a hybrid system, or have a generator that can recharge the battery but does not drive the wheels. We only consider EVs that can be plugged in to charge in this report.

Electrolysis
Electrolysis is the process of using electricity to split water into hydrogen and oxygen.

Energy Density
Energy contained in a fuel per unit of mass or volume.

Energy Performance Certificate (EPC)
An EPC gives a property an energy efficiency rating from A (most efficient) to G (least efficient).

EU Emissions Trading Scheme (EU ETS)
An EU wide system for trading greenhouse gas emission allowances which effectively sets an EU carbon price. The scheme covers more than 11,000 power stations and industrial plants in 31 countries.

Flexibility
The ability to adjust energy supply and demand to keep them balanced.

Fuel Cell Electric Vehicle (FCEV)
A vehicle which uses a fuel cell to generate electricity to move, instead of using a battery. These vehicles typically use hydrogen.

Gigawatt (GW)
1,000,000,000 watts, a unit of power.

Gigawatt Hour (GWh)
1,000,000,000 watt hours, a unit of energy.

Great Britain (GB)
A geographical, social and economic grouping of countries that contains England, Scotland and Wales. FES analysis largely covers energy supply and demand on a GB-basis but the Net Zero Emissions Target is on a UK basis (i.e. includes Northern Ireland as well).

Green Gas
In our scenarios, this is used to cover both biomethane and bioSNG (i.e. biomethane which is created by larger, more industrial processes).

Green Hydrogen
Hydrogen produced via electrolysis using zero carbon electricity.

Greenhouse Gas (GHG)
A gas in the atmosphere that absorbs and emits radiation within the thermal infrared range.

Grid Curtailment
This is when the output from a generation unit connected to the electricity system is reduced due to operational balancing.

Ground Source Heat Pump (GSHP)
Heat pump which absorbs heat from the ground. This heat can then be used to produce hot water or space heating.

Halogen Bulbs
High luminosity incandescent light bulbs, sale banned within the EU in September 2018.

Heat Pump
A device that transfers heat energy from a lower temperature source to a higher temperature destination. Can include ground source or air source varieties.

Heavy Goods Vehicle (HGVs)
A truck weighing over 3,500 kg.

FES 2020 / Glossary 200

Hybrid Heat Pump
An integrated heating system using an electric heat pump alongside a traditional installation such as a gas or hydrogen boiler.

Hydrogen Blending
When hydrogen is injected into the gas network and mixed with natural gas.

Hydrogen Boiler
Home heating technology which burns hydrogen (rather than natural gas) for space heating and hot water.

Hydrogen Combined Cycle Turbine (Hydrogen CCGT)
Combined cycle turbine that burns hydrogen (rather than natural gas) to generate electricity.

Internal Combustion Engine (ICE)
Traditional engine used in transport sector which is powered by fossil fuels such as petrol or diesel.

Industrial Cluster
Hub for industry all using the same local infrastructure e.g. hydrogen supply or carbon capture and storage plant.

Inflexible / Less Flexible Generation
Types of generation that require longer notice periods to change their output or have obligations that influence when they can generate.

Interconnector
Transmission assets that connect the GB market to Europe and allow suppliers to trade electricity or gas between markets.

Intermittent Generation
Types of generation that can only produce electricity when their primary energy source is available. For example, wind turbines can only generate when the wind is blowing.

Kilowatt Hour (kWh)
1,000 watt hours, a unit of energy.

Land Use, Land-Use Change and Forestry (LULUCF)
Net carbon emissions related to changes in land use and tree planting.

Light-emitting Diode (LED)
Electric light with higher efficiency and longer lifetime than conventional bulbs.

Linepack
The amount of gas stored within the gas network at any time.

Liquefied Natural Gas (LNG)
Formed by chilling natural gas to -161˚C to condense as a liquid. Its volume reduces 600 times from the gaseous form.

Liquefied Petroleum Gas (LPG)
A mix of propane and butane, used for heating homes in off gas grid areas as well as a number of other uses.

Load Factor
Load factors are an indication of how much a generation plant or technology type has output across the year, expressed as a percentage of maximum possible generation. These are calculated by dividing the total electricity output across the year by the maximum possible generation for each plant or technology type.

Loss of Load Expectation (LOLE)
Used to describe electricity security of supply. It is an approach based on probability and is measured in hours/year. It measures the risk, across the whole winter, of demand exceeding supply under normal operation. This does not mean there will be loss of supply for 3 hours per year. It gives an indication of the amount of time, across the whole winter, which the System Operator (SO) will need to call on balancing tools such as voltage reduction, maximum generation or emergency assistance from interconnectors. In most cases, loss of load would be managed without significant impact on end consumers.

Mega Tonnes of CO_2 Equivalent ($MtCO_2e$)
The equivalent of 1,000,000 tonnes of carbon dioxide, standard unit for measuring national and international greenhouse gas emissions.

Megawatt (MW)
1,000,000 watts, a unit of power.

Megawatt Hour (MWh)
1,000,000 watt hours, a unit of energy.

FES 2020 / Glossary 201

Methane Reformation
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 CO_2 capture.

Million Cubic Metres (MCM)
A unit of volume, used in the gas industry. 1 mcm = 1,000,000 cubic metres. For gas, in GB, a good guide for converting from energy in watt hours to gas volume in cubic metres is to divide by 11.

Natural Gas
A mixture of gases, primarily methane, suitable for transport through gas transmission and distribution networks.

Negative Emissions
When more carbon is removed from the atmosphere and stored by a process than is emitted into the atmosphere, this is termed negative emissions. For example with BECCS, carbon is removed from the atmosphere by the growth of the biomass as well as then being captured by CCUS.

Net negative Emissions
When negative carbon emissions are greater than positive emissions in a process or sector.

Net Zero
When the total amount of greenhouse gases emitted in a year reaches zero, after all emissions and all carbon sequestration has been accounted for. This is the current UK target for 2050.

Networked Energy Systems
The current gas and electricity transmission and distribution networks (included connected supply and demand) as well as potential future networks such as hydrogen.

Non-networked Energy
Energy supply or demand not connected to the networked energy systems.

Non-networked Offshore Wind
Offshore wind that is not connected to the GB electricity network.

Offshore Hub
Coordinated development of an offshore location that can connect to multiple offshore generation sites and provide a link between them and surrounding countries via electricity or gas interconnectors.

Peak Demand, Electricity
The maximum electricity demand in any one fiscal year. Peak demand typically occurs at around 5:30pm on a week-day between November and February. Different definitions of peak demand are used for different purposes. FES uses the Average Cold Spell (ACS) definition which is consistent with the treatment of demand in the electricity Capacity Mechanism.

Peak Demand, Gas
The level of natural gas demand that, in a long series of winters, with connected load held at levels appropriate to the winter in question, would be exceeded in one out of 20 winters, with each winter counted only once.

Peaking Plant
Electricity generators that operate only at times of peak demand when electricity prices are high.

Plug-in Hybrid Electric Vehicle (PHEVs)
A vehicle which has a battery which can be charged by plugging it in, as well as a petrol or diesel engine.

Residual Emissions
Remaining positive emissions in a given year that need to be offset by negative emissions to meet net zero.

Retrofit
In an energy context, to install energy efficiency measures to a home after its construction.

Road to Zero Strategy
The Road to Zero Strategy outlines how government will support the transition to zero emission road transport and reduce emissions from conventional vehicles during the transition.

Seasonal Flexibility
Storing energy in one season for use later in the year.

FES 2020 / Glossary 202

Shale Gas
Natural gas that is found in shale rock. It is extracted by injecting water, sand and chemicals into the shale rock to create cracks or fractures so that the shale gas can be extracted.

Shrinkage
Total losses of gas from the gas network.

Small Modular Reactor (SMR)
Nuclear reactors, generally 500MWe equivalent or less, designed with modular technology using module factory fabrication.

Smart Appliances
Electricity-consuming goods which are able to reduce their demand at defined times of the day, either by reacting to a signal or by being programmed.

Smart Charging
Charging units which have two way communication ability and that can react to external signals.

Smart Home Energy Management Systems
Smart controls that schedule and optimise energy consumption from appliances, heating and electric vehicles within the home.

Smart Meter
New generation gas and electricity meters which have the ability to broadcast secure usage information to customers and energy suppliers, potentially facilitating energy efficiency savings and more accurate bills.

Societal Change
The extent of future change to the behaviour and lifestyle of energy consumers across domestic, industrial and commercial sectors.

Supply Side Flexibility
Electricity generators or market participants adjusting electricity supply to meet demand.

System Operator
An entity entrusted with transporting energy in the form of natural gas or electricity on a regional or national level, using fixed infrastructure. The SO may not necessarily own the assets concerned. For example, National Grid ESO operates the electricity transmission system in Scotland, which is owned by Scottish Hydro Electricity Transmission and Scottish Power Transmission.

Terawatt Hour (TWh)
1,000,000,000,000 watt hours, a unit of energy.

Thermal Generation
Generation that uses a temperature difference produced by burning fuel to produce electricity.

Thermal Storage
A store of heat, for example in a hot water tank or phase change material, that allows heat to be stored and then released when it is needed.

Time of Use Tariff (TOUT)
A charging system that is established in order to incentivise residential consumers to alter their consumption behaviour, usually away from high electricity demand times.

Total Primary Energy Demand
Total input energy that is required to meet end consumer demand including conversion and transportation losses.

UK Continental Shelf (UKCS)
Comprised of those areas of the sea bed and subsoil beyond the territorial sea over which the UK exercises sovereign rights of exploration and exploitation of natural resources.

Ultra-low Emission Vehicles (ULEV)
Vehicles that use low carbon technologies and emit less than 75 g of CO_2/km from the tailpipe - includes BEVs, PHEVs and FCEVs.

Unabated Fossil Fuel Combustion
Burning fossil fuels without carbon capture, usage and storage (e.g. for heat or power).

United Kingdom of Great Britain and Northern Ireland (UK)
A geographical, social and economic grouping of countries that contains England, Scotland, Wales and Northern Ireland. FES analysis largely covers energy supply and demand on a GB-basis but the 2050 Net Zero Emissions Target is on a UK basis (i.e. includes Northern Ireland as well).

FES 2020 / Glossary 203

Vehicle-to-grid Technology (V2G)

Enables energy stored in electric vehicles to be fed back into the national electricity network (Grid) to help supply energy at peak times of demand.

Whole Electricity System

A collective term that is used to cover, but is not strictly limited to, transmission and distribution systems for electricity.

Whole Energy System

A collective term that is used to cover, but is not strictly limited to, transmission and distribution systems for both gas and electricity.

Whole Gas System

A collective term that is used to cover, but is not strictly limited to, transmission and distribution systems for gas.

Whole System

A collective term that is used to cover all interdependent systems associated with provision of energy and the emission of greenhouse gases; including systems such as transport, water, waste, hydrogen.

Whole System Flexibility

The management of energy demand and supply across fuels, for example the interaction between the natural gas and electricity systems due to the operation of gas-fired generation.

FES 2020 / Glossary 204

Continuing the conversation

Email us with your views on FES or any of our future of energy documents at: fes@nationalgrideso.com and one of our team members will get in touch.

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FES 2020 / 205

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FES 2020 / 206

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