

**INNOVATING
TO NET ZERO**

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This report identifies the technologies, products and services which are most important to meeting Net Zero. It recommends what needs to happen during this Parliament to deliver Net Zero levels of investment, infrastructure and innovation.

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FOREWORD

Leading the way on Net Zero

A clear, bold, binding goal can be a great catalyst. The UK's world-leading commitment to Net Zero by 2050 has focused minds in companies, communities, and institutions.



Philip New

Chief Executive Officer

It has energised the debate. But if we are to realise the goal, the target itself is a necessary, but far from sufficient, condition. We know that to get to Net Zero demands major upheavals in how we make, move, store and use energy. We know that this will require innovation – in technology of course, but equally in consumer propositions, market design, business models and system definition and design.

We have a great platform in the UK. We've led the way in decarbonising electricity generation, have a track record of evidence-based policy, an increasingly progressive regulatory ambition, a robust legacy energy system, world-class green finance capability and a strong and diverse research base that spans the whole energy system.

The brilliant British companies we work with every day are devising new platforms, offers, technologies and services: from new ways of generating nuclear power to storing and supplying energy; from managing our networks in a more flexible way to heating our homes and charging our cars; integrating the digital with the physical, creating solutions for consumers that will deliver clean economic growth.

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But, given the complexity, the uncertainty and the profundity of the change our energy system faces, stakeholders are increasingly asking where to start.

A good first step is to understand the type of journey we need to go on to get there.

In this report Energy Systems Catapult lays out a set of credible pathways for the UK to get to Net Zero. The pathways reflect a diversity of implementation approaches and highlight the consequences of differing levels of technology innovation and societal behaviour changes. They are not in any way prescriptive, but they do lay out the scale of the transformation and the potential for different technologies.

Such an approach helps scope the opportunity for policy and regulation to enable new technologies, propositions and business models to be developed, financed and deployed at scale and with pace. It starts to frame possible solution sets for the most challenging aspects of the transformation – like decarbonising home heating.

If this work can help build consensus for credible action it will have taken us all an important step closer to moving from aspiration to delivery, unleashing the innovation the transition to Net Zero depends on.

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Energy Systems
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EXECUTIVE SUMMARY

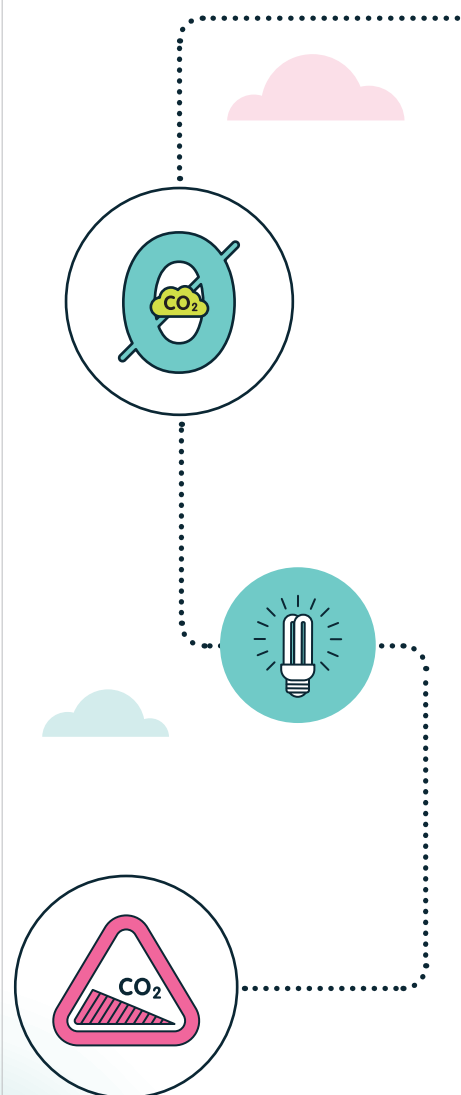
Rising to the challenge

Meeting the UK's Net Zero target will require unprecedented innovation across the economy. Innovation not just in new technologies, but in new ways of deploying existing technologies, new business models, new consumer offerings, and, crucially, new policy, regulation and market design.

Unleashing innovation at the pace and scale needed requires a deep understanding of how the different parts of the energy system interact; in short, taking a whole system approach.

This report updates Energy Systems Catapult's national Energy System Modelling Environment (ESME) to consider the potential pathways to 2050, and to help identify the technologies, products and services which are most important to meeting Net Zero. It recommends what needs to happen during this Parliament to deliver Net Zero levels of investment, infrastructure and innovation.

While the challenge is daunting, the commercial opportunity for those companies able to deliver the innovations needed is huge. This analysis will help identify those opportunities, and what may be needed to unlock them. While our assumptions should be challenged, our goal is to show 'what you have to believe' in order to deliver Net Zero.



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Electricity generation
may have to double
by 2050

Key messages

Net Zero narrows the set of viable pathways for the future energy system.

Where an 80% target allowed considerable variation in relative effort across the economy, with some fossil fuels still permissible in most sectors, Net Zero leaves little slack.

Success depends on innovation across the whole system; in technology, land use change *and* behaviour.

Net Zero requires switching to low carbon technologies wherever we can, tackling demand for hard-to-treat activities (aviation and livestock), and ensuring sufficient carbon sequestration to offset any residual emissions. Each of these elements faces significant barriers and technology and land use changes are constrained by maximum feasible deployment rates and competing uses of land.

So far, decarbonisation has mostly relied on 'upstream' changes in the electricity mix and reduced energy use in industry. Net Zero requires society-wide adoption of low carbon heating and transport technologies. It may also mean limiting growth in aviation demand and changing diets.

Our early public engagement suggests a general willingness to adopt new technologies (such as new heating or mobility) as long as these can deliver the same experiences as before. However, approaching the subject of dietary change or aviation often elicits a more resistant and emotional response. **Serious societal engagement is therefore essential to the UK's ability to meet Net Zero** given the nature and pace of the changes required.

Serious societal engagement is therefore essential to the UK's ability to meet Net Zero.

Even if demand for aviation and livestock products were eliminated by 2050, and technology deployment raised to even more ambitious rates, Net Zero could only be brought forward to 2045. Achieving an earlier target date would require non-linear reductions in demand (or breakthrough technologies for carbon removals). Our early public engagement around Net Zero makes us cautious of pathways that rely on widespread, rapid adoption of such changes.

CCS and bioenergy are both essential to delivering Net Zero. When the target was 80%, failure to deploy CCS had the highest cost impact of all sensitivities, but the target could still be met. Similarly, it was possible to meet the 80% targets without any scale up of biomass, albeit incurring higher system cost. With a Net Zero target, failure to deploy *either* option means foregoing the negative emissions essential to offsetting continued demand for aviation and livestock products. Our modelling finds it extremely difficult to meet Net Zero in those circumstances.

CCS deployment is essential for mitigating industrial emissions and can play a central role in hydrogen production. The power sector could act as an anchor for early CCS deployment but its long-term role here may depend on achieving very high (99%) capture rates.

Land use must be optimised to balance carbon sequestration with other priorities. New forestry can provide a net carbon sink for decades during growth and bring wider environmental benefits. Biomass crops, when regularly harvested for energy (coupled with CCS), offer more intensive and indefinite sequestration. To make an impact by 2050, planting must begin in earnest soon, supported by a deepening of the evidence base on the carbon and non-carbon costs and benefits.

Net Zero means a profound transition away from fossil fuels.

While an 80% target still saw fossil fuel's share of final energy use at 50%, Net Zero sees that fall to 25% (mostly in aviation and industry, where alternatives are hard to see).

Therefore, **zero carbon energy vectors require unprecedented scale-up to dominate final energy use.** With few exceptions, final energy must be delivered by vectors that are zero carbon at point of use, i.e. electricity, hydrogen and district heat. By 2050:

- **A new low carbon hydrogen economy will need to be created, delivering up to 300TWh** per annum, roughly equivalent to electricity generation today.
- **Electricity generation itself may have to double, or even *treble*** if most hydrogen is to be produced by electrolysis.
- **District heat may need to deliver up to 150TWh** per annum, up from 12TWh today.

CCS and bioenergy are both essential to delivering Net Zero.

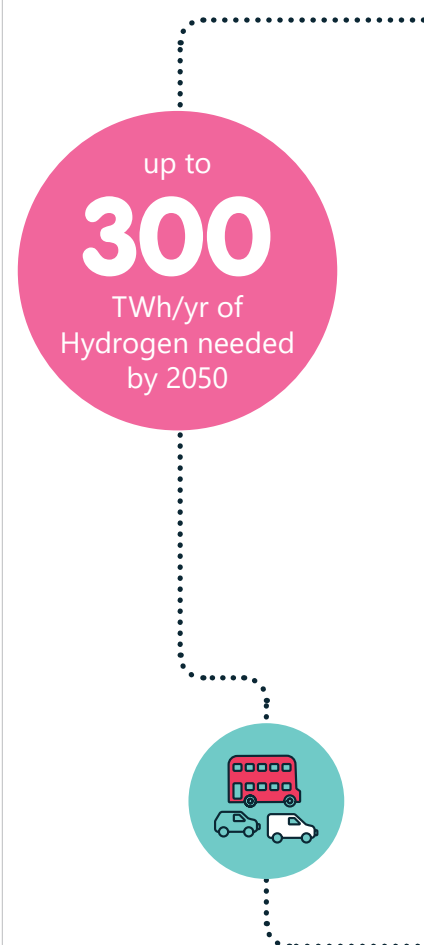
To deliver this, the UK must support innovation and deployment across a portfolio of low carbon energy conversion technologies:

- **For Electricity:** offshore wind (including floating turbines for deeper waters); large and small modular nuclear subject to demonstration and cost reduction; and CCGT with CCS as an important anchor in the early years (although this may now be limited to a transitional role if it is unable to increase its capture rates).
- **For Hydrogen:** steam methane reformation with CCS may offer the lowest cost route, while bio-gasification with CCS offers the co-benefit of negative emissions. But given implementation risks for these, electrolysis remains an important option for bulk production as well as offering unique opportunities for integration of renewables and more distributed hydrogen production. Advanced nuclear concepts are also emerging as a potential route to low cost hydrogen production.
- **For District Heat Networks:** industrial heat offtake and geothermal sources could contribute, subject to local availability. But if heat networks are to be deployed at scale, large heat pumps offer a proven solution, while small modular nuclear reactors offer potential for combined heat and power, subject to demonstration, and social and political acceptance.

Beyond bulk energy provision, a significant increase in different types of storage and flexibility is needed. While we have seen major innovation and deployment of fast-reacting battery technology in recent years, we are going to need similar innovations in multi-vector storage technologies across different timescales (from seconds to seasons), to manage extreme weather conditions with minimal reliance on unabated fossil fuel back-up systems. A significant opportunity exists for distributed heat storage in those millions of homes that will transition to heat pumps.

The transport sector requires the greatest increase in ambition from previous 80% pathways and must be fundamentally transformed by 2050. Emissions headroom allowed for continued fossil fuel use in every transport category, often with hybrid and plug-in hybrid vehicles for partial decarbonisation. For Net Zero, road transport requires the virtual elimination of fossil fuel consumption. Electrification is the most likely route, with hydrogen fuel cell vehicles playing an important role especially in heavier vehicles. Enabling smart charging will be essential to allow an efficient and smooth transition to electrified transport.

Emissions from shipping can be tackled through switching to hydrogen/ammonia-fuelled shipping, but global coordination will be required if UK emissions are to be substantially reduced.



Decarbonising heat will rely on deep retrofits for millions of homes and some mixture of electric heat pumps, hydrogen boilers and district heating depending on local circumstances.

Eliminating emissions from buildings is one of the most difficult challenges facing the energy sector, and requires significant technological and behavioural innovation. Our pathways suggest declining usage of the gas networks, as the deployment of heat pumps and heat networks gathers pace, weakening their economic case. If they are to continue operating, these networks will have to switch to hydrogen by 2045, which was not obviously necessary with an 80% target.

In some scenarios, parts of the gas network are decommissioned. In other areas these networks remain strategically important, especially where the average quality of the building stock means a full switch to electrified heating would be too costly. Here, gas networks are maintained despite reduced utilisation, supporting homes with hybrid heating systems. This underlines the importance of understanding local pathways to low carbon heating.

The uptake of unfamiliar low carbon heating technologies like heat pumps and heat networks will likely require **new market propositions which are as good or better for consumers than their current heating systems.** Innovation, including harnessing the potential of digital technology to give people more control of their heating and developing service offerings, will be needed.

Our pathways suggest declining usage of the gas networks, as the deployment of heat pumps and heat networks gathers pace, weakening their economic case.



up to
150
TWh/yr of District
Heat in 2050

Robust and enduring policies and regulation will be essential to building the necessary confidence with innovators to invest in low carbon products and services.

This report sets out an extensive programme of policy and regulatory reforms we think are necessary to unlock the innovation that our modelling analysis shows is required. These policy recommendations are detailed in 'What needs to happen during this Parliament' on page 50. These include:

1. Developing a balanced, economy-wide framework of **low carbon economic incentives** (comprising a mix of market, pricing and regulatory interventions) to shape market incentives for actors throughout emitting sectors of the economy.
2. Urgent development and gradual introduction of an enduring set of policies to fully decarbonise energy in buildings, crucially including **regulatory incentives to promote adoption of low or zero carbon heating** and changes to regulation of energy networks.
3. To reflect the different mix of low carbon solutions needed in different parts of the UK, introduce a consistent and robust approach to **Local Area Energy Planning**, potentially with the backing of a statutory framework. This will help identify the low carbon infrastructure and investment needed at a local level, and shape decision making by network companies, developers and planners.
4. Direct support for innovation and early deployment of **CCS and hydrogen production** in industrial clusters, including the development of investable funding mechanisms for CO₂ transport and storage infrastructure.
5. Fundamental **reform of power markets** to improve the efficiency of the system and unlock the potential of flexibility and distributed low carbon technologies. This includes providing more accurate time-of-use and locational signals, thus strengthening incentives for supply and demand to match user needs and local system circumstances.
6. Creation and adoption of an **open energy data and digitalisation governance framework** in line with recommendations of the Energy Data Taskforce. This can maximise the potential of digitalisation to enable tailored consumer-focused innovation, business models, market designs and consumer protections in the transformation of the energy system ahead.
7. **Development of tradable instruments such as carbon credits**, and associated market arrangements, to enable capital to flow to sectors where emissions reductions are being delivered most efficiently. This approach could unlock greater pathway flexibility and increase the scope for markets to reveal least-cost combinations.



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INTRODUCTION

The Net Zero Context

In 2015, the Paris Agreement committed all signatories to limit global warming to 2°C, and pursue efforts to limit this to 1.5°C.

In 2018, the IPCC published evidence on what would be required for a 1.5°C limit and the implications of not doing so.

Given this evidence, the UK Government asked for advice from the Committee on Climate Change (CCC). The CCC responded in May 2019, recommending a Net Zero emissions target by 2050. This was accompanied by supporting research, including ESC's Living Carbon Free¹ report which set out the implications for households.

The CCC report was released in the context of increasing public concern about climate change in the UK and around the world, with street protests, school pupils on strike, and public figures speaking out on the need to act urgently.

In June 2019, the Government amended the Climate Change Act from 80% to 100% GHG emissions reduction – or Net Zero – by 2050. 'Net' means balancing any residual emissions with an equal quantity of carbon removals from the atmosphere, as long as this takes place in the UK.

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Global context

The UK thus became the first major economy to adopt a Net Zero target, and many other countries have now followed, accounting for a substantial portion of global economic activity². While there are notable laggards, these countries can expect to face increasing pressure from the Net Zero bloc of countries as well as from domestic movements at grassroots, city or regional level, and increasingly from the private sector.

For many of the technologies necessary for Net Zero, there will be a strong global component in terms of research and innovation, early demonstration, and supply chains for deployment at scale. Wider global investment in these areas will be essential in enabling the UK to deliver on its targets. But Net Zero also presents a huge opportunity for UK innovators. The advantages gained through early demonstration and deployment of novel technologies and business models creates significant export potential. ESC has created support platforms for innovators for just this reason (see page 62).

Emissions Accounting

The analysis conducted here follows territorial emissions accounting, as legislated in the UK Climate Change Act. This measures all emissions that physically arise in a country, including in the production of goods destined for overseas markets.

As a *net importer* of traded goods, this ignores a significant proportion of the emissions that result from what we consume in the UK. Indeed, while territorial emissions have nearly halved since 1990, the carbon footprint associated with overall consumption in the UK has remained high³.

Paying close attention to these *consumption emissions* can help us avoid measures that reduce UK territorial emissions by simply offshoring hard-to-treat activities to other countries. It would also help UK citizens to understand and reduce the true global impact of our activities.

The CCC advice

The CCC's Net Zero report built upon their earlier work exploring individual parts of the energy system. These publications on land use, hydrogen, biomass etc drew on insights from several different sources, including modelling supported by tools such as ESC's Energy System Modelling Environment (ESME). The CCC set out:

- **Core actions** consistent with balanced pathways to reach 80% against 1990 levels;
- **Further Ambition** measures to achieve a stretch target in each sector. Taken together across all sectors, these add up to a reduction of roughly 96%;
- **Speculative** measures across various sectors which, in some combination, would be necessary to achieve 100% or Net Zero. These measures are typically higher cost, less mature, or rely more heavily on social change.



We have adopted the concepts of Further Ambition and Speculative measures for the analysis shared in this report (see page 16).

The central message from the CCC is the need for economy-wide change: there is likely to be a doubling of electricity demand driven by the greater electrification of heat and transport; Carbon Capture and Storage (CCS) is now a necessity; and the use of hydrogen will be needed in industry, heat and heavy transport sectors like HGVs and shipping. Supporting more sustainable lifestyles can also help to deal with those emissions that are hardest to reduce through technology.

What does our analysis add?

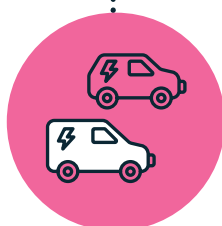
In this report, we detail new systems modelling conducted explicitly to meet Net Zero. This enables us to explore optimal pathways under different conditions, finding similarities and differences between them. Crucially, it allows us to understand how important individual technologies are in meeting the Net Zero target, partly through testing sensitivities. **This allows us to identify where deployment is most valuable and urgent.**

Such systems modelling **allows us to identify areas where innovation – the creation and deployment of new technologies, products and services – has the most potential value.** This may help identify where the greatest commercial opportunities lie and where policy attention is most needed.

This analysis draws out insights not just about what the 2050 energy system might look like, but also about the **potential pathways over the next 30 years**, as detailed in our scenarios on page 20.

Finally, before and since the CCC advice, other groups have shared their own views on how and when the target should be achieved. Some of these entail a more renewables-based approach, greater focus on demand reduction, pathways involving higher or lower reliance on biomass, or those that require dramatic changes in people's behaviours. Some groups have even called for Net Zero as early as 2025.

While the Net Zero discourse deserves a variety of perspectives, the analytical basis for these is not always made clear. In particular, ESC's wider Net Zero Insights programme includes early work assessing the public's willingness to significantly adapt their lifestyles, and suggests that it is right to be cautious about pathways that rely too heavily on aggressive reduction in carbon-intensive behaviours such as aviation. While assumptions should be challenged, **our goal is to show 'what you have to believe' in order to deliver Net Zero.**





Our Net Zero Insights programme

This modelling analysis is part of a wider programme exploring the implications of Net Zero across a portfolio of technologies and solutions. This includes engineering deep dives into the role of floating offshore wind; advanced nuclear technologies; storage and flexibility solutions; and hydrogen (including fuel cells) in buildings. We are also looking at the role of enabling trends, such as digitalisation of the energy system, and how this can help accelerate progress and reduce cost (but also creates new risks), as well as the market, policy and regulatory changes needed to achieve Net Zero. This fits within ESC's wider work on the future energy system.

Finally, we are engaging with the general public to test awareness around climate change and Net Zero, and to explore attitudes regarding the sorts of technologies and lifestyle changes described in this work. Early evidence suggests a general willingness to adopt new technologies (such as new heating or mobility) as long as these can deliver the same experiences as before. Conversely, approaching the subject of dietary change or aviation often elicits a more resistant and emotional response.

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TAKING A WHOLE SYSTEM APPROACH

ESC's mission is to unleash innovation and open new markets to capture the clean growth opportunity.

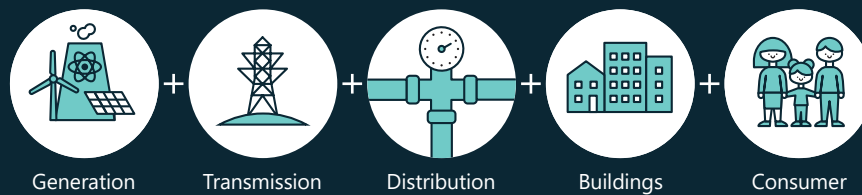
We work with industry, Government and academia to identify and overcome systemic barriers and unlock those opportunities that will transform the energy system and deliver maximum benefit to society.

Taking a *whole system approach* is integral to this mission, and our capabilities include coverage of:

- energy consumers, their expectations and attitudes
- energy end-use technologies in buildings, transport and industry
- energy vectors like power, hydrogen, heat, biofuels
- energy infrastructure for transmission, distribution and storage

What is Whole System thinking?

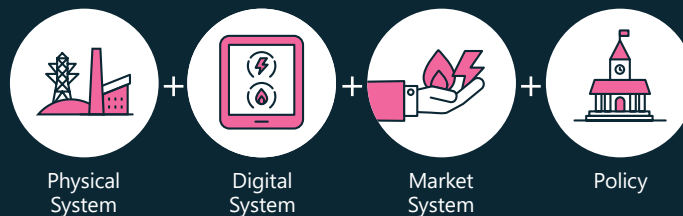
Joining up the system from sources of energy to the customer



Breaking down silos between different parts of the energy system



Joining up physical requirements of the system, with policy, market and digital arrangements



- energy integration at all levels from national, regional and local, down to individual buildings
- energy data and digitalisation
- energy markets, policy and regulation

Reflecting this approach, we have developed a set of modelling assets for every level of the energy system, from top-down, economy-wide whole system models, to models of the physics of individual housing types. We also have simulation tools and consumer research assets, which can help innovators explore and test their new business ideas.

We have a strong digital capability, which can provide platforms on which to test new ideas, manage datasets and extract insights from large quantities of data.

Our Insights Team have drawn upon a range of these capabilities and assets in preparing this report, but the key modelling tool we have drawn upon is our Energy System Modelling Environment, detailed on page 16.

Energy System Modelling Environment (ESME)

ESME was developed to evaluate the role of innovation in UK energy system decarbonisation, from energy resources and conversion through to end use in buildings, transport and industry. It is used by ESC, Government, industry, the Committee on Climate Change and academia.

ESME is an optimisation model and finds the least-cost combination of energy resources and technologies that satisfy UK energy service demands along the pathway to 2050. Constraints include emissions targets, resource availability and technology deployment rates, as well as operational factors that ensure adequate system capacity and flexibility.

Importantly, ESME includes a multi-regional UK representation and can assess the infrastructure needed to join up resources, technologies and demands across the country. This includes transmission and distribution networks for electricity and gas, and pipelines and storage for CO₂.

Since technology innovation is inherently uncertain, ESME was designed with a Monte Carlo mode, allowing us to run hundreds of simulations in one batch exploring different assumptions. This helps us identify 'low-regrets' technologies which feature consistently, or to understand the cost and performance characteristics required for individual technologies before these begin to deploy.

ESME is designed to be neutral in market, policy and regulatory assumptions. Policy analysis can draw upon insights from modelling, but these are typically not imposed on the model except in constructing specific scenarios. This approach allows for first examining the underlying cost and engineering challenges of meeting consumer needs, before considering whether and how to drive such outcomes.

ESME Net Zero update

ESME has been significantly upgraded so that credible transitions to Net Zero can be explored. These upgrades have drawn upon internal ESC expertise, key sources in the literature, and a series of workshops with sector experts.

Widening the scope of emissions

ESME is primarily a tool for exploring *energy systems*, where CO₂ makes up by far the largest share of GHGs. But emissions in other sectors affect the ambition needed in energy, including negative emissions. Accounting for all GHGs now allows us to better represent the impact of non-energy activities including livestock, land use change and forestry.

Expanding the technology option set

The previous options in ESME were sufficient for exploring 80% pathways. However, with tighter targets, ESME reached a limit of about 90% before running out of options for further abatement. This portfolio has now been enhanced and expanded. New options have been added for ships fuelled by hydrogen/ammonia, and options for decarbonisation of industry via electrification or hydrogen have been extended. Options for off-road mobile machinery to transition away from fossil fuels have also been added.

This new 'robust' option set enables ESME to reach 96%, equivalent to CCC's Further Ambition. From here, **further speculative measures are needed to reach Net Zero.**

Addition of Speculative measures

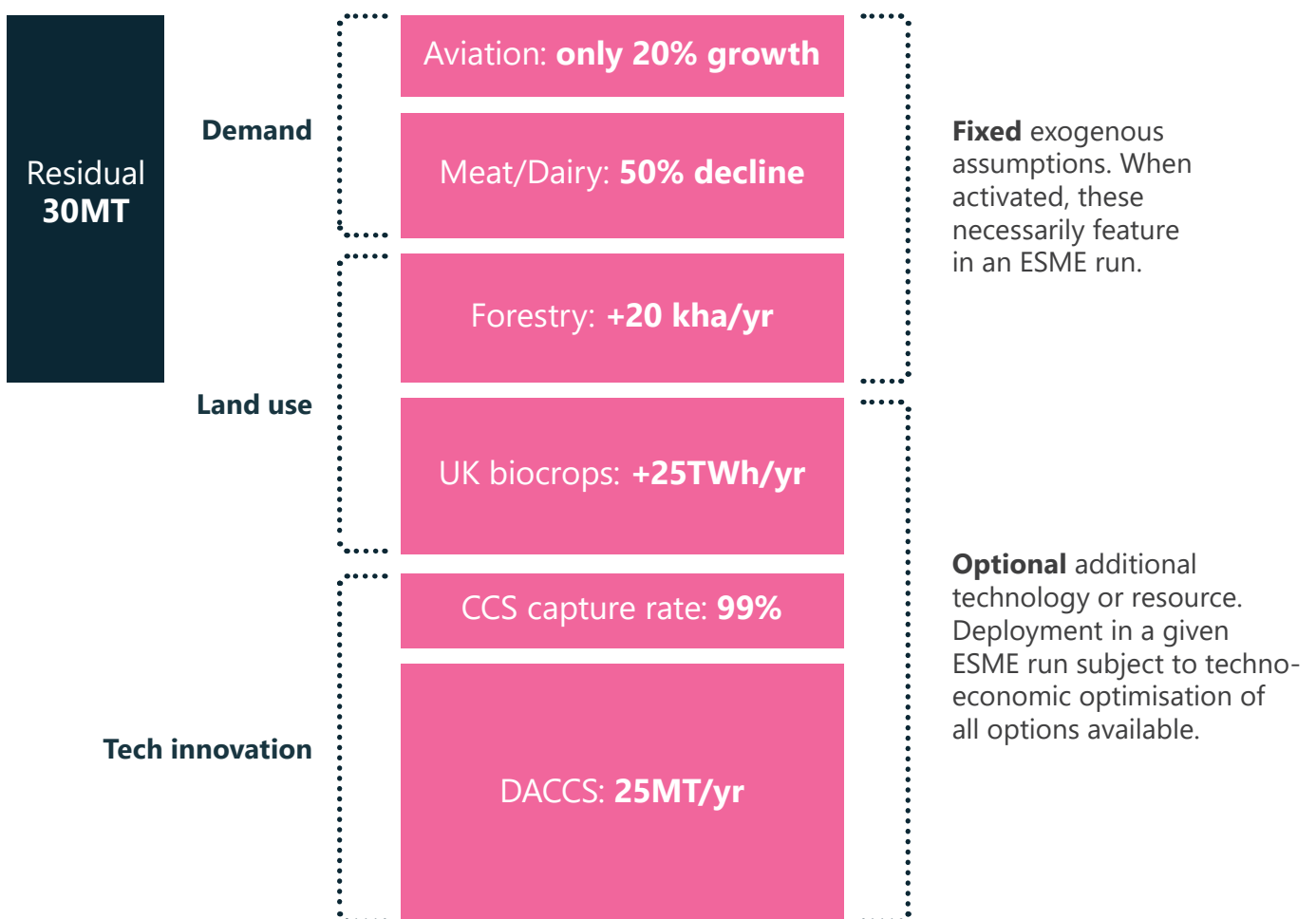
These comprise six measures including further technology innovation, behaviour change, and land use change:

- **Direct air carbon capture and storage.** Normally limited to a marginal role at 1MtCO₂/yr in 2050. Speculative allows this in 2040, scaling to 25 MtCO₂/yr in 2050.
- **99% carbon capture rate.** Normally limited to 95% capture rate. Speculative allows CCS to achieve 99% capture rates, with cost and energy penalties based on expert engineering assessment.
- **More UK biomass.** Normally the available sustainable quantity rises to ~120TWh/yr by 2050. Speculative allows for an additional 25TWh/yr.

- **More UK forestry.** Normally assumes tree planting of 30 kha annually to 2050 (i.e. 22 MtCO₂/yr sequestered in 2050). Speculative assumes 50 kha annually (33 MtCO₂/yr sequestered in 2050).
- **Reduced livestock.** Normally assumes a decline in meat/dairy consumption of 20% (delivering 8 MtCO₂e saving in 2050 versus today). Speculative assumes a decline of 50% (19 MtCO₂e saved).
- **Slower aviation demand growth.** Normally assumes an increase in passenger demand of 60% vs 2005 levels. Speculative holds this to only 20% growth.

In ESME, the first three represent *optional extra technologies or resources*. Activating these simply means making them available for the model to deploy if doing so would reduce overall system cost. The other three are fixed *exogenous assumptions*. When activated, they necessarily take effect, reducing the scale of emissions reduction required within the energy system.

Figure 1: Speculative measures for tackling residual emissions



Building scenarios

We have constructed a few different high-level scenarios to support our analysis, including:

- **FA96** – Further Ambition 96% target only, with no speculative measures.
- **TECH100** – Net Zero target with more technology-based measures: direct air capture, higher capture rates and extra biomass resource.
- **SOC100** – Net Zero target with more society-based measures: more UK forestry, reduced livestock and slower aviation growth.
- **BOB100** – Net Zero target with the 'best of both': technology and society-based measures.

BOB100 allows us to explore the largest possible 'solution space' for Net Zero pathways. However, planning on the basis that all speculative measures could be realised is inherently risky, so we prefer to apply these more selectively when choosing our 'core' scenarios (see next chapter).

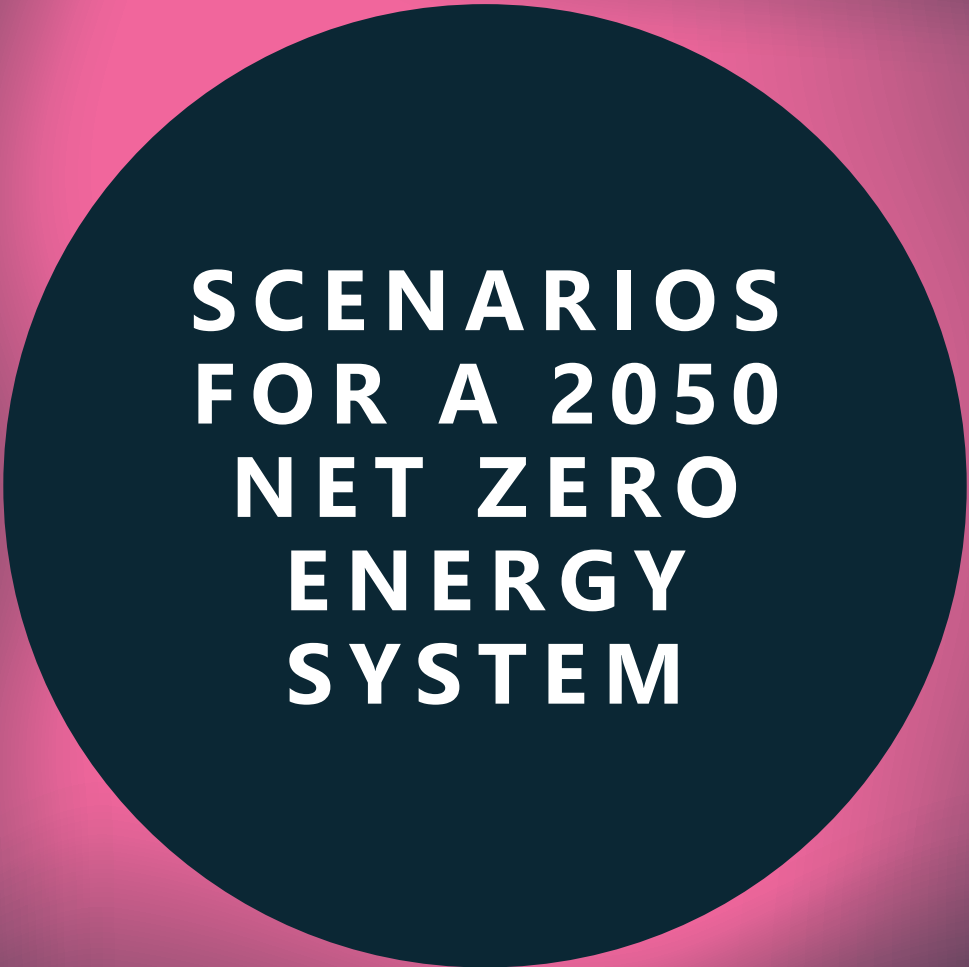
To generate a consistent Net Zero 'baseline' for our sensitivity runs, we started from the TECH100 assumptions. Our sensitivity runs include cases where a single solution is removed from the option set, such as No Biomass, No CCS or No (new) Nuclear. We also tested interesting combinations, e.g. ruling out Power CCS and Nuclear together to test the impact of No low carbon baseload.

We also asked: what would it take to achieve Net Zero earlier than 2050? This requires modifications to our exogenous demand assumptions that go beyond the speculative measures already discussed, resulting in a MAX sensitivity run (see page 45).

We laid the foundations for our core Clockwork scenario by using the TECH100 assumptions, while Patchwork uses the SOC100 set. More detail on the underpinning assumptions are detailed in the next chapter.

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**We also asked:
what would it take
to achieve Net Zero
earlier than 2050?**
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SCENARIOS FOR A 2050 NET ZERO ENERGY SYSTEM

This chapter describes two potential energy system pathways to Net Zero in 2050, Clockwork and Patchwork.

While these are not meant to be predictions or recommended pathways, they do explore two very different approaches to how the UK's decarbonisation targets could be met, highlighting some of the key challenges and opportunities any approach would face.

Clockwork – a centralised pathway to Net Zero

In Clockwork, coordination from central Government drives long term investment in strategic energy infrastructure. In the power sector, nuclear and wind generation are underpinned by policies that support development of the supply chain and workforce needed.

Recognition of the value of negative emissions leads to the creation of the necessary markets for the steady deployment of greenhouse gas removals technologies including carbon capture and storage (CCS), domestically grown biomass, afforestation and direct air carbon capture and storage (DACCS). Innovation in CCS pushes capture rates to 99%.

A supply of UK grown biomass is established, reaching 1.4 million hectares (mha) of land. This, along with residues from the 30,000 hectares of forest planted each year, provides 140TWh of domestic biomass in 2050.

Thanks to innovations in technology, policy and business models, the impact on people's lives is relatively modest. Indoor temperatures continue to rise to an average of 21°C by 2050 from around 18°C today. People still prefer to own cars and international travel demand continues to increase. However, a general shift towards vegetarian and vegan diets leads to a 20% reduction in meat and dairy consumption by 2050.

The UK population grows by five million from today to 71.5 million by 2050. This growth is concentrated in the South East, but there is a continued move towards suburban living.

Patchwork – a decentralised pathway to Net Zero

In Patchwork, central Government takes less of a leading role, resulting in a patchwork of regional low carbon strategies. A programme for large nuclear plants does not progress beyond Hinkley Point C and two others, although regions with a history of nuclear power favour small modular reactors (SMRs). In contrast, the popularity of renewables means offshore wind, distributed solar PV and other renewable energy technologies supply most of the electricity.

Without clear central policy on negative emissions and storage of CO₂, a UK biomass supply struggles to grow. However public support for woodland sees planting rates of 50,000 hectares per year, which is able to contribute to the domestic supply of 80TWh of biomass by 2050. A delayed recognition of the importance of negative emissions means the UK turns to biomass imports to top-up domestic supply. CCS is first deployed five years later than in Clockwork and capture rates do not go beyond 95%, while deployment of Direct air capture is negligible.

The population is very engaged with the climate change agenda adopting a number of lifestyle changes to help reduce greenhouse gas emissions. Consumption of meat and dairy halves by 2050. A combination of consumer choice and smart heating controls means the average indoor temperature of homes levels out at 19.5°C. International aviation demand slows to 2035, then begins to fall back.

The UK population grows by 8.5 million to reach 75 million by 2050. There is greater migration of people to cities leading to a slowing of growth in car travel demand as people live closer to work and have greater access to public transport.

Clockwork deep dive

Buildings and heat

Retrofit measures are applied to ten million homes at E-G rating, reducing their space heating demand by 20-30%. However, in many homes this leads to further 'comfort taking', with average indoor temperature following an upward trend to 2050. Despite increasing temperatures, new building standards and retrofits mean overall energy consumption for space heating remains similar to today.

Electrification

In thermally efficient homes, electric heat pumps are installed as standalone systems. In less efficient homes, these are typically installed as part of a hybrid system, with gaseous heating providing supplementary heat for peaks and cold spells. This arrangement reduces the strain on the electricity grid during peak periods and minimises the capital cost of home heating systems by sizing heat pumps to meet baseload heat only. By 2050, 58% of the UK's domestic space heat demand is supplied by heat pumps.

District heating

In major population centres around the UK, large district heat networks are rolled out from 2030 onwards. Since high uptake rates are essential to the economics of heat networks, local strategic planning is required to identify those areas where heat networks offer customers the best, most cost-effective solution.

Gas and biomass CHP plants help to seed early, small-scale networks. As these begin to grow and connect up, heat is also recovered from large thermal power plants. Eventually, as carbon constraints begin to limit the operation of CHP and thermal power plants, nuclear small modular reactors are deployed to provide the bulk of the heat into these networks. Gas CHP facilities remain in service at very low loads, providing flexibility and resilience, before this duty is taken over by hydrogen boilers by 2050.

Gas networks

Gas usage begins to decline in the 2030s, then more rapidly in the 2040s as deployment of heat networks and electric heat pumps gather pace. In some areas, parts of the gas network are decommissioned. In other areas these networks remain strategically important, especially where the average quality of the building stock means a full switch to electrified heating would be too costly. Here, gas networks are maintained despite reduced utilisation, supporting homes with hybrid heating systems comprised of an electric heat pump and gas boiler.

Those areas where networks are retained must undergo a hydrogen switchover, beginning in 2040. By 2050, most homes still connected to gas networks are being supplied with hydrogen.

Figure 2: Clockwork space heat production

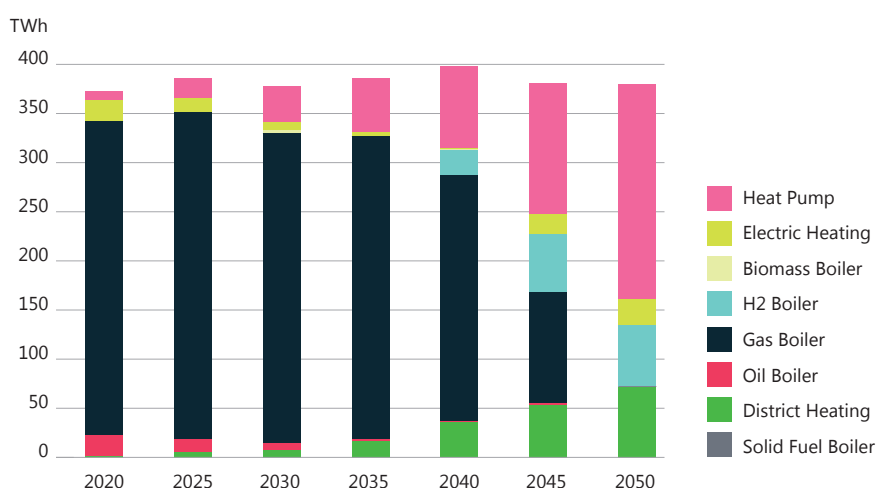
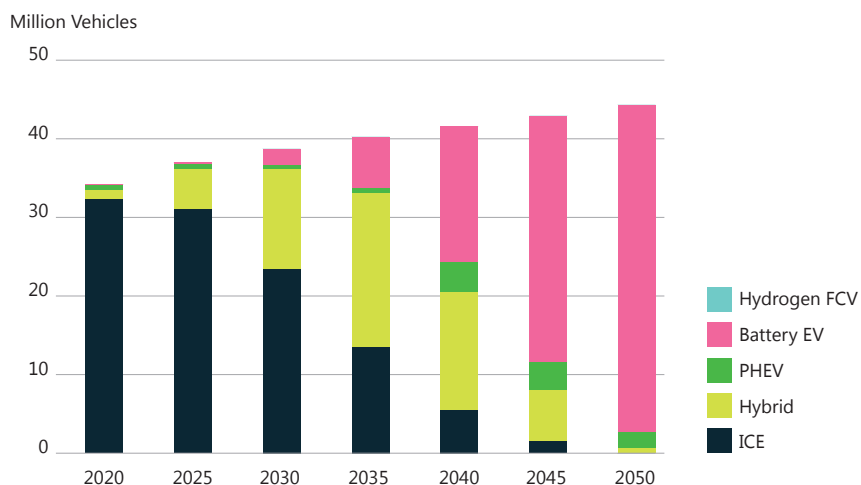


Figure 3: Deployment of cars in Clockwork



Increased electrification of road transport has multiple benefits: firstly decarbonisation, with petroleum products making up less than 10% of the energy consumed for transport in 2050, delivering a 97% reduction in the associated CO₂ emissions compared to 2020; secondly, improved energy efficiency, with 2050 energy consumption for road transport being just over a third of that in 2020 despite the numbers of vehicles on the road increasing; and finally, improved air quality from the virtual elimination of tailpipe emissions.

Transport

Demand for transport in Clockwork continues to increase with people less prepared to make lifestyle changes to reduce reliance on privately owned cars or curb their appetite for flights abroad.

Aviation and shipping

The number of international flights continues to increase, with the average distance flown by people in the UK reaching an average of nearly 7,500km per year by 2050. New engine and aircraft designs increase efficiencies through to 2050, improving the fuel consumption of aircraft. However, without new, low-carbon propulsion technologies, aviation is unable to move away from fossil fuels.

Heavy fuel oil ships are phased out completely by 2040. A transition to dual fuel ships burning a combination of fuel oil and natural gas starts in the 2020s. Hydrogen-fuelled ships become available in the 2040s. Most ships operating from the UK are fuelled by hydrogen in 2050 resulting in a complete decarbonisation of the sector.

Road transport

The Government ban on new ICEs prompts manufacturers to release a range of hybrid and electric vehicles (EVs). Plug-in hybrids see a relatively modest uptake, with EVs being the preferred option both from the point of view of the manufacturers, who focus efforts on producing vehicles with a single powertrain, and the consumer, now satisfied with the range possible on a single charge.

Hydrogen fuel cell cars are too expensive compared to EVs and fail to compete in this market. However, hydrogen is used in heavy goods vehicles as both a primary fuel and as a way of extending the range on battery electric trucks.

Industry

There is an overall growth in industry to 2050, but a combination of energy efficiency improvements and a gradual shift away from more energy intensive activities means industrial energy consumption actually decreases by 19% by 2035. Energy consumption levels off to 2050 as efficiency improvements are balanced against expansion of industrial activity.

Industrial carbon capture and storage

Some industrial sectors adopt carbon capture processes from 2030. CCS is predominantly applied to the heavy industries (iron and steel, chemicals, cement) located in industrial clusters. These are areas where industries are in close proximity to each other. Clusters tend to be located in coastal regions enabling access to the offshore CO₂ storage sites. By 2050, 28mtCO₂ is captured by industry directly.

Industrial fuel switching

In addition to efficiency measures and CCS, industries adopt a range of fuel switches from high carbon fossil fuels to biomass, hydrogen and electricity. Some industries also switch processes that use high carbon fuels to gas in an effort to decarbonise. Hydrogen replaces natural gas and liquid fuels in a number of industries including both clustered and dispersed sites. Hydrogen consumption in industry increases with the emergence of CCS in hydrogen production methods using natural gas or biomass. Industrial emissions reach roughly 12mtCO₂ in 2050.

Hydrogen

In 2050, around 250TWh of hydrogen is needed to meet demands for industry, space heat, flexible power generation and heavy-duty transport (including shipping). Emissions headroom created by 25MtCO₂ of DACCS and high capture rate CCS (99%) means 216TWh of hydrogen can be produced by steam methane reformation with CCS. The remaining 34TWh is produced by biomass gasification with CCS.

Geological storage of 660GWh of hydrogen is needed in 2050 to ensure homes with H2 boilers can be supplied with enough hydrogen during an extreme weather event during the winter. This is significantly less than the underground natural gas storage capacity on the system today (approximately 15,000 GWh).

Power

Clockwork sees extensive electrification of road transport, heating and industry which leads to 524TWh of electricity consumed in 2050 (up from around 300TWh in 2015). Of the electricity supplied, approximately 40% is delivered by onshore and offshore wind, and 50% by nuclear generation.

Flexible generation in 2050 is provided by 6GW of combined cycle gas turbines with CCS and 22GW of hydrogen turbines.

The emissions headroom created in other sectors, alongside short periods of operation, means capture rates of 95% on CCGTs are sufficient, providing a cost saving compared to 99% systems. These technologies provide a back-up role during the peak demand periods. Therefore, annual electricity supplied by these two technologies is approximately 1% of the total in 2050 (Figure 5). Further day-to-day flexibility is also provided by 8GW of electricity storage and 10GW of interconnectors.

Figure 4: Power generation capacity

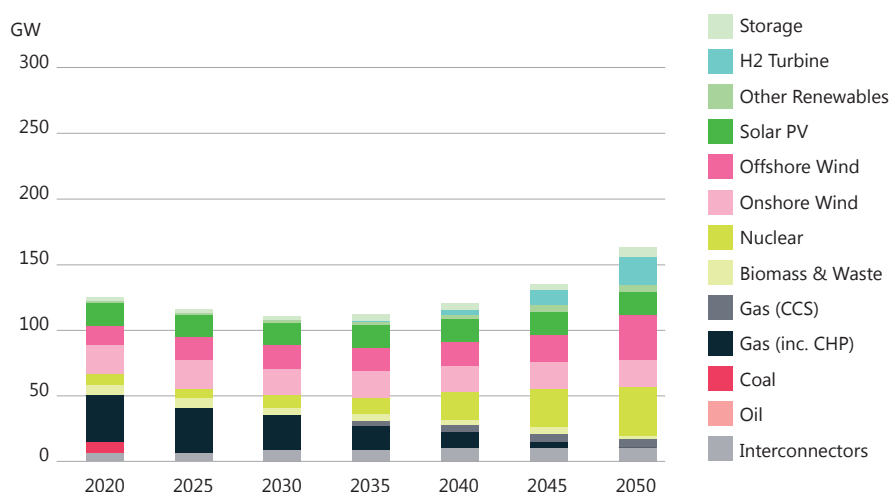
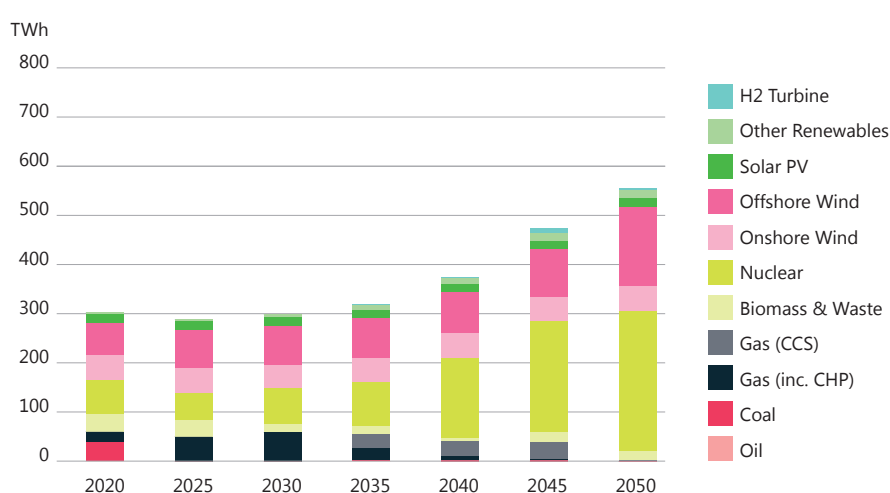


Figure 5: Electricity supplied



Patchwork deep dive

Buildings and heat

Around 11.5 million homes of E-G rating are retrofitted by 2050, reducing space heat demand by 20-30%. Greater urbanisation means more people live in high-density dwellings with lower heat demands. The Patchwork population seek to reduce their carbon footprints by making changes to their lifestyles. For example, changes such as wearing additional warm layers rather than turning up the thermostat, and adoption of smart heating to better control where and when heat is provided, means average indoor temperatures are limited to an average of 19.5°C by 2050.

Electrification

A steadily growing heat pump market increases people's confidence in the technology's ability to satisfy their heating needs. From the mid-2030s, when people are faced with the need to replace their gas boilers, many opt to overhaul their entire heating system. Heat pumps are installed in combination with hydrogen-ready boilers, which provide a boost of heat during cold days.

District heating

In Patchwork, there is greater migration of the population to major cities, which are more suited for district heat networks. Early heat networks are small and most of the heat is provided by gas and biomass CHP systems. Heat offtake from thermal power generators provides additional energy as heat networks grow.

However, as carbon constraints begin to limit operation of these plants, heat must be provided by other means. Solutions depend on the region with some areas making use of geothermal resources, whilst others rely on large-scale heat pumps. Some areas adopt nuclear small modular reactors, exploiting the waste heat from these plants.

Flexibility and resilience of the heat networks is provided by gas CHP plants that remain in operation for the peak periods. By 2050, natural gas peaking systems are replaced with large scale hydrogen boilers.

Gas networks

Gas boilers play an important role in providing space and water heating in homes until the mid-2040s. New boilers installed after 2035 are hydrogen-ready in preparation for the big switch in 2050 when natural gas ceases to play a role in domestic heating. These boilers provide peak heat during cold weather events and winter evenings for those homes not connected to a district heat network.

Figure 6: Patchwork space heat production

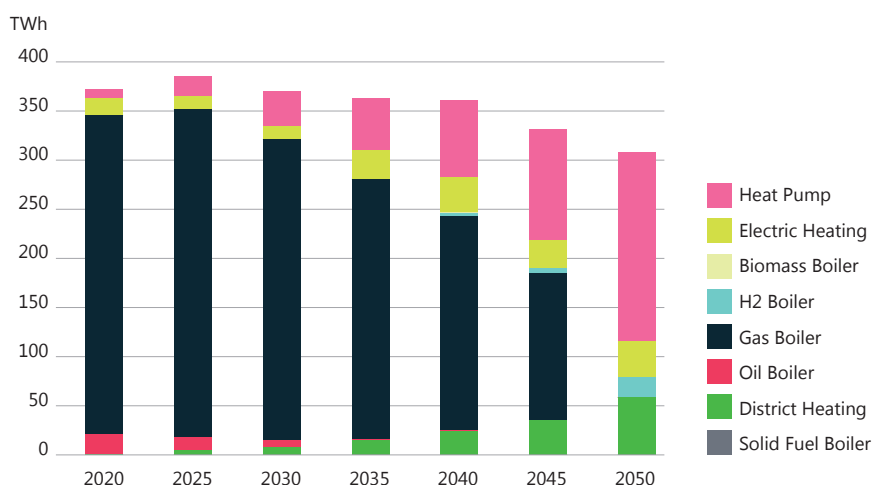
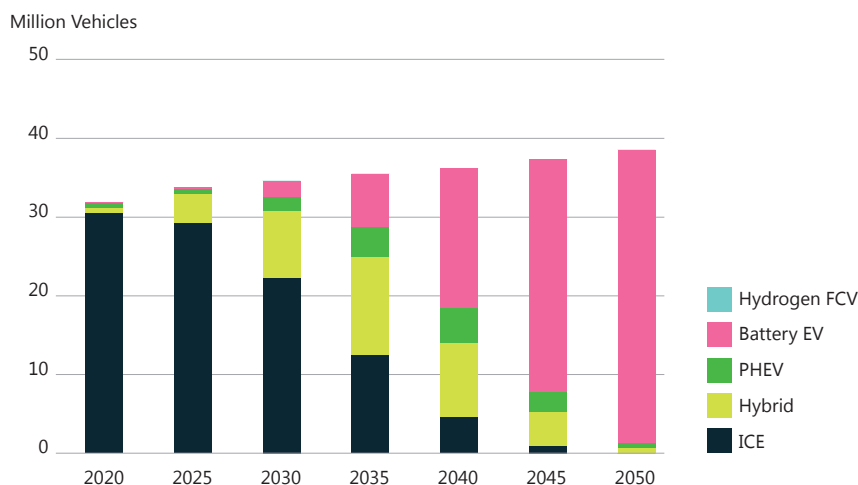


Figure 7: Deployment of cars in Patchwork

Transport

A combination of urbanisation, different working habits, and a positive public response to the need for climate action leads to a fall in demand for private car ownership. Instead a combination of public transport, walking and cycling is made possible by improved access to these transport modes and through effective town planning.

The flight shame movement resonates with a population that is concerned with reducing greenhouse gas emissions, and demand for international flights falls away from 2035.

Aviation and shipping

By 2050, the average distance travelled is 5,000km per person per year – equivalent to two short trips to Europe each year. These short haul journeys to the continent might one day be suitable for some form of low-carbon aircraft but this does not happen before 2050. So, to maintain an industry in a world where people are concerned with their individual carbon footprints, flight operators ensure that their aircraft are the most efficient on the market, retiring older planes when better ones become available.

Demand for international shipping rises steadily to 2050, partly in response to a shift away from air travel to Europe. However, by 2050, the international shipping fleet is almost entirely decarbonised through the use of hydrogen.

Road transport

Although private car ownership is less important to people in Patchwork, the number of cars on the road steadily increases to 2050. However, in response to the Government ban on ICEs and hybrids and consumer preference for low carbon transport, EVs become the most common type of car on the road by 2040.

Hydrogen fuel cell cars are less favoured due to their relative expense compared to EVs. Range anxiety and charging time is also less of an issue in a world where people are prepared to make changes to their behaviour and habits to accommodate low carbon options. Hydrogen finds its way into heavy goods vehicles either as a primary fuel or to extend the range of electric trucks.

5,000km

The average distance flown per person per year in 2050

Industry

In Patchwork, there is a decline in the traditional energy intensive industries as activity shifts towards high value engineering and services sectors. This, in combination with energy efficiency improvements, means industry in 2050 consumes approximately two thirds of the energy it does today.

Industrial carbon capture and storage

Due to a lack of national strategy on CCS, industrial CCS fails to emerge until 2035. CCS is deployed predominantly in industrial clusters where the remaining heavy industry is located, smaller industries that are closely located to clusters can also make use of the CO₂ pipelines laid for the larger point sources. Since these regions tend to be coastal there is good access to offshore CO₂ storage sites. By 2050, 13Mt of industrial CO₂ emissions are being captured. Net emissions from the whole of industry fall from approximately 100MtCO₂ today to 10MtCO₂ in 2050.

Industrial fuel switching

By 2050 industry as a whole has largely transitioned away from fossil fuels to the point that 68% of the energy required is provided by a combination of hydrogen, electricity and biomass. However, natural gas continues to play an important role in industry.

Use of hydrogen in industry is predominantly found in the dispersed industries. These industries may struggle to connect into a CCS network if they are located too far from an industrial cluster and so electrification and hydrogen provide low carbon solutions to provision of industrial heat.

Hydrogen

Production of hydrogen in 2050 is a mix of biomass gasification with CCS and electrolysis, producing 65TWh and 110TWh in 2050 respectively. A small amount of steam methane reformation is also deployed but failure to innovate CCS systems to achieve capture rates beyond 95% limits the amount of hydrogen that can be produced in this way to 11TWh.

Despite delays in CCS deployment and a lack of innovation in capture rates, biomass gasification remains of great value to the energy system because of the negative emissions that can be achieved. After 2035, a market for negative emissions begins to grow but a disjointed policy framework and scepticism from farmers means a supply chain of domestic biomass fails to reach its full potential. These factors combine to limit UK biomass to 80TWh in 2050 prompting the UK to import additional biomass at extra cost. The majority of this biomass is used in hydrogen production, with some being used in industry and power generation.

There is great public support for the planting of trees in an effort to reduce greenhouse gas emissions. Planting rates of 50,000 hectares per year of new woodland are achieved by 2050. Some of this woodland is planted on land previously set aside for grazing animals, which becomes available as meat and dairy consumption halves by 2050.



Power

Very high levels of electrification are seen in Patchwork, which is needed to decarbonise transport, heating, industry, and provide hydrogen by electrolysis. Patchwork is a high renewables scenario with 53% of the 700TWh of electricity coming from on and offshore wind. Other renewables such as solar PV, tidal stream and geothermal supply another 21%. Due to intermittent supply and lower load factors compared to nuclear power, a total of 190GW of renewables capacity is deployed.

A programme for nuclear power fails to materialise due to low public support and a lack of policy which would de-risk investment and drive costs down through learning-by-doing. As a result, nuclear generation is limited to three large generation III plants. In addition, there is a handful of small modular reactors in regions with a history of nuclear power, eager for the jobs this industry provides. Even with this low deployment scenario, nuclear plants still supply 23% of the electricity produced in 2050.

To ensure supply during cold periods with low wind speeds, 55GW of peaking plant is needed, including 30GW of hydrogen turbines. These make use of hydrogen produced by electrolysis during periods of high renewables output and low demand (such as the summer and overnight winter periods) and stored in salt caverns. Geological storage of 600GWh of hydrogen in 2050 provides a long-term storage option for electricity.

However, during cold weather events, hydrogen is also needed to provide domestic heat by hybrid systems. Competing uses of hydrogen during peak periods means 20GW of gas turbines operating with CCS are also necessary. Both the hydrogen and gas plants operate with a very low load factor, providing just 1% of the total electricity supplied in 2050. Interconnection with Europe and 4GW of electricity storage also support peak provision of power in 2050.

Figure 8: Power generation capacity

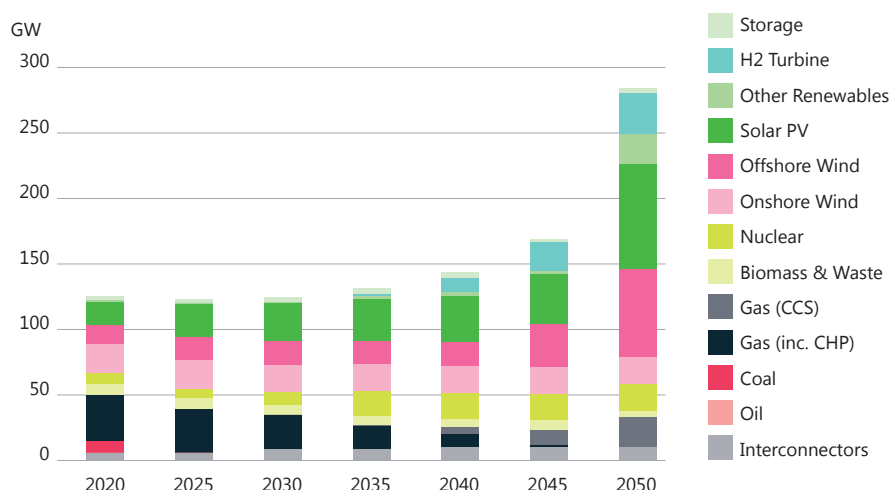
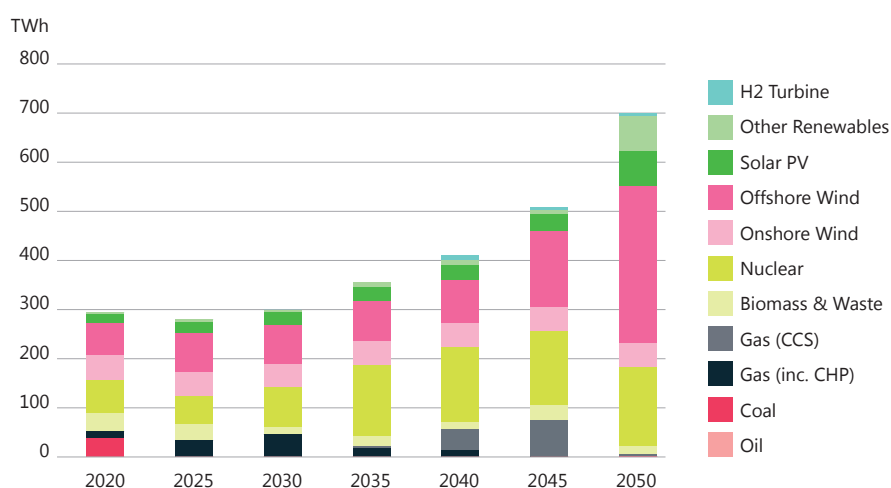


Figure 9: Electricity supplied





NET ZERO ENERGY SYSTEM INSIGHTS

The scenarios in the previous section allow us to illustrate the key features of individual pathways in some detail.

But the real power of models like ESME is in generating many such pathways under very different assumptions, to support decision-making under uncertainty. In this section we share the emerging insights from the wider set of runs conducted with ESME Net Zero to date.

The Net Zero solution space

In modelling, the set of all possible solutions to a problem is known as the solution space. For ESME, the problem is to meet energy service demands out to 2050, by deploying a set of technologies and resources, subject to a set of constraints, including carbon emissions.

Monte Carlo analysis gives us many different 'solutions', which act as a guide to the overall solution space. The edges of this space close in as the problem gets harder due to higher demands, fewer technology options, or tighter constraints (until, at a certain point, there are no solutions). The switch to a Net Zero emissions target has, unsurprisingly, significantly reduced the solution space.



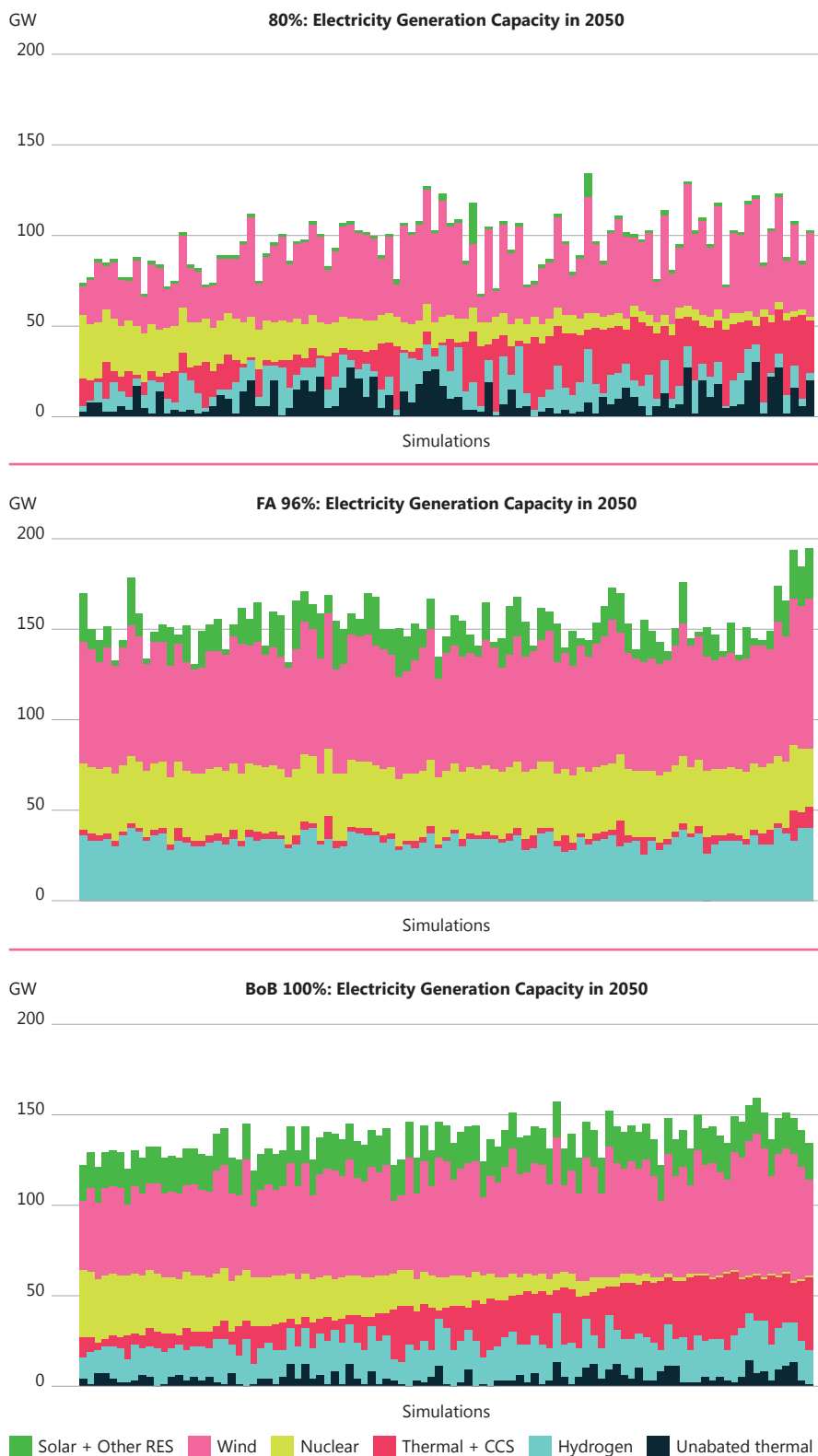
In ESME's Monte Carlo mode, demands and constraints remain fixed across simulations. This way we can establish, other things being equal, **the impact of particular technological innovations on the cost and configuration of the energy system**. In reality, demand trajectories are uncertain too, so we explore these through separate batches of runs based on alternative demand cases.

An 80% emissions target allowed for a sizeable quantity of residual emissions in 2050. This provided considerable slack and meant the possible solution space was relatively large. Although some technologies appeared prominently, in all cases they could be removed from the option set and the model could still meet the carbon target by configuring the system in some other way.

At Further Ambition 96% the system has very little slack. Certain technologies become indispensable regardless of cost and removing these from the option set leads to failure to meet the emissions target. Those simulations that do meet the target now closely resemble each other and many more constraints are binding, such as maximum deployment rates for technologies. Adjusting such constraints can have a significant impact under distressed conditions like this, so it is important that these are informed by proper engineering analysis and advice (see Timelines on page 47).

Achieving Net Zero requires the introduction of **speculative measures** (see ESME Net Zero update on page 16). Adopting all of these, including social and technological measures, reintroduces some slack and substitutability even though the emissions reduction constraint is tightened to 100%.

Figure 10: Range of outcomes for 2050 Power Capacity in three Monte Carlo batches (80%, FA96 and BOB100), one column per simulation



Power sector

The charts on the left are outputs from the power sector from three Monte Carlo batches corresponding to the old 80% target, Further Ambition (FA96), and a highly speculative Net Zero (BOB100). The charts depict 2050 power capacity across 100 simulations.

Moving from the 80% to FA96, the reduced variation across simulations is immediately apparent. In 80%, ESME has considerable freedom to respond to high/low cost trajectories for different technologies and select the cost-optimal combinations. In FA96, these cost variations still occur, but ESME has little freedom to adjust its choice of technologies.

In BOB100, sufficient speculative measures are added to overcompensate for the more stringent Net Zero target, thus we see more variation reintroduced across simulations. Some of the more specific factors behind these trends are discussed next.

Unabated thermal plant:

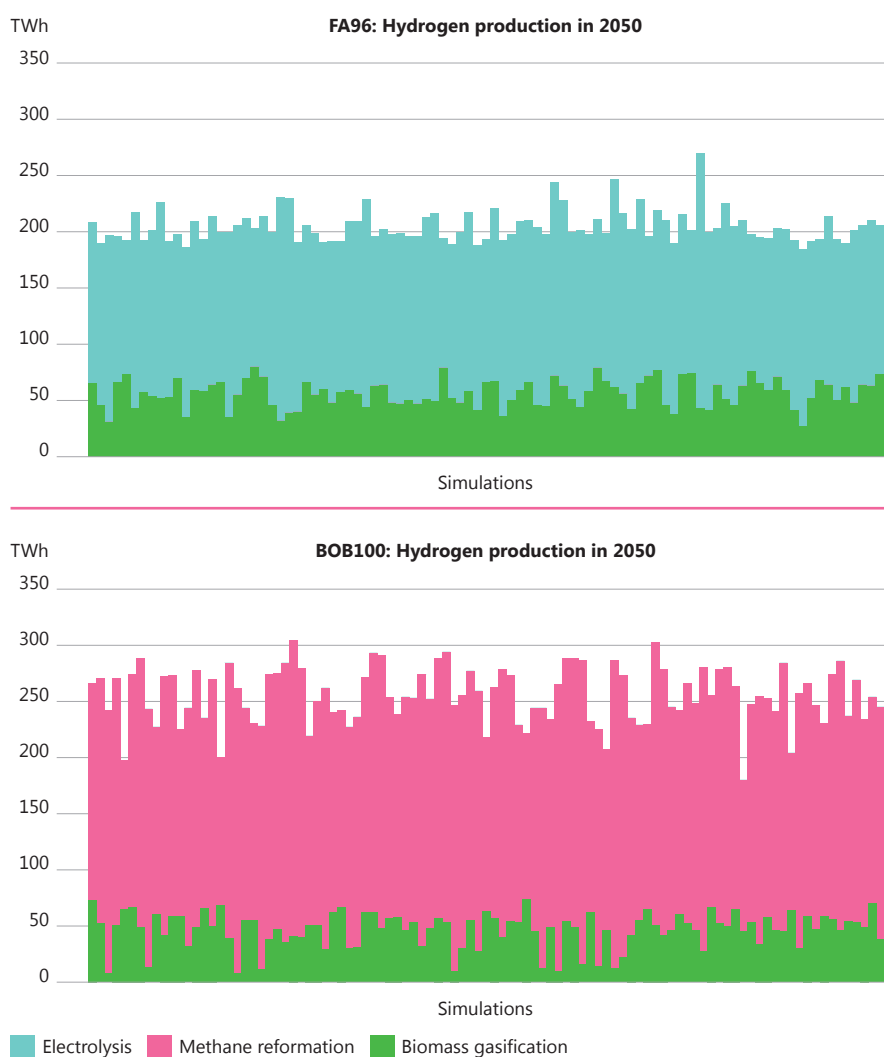
In FA96 there is no role for unabated thermal plant, such as open or closed cycle gas turbines due to the emissions, even at low load factors, making them uneconomic. However, in a BOB100 world, for some simulations a small amount of unabated thermal is deemed manageable, given negative emissions elsewhere.

Power CCS: For similar reasons, even CCS-equipped thermal plant is locked out of FA96. This is because carbon capture rates are capped at 95%, meaning 5% of combustion emissions still escape to the atmosphere, and the lack of any speculative measures means the overall emissions headroom in the system is severely constrained. This proves so prohibitive that nuclear is selected as the alternative baseload plant.

In the BOB100 world though, thermal CCS can achieve a 99% capture rate (and other measures elsewhere add some emissions headroom). Now, there is a clear competition between this technology and nuclear.

Overall capacity: These features also help explain why the simulations in BOB100 have lower power capacity in general, compared to FA96. In 2050, hydrogen becomes an essential energy vector in either world (see Figure 11). In FA96 this is mostly produced through electrolysis, pushing up electricity demand considerably.

Figure 11: Hydrogen production by volume in 2050 across two batches of Monte Carlo runs (FA96 and BOB100), one column per simulation



In BOB100, greater emissions headroom and the 99% capture rate makes steam methane reforming an attractive technology for production of the vast quantities of hydrogen needed in 2050. In fact, BOB100 tends to involve greater quantities of hydrogen overall than in FA96, since lower-cost hydrogen makes it more competitive against electrification in sectors like heavy-duty transport.

This analysis suggests that innovation to achieve 99% capture rates could prove transformative for the prospects of CCS in power and hydrogen (also see CCS section on page 34) beyond 2040.



System-wide sensitivity analysis

Land use for biomass and forestry

Forestry

In line with the CCC and others, our central assumption sees expansion of forestry from 13% today to 18% of UK land by 2050, or 4.8 Mha. New forestry acts as a carbon sink during its growth, before levelling off in later years. Allowing for this, and assuming steady tree planting over the 30-year period, this expansion would provide carbon removals of -22 MtCO₂e annually in 2050.

In addition to acting as a carbon sink, afforestation (and other habitat restoration) would support the recovery of biodiversity across UK ecosystems, and increase the amount of green space for people to enjoy.

Biomass

Dedicated biomass crops are an important part of a cost-effective low carbon energy system. Like forestry, biomass crops sequester carbon from the atmosphere during growth. When harvested and processed for energy, this has the potential to be a near carbon neutral resource⁴. When bioenergy is combined with CCS (BECCS) the sequestered carbon can be removed from the atmospheric carbon cycle permanently, resulting in negative lifecycle emissions.

Unlike forestry, where sequestration from a given land area will eventually level out, regular harvesting of energy crops gives the potential for sequestration to be sustained indefinitely⁵.

Biomass resource can be exploited through simple combustion for power or heat, or through conversion into liquid bio-fuels, bio-methane or hydrogen. Since conversion to bio-fuels and bio-methane transfers some of the carbon back into the atmosphere upon use, greater negative emissions are derived from BECCS processes that deliver carbon-free vectors, like electricity and hydrogen.

But the relative substitutability of different applications also matters. Since there are more low carbon options for power generation, limited biomass resource tends to be prioritised for hydrogen production (or hard-to-treat industry processes).

Today, dedicated biomass crops are negligible, with most UK-sourced biomass coming from agricultural and forestry residues (and the rest imported). Our central assumption sees a steady expansion of biomass on marginal agricultural land, covering 1.4Mha by 2050.

An argument can be made in favour of using this land to support further acceleration of tree planting, instead of biomass crops. There are important considerations here in relation to biodiversity, but the more intensive growth and sequestration from biomass crops means that foregoing this in favour of forestry would reduce the annual 'yield' of negative emissions.

In energy terms, 1.4Mha by 2050 provides a resource of 120TWh annually or roughly 5% of primary energy consumption today. In emissions terms, this delivers -34 MtCO₂e of sequestration in 2050.

We also assume a quantity of biomass imports, although this is limited to 34TWh annually in 2050, reflecting international competition for this scarce resource. This provides a further -9 MtCO₂e in 2050.

Under our central assumptions, the UK could achieve -65 MtCO₂e of carbon sequestration annually in 2050.

For an 80% target, our analysis showed it was possible to manage without expansion of biomass, though this had a significant impact on costs, pushing up the national abatement cost by ~50%.

In a Net Zero context, the impact is more profound. We anticipate continued emissions from aviation, livestock, and parts of industry, meaning the system *requires* negative emissions if the target is to be achieved. Given this, in our No Biomass sensitivity, Net Zero cannot be met. The system is left with residual emissions of 40 MtCO₂e in 2050 (after accounting for forestry and direct air capture).

The absence of biomass means substitutes must be found. For hydrogen production, the cheapest alternative would normally be steam methane reforming with CCS, but the lack of emissions headroom now means even the small residual emissions from this process are prohibitive.

This forces reliance on higher cost electrolysis instead, and since hydrogen is now higher cost, there is a more general shift in the direction of electrification elsewhere in the economy. Altogether 2050 electricity generation shifts from ~550TWh in the baseline to ~750TWh in a No Biomass case.

Innovation needs for biomass:

- Deepen the evidence base around optimal land use and land management to improve yields, maintain soil quality and biodiversity.
- Improve biomass feedstock improvement techniques to remove impurities prior to energy conversion.
- RD&D of biomass conversion technologies, especially gasification for hydrogen production.
- Maximising the value of biomass will rely on CCS (see page 34) to enable negative emissions.



We anticipate continued emissions from aviation, livestock, and parts of industry, meaning the system *requires* negative emissions if the target is to be achieved.



Carbon Capture and Storage (CCS)

CCS encompasses a family of technologies with applications in the production of various energy carriers (electricity, hydrogen, bio-methane and liquid bio-fuels), and in industrial processes like steel and cement manufacturing. In combination with biomass, CCS can help to generate negative emissions, alleviating the need to eliminate activities that are hard to treat, like aviation.

In an 80% context, because of its application across so many parts of the energy system, CCS had the highest opportunity cost of all technologies tested. Removing CCS doubles the overall abatement cost, but the target can be met.

For Net Zero, a paradox emerges, where CCS in the Power sector begins to retreat by 2050 (due to residual emissions), yet CCS overall becomes more essential than ever, given its role in industry, hydrogen, BECCS and direct air capture.

In our No CCS sensitivity, all these applications are unavailable and the Net Zero target is missed, with net annual emissions of 70MtCO_{2e} in 2050.

In this No CCS system, industrial CO₂ goes uncaptured, and other sectors must further minimise CO₂. Heating, transport and industry are all heavily electrified (and district heat networks extended) to minimise the need for hydrogen. Since unabated steam methane reforming is not an option and even biomass gasification (without CCS) has a small net positive carbon footprint, any hydrogen that is required must be produced via electrolysis.

The high demand for electrolysis puts additional strain on the power sector, which must generate ~820 TWh in 2050 (vs ~300TWh today).

Innovation needs for CCS:

- Globally, there are now more than 50 large scale CCS facilities (19 in operation). For the UK, the priority should be to catch up in terms of demonstration and deployment.
- Direct Government support is likely needed for the infrastructure to transport and store the captured CO₂, giving confidence to the private sector to back individual projects, including for industrial facilities, hydrogen production and power.
- By 2050 very high capture rates may prove critical given the lack of emissions headroom. For steam methane reforming, operating on a constant basis, 99% may be achievable. For power plants, this is likely to prove challenging when ramping up and down for load following.
- Nevertheless, CCS can play a transitional role in the power sector over the next 30 years, by offering immediate opportunities for anchor projects as infrastructure is rolled out. Achieving the highest feasible capture rates here would help extend the life of these plants.



Three key energy vectors

Energy in the UK currently reaches the end user via three principal vectors: petroleum, gas and electricity. In 2015, this was split roughly 45% oil/petroleum, 30% gas, 19% electricity (plus 4% biomass, 2% coal, 1% network heat).

Overall, about 75% of final energy delivered to the end user is fossil fuel. Since electricity is zero carbon at the point of use, an obvious decarbonisation strategy is to increase electricity's share of final energy use, while displacing fossil fuels in electricity generation.

Other zero carbon energy vectors (at point of use) include hydrogen and district heat. At present, production of hydrogen for energy purposes is virtually non-existent, while nationally the share of energy delivered by district heat networks is negligible. In a future low carbon energy system, both of these will likely have a very significant role where they provide a more practical or cost-effective alternative to electricity (as, in the case of heat networks, they already do in some European markets). This assumes they can be produced in a low carbon way.

To meet an **80% target**, fossil fuels still made up 50% of final energy demand (30% petroleum, 20% gas, with electricity making up 30%). While this may seem counterintuitive, the retirement of coal power plants (and deintensification of industry since the 1990 baseline) means that much of the 80% reduction is achieved 'upstream', limiting the impact on final energy use.

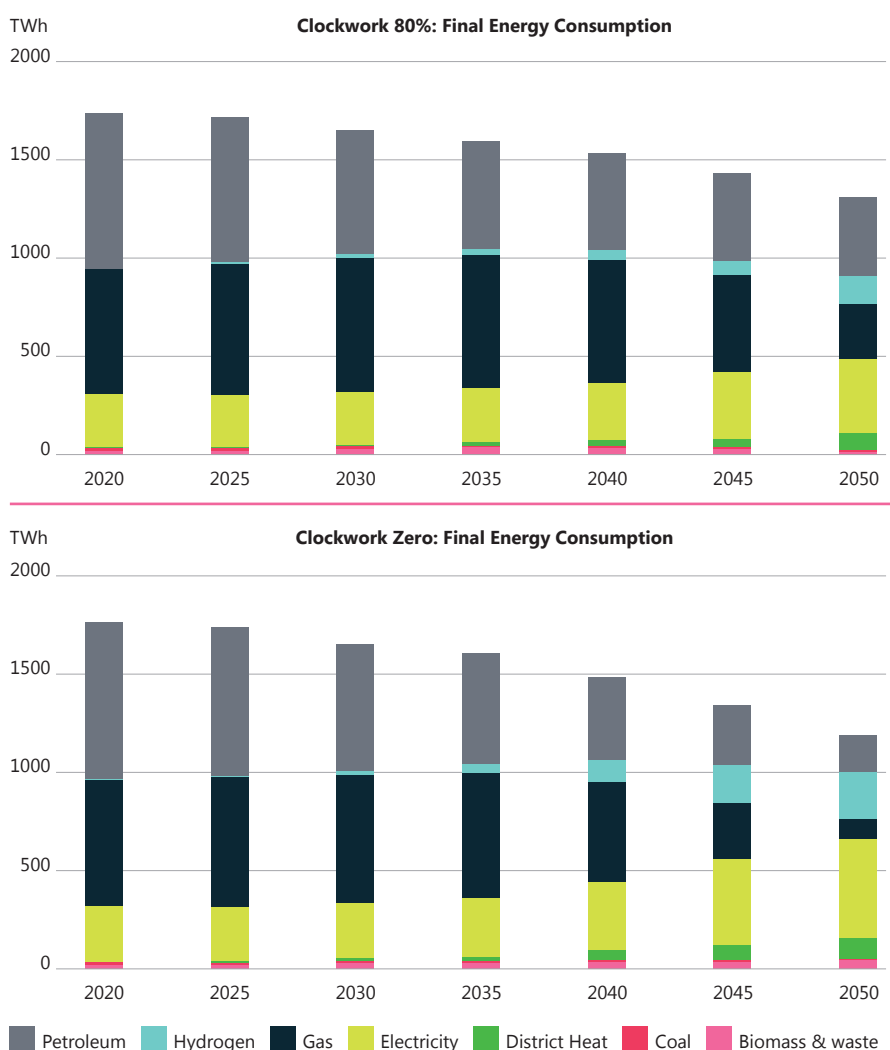
Heat networks provided around 5% of final energy. Hydrogen emerged as a new energy vector in hard-to-electrify applications, providing around 10% of final energy. Biomass and coal made up the remaining 5%.

To meet **Net Zero**, a more profound transition is required. Negative emissions can help counter residual emissions from activities like aviation, but wherever possible delivery of final energy by fossil fuels is substituted out. As a result, the share of fossil fuel in the final energy mix falls to 25%. See Figure 12.

In Clockwork, a new trio of zero carbon energy vectors now make up three quarters of the mix – electricity at 43%, hydrogen at 20% and district heat at 10%.

Since most of the remaining fossil fuel goes into industry and aviation, the mix of energy vectors delivered to households is profoundly different from the previous 80% pathway.

Figure 12: Final energy consumption for 80% and Net Zero targets



Electricity

For an 80% target, analysis typically generated a wide range of potential electricity sector outcomes (see page 30), with considerable variation in the mixture of nuclear, gas CCS and wind.

For Net Zero, much now depends on wider system assumptions. When speculative measures are limited, the emissions headroom is so heavily constrained that CCS at 95% capture rate is not low carbon enough, leaving a stable balance between nuclear and wind. Where more headroom is available, and innovation can deliver 99% capture rates for CCS, this can still be competitive against nuclear, as a form of dispatchable, baseload generation.

Partly as a result of its remarkable cost reductions in recent years, wind has secured its place as a more robust feature of any low carbon electricity system. With greater electrification required, floating offshore wind can unlock a large reservoir of energy resource in UK waters. Other renewables (led by solar PV and tidal stream) can make an important addition to this as part of a balanced mix.

Box 1: Storage and Flexibility

Because of greater intermittent renewable penetration, Net Zero pathways have a greater requirement for system balancing.

This can be achieved through supply side flexibility, demand side flexibility and energy storage in various forms.

	Clockwork		Patchwork	
Energy storage in 2050 (non-fossil)	Volume (GWh)	Power Rating (GW)	Volume (GWh)	Power Rating (GW)
Electricity storage	35	8	29	4
Heat storage (Buildings)	365	182	352	176
Heat storage (District heat)	290	72	328	82
Hydrogen storage	657	164	601	150

Although ESME provides a robust method to evaluate daily and long term balancing, ESC's new **Storage and Flexibility Model** (SFM) has been developed to provide more granular analysis.

Using SFM, we see similar macro-level trends as identified here, with similar storage technologies selected. However, we see further value attributed

to technologies that can provide services previously met by fossil fuels (e.g. inter-day/week storage) and frequency services previously supported by large quantities of spinning thermal plant.

As part of our ongoing Net Zero Insights programme, **we will publish more detail on the role of storage and flexibility solutions.**

In our analysis, we see cases at either end of the spectrum where nuclear or gas CCS has fully displaced the other as part of a feasible system solution. This is confirmed from specific sensitivity runs we have performed with no nuclear and (separately) no gas CCS.

Crucially, when we rule out *all power CCS*, the overall energy system falls short of Net Zero by 5MtCO₂. This is because energy from waste (EfW) with CCS is always a small but important part of the mix in 2050. Since waste contains some biogenic content, it counts as a form of BECCS, generating negative emissions. When we rule out all CCS from power these negative emissions are foregone, hence the shortfall.

We took the No Power CCS case and stretched it further by ruling out nuclear as well, implying a system with *no low carbon baseload*. Residual emissions are higher again, but not by much, at 6MtCO₂. The more profound impact is on overall system design: without the preferred 35GW of baseload nuclear, a combination of other technologies come in, with wind and solar capacity each climbing to ~100GW, and peak capacity from hydrogen turbines (and distributed fuel cells) rising to 58GW.

Innovation needs for electricity generation:

- Support a basket of options, given ongoing uncertainty. For wind, this includes RD&D for floating turbines, but also continued significant deployment of fixed offshore wind farms. All our scenarios see expansion of onshore wind farms in the near term, given their proven cost effectiveness.
- For nuclear, our previous analysis has shown how a carefully designed programme that engages all of the key stakeholders with a shared focus on the key characteristics of low cost and high quality construction can start the UK down the path to affordable nuclear power⁶.
- For Power CCS, the key will be understanding feasible capture rate potential under different operating conditions. Very high capture rates may be possible under a stable operating environment but ramping from a cold start is likely to introduce a capture rate 'penalty', meaning lower average capture rates if the plant is operating flexibly.
- As part of our ongoing Net Zero Insights programme, we will publish analysis on the role of storage and flexibility solutions in due course.

Hydrogen

For an **80% target**, hydrogen was a strategically important energy vector, but the overall quantity was typically limited to around 100TWh in 2050.

For **Net Zero**, greater hydrogen switching is now required across industry, heavy transport and shipping, meaning annual volumes in the range of 200-300TWh. **This means creating and building an entire new energy sector within 30 years** to deliver energy volumes potentially approaching that of the power sector today.

The optimal mix of hydrogen generating technologies is uncertain. Biomass gasification with CCS is typically deployed but is unable to deliver the mass quantity of hydrogen needed.

With speculative innovation measures, steam methane reforming at 99% capture rate looks highly appealing for hydrogen production. Any such facilities would produce constantly throughout the year, with the surplus during summer being placed into geological storage for use in winter.

Without speculative innovation measures, methane reforming at a 95% capture rate is too high carbon to meet Net Zero. In that case, electrolysis is preferred, but at higher cost this makes hydrogen less appealing overall.

We also tested the possible role of **advanced nuclear for hydrogen production**, drawing on data from one of the engineering deep-dives in our wider Net Zero Insights programme.

The Japanese Atomic Energy Agency (JAEA) has demonstrated hydrogen production from a sulphur-iodine cycle using the heat supply from high-temperature gas-cooled reactors (HTGR).

Across a range of cost assumptions, deployment of these HTGRs looked favourable in ESME, with annual production of 50-100TWh of hydrogen in 2050.

Innovation needs for hydrogen production:

- Very high carbon capture rates may be critical to ensuring a role for steam methane reforming (SMR+CCS).
- Electrolysis appears a more expensive option, but innovation (including learning by doing) can bring down cost and improve performance. Demonstrating electrolysis at scale in the 2020s should be a priority given implementation risks with SMR+CCS (which, if proven successfully, may then compete to deliver lower cost hydrogen to the consumer).
- Advanced nuclear technology for production of hydrogen could be an important new option, particularly where these facilities can operate flexibly between generation of electricity, hydrogen and heat, supporting multiple end use applications.

District Heat

The roll-out of district heat networks was an important feature of our whole systems analysis for an **80% target**. Depending on the cost effectiveness of other solutions, the share of all UK buildings' heat coming from district heat networks in 2050 would typically range from 10-25%.

A **Net Zero** target likely means more – and more extensive – district heat networks across UK cities as gas networks are retired. In our Further Ambition case (FA96), the overall share of buildings space heat coming from district heat networks ranges from 25–40%.

Where more speculative measures are introduced the ability to generate low-cost clean hydrogen means the regional gas networks can continue to be used, and the roll-out of district heat networks is more limited, ranging from 10-22% of all space heat.

For Net Zero, energising district heat networks by operating gas-fired combined heat and power (CHP) facilities becomes prohibitive. Biomass CHP facilities could offer a near carbon-neutral source, but we saw earlier how biomass is preferentially directed towards facilities incorporating CCS. This is better suited to a small number of large-scale facilities (to minimise CO₂ pipeline infrastructure), and therefore likely to be incompatible with more distributed CHP facilities for district heat networks.

Geothermal energy (for heat and power) is heavily constrained geographically, but in those regions with suitable geology, such as Cornwall, this could provide an important supplementary source of energy for district heat networks.

Where speculative measures enable a continued role for large thermal CCS plant in the power sector, heat offtake from these can provide a valuable source for heat networks in the medium term, although this may become less reliable over time due to declining load factors by 2050.

Large-scale heat pumps typically make up a large proportion of energy for heat networks. This relies on wider aspects of power system design, like ensuring sufficient capacity to meet peak heat demand, especially in the case of high renewables penetration.

The accompaniment of large-scale heat storage would alleviate some of this pressure by smoothing out the demand for electricity and providing a reliable source for provision of heat during daily peaks. In addition to heat storage, further reserve capacity is likely to be needed to cope with extreme cold weather events. For this, the simplest low carbon solution would be large-scale boilers fuelled by hydrogen.

Small modular nuclear reactors (e.g. 300 megawatts) offer the potential for combined heat and power as part of a more distributed energy system, but will require these small reactors to be sited closer to population centres (e.g. within 20km). Crucially, this will depend on political and social acceptance. Areas with a history of nuclear energy facilities and the associated job opportunities this can bring are likely to be the first to support early trials. In the meantime, local area energy planning will require careful phasing to maintain the option of plugging in nuclear SMRs subject to successful demonstration.

Innovation needs for network heat:

- Robust, consistent and detailed **local area energy planning** will be essential to understand the optimal phasing of heat network deployment in any given region, building out from urban centres to more suburban areas over time. Options for heat supply, storage and peak reserve can be evaluated for each phase of network deployment.
- UK deployment of tried and tested solutions elsewhere in the world, including geothermal, heat pumps, heat storage will deliver cost reductions through learning-by-doing.
- Nuclear small modular reactors require support through the design and demonstration stages. It is crucial that their full potential for combined heat and power is recognised and demonstrated.

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In addition to heat storage, further reserve capacity is likely to be needed to cope with extreme cold weather events.

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Energy end use

Buildings and heat

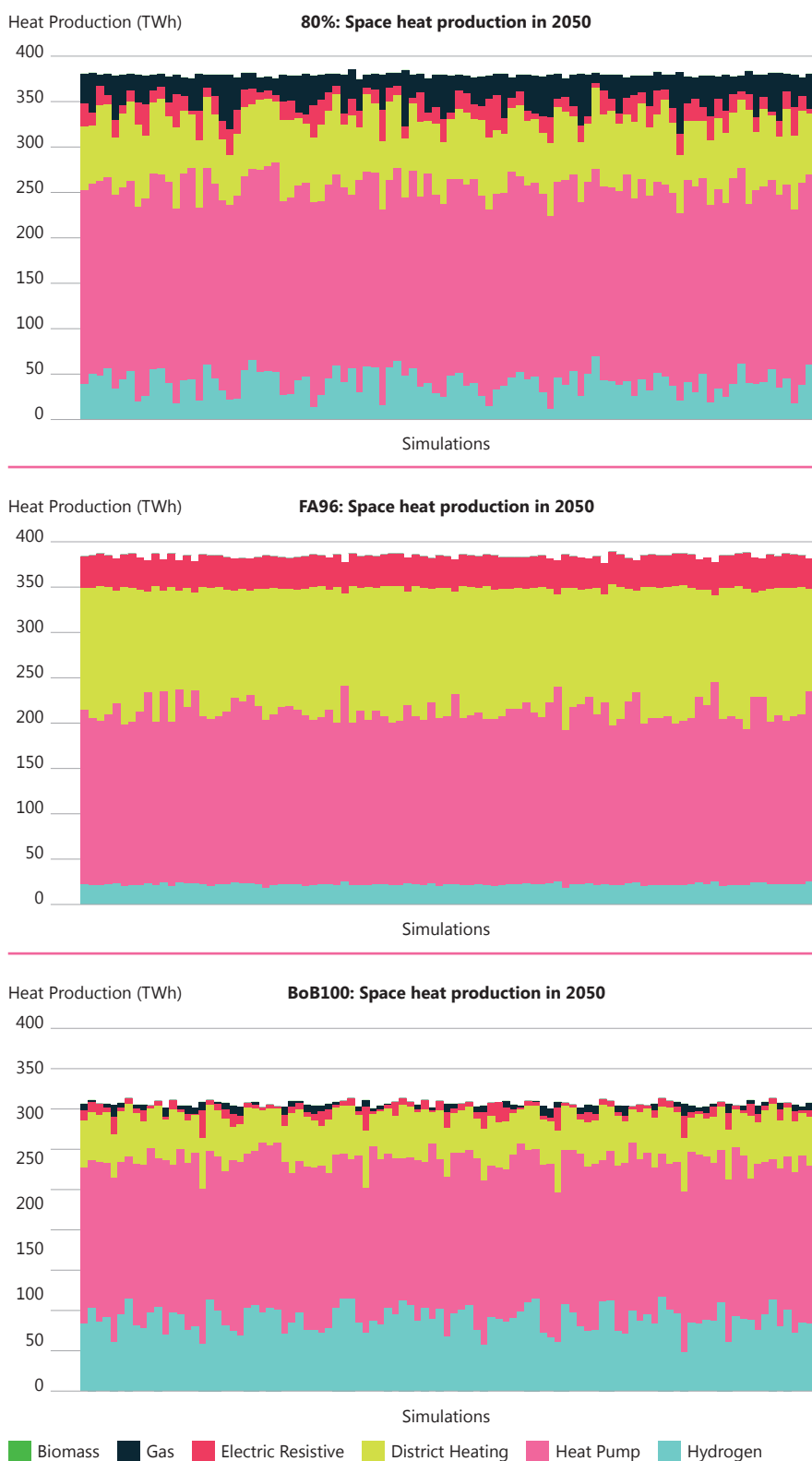
Space heating accounts for the majority of energy use and emissions within buildings, and also presents the greatest system design challenge, given the need for significant capacity for extreme cold weather events.

At present, the gas network ensures instantaneous heat provision to the majority of homes through gas boilers. In a decarbonised energy system, a combination of measures will be required to replace this in a way that provides consumers with the same (or a better) experience.

Our 80% pathways typically included: large-scale retrofits to improve thermal efficiency, district heat networks in cities and towns, and electric heat pumps deployed across the remainder of homes. For many of these heat pump installations, a connection to a gas network was retained to support peak heating, meaning the heat pumps could be smaller and cheaper.

For Net Zero, the mix of solutions looks broadly similar: retrofits, district heat networks, electric heat pumps retaining a connection to gas networks to support back up boilers. One major difference is, where gas networks and boilers continue to have a role in supporting peak heat, these must be almost exclusively converted to hydrogen by 2050.

Figure 13: Space heat production in 2050 across three batches of Monte Carlo runs (80%, FA96 and BOB100), one column per simulation



Another key difference is the time available to make the transition. Previously, we still saw a small, but measurable, amount of gas consumption in 2050 for heating. The new carbon target prohibits this and forces all emissions out of the sector. This suggests a transition period five years shorter than before, with the entire UK building stock moving to low carbon heating by the late 2040s.

For whole house retrofits, which can be expensive, there is a careful cost/benefit consideration. Some dwellings constitute 'low hanging fruit', and it makes good sense to treat these urgently. As we progress through the building stock though, costs increase and more modest efficiency gains becomes sub-optimal. Of the 25m existing dwellings that will still be in use in 2050, typically around 10m of these undergo a 'whole house' retrofit in our modelling.

For some buildings, improved thermal performance will enable them to rely solely on heat pumps, along with heat storage. For others, the rate of heat loss in extreme cold periods means they will still require a boiler to supplement the heat pump, at least on current understanding.

Although boilers would still have a role in many homes, there is a significant reduction in gas network capacity requirement by 2050. The implications of this for gas distribution networks in particular areas will depend on a variety of factors, but for many of these, declining connections and lower energy throughput will challenge the economic case for continued operation.

This is further complicated by the need to transition all such networks from natural gas to hydrogen for Net Zero. Given these challenges, some decommissioning of parts of gas distribution networks should be anticipated. The potentially stark differences between regions underlines the case for Local Area Energy Planning to identify pathways based on local conditions, and that enjoy local consent.

In our Monte Carlo analysis, there is a marked difference in the share of heating from different sources. Moving from 80% to tighter targets without speculative measures means natural gas use must be eliminated. But the potentially high cost of hydrogen production can make a simple hydrogen conversion strategy expensive. Instead heat networks are more extensively deployed, accounting for 25-40% of all space heat.

With all speculative measures activated, hydrogen has a larger share of overall space heat production, and heat networks now account for only 10-22% of heat network provision, a similar share to the 80% pathways. These measures include behavioural change whereby average indoor temperatures level out (as described in Patchwork), meaning lower annual energy consumption in 2050.

Innovation needs for buildings and heat:

- Increasing RD&D of whole house retrofit packages across a wider set of housing archetypes will help reduce cost, improve performance and clarify what can affordably be achieved across a diverse building stock in different parts of the country.
- Early demonstration of 100% hydrogen networks and boilers is essential to prove the safety and maintain this as an option.
- Demonstration of integrated solutions comprising hybrid heat pump and boiler systems.
- RD&D of heat storage technologies with potential to substitute for gas boilers as back up for heat pumps.
- Roll out of smart multi-zone controls to support more efficient energy use while maintaining or improving existing levels of comfort.
- Innovation in business models to deliver low carbon heating solutions that consumers desire is as important as technological innovation.
- Local area energy planning to understand the optimal combination of different solutions, based on local resources (and constraints).

Transport

ESME covers all road and rail transport as well as shipping and aviation. For aviation, there are no likely alternatives to kerosene-fuelled aeroplanes by 2050, so any measures to mitigate emissions are focused on overall demand (see Sustainable Lifestyles on page 44). For all other modes, demand can similarly be adjusted, but a range of low carbon technology options exist.

Compared to Buildings (page 40), the transport solution space has seen a significant transformation in moving from 80% to Net Zero.

In an **80% context**, with a sizeable carbon budget still available in 2050, road transport could continue to rely on extensive use of fossil fuels (in the absence of policy intervention). Cars and vans would transition first to hybrid and plug-in hybrid electric vehicles. For heavy duty vehicles and ships, we would typically see a transition to dual-fuel solutions, with natural gas helping to displace liquid fuels.

For **Net Zero**, cars and vans undergo a comprehensive shift to electric vehicles by 2050, with a minor share for hydrogen fuel cell vehicles in some simulations. Given the replacement rate for new vehicles to penetrate the overall car fleet, this implies new vehicle sales must be all electric (or hydrogen) from the mid-2030s onwards.

Figure 14: Car fleet in 2050 across two batches of Monte Carlo runs (80% and FA96), one column per simulation

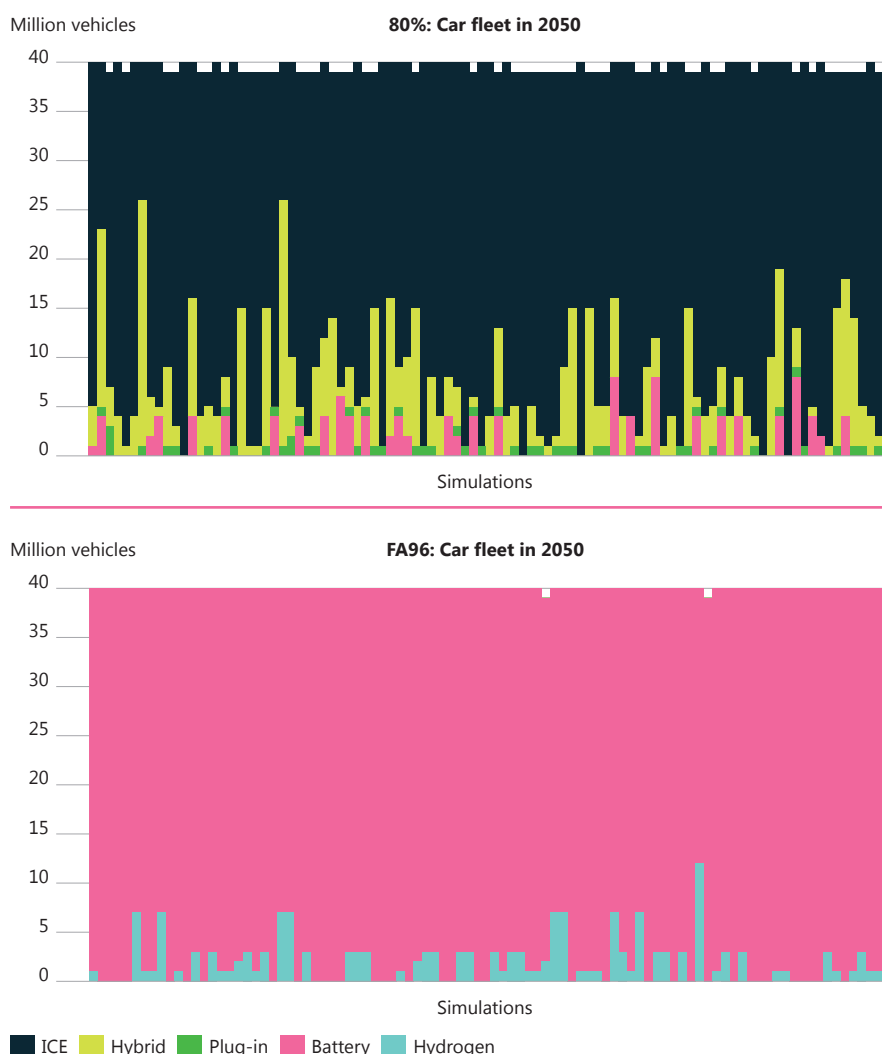


Figure 14 shows the results for the 2050 car fleet in the 80% and FA96 Monte Carlo runs.

Recent policy announcements have signalled an end to the sale of new ICEs, hybrids and plug-in hybrids from 2035. Incorporation of such a policy in the modelling would effectively 'lock-in' an all-electric/hydrogen outcome for this sector.

The key challenge from such a rapid increase in electric vehicles is its impact on the power system and the willingness of consumers to use smart charging. Previous ESC work, including consumer trials, have tested the interaction between consumer expectations, EV charging infrastructure and strategies for smart charging⁷. We also chaired the EV Energy Taskforce⁸, which highlighted that effectively-managed integration of EVs can *improve* electricity network efficiency and system resilience, while limiting the need for new infrastructure to meet growing electricity demand.

This has provided greater confidence that the transition to EVs can be managed without significant system impacts.

In heavy duty vehicles too, Net Zero pathways involve a significant shift to electrification by 2050, although dual-fuel vehicles are again seen as a transition technology along the pathway. Since we introduced hydrogen ships in the recent update, shipping transitions across to this technology almost completely by 2050.

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The key challenge from such a rapid increase in electric vehicles is its impact on the power system and the willingness of consumers to use smart charging.
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Innovation needs for transport:

- Roll out of public charging infrastructure needs to be accelerated to avoid constraining mass adoption. Smart charging (and vehicle-to-grid) can assist with the smooth integration of EVs, but will not entirely mitigate the need for network reinforcement, which should be carefully coordinated with local area energy planning more generally (also considering electrification of heat).
- Long term planning and coordination will be required to support the deployment of infrastructure for low carbon heavy duty vehicles. The potential for a short-lived transition through natural gas dual-fuel vehicles requires consideration, as do the consequences of foregoing this step.
- For shipping, while the rollout of hydrogen-fuelled ships looks attractive in our modelling from a carbon abatement perspective, inertia is a significant feature of this sector. Coordination will be essential to ensure deployment of hydrogen fuelling at UK ports, including access to affordable hydrogen from proximate production facilities, low cost transportation, or potential on-site production via electrolysis.

Industry

In ESME, Industry covers sectors such as Metals, Chemicals, Food and drink, Refining and Agriculture. ESME includes a range of fuel switching options for different sectors and processes, depending on the particular activity undertaken. Options include electrification or switching (from coal/oil) to gas, to hydrogen or to biomass. In addition, CCS can be applied to processes still using fossil fuels.

In an **80% context**, ESME allowed for emissions reduction down to 49MtCO₂ in 2050. Essentially, industry was seen as one of the 'hard-to-treat' sectors where emissions reduction was more modest compared to e.g. power, heat and transport.

For **Net Zero**, we have updated our representation of Industry. This now results in further fuel switching to electricity and hydrogen for space heating in industrial buildings, and hydrogen boilers for drying and separation and other subprocesses. The maximum effort now leaves just 15MtCO₂ of residual Industry emissions in 2050 (any less would rely on deindustrialisation).

Understanding how the sorts of fuel-switching options adopted across different industry sectors can integrate with wider energy system planning in local areas is an important challenge for the energy system. This includes the reuse of recoverable heat from industry processes for local heat networks, and co-location of hydrogen production facilities with industrial clusters, where CCS infrastructure can be concentrated most cost-effectively.

Innovation needs for Industry:

- Integration of decarbonisation roadmaps for industrial clusters with local area energy planning more generally.
- Demonstration of the safety of hydrogen switching for industrial processes.
- Deployment of CCS for those industrial sectors/processes where fuel switching is impractical.

Understanding how the sorts of fuel-switching options adopted across different industry sectors can integrate with wider energy system planning in local areas is an important challenge for the energy system.

Sustainable lifestyles

In our previous analysis for an **80% target**, we explored the potential impact of different demand trajectories, but the slack in the 80% target meant it was possible to support a 'lifestyle as usual' approach if this is what people preferred.

Many household activities could continue to rely on fossil fuels, albeit to a lesser extent than today. The remaining carbon budget allowed for a proportion of the car fleet to remain as ICEs, and any transition was often modest, involving more hybrid and plug-in hybrid vehicles than pure battery EVs. Heating our homes involved a transition to lower carbon alternatives, but again these were often hybrid solutions, where heat pumps were coupled with natural gas boilers.

Elsewhere, we assumed no dietary change and assumed ever increasing aviation demand in line with Government projections.

For Net Zero, the role of individuals and their lifestyle choices comes to the fore. For heating and transport, consumers' willingness to adopt unfamiliar technologies, like EVs or heat pumps, becomes more important. Moreover, there is more need to explore some limits on hard-to-treat activities, such as aviation demand and dietary change.

In our central assumptions, **aviation demand** in 2050 climbs to 60% above 2005 levels, though progress in technology and logistics means overall emissions are relatively unchanged at ~30MtCO₂. Aviation therefore relies on breakthrough innovation elsewhere to ensure sufficient quantities of *negative emissions* to offset this.

More sustainable alternatives to holiday (and business) travel would reduce the reliance on offsets. For example, if 2050 aviation demand reached only 20% above 2005 levels (as per our speculative measure), this would equate to an annual saving of 4MtCO₂. In their own analysis, the CCC consider a 20% growth limit. Since recent figures suggest demand has already exceeded 20%, this would imply an absolute reduction in aviation demand from now to 2050, in the context of a growing, increasingly affluent, population.

We have not investigated the potential impact of *flygskam* or flight-shaming on future aviation demand, and in other parts of the discourse commentators have gone much further than our speculative adjustment. In our maximum scenario described on page 45, we even consider the impact of eliminating aviation altogether by 2050.

Meanwhile, our central assumptions have 2050 **meat and dairy consumption** declining by 20% versus today, reducing emissions by 8 MtCO₂e/year. Achieving a UK wide reduction of 50% by 2050 would deliver emissions savings of 19 MtCO₂e/year.

Interactions between diet and the energy system are significant. A transition away from current levels of livestock would free up UK land for other uses, including afforestation and biomass crops, both enabling carbon sequestration and the latter providing a versatile resource for the energy system.

While there is considerable opportunity for changing patterns of demand in aviation and diet to contribute to Net Zero, we have not assessed the potential negative consequences if demand were significantly increased. Our survey on Net Zero awareness and engagement among the general public gives us reason to guard against 'baking in' excessive optimism into our modelling.

Innovation needs to support sustainable lifestyles:

- Provision of information including real-time data to support sustainable consumption and activity planning, including the potential for public campaigns. Understanding what messages works in such campaigns is a potentially important area for research and innovation.
- Continued RD&D into meat-free and dairy-free alternatives.



How fast could we decarbonise?

With our current assumptions for aviation, livestock and industry, these sectors will always generate residual emissions in our pathways. Meanwhile, deployment constraints on negative emissions technologies like BECCS and DACCS mean these take time to make an impact at scale.

Achieving Net Zero significantly earlier than 2050 in our modelling requires extra effort beyond even our speculative measures. Looking across analysis and commentary by other groups, there do not appear to be any significant additional low carbon technological solutions. Instead, most of the additional ambition is achieved through deep demand reduction.

To test the impact of this, we constructed a MAX case where aviation demand and livestock emissions fall to zero by 2050. This lowers the residual emissions trajectory sufficiently that negative emissions are able to balance these earlier, achieving Net Zero in 2045.

Other parts of the energy system are decarbonised on a highly accelerated timescale. Emissions from buildings are eliminated by 2040. Given the pace of change today, this would require an incredible step change in deployment of building retrofits, low carbon technologies and networks. Emissions from all road transport are similarly ended by 2040. Sales of petrol/diesel vehicles would effectively have to stop by 2025 at the latest, including for heavy goods vehicles, requiring immediate deployment of the infrastructure for recharging and refuelling these (and for generation of the zero-carbon electricity and hydrogen to support this).

In short, this MAX pathway involves a rate of change for power, heat and road transport that pushes against the bounds of plausibility. Achieving Net Zero any earlier than 2045 cannot rely on further acceleration of these. Instead, it would have to be through more rapid (non-linear) reductions in aviation and livestock emissions (or more rapid scale up of sequestration measures).

Costing Net Zero

When we look at cost-optimal pathways that meet our energy needs subject to a carbon target, an obvious question arises: what is the carbon target costing us? That is, what would the energy system cost in a counterfactual case where we meet the same needs but without worrying about carbon?

In energy system modelling, we can assess the cost of a pathway with and without a carbon target, and the difference between these is known as the *abatement cost*. We and others had previously estimated this to be somewhere in the range of 1-2% of GDP by 2050 for an 80% target.

But the issue of cost is a highly sensitive one. Crucially, we do not include any representation of the additional cost to the UK from failing to tackle climate change in the counterfactual. This is further complicated by the fact that UK action is not necessarily correlated with global action, so in principle we could face these damages even if we *are* reducing our own emissions.

Nevertheless, global estimates of damages from failure to reduce emissions are many times greater than the cost of mitigation. Additionally, as the Net Zero discourse has shown, there are various co-benefits of decarbonisation that are absent from energy system cost calculations, such as improved health and biodiversity. A complete assessment of the cost of Net Zero ought to include all of these.

Still, our investment for a low carbon future should be as economically efficient as possible, to avoid crowding out spending in other important areas. Good management of scarce financial resources can also open the possibility of over-delivery and an earlier Net Zero economy.

Investment in most of the technologies to deliver Net Zero is likely to be privately financed. We therefore take account of private firms financing costs in ESME by applying an assumed cost of capital of 8% to capital expenditures on all technologies. The model then discounts annualised costs (and benefits) to a net present value using the social discount rate of 3.5%. Both these steps are in line with Green Book guidance and common to many models.

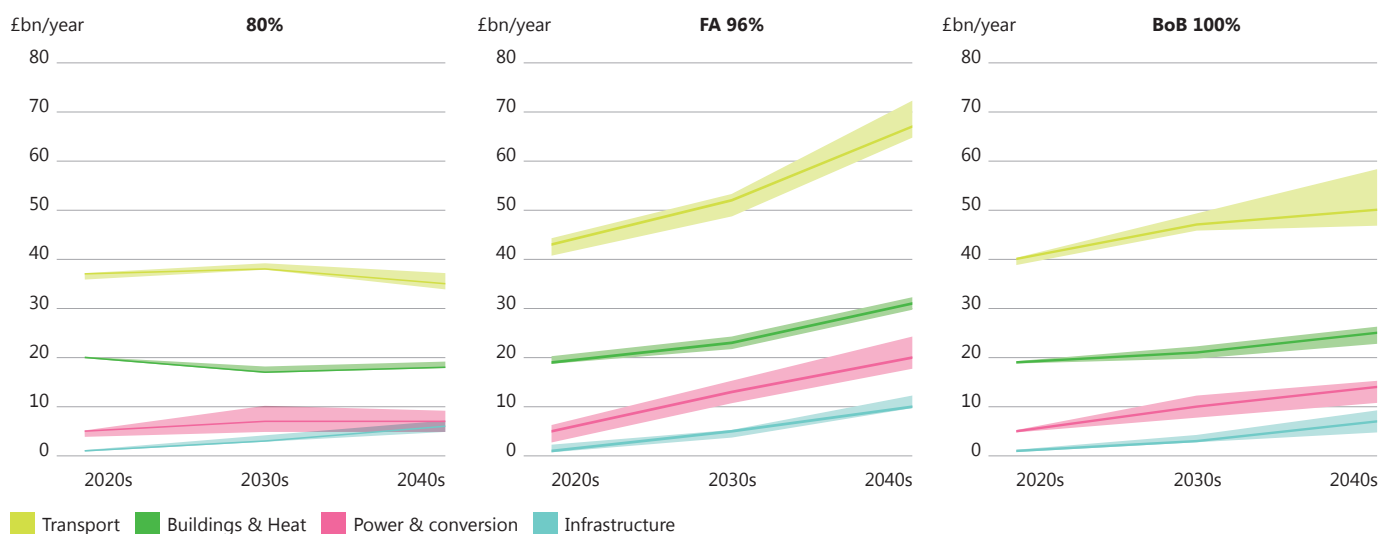
The cost of private finance for any specific technology is likely to vary over time and in line with capital market perceptions of risk, including a strong element of policy-related risk and the level of experience in deployment. By applying a common assumed cost of private capital across all technologies, the modelling approach optimises the mix of technologies on the basis of underlying costs and performance characteristics, rather than current market and policy arrangements. This prevents the modelled choices from reflecting current policy choices and market perceptions of risk for different technologies. Experience in deploying technologies is taken into account in technology cost assumptions (for example, cost assumptions for offshore wind have been updated to take account of cost reductions following deployment).

Low carbon systems are currently characterised by a shift towards more capital-intensive technologies (e.g. wind power and electric vehicles vs gas CCGTs and internal combustion engines), and the choice of private cost of capital does not materially affect this. However, a higher cost of capital will tend to inflate the apparent cost imposed on consumers of achieving Net Zero.

In the recent advice to Government, CCC found that – due to demonstrated cost reductions in a range of low carbon technologies – their estimates of abatement cost for Net Zero fall within the same cost range previously associated with 80%, that is 1-2% of GDP in 2050.

With an 8% private cost of capital in ESME, Net Zero abatement costs look higher, in the range 2-3% of GDP. However, test runs with a lower cost of capital – which has been evident in many low carbon investments, including mature renewables – show the ESME runs in the 1-2% range. This underlines the importance of stable and credible policies that successfully reduce the cost of capital demanded by private sector investors for a broad range of clean, capital intensive technologies (as we have successfully seen with renewables).

Figure 15: Capital investment needed in each sector for three batches of Monte Carlo runs (80%, FA96 and BOB100). Shaded area describes the range across simulations.



Investment opportunities

The transition to a Net Zero energy system will create economic opportunities for innovators across all sectors of the economy. The charts above show the range of capital investment in each of the key sectors: Power and conversion, Transport, Buildings and Infrastructure.

For an **80% pathway**, despite the carbon budgets tightening over time, cost reductions in low carbon technologies ensure the capital investment requirement is held fairly constant over time.

In the FA96 case, where the target is strengthened but no speculative measures are available to assist, a significant increase in investment is required. This is true across all sectors, but especially pronounced in the case of transport with a rapid shift to (more capital intensive) electric vehicles, including heavy duty.

The addition of speculative measures (including overall lower demand) more than compensates for the tighter target, reigning in total investment need.

Timelines

The pace and scale of change required to meet Net Zero is profound. It requires the urgent introduction of robust policies which will unlock both significant innovation and large-scale capital investment. An important consideration is the deployment profile for the necessary technologies.

Figure 16 shows a steady, linear deployment to get from where we are today to where we need to be in 2050. Taking the example of domestic low carbon heating systems, we have 30 years to install low carbon systems in the UK's 28.5 million homes. A linear deployment would entail around **one million installations per year**.

However, in 2019 fewer than 12,000 renewable heating systems were accredited under the Government's Domestic Renewable Heat Incentive (RHI)⁹. Currently, the workforce, supply chains, business models and policies are simply not in place to deliver at such a high rate.

The assumptions within ESME reflect a profile closer to that shown in Figure 17. There is a delay before the deployment can begin, and when it does, it starts slowly (reflecting the fact these are sometimes unfamiliar technologies) before the rate increases (potentially exponentially) up to a maximum deployment level.

The delay at the start of this profile is a critical phase. This is where technology, policy, regulation and finance mechanisms need to be developed, demonstrations undertaken, and supply chains and workforce skills built up. This all needs to be done before roll-out at any meaningful scale can begin. But experience in some parts of the energy system, such as renewables, shows that with the right combination of market incentives, rapid scale up and cost reduction can be achieved.

Figure 16: Deployment profiles

Deployment of X

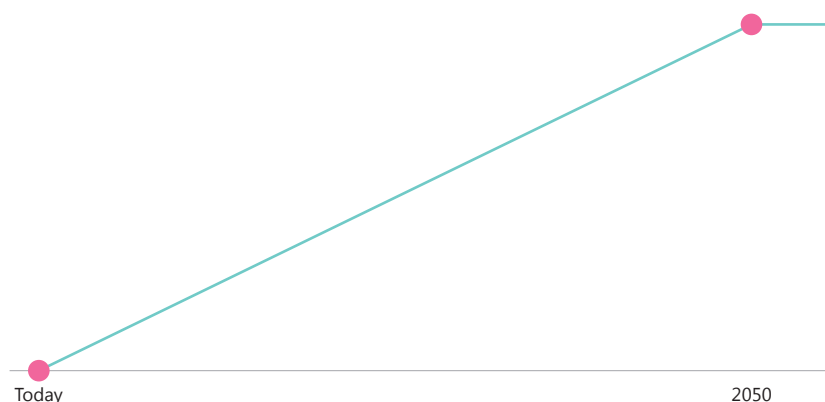
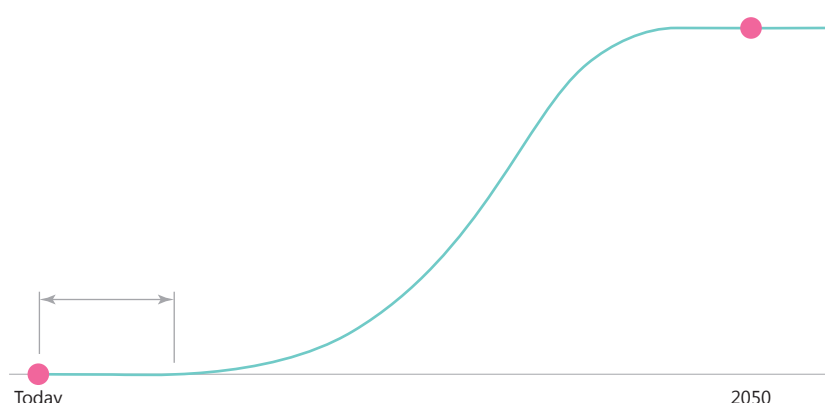


Figure 17: Deployment profiles

Deployment of X



Place and Local Area Energy Planning

The modelling discussed in this report primarily focusses on the national context, though we have also emphasised the importance of place-based aspects of the energy system transition, for example through creation of industrial clusters to better focus development efforts around CCS, H2 production or process heat. We are also seeing significant appetite for smart local energy system projects, including through the Prospering from the Energy Revolution programme.

Robust **local area energy planning** can help understand the pathways for low carbon heating, transport and electricity systems, identifying priority projects and infrastructure investments. This will help deliver both a cost-effective transition and secure democratic consensus for the necessary changes. Such plans and strategies would be developed in light of local priorities, demands, current infrastructure and resource availability, as well as the regional and national systems they are linked to. They should be developed in collaboration with a broad range of stakeholders (local authorities, energy networks, industry bodies, community groups, etc).

Local Area Energy Plans (LAEPs) need to be connected at regional and national levels in an iterative assessment and feedback process. Cumulatively, such plans can help inform the development of nationally strategic resources (such as CCS or hydrogen production facilities). This requires the use of a consistent and robust methodology across different locales.

For local and regional plans to have impact, there must be enabling mechanisms within central planning and wider policy frameworks to give them power, including potentially the network price control process.



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**WHAT NEEDS
TO HAPPEN
DURING THIS
PARLIAMENT?**



The pace and scale of change required to achieve Net Zero effectively and efficiently by 2050 suggests that the policy ecosystem will need three key attributes:

- Policy will need to deliver **credible long-term signals** to incentivise innovation and private sector investment to develop and deploy a range of existing and new technologies.
- Policy needs to **shape markets** so that private sector capital flows to deliver an efficient mix and phasing of emissions reduction across the economy.
- As well as shaping markets, policy will need to underpin investment in **strategically important enabling infrastructures and technologies**.

Our Rethinking Decarbonisation Incentives¹⁰ project looked at the balance of carbon-related policy signals across different sectors (see Figure 18) and highlighted the potential to substantially strengthen and improve the coherence of carbon policy across the economy. This implies a framework that is broadly technology-neutral, but does not necessarily rely on an economy-wide carbon pricing instrument, such as a carbon tax or an emissions trading system.

Decarbonisation policies, including both incentives and obligations or standards, can be designed with specific sectoral features in mind. However, by building links between sectoral policies, especially by developing tradable instruments such as carbon credits, the UK can unlock greater pathway flexibility and increase the scope for markets to reveal least-cost combinations.

By building links between sectoral policies, especially by developing tradable instruments such as carbon credits, the UK can unlock greater pathway flexibility.

In addition, policy must also recognise the role that negative emission technologies, bioenergy, and wider land use policy will have, alongside potential changes in consumer behaviour.

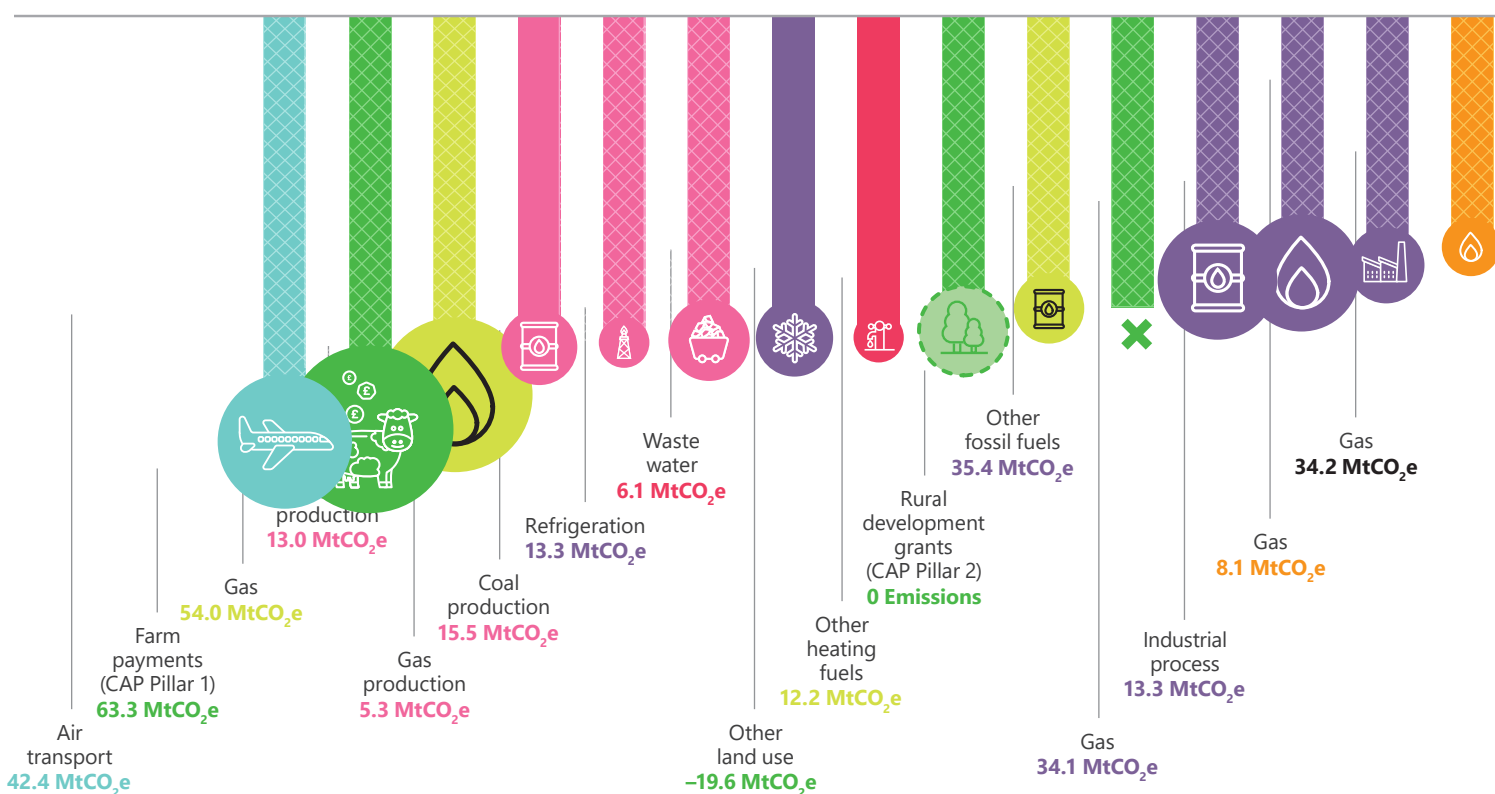
This chapter provides key policy recommendations for Government to introduce in the near-term to support the development of an economy-wide carbon policy framework for Net Zero.

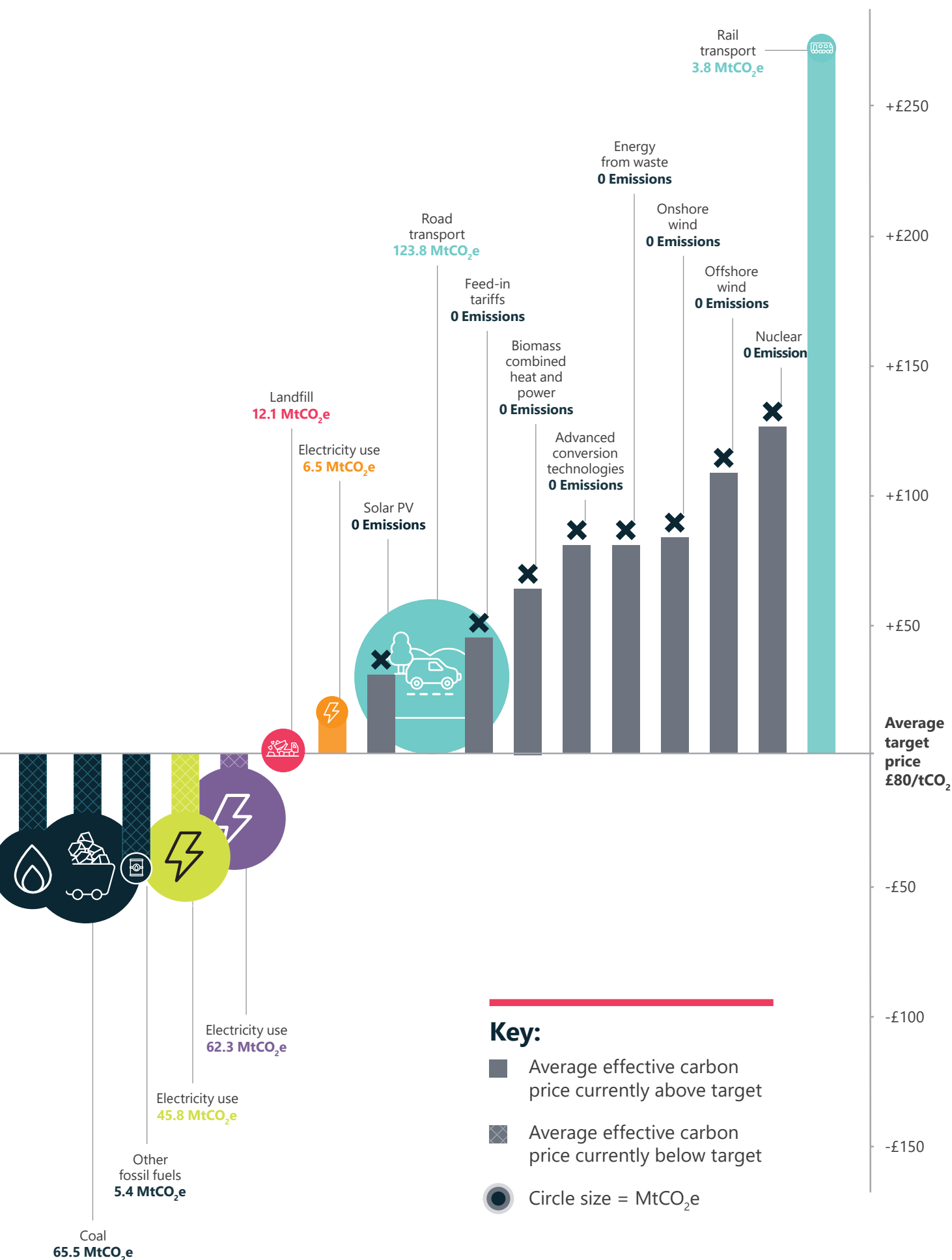
Figure 18

Effective carbon prices and emissions in the UK by sector

Sectors:

- Power Generation
- Fossil Fuel Production
- Transport
- Business
- Residential
- Public
- Agriculture, Forestry, and Other Land Use (AFOLU)
- Waste





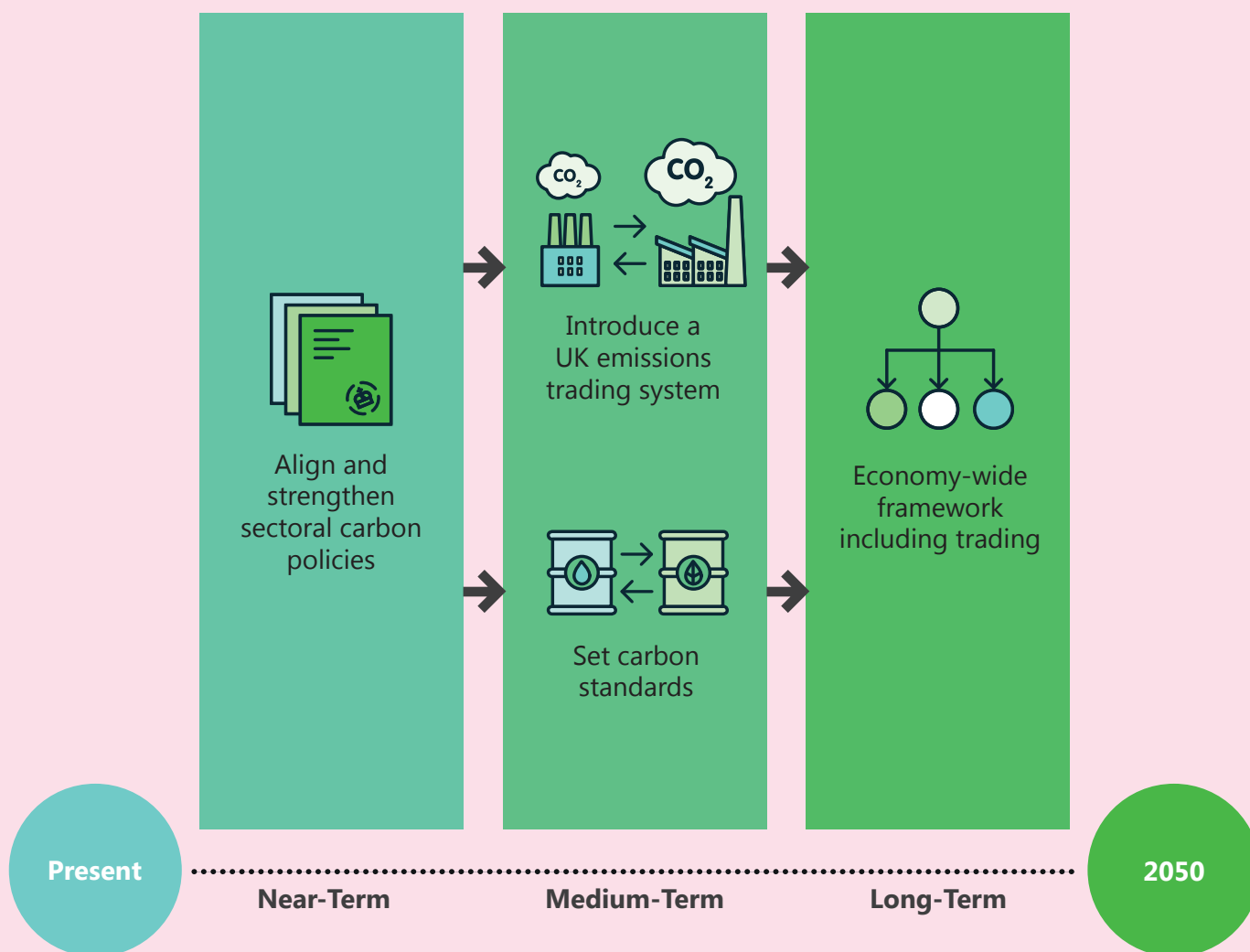
The potential direction of travel for carbon policy to 2050

The immediate challenge for carbon policy is to improve the alignment of existing policies and to strengthen policy where there are clear gaps.

In the medium-term the UK could strengthen the role of both:

- Emissions trading – the UK could extend coverage and increase ambition, particularly if it introduced its own emissions trading system.
- Sectoral decarbonisation policies – the UK could introduce new carbon standards for buildings and potentially road transport, and it could create new incentives for climate-friendly land use choices.

These steps would open the potential to create an economy-wide carbon policy framework to deliver Net Zero efficiently. Carbon credits could be tradeable between mechanisms and sectors, and linked to a marketplace for UK based certified methods of greenhouse gas removal (e.g. sustainable afforestation, BECCS, DACCS, etc.).



Electricity

Policy has already driven significant decarbonisation of the electricity sector, but there is still an important role for policy reform to:

- Enable the assembly of an efficient and complete zero carbon system that matches the changes in low carbon technologies, including distributed technologies;
- Enable investment to produce sufficient quantities of zero carbon electricity and associated network improvements, and
- Shape the most efficient role for electricity in supporting heat, transport, and industrial decarbonisation.

In addition, electricity markets need to more effectively signal the spatial and temporal value of zero carbon electricity, to meet new demands and unlock the potential of technologies that can provide greater system flexibility (such as batteries, demand side response, and the integration of electric vehicles).¹¹

Over the course of this Parliament, policy should focus on:

- Large-scale developments, such as new nuclear, which will require significant support from Government. This could come in the form of the recently proposed Regulated Asset Base (RAB) model¹² to secure private investment or alternative models of risk allocation to keep the cost of capital as low as possible (see Costing Net Zero). Government should also bear down on the costs of nuclear new build projects, potentially taking a fleet approach which learns from previous reactor builds and implementing a well-designed programme that incorporates multiple project performance and cost reduction opportunities¹³.
- R&D funding and deployment support for new and emerging technologies that are key for Net Zero, for example, floating offshore wind and small modular reactors (SMR).
- Stimulating efficient demand reduction and/or flexibility through supporting appropriate energy efficiency measures, building regulation, and product standards. For example, by developing more accurate measurement of the carbon performance associated with energy use choices in buildings and equipment.
- Improved market price signals to incentivise efficient use of the system in time and space. This includes reforms to ensure more accurate time-of-use and locational signals to strengthen incentives for supply and demand to match user needs and local system circumstances.¹⁴
- Strengthen network price controls to support decarbonisation by incentivising and taking account of whole systems local area energy planning that enables improved forward planning, and multi-vector network investment decisions.



Transport

Transport accounts for a third of UK emissions and continues to rise.¹⁵ Stronger policies are required to drive decarbonisation and low carbon journey choices.

Our work suggests that key reforms over the course of this Government could include:

- A phased approach to the ban on the sale of new diesel and petrol cars and vans during the 2030s, extending to cover all internal combustion engine (ICE) and hybrid vehicles.¹⁶
- Initial rebalancing of the way Government taxes mobility, for example, using road usage charging to replace fuel duty as a source of revenue.¹⁷
- A process to deploy a national and interoperable charging infrastructure, including rapid chargepoints on trunk roads, with integration into local area energy planning and network investment planning processes.¹⁸
- Support for emerging technologies, such as hydrogen fuel cells for use in HGVs.¹⁹
- Developing incentives to influence aviation choices, for example, through an obligation for airlines to sequester a proportion of their emissions.

Buildings

The current policy framework for decarbonising buildings is complex, but ultimately too weak and fragmented to drive innovation or the right mix of measures that influence the carbon performance of buildings.

Government should begin to develop an integrated long-term policy framework for zero carbon buildings. It should be broadly technology neutral, but informed by local planning and prioritisation processes, particularly for collective choices around upgrading buildings in a particular area and energy network infrastructures. It will also have to reduce fuel poverty and ensure that vulnerable customers are neither left behind nor bear the brunt of the cost (including being aware of new types of vulnerability that will emerge with greater digitalisation of the energy system).

Over the course of this Government our analysis points to the following policy priorities:

- Fund a new wave of place-based building energy improvement and retrofit projects to enable regions to invest strategically and upskill heating technicians and installers. Localities and regions could compete for funding under national guidance, but with the freedom to develop their own strategies and targeting local priorities such as fuel poverty.
- Roll out a robust Local Area Energy Planning process in order to build consensus, guide planning, shape new developments and co-ordinate collective infrastructure choices and investment priorities. ESC has developed a prototype for this style of local energy planning, a version of which could be rolled out immediately.²⁰
- Make energy networks invest for Net Zero, with Ofgem re-engineering its RIIO processes and guidance, for example, by setting explicit outcome-based delivery incentives that reward network companies when they invest well and demonstrably enable cost-effective decarbonisation.

Government should begin to develop an integrated long-term policy framework for zero carbon buildings.

- Phase in new carbon performance rating requirements for all buildings. This could be implemented by replacing the existing EPC rating system with a smarter, more accurate and valid new system of Carbon Performance Certification. An obligation could be initially introduced on social housing and privately-rented properties, eventually extending (with long lead times) to all owner occupied and hard-to-treat properties.
- As these obligations are phased in, reduce reliance on technology subsidies like the Renewable Heat Incentive (RHI) over time.
- Introduce a new carbon credits scheme to reward bill payers who reduce their actual (i.e. measured) energy emissions. The credit scheme could be linked to the new system of Carbon Performance Certification and operated by energy suppliers using smart metering data. Customers that outperform low carbon performance benchmarks would be rewarded with credits (while requiring customers with poor carbon performance to purchase credits).
- Open up competitive markets for new long-term low carbon finance products. Financial efficiency and risk reduction can be maximised by linking repayments to property ownership (through mortgage-style products) or to energy bill payers (through an adapted Green Deal regime).

**“
Roll out a robust Local Area Energy Planning process in order to build consensus, guide planning, shape new developments and co-ordinate collective infrastructure choices and investment priorities.
”**



Industry (including CCS, Bioenergy, and Hydrogen Production)

Industry requires stronger policy incentives to invest in emissions reduction through improving industrial processes, fuel switching, and innovation in technologies such as CCS (and more broadly negative emissions).

Government should prioritise developing and establishing a long-term policy framework for industrial decarbonisation, including developing rewards for delivering verified negative emissions. This could also substantially improve the investability of CCS, domestic biomass supply chains, and hydrogen production. The industrial decarbonisation policy framework should be designed in ways that minimises carbon leakage impacts (i.e. reduces offshoring of industrial emissions) and must account for asset turnover rates.

Over the course of this Government our analysis suggests that policy development priorities should include:

- Developing post-Brexit arrangements for emissions trading in the UK to ensure that incentives on industrial emitters are maintained and strengthened progressively over time. The UK will have more opportunity to extend the scope and strengthen the stringency of emissions trading if it were to develop a standalone UK ETS.
- Over time, a UK ETS could also be designed to include new mechanisms to reward delivery of verified negative emissions with carbon credits.
- Regardless of whether the UK remains within the EU ETS or develops a linked or standalone UK ETS, policy makers should explore the introduction of output-based performance standards²¹ and other approaches (e.g. border carbon adjustments) to replace the free allocation of allowances in ways that maintain strong incentives to reduce emissions while minimising competitiveness impacts.
- Direct support for innovation and early deployment of CCS and hydrogen production in industrial clusters, including the development of investable funding mechanisms for CO₂ transport and storage infrastructure.²² This should sit alongside support for non-cluster based industry.

Our modelling points strongly to the strategic importance of the UK expanding the 'solution space' for the whole energy system, including industrial decarbonisation, by developing the infrastructure and value chains required to support CCS, sustainable biomass production and conversion, and low carbon hydrogen production. All three of these elements appear in a wide range of analysis of cost-efficient energy transitions, which also suggests:

- While there are other potential sources of low carbon electricity, the power sector remains an attractive option as a low risk sector for early CCS development (i.e. before 2030), because of its relatively low trade exposure and existing support mechanisms²³. This could act as an anchor for CCS deployment in industry, in particular for clusters. Gas power CCS in proximity to industrial clusters may well represent the most straightforward, deliverable, and best value approach to early deployment at scale of CCS.
- Modelling points to the high strategic potential of advanced methods of gasification, including biomass gasification with CCS to underpin hydrogen production while also delivering negative emissions of high economic value in the medium-term. The potential of biomass gasification with CCS to open a UK negative emissions value chain suggests that there is a strong case for strategic innovation funding of clean gasification with CCS plants.

Digitalisation

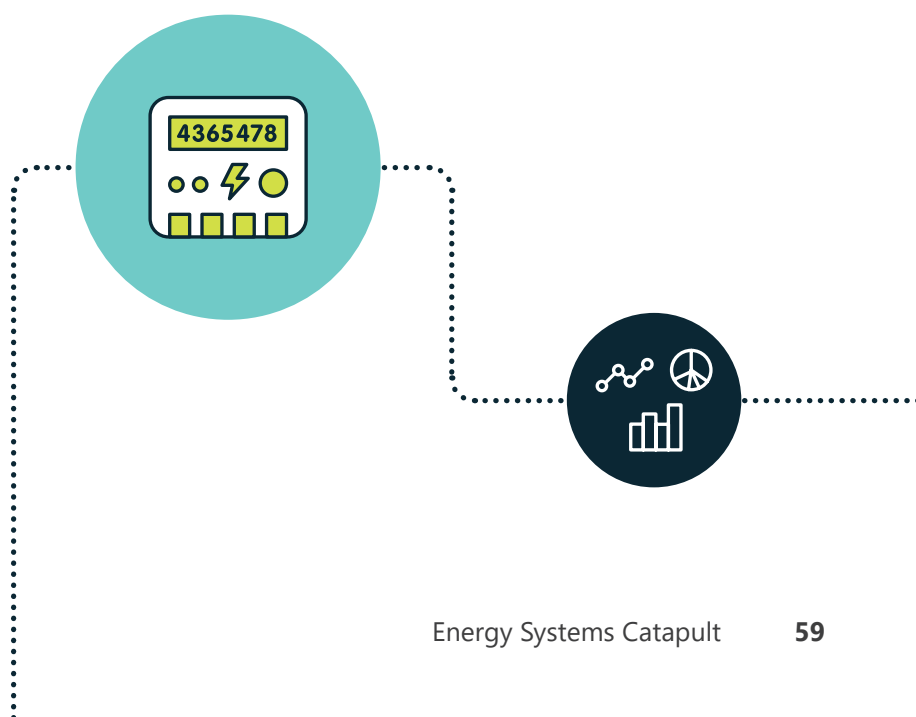
Alongside decarbonisation, the other big trend effecting the future energy system is digitalisation. Digitalisation is the process of moving towards a system which utilises the collection and sharing of data between devices connected through digital communications, and the analysis of that data to improve the system's, or an organisation's processes and operation. It could help minimise costs and ensure security of supply, it will allow greater choice, better service and more convenience for consumers, and open opportunities to extract value, innovate around propositions and services, and welcome new entrants.

Digitalisation has already transformed many sectors, and is beginning to change the energy system. It will likely become a crucial component of any future energy system. As discussed in this analysis, the challenge of meeting the Net Zero target will require many changes to the electricity generation mix, the way heat and transport are provided, the interaction between energy vectors, and the overall complexity of the system and components connected to it. For the system to continue providing the service required under these new conditions, digitalisation is essential.

There are challenges, however. These include interoperability (consumer, commercial, data, device, physical and vector), data availability and gaps, security, and privacy. There are roles for policy makers, regulators, manufacturers, service providers and consumers in addressing these challenges. The Energy Data Taskforce²⁴ focused on the challenges around data gaps. It advocated stepping up the rate of digitalisation, and intelligent utilisation of monitoring and modelling/data science to address the gaps in the most cost-effective way possible.

Government and the regulator should prioritise the creation and adoption of an open energy data and digitalisation governance framework in line with recommendations of the Energy Data Taskforce. This can maximise the potential of digitalisation to enable tailored consumer-focused innovation, business models, market designs and consumer protections in the transformation of the energy system ahead.

Digitalisation is the process of moving towards a system which utilises the collection and sharing of data between devices connected through digital communications.



Our capabilities

Energy Systems Catapult has developed a range of unique Capabilities to help innovators, SMEs, industry, academia, regulators and Government to transform the UK energy system to meet carbon reduction targets and achieve our clean growth ambitions.



Modelling

Expert whole energy system modelling and analysis provide better understanding of the costs and benefits of different technologies, system designs and low carbon pathways.

This includes:

- Internationally peer reviewed Energy System Modelling Environment™ (ESME): to inform government policy and industry decision-making.
- EnergyPath Networks™ Local Energy System Modelling, to inform and support local authorities with cost effective low carbon energy transition.

- Home Energy Dynamics: models interactions between domestic heating systems, controls, building fabric, weather and consumer needs.
- Storage and Flexibility Modelling provides the most comprehensive multi-vector energy system design model used to address the role of energy storage within future energy systems.

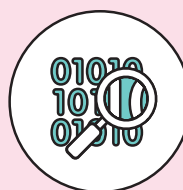


Consumer Insight

Combining cutting-edge data science, user experience design thinking and in-depth consumer data so innovators see beyond what people say to understand what they do.

This includes:

- Energy specific market research, digital design and consumer trials for energy innovators to test new products, services and business models in real-world homes.

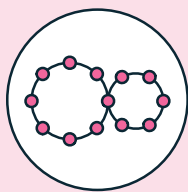


Digital and Data

Emerging digital enablers, such as artificial intelligence (AI), big data, internet of things (IoT) sensing and machine learning are expected to play a central role in transforming energy systems, driving innovation and economic growth.

This includes:

- Advanced data science with algorithms and artificial intelligence, alongside a Living Lab of 100 real-world homes connected to a cloud-based digital platform for testing innovative products, services and business models with consumers.



Systems Integration

We explore and define a future energy system that integrates the disparate physical, digital and market systems, within a backdrop of rapid technological and societal change.

This includes:

- Expertise and guidance in systems engineering and integration for businesses to integrate products and services into a future energy system.
- Dynamic energy systems architecting and simulation tools and expertise, and business model innovation.



Infrastructure and Engineering

Our Infrastructure and Engineering team has deep specialist knowledge and practical experience taking a whole system perspective. We cover technology development and deployment that considers the technological, engineering, economic, regulatory and policy implications for innovations and investment decisions.

This includes:

- Expertise across nuclear, renewables, bioenergy, carbon capture and storage, industry, hydrogen, networks, energy storage, and transport.



Markets, Policy and Regulation

Reformed markets, policy incentives and regulatory frameworks are essential to drive investment and innovation in a smart low carbon energy system.

This includes:

- Policy, regulatory and market design expertise, combining a deep understanding of technology, economics and energy policy design, informed by cutting-edge modelling and evidence-based analysis.

“Achieving a net zero economy in an affordable way; that goes with the grain of consumer behaviour, understands the complex infrastructure challenges, and can help innovators unlock the value in the energy markets of the future is going to require innovation on an unprecedented scale.”

To work with us, visit
es.catapult.org.uk
and email us at
info@es.catapult.org.uk

Our platforms

Energy Systems Catapult has created a range of Service Platforms that are a route for innovators and other energy sector stakeholders to work with the Catapult and access our unique Capabilities.

We take a whole system view of the energy sector, helping us to identify and address innovation priorities and market barriers, in order to decarbonise the energy system at the lowest cost.



Living Lab

We have upgraded 100 real-world homes with room-by-room sensors and smart heating controls to form the Living Lab - a place where innovative businesses can rapidly design, market-test and launch smart energy products and services.

Living Lab 2.0 will be an agile and scalable national capability for industry, policymakers and regulators to test energy innovations, business models, market arrangements, policies and regulations with real consumers – as we move towards a Net Zero carbon future.



Innovator Support

The Innovator Support Platform (ISP) provides tailored support to small and medium sized energy firms as they develop new products, services and grow their businesses.

The ISP delivers support across three tiers: Universal support available to all SMEs via our a new digital Innovator Support Portal, and Incubation and Acceleration support to help SMEs commercialise and prepare for investment, including business model development, consumer value propositions, service and solution design testing/feasibility and product road mapping.



Insights and Evidence

The Insights and Evidence team delivered the Innovating for Net Zero report. We deliver independent insights and evidence to help government, academia, and businesses identify innovation priorities towards delivering a low carbon economy and helping businesses overcome systemic barriers and accelerate their products, services and value propositions to market. The team works with the Department of Business, Energy and Industrial Strategy, the Committee on Climate Change, as well as energy research and environmental organisations and industrial partners such as Rolls Royce, Shell and EDF.



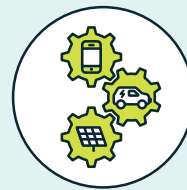
Major Programmes

The Major Programmes team is a centre of excellence for delivering large, complex, innovative, multi-capability decarbonisation projects, specialising in place-based decarbonisation of the built environment. They recently completed the £30million, 5-year Smart Systems and Heat programme, the UK's largest smart project aimed at decarbonising heat through consumer-focused trials and local area energy planning. They are currently managing the £16.5 million Electrification of Heat Demonstration Project for the Department of Business, Energy and Industrial Strategy. Other work includes advising the Department for Education on their approach to decarbonising schools, working with industry partners on decarbonisation plans for complex commercial sites, and establishing a skills academy to build a supply chain able to decarbonise the UK's housing stock.



International

International Support aims to help connect UK innovators and businesses to overseas markets, expertise and opportunities. SMEs can register through our new Innovator Support Portal to register with our growing a supply chain database for global growth. The Catapult is now active in North and South America, Africa and Asia and is in a strong position to become the 'go to' organisation for UK energy innovators wishing to export, and foreign direct investors wishing to invest in the UK's smart energy system.



Energy Revolution Integration Service

UK government is investing in research and industry to develop the smart energy systems needed for the future, through the Industrial Strategy Challenge Fund – Prospering from the Energy Revolution. Energy Systems Catapult is playing a central role through the Energy Revolution Integration Service (ERIS), providing expert whole system guidance and support to selected projects, as well as collaborative opportunities for shared learning.



Modern Energy Partners

Modern Energy Partners (MEP) is a ground-breaking collaboration within Government that seeks to develop a mechanism that enables the public estate to achieve at least 50% untraded carbon emissions reductions by 2032 against a 2017 baseline, through a combination of innovative and established technologies.

MEP will achieve its purpose by using the scale and diversity of the public sector estate to set precedent, developing a standardised approach and best practice and building confidence through proven delivery on site.



Endnotes

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- ² Energy and Climate Intelligence Unit (2020). Net Zero Tracker. <https://eciu.net/netzerotracker>
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- ²¹ Output-based standards can be used to provide pricing incentives for certain industries to reduce their GHG emissions while maintaining their competitive position relative to international peers. Instead of paying a charge on the fuels that they purchase, industrial firms face a carbon price on the portion of their emissions that are above a specific level, which is determined based on relevant output-based standards (emissions per unit of output). The output-based standard is set at a level that represents best-in-class performance (top quartile or better) in order to drive reduced emissions intensity. A firm that reduces emissions below its limit can generate and sell surplus credits. The result is that companies have an incentive to reduce emissions and support clean innovation while minimising the total cost they pay.
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Energy Systems Catapult supports innovators in unleashing opportunities from the transition to a clean, intelligent energy system.

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