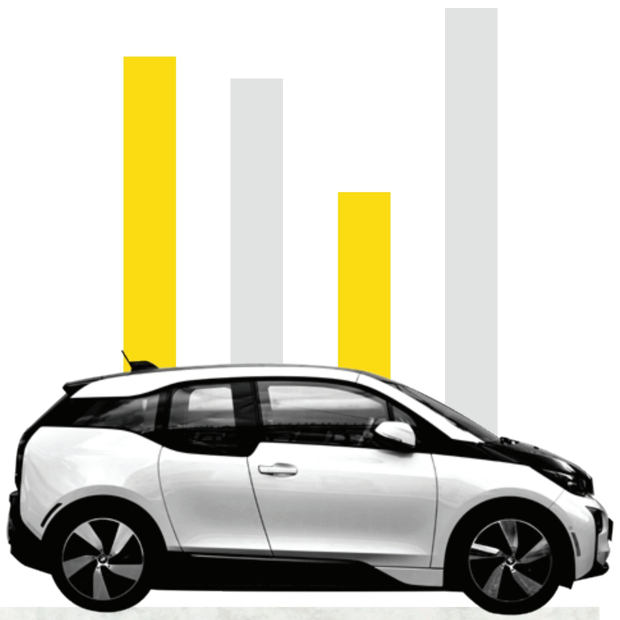

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Renewable Nation: Pathways to a Zero Carbon Britain

Contents

Foreword

Philip New
CEO
Energy Systems Catapult

June 2019 saw an historic moment. The UK Government passed legislation to reduce greenhouse gas emissions to zero by 2050. This landmark law will serve as a lodestar for future energy policy and inform major decisions across successive governments. The challenge it presents is none other than the wholesale transformation of the British economy and our society away from its historic dependence on fossil fuels.

Predicting the future is never easy and sometimes foolhardy. But the challenge posed by net zero means we need to imagine a world which is radically different to the one we currently live in.
The work to end Britain's contribution to climate change should not be delayed. The urgency to cut emissions is clear, but many of the changes will need engagement from all sections of society. And the energy industry has a central role in supporting this transition.

Net zero means we have to think differently both about the decisions we make now, and the long-term impacts they will have on the energy system. 2050 may seem like a long time away, but in reality, we are already creating that future. The difficulty is in knowing the impact of today's decisions and the limitations they will impose on a future energy system.

With that in mind, Good Energy commissioned Energy Systems Catapult to undertake modelling on a set of innovative scenarios to achieve net zero. These scenarios were created to test current thinking around the technologies we need; to imagine different versions of the future; and to promote debate around the choices we need to take.

Some of these pathways offer unique constraints on the energy system – a deliberate approach to test how it could cope under conditions which are rarely modelled. The results offer fresh insight into how we can cut emissions quickly, cheaply and with technologies which are readily available to the UK.

The report paints a picture of the future which is both cost effective and inclusive. Current progress on decarbonisation has largely left out consumers with few behavioural changes required of British households. The next stage of the journey will need to involve everyone with significant engagement to cut emissions from our homes and our lifestyles. The report's results point to a significant role for consumers and a clear opportunity to engage people with new green products. It also underlines the importance of rapid testing and demonstration of new low carbon solutions to get them ready for the rapid scale-up that will be necessary to meet our targets.

This challenge also comes with many positive outcomes – warmer homes, new jobs, and transformational clean tech.

The road to net zero may seem more like an uphill climb, but the task can be made easier with a diverse set of perspectives and by challenging our assumptions about what is possible. This process will fast-track the development of new ideas and innovations which will be crucial in the near future.

The report paints a picture of the future which is both cost effective and inclusive

Introduction

Juliet Davenport
Founder
Good Energy

When I set up Good Energy in 1999 it was with a very specific purpose. As the UK's first 100% renewable electricity supplier, we would enable ordinary people to be a part of the solutions to climate change.

Simultaneously, at a time when Britain only generated around 2% of its electricity from renewables, we would exist to challenge the energy industry. To move it forwards.

In the intervening 20 years renewables have come a long way. That we can power the whole of the UK with renewables has always been a founding principle of Good Energy's, and now our electricity is about 40% of the way there.

That achievement is significant, driven by innovations such as the Feed-in Tariff scheme, which was based on the Good Energy's own HomeGen scheme, allowing people to turn their homes into small power stations. Alongside huge investments in onshore and offshore wind, falling costs to develop renewables which have shed the need for subsidies in many cases. But the rest of the path to the net zero goal the UK government has set is going to be harder.

That is why we set about creating this report. There are many pathways to a zero carbon Britain but speaking as someone who has seen first-hand how vested interests can divert or hamper progress, there are more than a few among the solutions being touted today.

We wanted to see what a route to zero carbon would look like if you stripped all of that away. No mythical technologies, no false dawns, no over promising to under deliver. A pathway built on what we know works today — renewables. Leading to an energy system designed to work for the customers of the future, move away from a centralised system, installed by the historic government and big business approach.

By asking questions seldom asked, we set out to challenge the energy industry.

The result is a hugely inspiring vision of a zero carbon Britain which is greener, fairer and whilst ambitious, eminently achievable. As long as we keep moving forwards.

Executive Summary

This report provides new findings on the need to transition the UK to zero emissions within a generation.

Good Energy worked with Energy Systems Catapult (ESC) to undertake detailed energy modelling on a range of different scenarios to achieve a net zero economy by 2050. The results were obtained through the use of two separate models which tested ideas rarely examined by the energy industry.

We found that some of the major changes in energy usage could be achieved long before the 2050 target, with the benefits of a zero-carbon power sector realised within a decade.

One of the main aims of the report was to interrogate how traditional energy modelling can lead to two major biases, and what the outcomes might be if these are corrected. We created six distinct scenarios, which tested the energy system in different ways. This report will largely compare the differences between two: The **Baseline** scenario, which takes an orthodox approach to net zero, and **Zero Carbon Britain**, a high renewables world informed by the lessons learned in other scenarios.

The aim of this approach was to see if we could achieve net zero by only using renewable technologies and through realistic government policies. The restrictions imposed by this philosophy did not have a significant impact on the overall system cost, with our Zero Carbon Britain scenario projected to cost between 0% and 1.5% of GDP in 2050, in line with current assessments made by the Climate Change Committee[1] A key finding from this research is the strong potential to build out a very high renewable, low nuclear, zero fossil fuel system and remain cost competitive.

> **We found that some of the major changes in energy usage could be achieved long before the 2050 target**

Research Approach

Energy modelling is an incredibly powerful tool for aiding policy and investment decisions. Modelling should not be seen as an exact plan for the future but as a way of assessing broad trends and the complex interactions between technologies.

We believe errors in energy modelling are usually caused by two main issues:

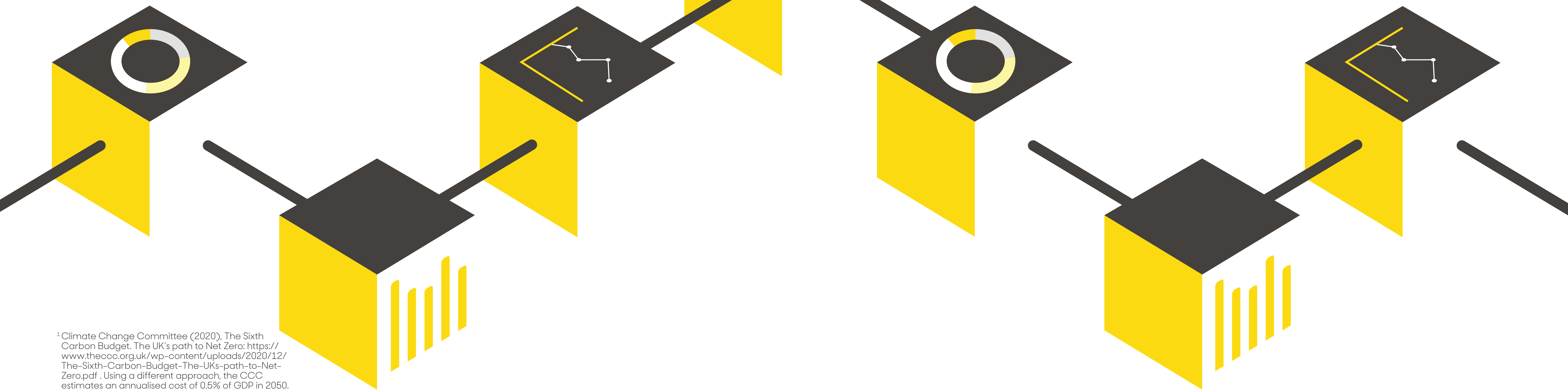
1. Limits in modelling technique or computing power.
2. Bias in selecting the inputs and assumptions. This leads to a tendency to favour current dominant technologies.

Issue one is limited by the technology of the day, but having different parties produce the modelling helps to mitigate this problem. However, even multiple independent parties can be affected by the same consistent biases which can lead to bad policy and investment decisions. These concerns informed how we approached this report.

We believe current energy modelling has two main biases which we wanted to correct for in our work. These are:

1. Lack of granularity in modelling techniques falsely benefit nuclear and wind power, underestimating the difficulties caused by combining these two technologies.
2. Nuclear cost predictions are incredibly low when compared to real life projects being developed today.

There is value in investigating a scenario without new nuclear or gas plant in the energy mix. First, it quantifies how much value large generators provide the energy system. Second, it is prudent to plan for a scenario where these technologies cannot be built out due to stricter carbon budgets, high financial costs, or low public support.



[1] Climate Change Committee (2020), The Sixth Carbon Budget. The UK's path to Net Zero: https://www.theccc.org.uk/wp-content/uploads/2020/12/The-Sixth-Carbon-Budget-The-UKs-path-to-Net-Zero.pdf . Using a different approach, the CCC estimates an annualised cost of 0.5% of GDP in 2050.

Key Findings

The electrification of everything

The single most consequential finding across all scenarios is a significantly increased role for electricity across all energy demand.

The modelling shows the energy system changing dramatically, mainly due to the electrification of transportation and heat. Total energy demand doubles on current rates and peak demand quadruples. All scenarios see the electricity sector expanding to accommodate the increased needs of heating and transport, even though multiple other options (such as hydrogen) are available. A net-zero electricity system in 2050 will need to be at least four times larger than today. A mixed heat supply system is deployed in all cases, but the electrification of heat – predominantly via heat pumps – is a key solution throughout.

People will power the way to net zero

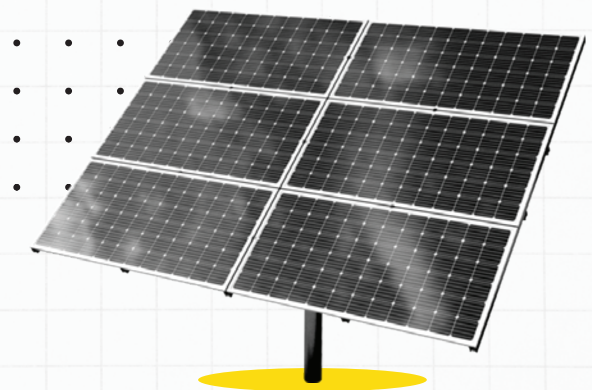
Progress in cutting carbon emissions has so far avoided the need for serious behavioural change. However it will be impossible to exclude households from the next stages of decarbonisation. Large-scale changes will be made to household energy usage. The role of the passive 'consumer' of energy will shift to active engagement in essential storage, flexibility, and generation services.

The net zero home will have very high levels of energy efficiency, home energy storage, and roof-top solar panels. The importance of reducing costs to customers and creating innovative green products is clear to ensure high levels of engagement. Reducing peak demand of households will be essential in making the system possible, any investment in energy efficiency, smart charging or home storage negates the need to spend money on more generators and wires to only be used a few times a year.

Renewable power dominates the energy system

A system with very high volumes of electricity demand led the modelling to pick wind and solar power as the cheapest technology to meet the majority of this demand. These two technologies will provide the backbone of the future energy system. Even when allowed to build out nuclear and gas, the modelling predominantly chose wind and solar due to low costs.

The Zero Carbon Britain scenario sees renewable technologies meeting 98% of all electricity demand with additional support from marine and geothermal energy. This pathway offers a resilient, cost-effective route to zero carbon by 2050 without the need to build new nuclear or gas power plants.



Storage and flexibility become indispensable

Energy storage technologies will become an essential tool in balancing supply and demand. This is to ensure the resilience and security of a system which will be run almost entirely on renewable power. The full range of technology types will need to be deployed, from large-scale battery units to pumped storage, amounting to 400 gigawatt hours of supply. There is significant potential for millions of home storage units to support the system and these storage options will become clearer as the industry matures.

The 2050 energy system will need flexibility built into its core way of working, with a variety of clean technology options working in tandem with renewables to service demand. Millions of new electric vehicles will provide the capacity to shift their demand by up to 60%. Smart charging options, such as vehicle-to-grid or vehicle-to-home, will be designed to support this effort.

Costs remain competitive

Both the Baseline and Zero Carbon Britain scenarios solve net zero with costs remaining at 0%–1.5% of GDP per year out to 2050. This provides good evidence that the target can be achieved with different options, but at a similar cost.

The Zero Carbon Britain scenario provides the energy system with very cheap renewable power. This future system still requires significant investment in energy infrastructure to provide back-up capacity and essential grid services. Back-up costs are a requirement of all scenarios and are not unique to a high renewables future. In addition, these costs could be reduced by up to half through programmes to reduce energy demand and further innovations to improve the performance of renewable power.

Executive Summary *continued*

Five Principles for Net Zero

Building on the findings of the modelling, we developed five principles to guide policy decisions and thinking around achieving net zero.

Our approach recognises the challenge as greater than an economic or mathematical calculation. Reaching net zero requires policymakers to consider how all sections of society will be impacted by the transition and how they can benefit.

01 Doing the known now

Some of the solutions to net zero are already known and can be deployed immediately. Acting now will greatly affect the ease and speed with which the transition can be made.

These solutions include addressing Britain's very low rates of energy efficiency in buildings; removing barriers to mature renewable technologies; and increasing net zero innovation funding to 1.5% of GDP. These are straightforward but require political will and ambition to be achieved at pace.

02 Unleashing people power

Net zero offers the potential for long lasting, positive impacts to the way people live their lives. Policy decisions need to be made with consumer support and protections built in from the outset. All communities and households need to participate in the energy transition, especially those from deprived areas and low incomes.

A long-term plan is needed to empower and engage consumers with the clean technologies which will become part of their homes. This is the role of business, government and the third sector.

03 Embrace diverse technologies

Replacing our sophisticated, high-carbon economy is complex and will need more than a one-size-fits-all approach. The closer we get to zero emissions, the more we will need to adopt policies which apply tailored, local solutions to decarbonisation.

Embracing diversity will result in a future energy system with clean technologies working on different parts of the economy to ensure security of supply. Net zero markets and R&D funding will be needed to usher in the full range of these technologies.

04 Making the best of Britain

Britain's natural renewable resources offer an unrivalled opportunity to cut emissions and grow new economic industries. The growth in wind and solar power will need support from marine energy, geothermal and bioenergy. Britain is ideally placed to develop these technologies and spread the economic benefits across the country.

Applying Britain's strong academic and research capabilities to net zero problems will be essential. Innovation spending in this area needs to match the scale of the challenge.

05 To 2050 and beyond

The decisions we make now will have a lasting impact on the makeup of the energy system and the opportunities of future generations living with the impacts of climate change. Ending Britain's contribution to global heating is a long-term project and 2050 is, in part, just a political deadline.

Our decision making should not be confined, or constrained, by the 2050 target date. Nor should it set us on a pathway which might lock out future innovations that could help achieve net zero earlier. Not only could parts of the economy decarbonise before this date, but we need a plan for how emissions will be subdued long into the future.

Methodology: the energy models we used and why

The Energy Systems Catapult (ESC) is a recognised authority on energy modelling, with a strong track record of delivering insights into the future of the UK energy system.

Its work is supported by several powerful analysis tools. The Energy Systems Modelling Environment, or ESME, has been a staple of UK energy systems analysis for many years. It is a peer reviewed, least-cost optimisation model designed to explore technology options for a UK energy system with carbon constraints applied. It explores the power, transport, building and industrial sectors and the underlying infrastructure, in five-year time steps out to 2050. However, like other energy models it does not provide detailed granularity.

The UK's population is assumed to grow by 8.5m people to reach 75m by 2050, with the greatest levels of growth seen in metropolitan areas.

ESC's Storage and Flexibility Model (SFM) was also used to provide a greater level of detail into how the energy system might function under our chosen scenarios. SFM's platform produces highly granular dispatch information and explores the different roles and responsibilities of energy technologies and services in 2050, on an hour-by-hour basis. The results section is focussed on the SFM models output unless otherwise stated.

Pathways to a Zero Carbon Britain

There are many possible pathways to achieving net zero. Our research was informed by this – we took an iterative, scenario-based approach, beginning with a moderate 'reference' view of the UK's decarbonisation pathway. From there, we worked with ESC to develop alternatives which deviated from our starting point, typically by making changes to the technology costs, availability, and performance. This helped simulate both accelerated development or increased support for some low-carbon solutions, or alternatively, futures where some of those solutions have failed to deliver on current expectations. The learnings from these scenarios were then incorporated into our Zero Carbon Britain scenario to test whether large plants, such as nuclear and gas, are essential to provide a reliable and efficient energy system.

Baseline

This was our reference scenario. We chose to use the 'patchwork' framework ESC has used in previous research. This framework provides a useful starting point to assess how a decentralised energy system can be successfully utilised in the future, as it envisions a world without extensive central planning of energy, and where working and living patterns evolve gradually.

The UK's population is assumed to grow by 8.5m people to reach 75m by 2050, with the greatest levels of growth seen in metropolitan areas. Other features of this scenario include a certain degree of lifestyle change as we head towards 2050. People will travel less for business, and we will see moderate changes in dietary preferences.

The scenario was designed to align with the accepted orthodoxy in energy modelling with a few changes to outdated assumptions. The vast majority of assumptions used in this scenario are consistent with those presented in ESC's ESME dataset. However, some changes were made to bring those assumptions in line with recent trends and developments:

- The starting costs of large nuclear plants were updated to those quoted for Hinkley Point C, and reduce gradually over time, in accordance with a widely accepted 'learning-curve' for future nuclear power stations. The modelled costs of wind and solar power were updated, bringing them into line with the recently published 2020 BEIS Cost of Generation Report.[2]

All consequent scenarios were constructed with the Baseline assumption set as a foundation.

[2] BEIS (2020), Electricity Generation Costs: https://www.gov.uk/government/publications/beis-electricity-generation-costs-2020

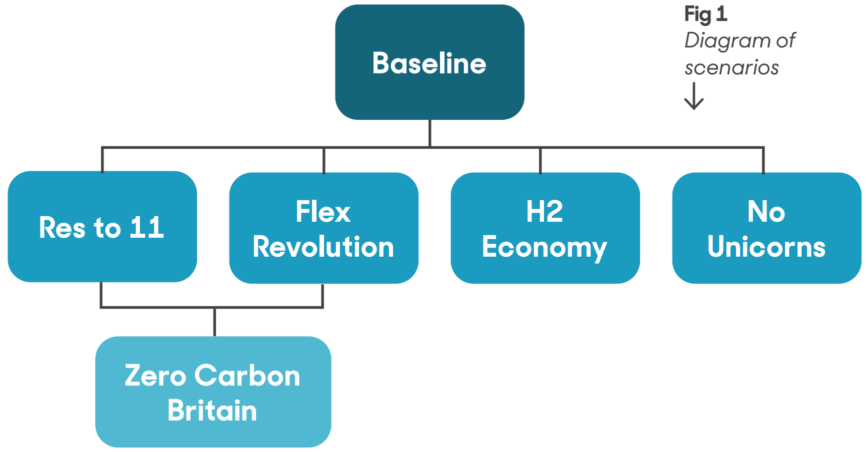


Fig 1
Diagram of scenarios

Flex Revolution

Customer engagement with energy is accelerated, enabling more decentralised solutions for generation and storage, such as high levels of smart electric vehicle charging. The model remains able to call on gas turbines, nuclear power stations and fossil derived hydrogen.

Renewables to 11

Consistent with a world where innovation within the major renewable technologies progresses at pace, with wind and solar power continue to reduce in cost and de-risk as investments. This focus leads to the removal of fossil fuels – including for hydrogen production – and nuclear power from the future energy mix, except for Hinkley Point C.

No Unicorns

This counterfactual scenario represents a world where key innovation steps deemed necessary to bring on nascent technologies – the 'Unicorns' are either delayed, or absent. Carbon capture technology is limited to industrial processes, and electrification of heat is slowed. Despite this, a reliance on Direct Air Carbon Capture, another unicorn, was needed to reach net zero, and at high cost.

Hydrogen Economy

This scenario envisions a world where a broad switch from natural gas to hydrogen is a key enabler of decarbonisation. No restrictions are placed on the use of fossil fuel derived grey and blue hydrogen. Carbon capture technology is assumed to develop to the point of delivering a 99% capture rate.

Zero Carbon Britain

This is our final scenario which built on the findings from other aspects of the modelling. The scenario includes high levels of development for wind and solar power but also for emerging renewable technologies with strong potential, such as wave and geothermal power. This is combined with a consumer driven home storage and self-generation, enhanced with increased levels of electric vehicle smart charging. Zero Carbon Britain is a future where political certainty and innovation drive down renewable costs and promote consumer engagement.

Results

Electricity

- Electricity system is fully decarbonised by 2030, with renewables generating 84% of the energy. By 2050 150 GW of wind and 210 GW of solar are supported by 34 GW of other renewables such as marine and geothermal to provide a fully decarbonised, 98% renewable system.

Heat

- The vast majority of heat demand is electrified (81%), supplemented by hydrogen (9%) and geothermal and solar thermal (10%).
- Stress on the electricity grid by this increased demand was managed by significant investment in energy efficiency retrofitting and heat storage.

Transport

- 90% of transport is electrified, 4% of energy comes from liquid fuel and 6% from hydrogen.
- Smart EV charging is essential for the operation of the grid, it was estimated that 60% of EV charging load can be considered flexible.

Hydrogen

- Hydrogen production is large (89 TWh) but is mainly used for hard to decarbonise sectors such as industry and certain forms of heavy transport.

Costs

- Both main scenarios had very similar total energy system costs: £126 bn & £126.4 bn year, for Baseline and ZCB respectively.
- Depending on how we scale current energy costs to 2050 population, net costs of decarbonisation are between £14 bn - £49 bn per year.

Results: Electricity

The power sector has undergone huge disruption over the past decade

In 2010, renewable electricity provided less than 7% of Britain's power needs; in 2020, that figure reached 42%. Furthermore, carbon emissions from power stations were 71% lower in 2019 than in 1990.[3] This progress accounts in large part for the UK's overall success in cutting emissions across the entire economy and is not replicated in heating or transport.

Our scenarios offer strong reasons to continue this progress in power. The modelling finds that extending electrification to cover heating and transport is the preferred route to achieving zero emissions by 2050. However, a power sector which provides the heavy lifting across all energy demand creates significant challenges which need to be addressed now. Work will need to be undertaken to create a decentralised and flexible system which has very high levels of energy storage of different kinds.

In addition, one of the key findings of the report is that electrification can be done quickest with renewable power and with equal costs to other technologies. By 2050, renewable technologies will provide around 98% of all electricity demand, with the remainder of electricity coming from the Hinkley Point C nuclear power plant, which will still be in operation.

A focus on renewable power means immediate and substantial declines in UK carbon emissions. Our final Zero Carbon Britain (ZCB) scenario sees carbon emissions in the power sector virtually eliminated by 2030. This system is achieved without developing new nuclear power, or reliance on Carbon Capture and Storage (CCS).

Wind and Solar Dominate

Renewable power in the scenarios represent a range of different technologies able to play different roles to balance supply and demand. However, across the board, wind and solar power will provide the backbone of Britain's future energy mix, because of their low cost and Britain's enviable wind resource.Latest figures show current wind and solar capacity sits at 37 GW,[4] generating over 77 TWh in 2019, or 25% of Britain's electricity needs. By 2050, this will need to increase to between 338 - 360 GW. On average, generation from wind and solar will increase seven-fold to over 500 TWh.

In the ZCB scenario, a blend of nascent, homegrown renewable technologies will come online to support this growth. The development of tidal (23 GW) and geothermal energy (9 GW) can provide important contributions to security of supply.

→ **Fig 2** *Electricity Capacity and Generation*

[3] BEIS (2020): 2019 UK greenhouse gas emissions, provisional figures. This year provides a more accurate comparison than the impacts of 2020.
[4] BEIS (2020), Digest of UK Energy Statistics: https://www.gov.uk/government/statistics/digest-of-uk-energy-statistics-dukes-2020

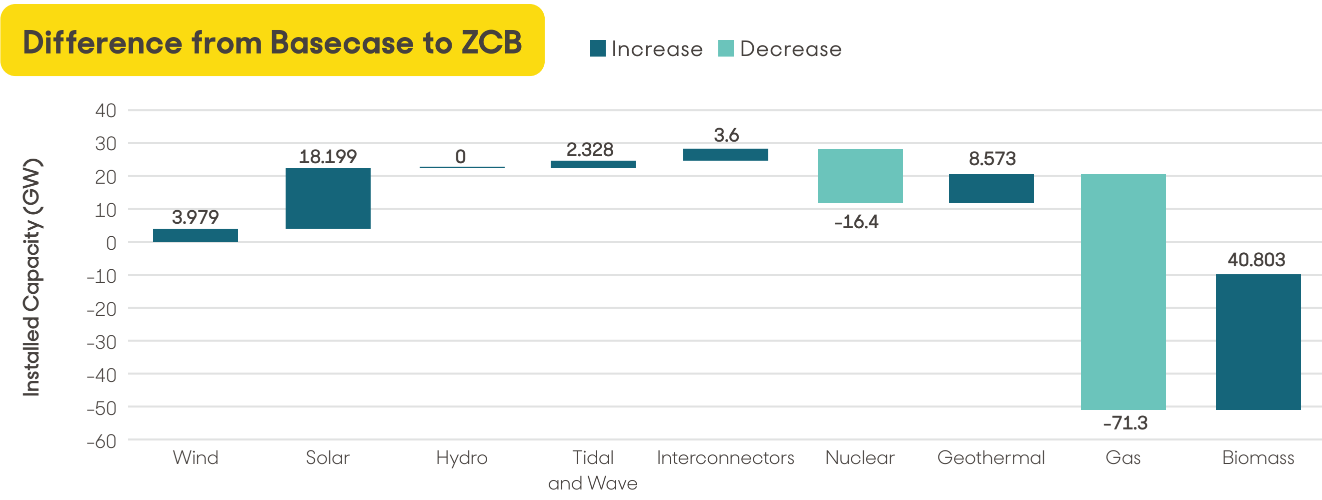


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Fig 3
Capacity difference Baseline to ZCB

Baseline vs. Zero Carbon Britain

The ZCB scenario has slightly more wind and solar than Baseline but the main difference is the balancing and supporting technologies. Greater energy efficiency allows for a lower total installed capacity meaning geothermal technology can replace most of the nuclear power. Backup generation is now provided by other renewables and biomass instead of gas. Battery storage capacities are also similar with ZCB installing 8GW less storage.

The Dash from Gas

There is much debate surrounding the application of carbon capture technologies and the potential for their use to prolong the life of gas plants. We thought it would be prudent to let the model experiment with gas plants fitted with CCS units in several scenarios – including the Baseline. As early as 2030, the only use for a gas plant, CCS or otherwise, is for providing backup capacity for only the most extreme weather events. But even then, the ZCB scenario shows how it is possible to use renewables to provide this backup instead.

No role for nuclear?

One of the key attributes of the ZCB scenario is the absence of new nuclear power. Much of the current modelling work on net zero has included a strong role for new nuclear plants over the next 30 years, based on optimistic cost reductions that are not borne out from 65 years of nuclear experience in Britain.[5]

Our approach was different. We wanted to imagine how a net-zero system could exist without this technology, providing a unique vision of the future and a set of new options for policymakers. A separate reason for excluding nuclear power is the difficulty in balancing the technology with renewables. The energy system in the modelling needs greater flexibility without adding further inflexible capacity to the mix. A recent example of this was the unusual case of National Grid paying a nuclear plant, Sizewell B, to reduce its output during a period of low demand and high renewable generation.[6]

Adding both more nuclear power and more renewables will likely lead to higher costs for consumers and much higher levels of constraints for wind generators. We have found that beyond the existing Hinkley Point C plant, new nuclear is both unnecessary to reach net zero and would be difficult to manage alongside such a large fleet of renewables.

Demand Changes

Energy demand increases in all scenarios due to the wholesale electrification of heating and transport. Meeting the challenges of a fully electrified system will come with difficulties and costs attached. This is true regardless of the energy technologies chosen to provide the bulk of new generation. Any current system trying to meet the changes in demand shape and volume would struggle, especially when considering the need for more transmission and distribution infrastructure.

Electricity demand increases significantly with total energy requirements doubling and peak demand quadrupled. There is also much greater seasonal variation than today due to the electrification of heat. Winter peak demand in the UK is usually around 25% higher than summer[7]; in the Baseline scenario it is 100% higher. This is one of the reasons why the modelling chooses wind power in such high volumes.

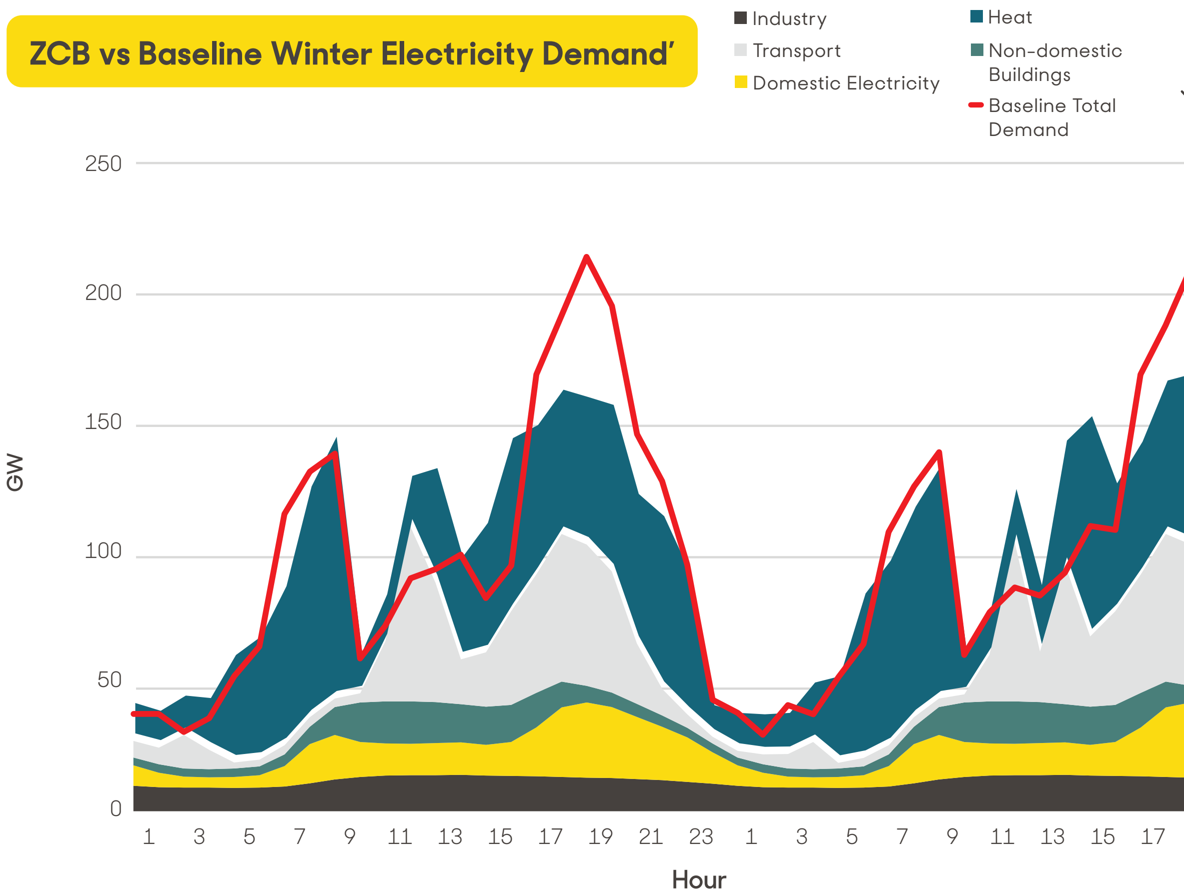

Fig 4
ZCB 2050 Winter Elec Demand ↓

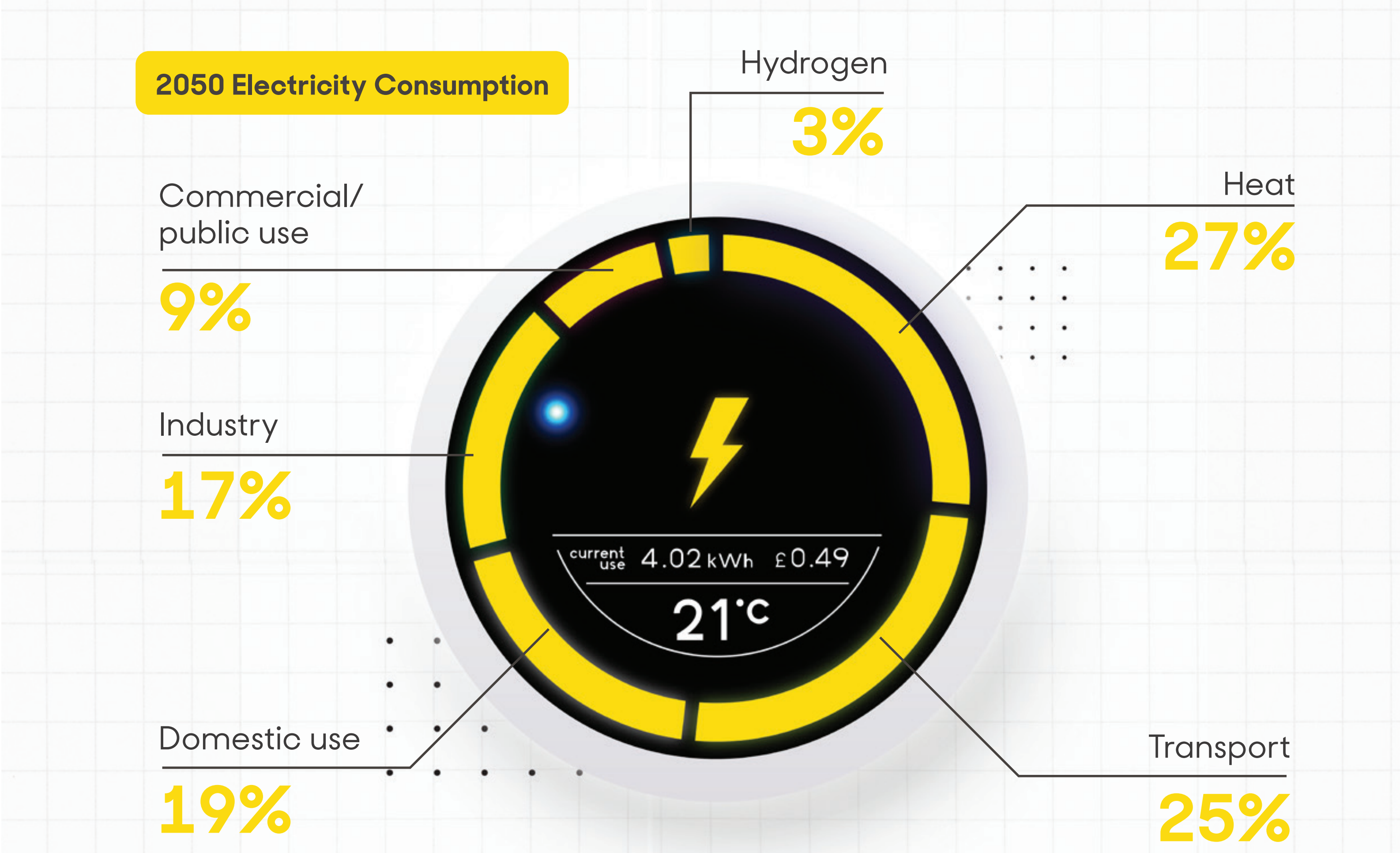

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Fig 5
Zero Carbon Britain Scenario – 2050 Electricity Consumption

[5] Michel Berthélemy and Lina Escobar Rangel (2015) – Nuclear reactors' construction costs: The role of lead-time, standardization and technological progress. In Energy Policy Volume 82, July 2015, Pages 118-130. https://doi.org/10.1016/j.enpol.2015.03.015 and Max Roser (2020): Why did renewables become so cheap so fast? And what can we do to use this global opportunity for green growth? In Our World in Data: https://ourworldindata.org/cheap-renewables-growth (sub-section: Why did nuclear power get more expensive? What can reverse that trend?)

[6] National Grid ESO (2020). Decision to extend contract with EDF to turn down output from Sizewell nuclear power station: https://www.nationalgrideso.com/document/171336/download
[7] National Grid ESO Data Explorer: https://www.nationalgrideso.com/data-explorer (accessed March 2021)

Fig 6
Electrical Storage Capacity
→

System Changes

To electrify the majority of energy demand creates significant changes to the daily profile of the electricity system and between seasons. The result of high levels of renewable power means managing the system in a different way.

The UK is currently in the early stages of deploying flexible energy technologies to respond to the rise in variable renewable generation. This will have to increase significantly over the coming decades to ensure security of supply and cope with extreme weather events. The need for high levels of energy efficiency, heat storage, and smart electric vehicle charging will all become significant as the system electrifies. The system struggles to provide for the very high levels of power demand when temperatures are low, this is why the high levels of energy efficiency in the ZCB scenario provides for a much more efficient system – it is much easier to insulate housing effectively than build even more generators and wires.

The UK's current total electricity capacity sits at 104GW.[8] All our scenarios see the sector expanding to accommodate the increased needs of electrifying heating and transport. The total installed capacity for a net-zero electricity system in 2050 will be over four times larger than is currently installed.

Storage Opportunity

Energy storage will play a key part in any future net-zero future. The industry is in its early stages but is growing rapidly and this will need to continue. Industry data shows that in 2012 there were only 2MW of battery storage planning applications in the UK; in 2021, that figure has climbed to 16.1 GW of capacity in operation, under construction, or planning.[9]

An energy system which is run almost entirely on renewable power will need energy storage as an essential component in balancing supply and demand. In practical terms this means a requirement to have 140GW of storage operating throughout the year. Our modelling provides options to develop storage both in people's homes and at utility-scale.

As can be seen above the major use of storage is to shape the daily output of renewables to meet demand. Due to heating and transport being electrified the evening demand is incredibly high, most of the work storage is doing is 'moving' renewable energy from overnight and daytime to the evening and morning peaks. Doing this on a domestic level will lead to large savings in transmission upgrades.

> **The result of high levels of renewable power means managing the system in a different way.**

Energy storage will play a key part in any net-zero future. The industry is in its early stages but is growing rapidly and this will need to continue.

[8] BEIS (2020), Digest of UK Energy Statistics (p.94)
[9] RenewableUK https://www.renewableuk.com/news/550773/UKs-total-pipeline-of-battery-storage-projects-now-stands-at-over-16-gigawatts.htm

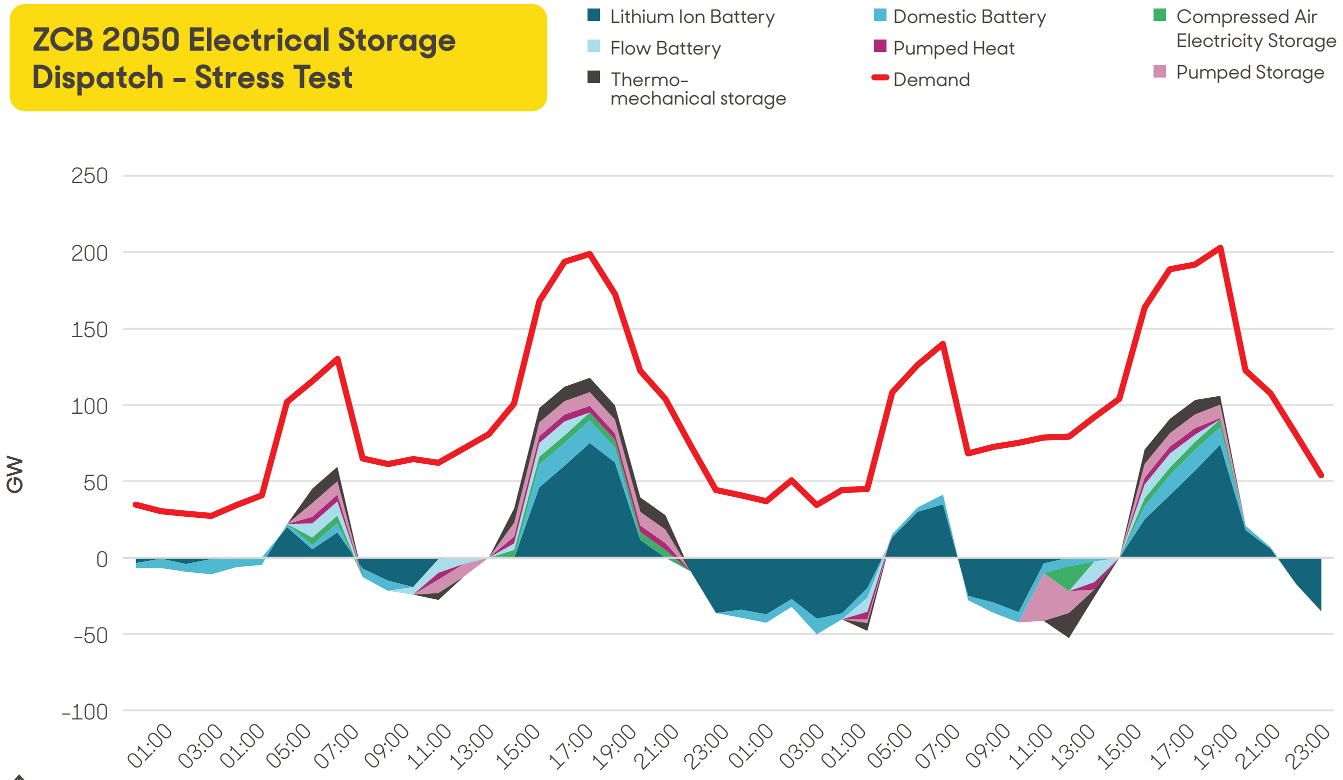


Fig 7
Electrical Storage Dispatch

Energy Storage Technologies

Lithium-ion

The model uses huge amounts of electricity storage, mainly utilising lithium-ion. This technology is incredibly fast reacting and can provide very high-power outputs so is perfect for grid balancing and ancillary services, the need for which is currently ~ 5-10GW. However, the system deploys over 100GW of lithium-ion. The use of the remaining Li-ion is mainly for bulk electricity storage, e.g., moving energy from middle of day to evening, which it isn't ideally suited but has been chosen for economic reasons.

Using lithium-ion for bulk electricity storage is akin to using thousands of watch mechanisms to lift an elevator. It will work but the precision of the watch mechanisms isn't fully utilised, and the heavy loads will wear out the precise mechanisms faster. Lithium-ion isn't ideal for bulk storage because fully charging and discharging the battery degrades it slightly. This is why it's best not to fully charge the battery in your mobile if you want it to last a long time.

The model has chosen this technology for bulk storage because the sheer number of lithium-ion batteries being produced is pushing prices incredibly low, whereas other technologies haven't reached this mature stage. There is a real potential for using end of life electric vehicle batteries as grid scale storage. We should start researching how best to design batteries so they can be reconditioned to provide a second life capacity. Either way when the model denotes lithium-ion storage the vast majority of this could be replaced by other technologies if they turn out to be cheaper.

Liquid Salt

Liquid salt is a storage technology which works by using surplus electricity to heat salt up to 300 degrees and then stored in large insulated tanks. When electricity is needed this stored heat is used to create steam which turns a traditional steam turbine. This is potentially interesting in a UK context as there are a number of mothballed and soon to be decommissioned coal power plants with steam turbines and other infrastructure already in place. As the main cost of liquid salt storage is the turbine, these old coal power plants could be converted to large storage plants at a relatively low cost. The ZCB scenario has 40GW of biomass backup which could be fitted with liquid salt storage allowing it to offset the need for some of the lithium-ion storage needed.

Consumers

One of the key conclusions from the results is the importance of consumers in achieving the UK's carbon targets. The Committee on Climate Change has stated that over 60% of the measures needed to reach net zero will need societal or behavioural changes.[10] Our findings support this view and explore the potential for deploying net-zero solutions in people's homes.

The opportunity comes from households providing key services to the electricity grid: generating, using, storing, and sharing clean power. Roof-top solar panels are one such example. In the 2010s, this technology grew from a very low base to one million solar sites.[11] Much of this growth was fuelled by the decline in the cost of solar panels and the financial support provided by the UK government's Feed-in Tariff. This financial scheme closed to new entrants in 2019 and uptake of roof-top solar has since stalled.

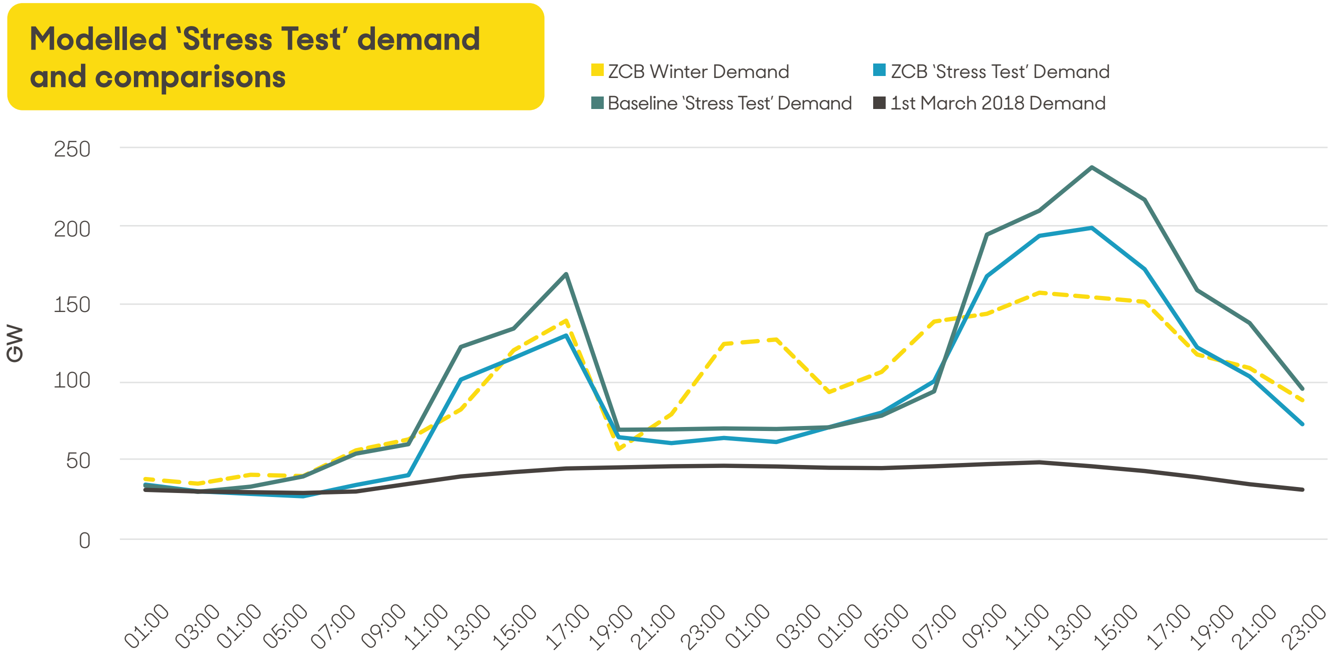
With the right financial support mechanism, targeting all sections of society, roof-top solar growth can be revived. There are an estimated 3% of households which have installed roof-top solar panels.[12] Our future energy system envisages this figure increasing to around half of all British homes – a total of 13.5 million domestic solar installations. One large difference between the Baseline scenario and ZCB is displacing 36 GW of grid-scale solar power with domestic solar.

Domestic battery storage can work alongside solar PV to store power at different times of the day. As this technology develops, it will need to play a major role in supporting a net-zero electricity system. As evening peak demand is so high in this new energy system, it is best to generate and store energy more locally to reduce the need for further transmission and distribution upgrades. These costs are already 25% of a customer's bill[13], and might increase significantly if steps are not taken to avoid this.

Our scenarios see domestic storage capacity ranging from 23 - 55 GWh. The impact would be widespread adoption of home storage technologies, equivalent to between 1.5 - 4 million Tesla Powerwall-sized batteries in people's homes. Uptake is higher in scenarios where low discount rates are used to simulate support mechanisms for consumer purchases. The variance here shows the importance of policy decisions in driving positive engagement with the energy system.

[10] Climate Change Committee (2019), Presentation on Net Zero: The UK's contribution to stopping global warming: https://www.theccc.org.uk/wp-content/uploads/2019/05/Net-Zero-Chris-Stark-Presentation.pdf (slide 13)
[11] BEIS (2021) Solar photovoltaics deployment: https://www.gov.uk/government/statistics/solar-photovoltaics-deployment (accessed March 2021)
[12] Ibid.
[13] Ofgem (2019) State of the energy market: https://www.ofgem.gov.uk/system/files/docs/2019/11/20191030_state_of_energy_market_revised.pdf

Fig 8
Stress test electrical dispatch 2050, Baseline and ZCB



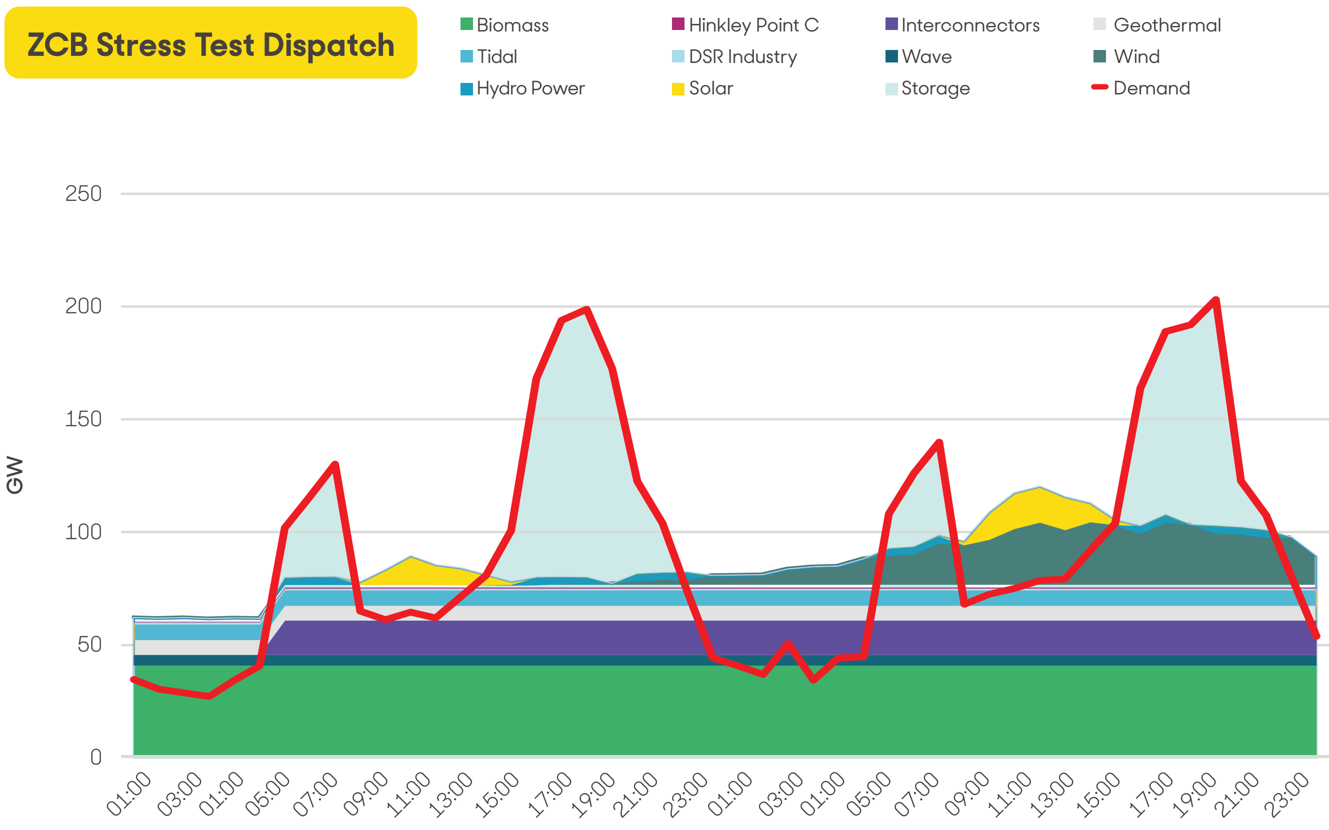


Fig 9
ZCB Stress Test dispatch

Passing the stress test

Any future net-zero energy system needs to ensure security of supply and account for extreme weather conditions. This would be true of any system with very high levels of renewables, but climate change will also put the grid under extreme levels of stress.

To ensure an energy system can perform under all conditions, ESC's models put them through a stress test. This provides useful insight into the likely impact of a worst-case scenario and how any would-be energy system might cope. One of the benefits of using the SFM model is that it was able to show these outcomes in granular detail out to 2050. This means we can test whether a renewables-led energy system can provide the necessary security of supply.

The test simulates a rare occurrence when there are very low temperatures coupled with very low wind and solar output over the course of an entire week. This creates an energy system stress event more extreme even than the so-called 'Beast from the East', the cold weather event which impacted Britain and Ireland three years ago.

The energy choices we make in the short term will inform the future net zero system in 2050.

In March 2018, during this very cold spell, wind power output was still high. In contrast, the stress test modelled creates conditions which are very unlikely to occur; for example, at one point 150GW of wind generates only 0.9GW of power. This is artificially low – an enormous wind portfolio with wide geographical distribution would likely yield more in almost any circumstance.

The difference between 2018 and 2050 is that the electricity and heat systems were relatively distinct. On 1st March 2018, as temperatures dropped to a low of -14C [14], electrical demand rose 10%, but only reached a high of 53GW. Gas demand, however, catering for the vast majority of UK heat, rose to 241GW.[15] In 2050, as will be outlined in the subsequent chapters, the provision of heat and transport will rely largely on the power sector, and so the strain of extreme weather on the electricity system will be increased. Peak 2050 electrical demand in our modelling therefore ranges from 199GW in the more flexible renewables-led scenarios, to 237GW with a more centralised approach.

These kinds of hypothetical scenarios are often posited as reasons why energy systems cannot be based on a backbone of renewables. However, when presented with these challenging conditions, our ZCB scenario passed the test, with considerable amounts of electrical storage capacity on hand to combine with a smaller amount of biomass backup generation to stand in for the missing wind and solar. Interconnectors to other European countries also provided 15GW of additional generation to support peak demand. This is eminently more preferable than the Baseline scenario, which despite having a larger fleet of nuclear power stations, requires 51GW of fossil fuel, natural gas backup capacity to plug the gap.

Despite passing the stress test, we should investigate methods to reduce demand during winter evenings and other periods where demand is typically higher. Any reduction in this demand would reduce the costs of the transition dramatically, especially when considering the transmission and distribution network capacities.

[14] Drax: https://www.drax.com/wp-content/uploads/2018/04/Drax-Electric-Insights-Beast-from-the-East-Special-Report.pdf
[15] UKERC: https://ukerc.ac.uk/news/gas-consumption-during-beast-from-the-east/
Drax: https://www.drax.com/wp-content/uploads/2018/04/Drax-Electric-Insights-Beast-from-the-East-Special-Report.pdf

Diversity of renewable technologies

We established that across all scenarios electricity demand will be very high in the future – equivalent to more than doubling current total demand. The foundations of this energy mix will be laid by wind and solar power, but a wide array of renewables will be needed in supporting roles.

These contributions can be provided by renewable technologies which are not currently at commercial scale in Britain. The findings illustrate this diversity; between the Baseline and ZCB scenarios there is 28-38GW of renewable capacity provided by technologies other than wind and solar. Using these resources alone could meet a very large portion of existing demand. The bulk of this new generation in both outcomes is provided by tidal power, sitting at 23GW. The ZCB scenario sees an additional 2GW provided by wave power, 9GW from geothermal, and 4 GW of hydro.

These results are ambitious, but achievable with recognition and support from government[16] and continued business investment. The potential for developing marine energy has long been highlighted by industry and government , but current capacity for both wave and tidal power is low, remaining at around 22MW.[17] Similarly, geothermal energy is largely undeveloped in the UK, and estimates vary on its potential. A 2012 study found the technology could provide 20% of the UK's electricity and all of its heat demand.[18]

The benefits delivered by these other renewable technologies stem from their differing attributes when compared to wind and solar power. Geothermal plants, for example, are available twenty-four hours a day and independent from the weather. These complementary technologies will be increasingly important as the energy system becomes electrified and more dependent on wind and solar power.

Renewable power will continue to grow and dominate.

[16] A high of 38GW. ORE Catapult (2018): Tidal Stream and Wave Energy Cost Reduction and Industrial Benefit https://ore.catapult.org.uk/app/uploads/2018/11/Tidal-Stream-and-Wave-Energy-Cost-Reduction-and-Industrial-Benefit.pdf

[17] BEIS (2020) Digest of UK energy statistics: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/924591/DUKES_2020_MASTER.pdf (p.89)

[18] SKM (2012) Geothermal Energy Potential in Great Britain and Northern Ireland: http://www.skillsandgrowth.co.uk/wp-content/uploads/2018/03/Jackson-2012.pdf

The arrival of new technologies

The energy choices we make in the short term will inform the future net zero system in 2050. The difficulty in making these choices is compounded by the unknown progress of new and maturing technologies. For example, the rapid decline in costs for wind and solar power over the past decade has transformed this technology into Britain's cheapest source of new electricity. Our future energy mix will undoubtedly be influenced by other technologies which are currently undeveloped or even undiscovered.

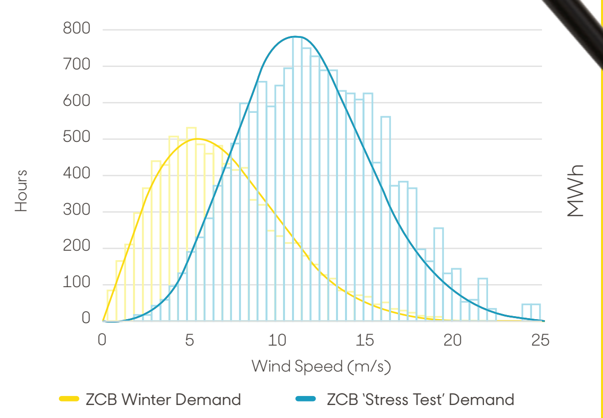
The need to accommodate new innovations has guided our approach in this research. The modelling has prioritised mature technologies to allow for a new, flexible low-carbon technology to develop within the next thirty years. This means an energy system which is both competitive on cost and with opportunities to reduce costs further. The outcome of the ZCB scenario meets these criteria.

Renewable power will continue to grow and dominate. These power projects are cheap, quick, and straightforward to develop, allowing new technologies to be easily incorporated in the future. In contrast, an energy system which has high levels of large inflexible energy plants, with uncertain costs and longer build out times, will mean new technologies have no room to be included. This is likely to lead to unnecessary costs and make the transition harder.

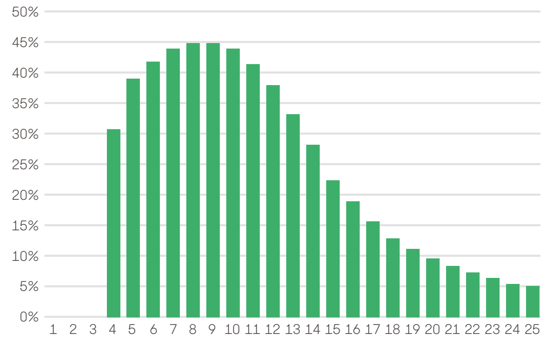
Increasing Wind Power Efficiency

There is also a strong case for developing increased diversity within different renewable technologies. Wind power is an excellent example of this. In the UK, the most common wind speeds we see are between 3-6 m/s; however, because of the relationship between wind speed and power (doubling the wind speed increases power 8-fold), the maximum amount of energy can be found between 10-15 m/s, even though this occurs much less often. Current wind turbines have been designed to maximise total yield; however, it would now be beneficial to the system if wind would generate less energy overall but more often.

The graph opposite shows the power coefficient for a typical offshore wind turbine (V-90). The turbine only reaches maximum efficiency at 9 m/s and does not generate at all below 3 m/s. When large capacities of wind are built out, the system doesn't need performance at moderate to high wind speeds but needs power when wind speeds are low. We should investigate ways to build wind turbines which perform better at low wind speeds, even at the cost of lower annual yields, for example, derating generators. If wind yields at lower wind speeds could be increased the total installed capacity of the wind fleet, and therefore the system cost, could be lowered.



CP - Vestas V90



Curtailment as an opportunity

Curtailment of generation capacity can occur either when there is insufficient grid infrastructure to transport electricity to places where it is needed, or during periods of high electricity production and low demand.

At present, National Grid will instruct generators to limit the amount of power they are adding to the system and will compensate for the loss of revenue. While this is often perceived to be a waste of electricity, it is currently the cheapest way of managing the energy system. Renewable generators are often constrained as the quickest and most cost-effective technologies to perform this service. Wind turbines, for example, are highly flexible and can change their power output in seconds.

All scenarios see extensive levels of constraints placed on variable renewable generation. This is primarily due to the need to develop large amounts of wind and solar to meet peak electricity demand (even at low to medium wind speeds), and, additionally, to meet demand during periods of extreme stress on the energy system.

The greatest amount of curtailment will typically occur during summer periods where demand is lower but solar production higher; and similarly overnight where wind power is generating significantly more than overall demand. The amount of installed wind capacity in the final ZCB scenario is 150GW, slightly below peak demand at 200 GW, but significantly above mean and median demands (78 & 69 GW respectively). This means that on any occasion the wind fleet is generating maximum output it is highly likely there will not be enough demand to absorb all of this energy.

The high levels of curtailment in our scenarios would be exacerbated if inflexible generation, such as nuclear or gas, are included. Therefore, we need sufficient commercial mechanisms in place now to ensure we utilise the increased volume of renewable generation and avoid current practices of turning off renewables to keep gas online.

The narrative around curtailment has largely been confined to the counterintuitive notion of paying generators to switch off, or how the practice is wasteful. It is time to revisit this conversation and look to how we can reduce curtailment and turn the plentiful supply of cheap renewable electricity to our advantage. Improving grid infrastructure, including adding new subsea power cables to continental Europe, will provide some breathing room for managing surplus generation. However, this alone will be insufficient to prevent curtailed volumes from increasing out to 2030 and 2050. In the future, we will need inventive ways to increase the consumption of renewable electricity at times where the sun is shining and the wind is blowing.

Improving grid infrastructure, including adding new subsea power cables to continental Europe, will provide some breathing room for managing surplus generation

One option not fully explored in our modelling is that excess renewables are used to generate green hydrogen to be stored and used at a later date. This would have a secondary benefit of reducing the resource costs associated with procuring biomass, which is typically the models preferred method of hydrogen production. SFM is not capable of fully exploring hydrogen production as a way to 'soak up' curtailed power – it sees curtailment as being a 'free' option, and so will turn generators off before building out comparatively expensive alternatives. The reality is that the business cases for wind, solar and electrolysers would likely dictate that power would be diverted to hydrogen production before being turned off. Other options include deploying even more utility-scale batteries alongside renewable projects, or higher levels of demand flexibility among industrial energy consumers.

Results: Heat

In order to meet our climate objectives, we need to thoroughly transform and upgrade the way we heat our homes and businesses.

Emissions in the residential sector have only reduced by 17% since 1990 – compared to 71% for the power sector.[19] The primary reason for this is poor energy efficiency and a reliance on fossil fuel heating, with very low penetration of renewable alternatives. Around 85% of UK homes are connected to the gas grid, the majority of the remaining 15% use oil or liquid petroleum gas.[20]

The recent debate on how to decarbonise heat mainly focusses on should we electrify as much as possible through heat pumps and in-home thermal storage, or retrofit the existing gas grid for hydrogen heat. The modelling explores both options and chose electrification as the cheapest and most efficient method of decarbonising.

Heat Supply

Across all scenarios, we see swift changes by 2030, namely the rapid uptake of heat pumps both domestic and larger heat pumps connected to district heat networks. In the ZCB scenario, where we see a faster push to decarbonise across the board, electricity is providing 46% of heat demand by 2030.

In all scenarios there is a large amount of electric resistive heating, which is favoured by the model in certain circumstances. One explanation for this is the greater level of low-marginal cost renewable power being generated means that the model chooses lower CAPEX, lower efficiency options even if this causes problems during the 'stress test'. Alternatively, it may be because newer, efficient houses require very low levels of heating which can be cheaply provided by resistive heat. This shows that if we can lower the capital costs of heat pumps and make them more financially attractive as propositions, they would be able to make our energy system much more efficient. By replacing the resistive heating units with air source heat pumps, required heat production could be reduced by 55TWh (15%) a year, and a reduction in peak demand by 30GW (12%).[21] More efficient ground- or water- sourced heat pumps would deliver even greater reductions.

Heat Networks

One of the most significant results in the heat sector was the inclination towards district heat networks, which cater for huge amounts of heat demand in many other countries, particularly in metropolitan centres. Around 64% of Danish homes are connected to a heat network. This has been brought about by careful long-term city planning and 'obligations to connect' to heat networks where it is deemed the most appropriate or efficient heat source.[22] However, they have not had anywhere near the same degree of success in the UK, with only 2% of homes currently receiving their heat supply this way.

District heat is a highly efficient heating solution for high-density population centres. Most of the district heat deployed in all scenarios is provided by large scale water, or ground based heat pumps, with a small role for geothermal in the two main scenarios, and nuclear small modular reactors in the Baseline.

CHProbably not?

In scenarios where the model has been permitted to continue using fossil fuels, there is a large buildout of gas-fired micro-CHP as a heating solution by 2030, only for them all to be replaced with electrical solutions by 2050. This, along with a significant uptake of H2 boilers before 2030 (which again are usurped by electrification before 2050) are good illustrations of the differences between modelled electricity systems and the real world. The SFM model will choose the lowest-cost route to net zero and in some cases the decisions may challenge the practicality of certain technology options.

It is unlikely that >50% of heat demand will be able to pivot to a new fuel type in less than a decade, and unlikelier still that having done so, it will pivot again to something completely new heat vector soon after. In situations such as these it would probably be more efficient to skip the transition technology (in our case either micro-CHP or hydrogen) and move straight from the current gas heating system to an electrical solution.

[19] Department for Business, Energy and Industrial Strategy, Final UK greenhouse gas emissions national statistics: 1990 to 2019
[20] Energy Networks Association (2021): https://www.energynetworks.org/creating-tomorrows-networks/
[21] Assuming a conservative Coefficient of Performance of 3.0.
[22] Energistyrelsen, Regulation and planning of District Heating in Denmark, p.12

Building Heat Production

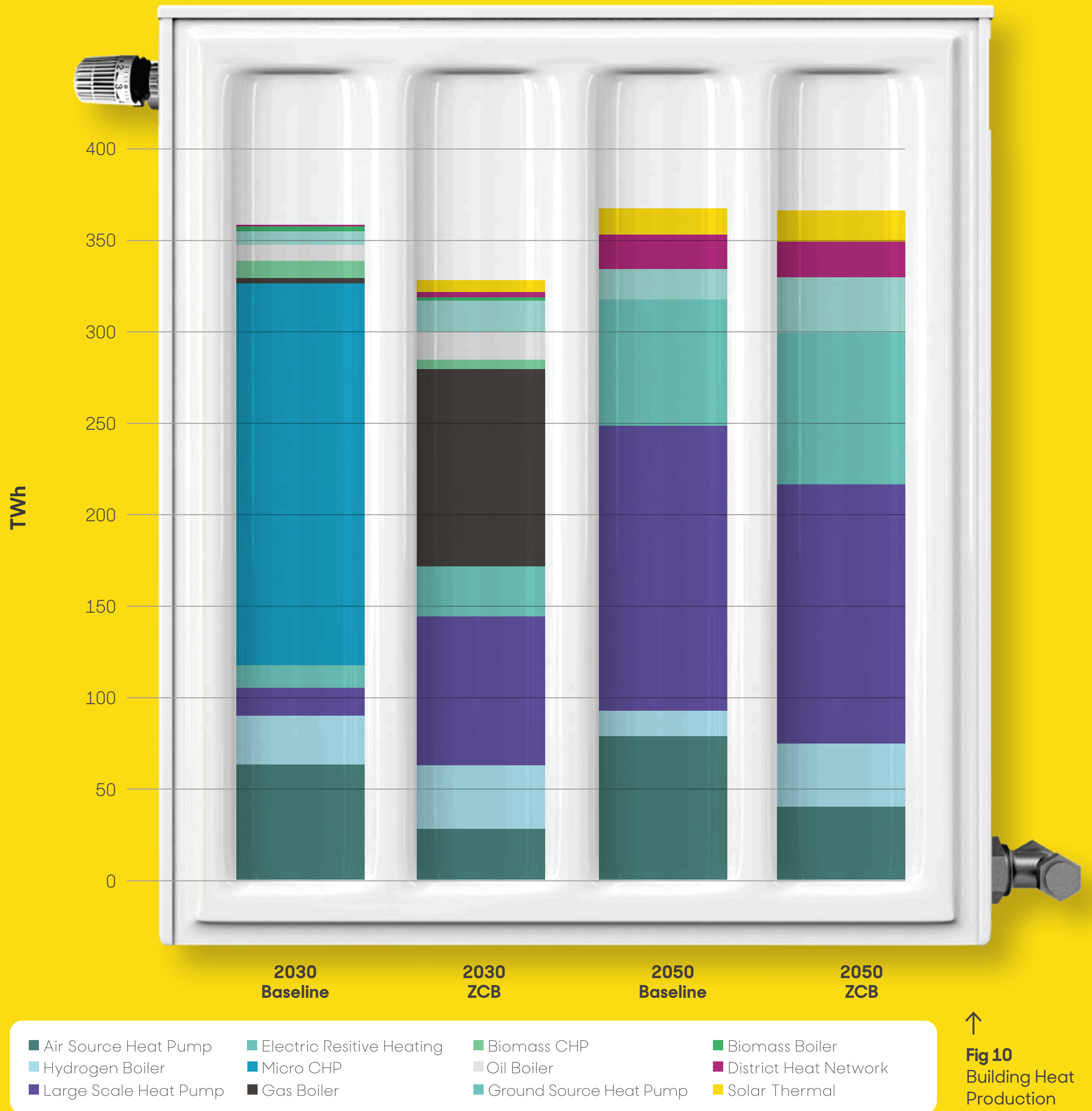


Fig 10
Building Heat Production

Nuclear Heat

One of the reasons Small Modular Nuclear Reactors (SMRs) perform well in the modelling is that they produce large amounts of waste heat even in very cold periods. The model chooses to take advantage of this by locating some SMRs near population centres so the waste heat from the reactors can be used to heat homes through district heating.

Using excess hot water from nuclear power stations to heat homes has been done previously in the Soviet Union, but seems less plausible in modern day Europe. It is difficult to imagine millions of people willing to live in very close proximity to a nuclear reactor, and have their heating provided by a nearby nuclear power station.

Heat Demand

Between now and 2050, the main scenarios taken forward see reductions in 'peak heat', relative to estimates of present-day UK heat demand. The key driver for this is electrification; in 2021, due to the high proportion of natural gas heating, the power and heat sectors are relatively separate entities, with a degree of linkage, but nowhere near the levels of interdependence we see after heating is electrified. Electrified heat solutions such as heat pumps with efficiencies exceeding 300% mean that the total level of heat demand is lower than if it were being met with 90% efficient condensing gas boilers.

Nevertheless, the result is higher and longer peaks in electrical demand – which would leave the energy system struggling were it not to take two actions deployed to some extent in all of our scenarios:

- Extensive retrofits to rectify the inefficiency of the UK's building stock.
- High levels of thermal energy storage being used to smooth daily peaks in demand, reversing recent trends toward combination boiler systems.

Energy efficiency

The modelling shows that heat demand causes considerable stress on the energy system, meaning the most efficient way of operating is to reduce demand (especially when it comes to heat) as much as possible. A main differentiator between the Baseline and ZCB scenarios is the reduction in winter peak heat demand and therefore a reduction in overall system costs and increase in security of supply.

UK housing stock is the oldest in Europe and inefficient heat wise, with around of 37.8% of dwellings built before 1946, compared to 24% in Germany and Sweden. A recent tado° study showed[23] that European housing stock

Home temparature loss after 5 hours

With a temperature of 20°C inside and 0°C outside

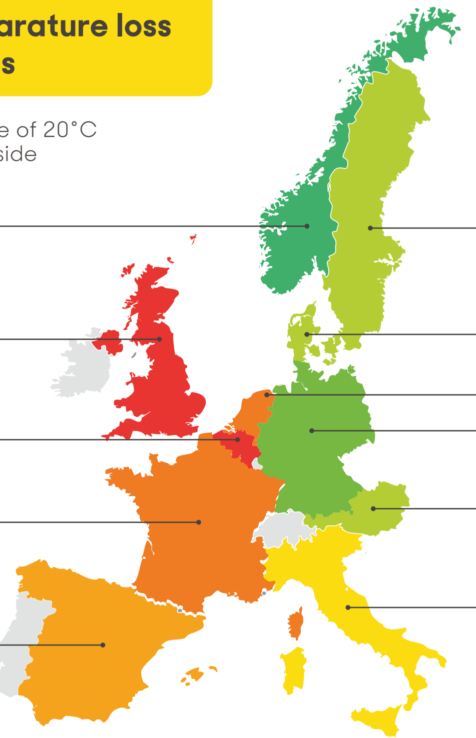


Fig 12
Results from a tado° study on the performance of European housing

is significantly more energy efficient. However, over a third of Danish housing also predates 1946, and yet they have some of the continent's best performing buildings – which shows that poor performance is perhaps less a consequence of age, and more one of policy.

For all scenarios, both ESME and SFM chose to install extensive energy efficiency retrofit measures, ranging from wall and loft insulation and draught stripping, to window and door replacement, and thermostatic radiator valves and zoned heating controls. There is a greater degree of uptake in ZCB, where it is assumed that there are policies in place to reduce the cost to the consumer of home improvement, which delivers a 10% reduction in peak winter heat demand relative to the baseline. The reduced heat demand increases security of supply during very cold periods.

Energy efficiency retrofitting

As such a large number of houses need to be retrofitted with extensive energy efficiency measures, it is important that this work is done quickly, cheaply and at very high quality. An interesting comparison to this national rollout is that of smart meters, where 53 million meters need to be replaced with newer versions. This has been undertaken very differently in France compared to the UK. In France, this is done almost exclusively by one company, Enedis, which manages 95% of the network, whereas in the UK energy suppliers are responsible. This has led to inefficiencies and higher costs. Learnings from the smart meter programme should be used when designing a comprehensive energy efficiency retrofit programme, where local actors such as local authorities and distribution operators could be tasked with installing energy efficiency as an alternative to network upgrades.

[23] Tado (2020): UK homes losing heat up to three times faster than European neighbours

Thermal Storage

Alongside energy efficiency thermal storage is chosen by all scenarios as a low regret option, with extensive capacity deployment coming before 2030. This is in advance of the large amounts of electrical storage used to support the power system.

Thermal storage helps to smooth demand to a certain extent, and partly decouple the power sector from the real time provision of heat. This is demonstrated clearly in our modelling, where thermal storage is providing a significant amount of heat demand, reaching upwards of 65GW in certain periods.

This would be a change from the recent trend of installing combi-boiler solutions designed to be as small as possible. While they may save space, they offer no potential in terms of thermal storage. SFM models thermal storage predominantly as hot water tanks, but it is just as likely that heat batteries using 'phase change materials' to capture energy may be built en masse as they are smaller and may suffer reduced heat loss.

Solar Thermal Rising

Using solar energy for power generation is relatively commonplace in the UK with 13.5GW of total installed capacity, thanks to the success of the Feed in Tariff scheme. Using it for heating is less widespread, but there are signs this might be changing. Solar thermal is by some distance the most popular low-carbon heating solution among those who have applied for the Green Homes Grant – making up 55% of all in all voucher applications.[24]

When used in combination with a hot water cylinder or heat battery, solar thermal installations can be an efficient and cost-saving way of producing heat in the home. In our model, it is most likely being deployed to provide a similar service to thermal heat storage – decoupling about 5% of heat demand from the power sector.

Hydrogen for Heat

Across all scenarios hydrogen only caters for between 2-10% of heat in buildings, barring the extreme event used as a stress test. During those periods of extraordinary weather, hydrogen deployment for heat picks up, indicating that there is a possibility that hybrid appliances could play a role.

In our initial ESME scenarios, we chose to use one scenario – Hydrogen Economy – to explore the prospects of a future energy system where extremely high CCS capture rates lead to an early decision to hydrogenise the gas network. The Hydrogen Economy scenario did not lead to a green hydrogen revolution, but in fact relied on fossil fuels for 82.5% of the hydrogen produced and built out no electrolysis or green hydrogen at all. On this basis, we decided not to proceed with the scenario in the next stage of the modelling.

The Baseline scenario was permitted the use of blue, fossil hydrogen in the more detailed SFM modelling. Interestingly, while this built out a reasonable amount of hydrogen infrastructure by 2030, this scenario ended up with the lowest penetration of hydrogen for heat in 2050.

2050 ZCB Heat Dispatch

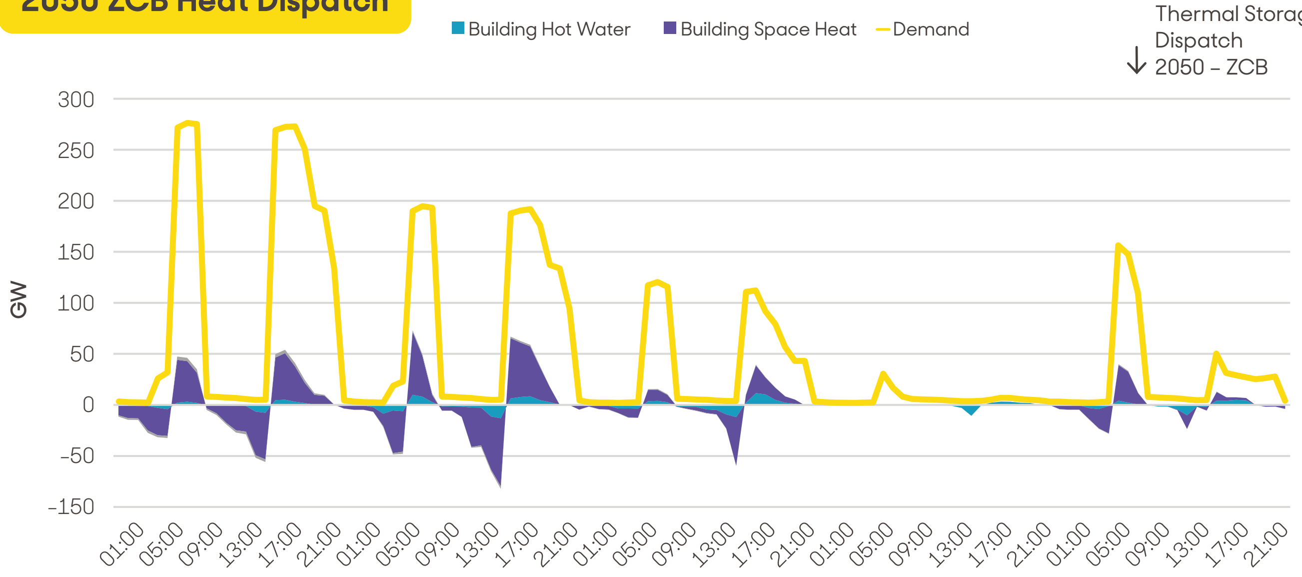


Fig 11
Thermal Storage Dispatch
2050 – ZCB

[24] Green Homes Grant voucher release (February 2021): https://www.gov.uk/government/statistics/green-home-grant-vouchers-release-february-2021

Results: Transport

In 2050, most vehicles are EVs with electricity supplying 90% of the required energy.

The rest is supplied by hydrogen (6%) and liquid fuel (4%). Total primary energy for transport drops dramatically from 417 TWh in 2030 to 158 TWh. This is due to the greater efficiency of electric engines compared to internal combustion engines (ICE). An average ICE efficiency is 20-35% whereas battery electric vehicles (BEV) are 85-90% efficient.[25] Two additional benefits of this electrification will be a possible balance of payments benefit as the fuel no longer needs to be imported and significant public health benefits especially in cities due to less air pollution.

One of the limitations of the model is the conservatism with which it treats the coming change in road transport throughout the 2020s. There is a dramatic shift from ICE vehicles to battery electric vehicles between 2030 and 2050, but the model anticipates only 300,000 BEVs on UK roads by 2030. This is only a 20% increase from the time of writing and is out of step with the speed of transformation anticipated by the industry. We recognise that there will be a significantly greater uptake of BEVs before 2030 than modelled, and this will mean that the change in the electricity system required to facilitate the added demands of vehicle charging will be brought forward as well.

By 2050, the transport sector's electricity demand reaches 151 TWh, which is roughly half of today's total annual electricity demand. If most of this charging took place in the evening when people arrived home from work, or in very cold periods, this would create severe stress on the electricity system, and would require upgrades to existing infrastructure to deliver the power. This reinforces the use of smart charging as a necessity and a significant opportunity to absorb excess electricity during the day whilst the sun shines or overnight.

ZAP MAP

The electric vehicle market in 2050: A view from Zap-Map

At present, cars and vans represent around one fifth of UK domestic CO2 emissions. If we continue to demand mobility, mass adoption of EVs, powered by renewable energy, is the only realistic way to significantly reduce this impact. And sales of plug-in vehicles are increasing. 2020 was a huge growth year for plug-ins, with over 175,000 registered in the UK – an increase of 66% on 2019.

But green mobility is more complicated than just selling EVs. As we decarbonise transport over the next 30 years, other key changes will be just as important. For the UK to reach net zero, we will need to create a highly evolved and smart transport system. Decarbonising cars and vans by 2050 will involve three major transitions: changes to vehicles, widespread renewable electrification, and a fully decentralised data layer holding the system together.

A disruptive market

By 2050, the automotive sector will come to be dominated by EVs. This is in large part due to a government decision banning the sale of new internal combustion engine (ICE) vehicles by 2030.

Industry forecasts show that EVs will soon be as affordable as ICE models, with price parity a possibility as early as 2024.[26] With these forecast production cost reductions in mind, it is evident now how important EVs will be to car manufacturers who want to operate a successful commercial enterprise.

Although a question remains over the role hydrogen might play in long-haul and heavy transport, it is highly likely that the majority of the UK vehicle fleet will be fully electric by 2050. Indeed, as pure-electric vehicles become cheaper, plug-in hybrids – a popular choice of company car – may also be remembered as a short-term transition technology on the road to a fully electric future.

In this changing, and highly disruptive, market, we can expect to see the emergence of many more new auto brands. The way consumers interact with cars will change too. App-based companies like Onto already offer inclusive subscriptions to electric cars on a monthly basis.

By 2050, the automotive sector will come to be dominated by EVs.

Charging networks

A new EV charging infrastructure is springing up that signals a wider reliance on electricity as the transport sector shifts away from fossil fuels. The UK now has over 24,000 public charging devices across over 15,000 locations.[27] Home and workplace chargers are even more numerous. Over 140,000 domestic charge point installations have already benefited from the government's £350 home charge point installation grants.[28]

With nearly 500 public chargers being added each month, the UK charging network is set to dramatically expand over the coming decade, the number of charging locations already having passed the number of petrol stations back in 2019. The government has pledged £1.3bn to further accelerate the roll out of charging infrastructure on motorways and major A roads, in homes and businesses and on-street.

Electrification also presents exciting opportunities for automation. Innovative solutions have already meant that payment has largely become data-driven using contactless or via apps. By 2050, it is highly probable that payment will be fully automated with not even an app tap being required.

Getting smart

The effect of this growing reliance on electricity will require a step-change in national strategy. As EV sales accelerate towards mass adoption, we will have to think carefully about how we route sufficient power to these vehicles.

Generating enough energy is not an issue. The challenge lies in getting power to 30 million+ EVs (by 2050) using the existing electricity infrastructure. If too many EV owners plug in at home simultaneously, it could overload local substations. This reinforces the need for smarter charging and spreading the distribution throughout the day – also known as time-shifting. In the future, when millions plug their EVs into their 7kW home chargers after work, smart meters will control when those EVs charge – and wait until the best time to do so.

The use of renewables to generate electricity also poses new challenges to the grid, which will not only have to deal with time-shifting, but also the peaks and troughs of wind and solar power. Here, millions of EVs plugged into the grid can be a great opportunity. All excess energy – produced, for example, on very windy and sunny days – can be used for charging, energy that might otherwise go to waste.

A smart transport system will therefore enable intelligent distribution of clean power to millions of EVs across the country. For it to function optimally, we will need to invest in data solutions at a business and domestic level. Businesses will be key to tracking EV charging locations and behaviours. This will not only provide greater visibility of the low-voltage network, but avoid the need for new energy infrastructure.

[25] Jorge Martins, Francisco P. Brito, Delfim Pedrosa, Vítor Monteiro, João L. Afonso Real-Life Comparison Between Diesel and Electric Car Energy Consumption, in Grid Electrified Vehicles: Performance, Design and Environmental Impacts, pp. 209-232

[26] UBS Bank (2020): Tearing Down the Heart of an Electric Car Lap 2 https://www.ubs.com/global/en/investment-bank/in-focus/2020/heart-of-electric-car.html

[27] Zap-Map (2021): EV Charging Stats 2021: https://www.zap-map.com/statistics (accessed May 2021)

[28] Department for Transport (2020): Government takes historic step towards net-zero with end of sale of new petrol and diesel cars by 2030 https://www.gov.uk/government/news/government-takes-historic-step-towards-net-zero-with-end-of-sale-of-new-petrol-and-diesel-cars-by-2030

Results: The role of hydrogen

A sizeable hydrogen system was created across all scenarios, but with targeted uses across the economy.

Between 90-160 TWh of hydrogen is used across the Baseline and ZCB scenarios, but its primary roles are for hard to decarbonise sectors, such as industry and shipping. Hydrogen plays a smaller, but still important, role in both the net-zero heat and transport sectors. As we approach 2050, cost reductions in electrified technologies, such as heat pumps, creates a specific role for hydrogen production to be used in sectors with higher emissions. Nevertheless, hydrogen-powered shipping, heavy off-road mobile machinery and boilers are in widespread use.

The ZCB scenario limited hydrogen to be used only when created through biomass gasification, or through a process of electrolysis. This is called 'green hydrogen'. 'Blue hydrogen', which is created through natural gas but with emissions captured after the process, was available to the Baseline scenario.

Green hydrogen is a key requirement to achieve net zero by 2050.

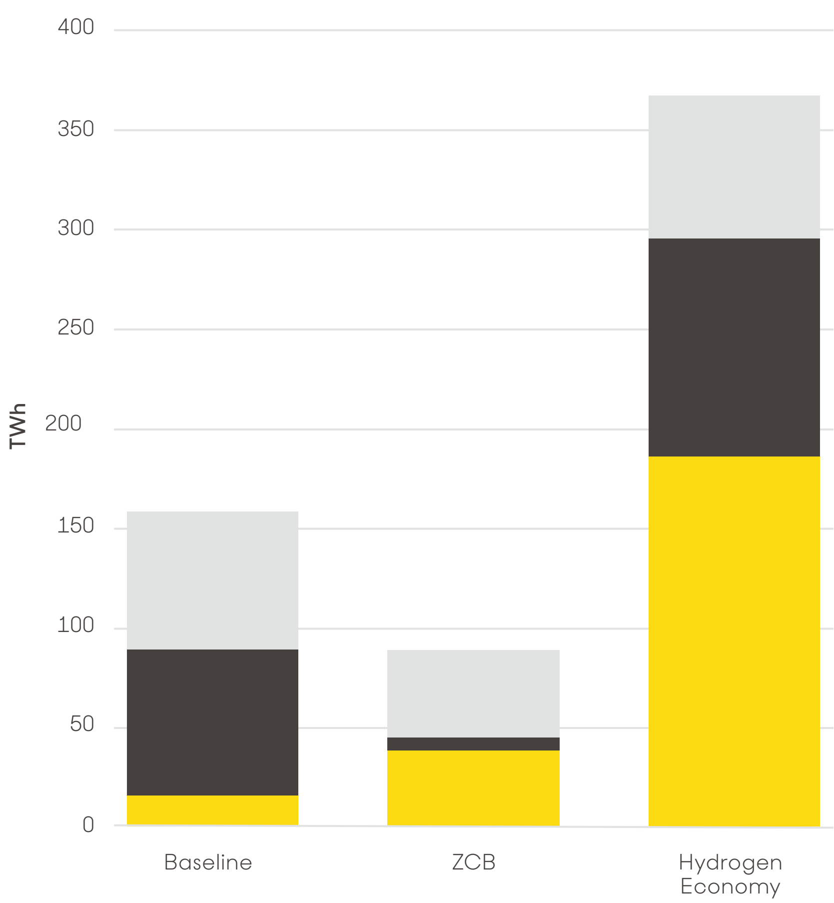
Because of the high cost of electrolysers and lower efficiency rates, the modelling rarely chooses electrolysis over alternatives. When given the ability only to produce green hydrogen the model uses this for hard to decarbonise sectors but prefers electrification for heat and batteries for energy balancing.

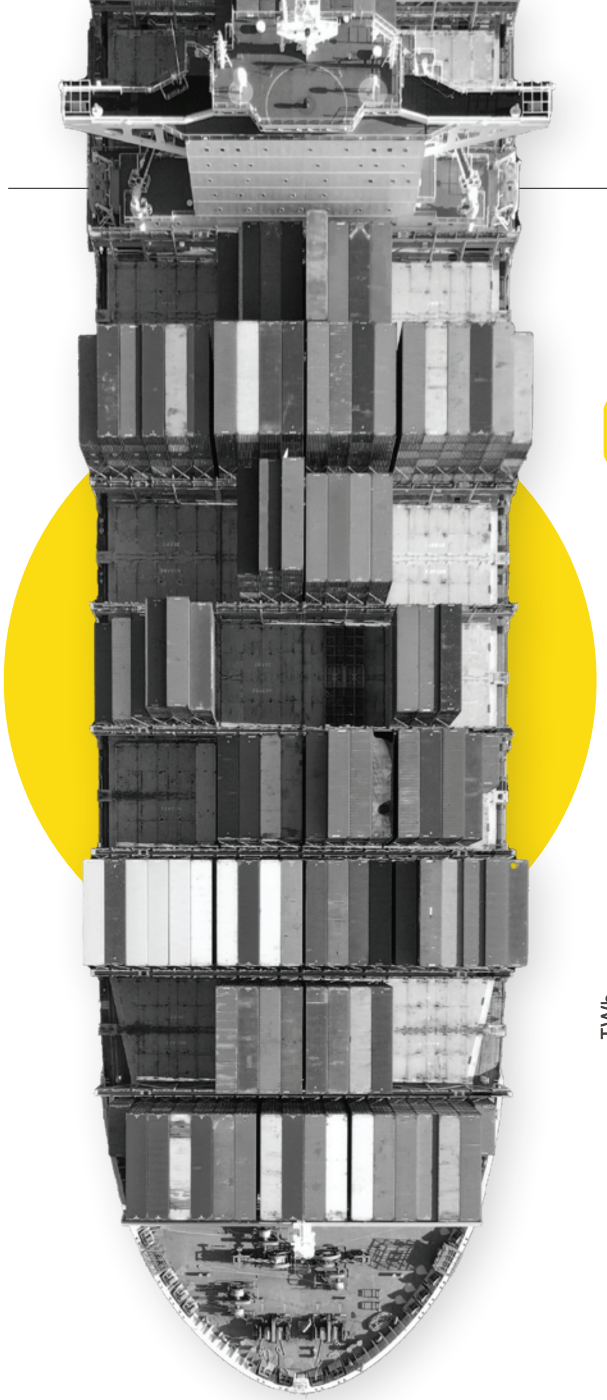
Green hydrogen is a key requirement to achieve net zero by 2050. Across all scenarios biomass gasification with CCS provides the bulk of hydrogen production (71TWh in Zero Carbon Britain) which is chosen because of its dual role: hydrogen is a very useful fuel for hard to decarbonise sectors of the economy and produces a large amount of negative emissions, enough to offset both aviation and shipping in the Baseline scenario.

2050 Hydrogen Consumption

Fig 13
2050 Hydrogen Consumption

Local Distribution Network ■ Industry ■ Transport

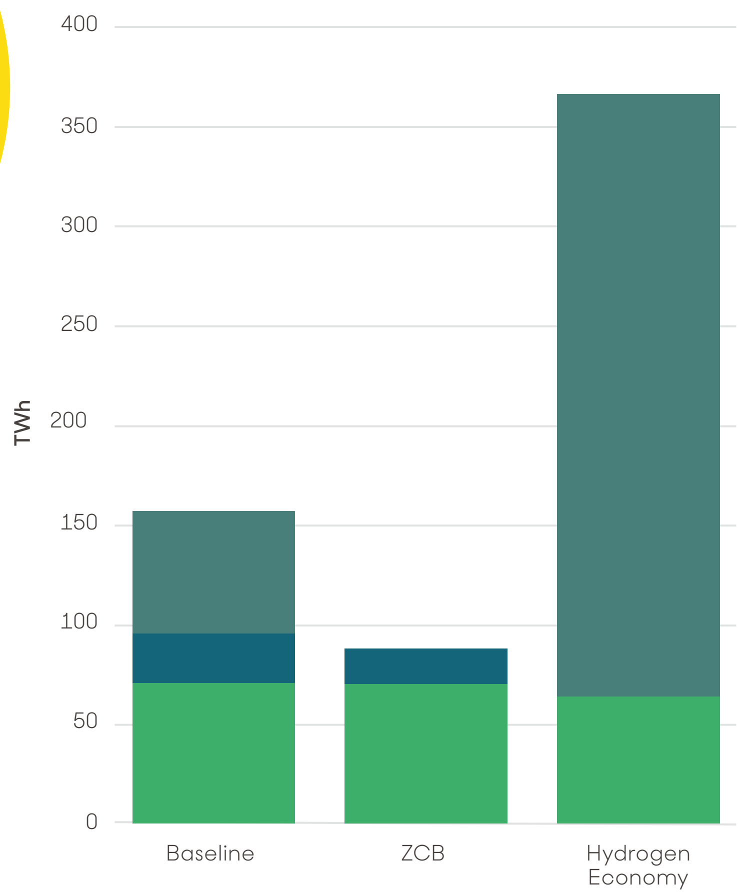




2050 Hydrogen Production

Fig 14
2050 Hydrogen Production

Biomass with CCS ■ Electrolysis ■ Gas

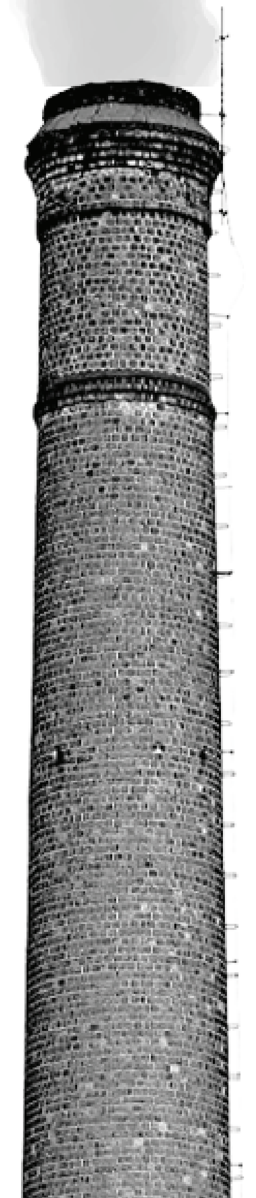


Hydrogen Economy

The Hydrogen Economy scenario was created to investigate how much of the system hydrogen could supply where all forms of hydrogen were allowed to play a role, with innovation leading to 99% carbon capture rates. As expected, the scenario utilises a lot of hydrogen (370 TWh), but because of high CCS capture rates the model replaces green hydrogen from electrolysis with blue hydrogen. One of the findings of this scenario is the likelihood for blue hydrogen to dominate unless a regulatory regime supports renewable alternatives. Furthermore, cost reductions in green hydrogen will be impeded if there is an outsized focus on blue hydrogen

The ESME model shows results in 5 year steps, allowing users to see the pace of buildout for some of these technologies. The modelling shows a very fast switch from blue hydrogen to green between 2045 and 2050 as emissions from blue hydrogen are no longer acceptable. In 2045, 75 TWh of blue hydrogen is completely switched to green hydrogen in just 5 years. In reality this pace of change may not be possible both practically and politically and shows the risks of developing a transition technology which cannot be used in 2050.

Emissions



The key target for the research was to develop scenarios that achieve net zero emissions by 2050, in line with the UK's legal commitments as of summer 2020.

Countdown to net zero

The modelling achieves this target with a minimal number of residual emissions in 2050. Scenarios conducted by the SFM modelling found Baseline reduced emissions by 96.7% compared to 1990 levels, whereas the ZCB scenario created a 97.1% reduction in 2050. This was achieved without widely using speculative technologies such as direct air carbon capture (DACC), accounting for only one million tonnes of carbon reduction in 2050. The ZCB scenario decarbonises slightly faster (and therefore has lower cumulative emissions) than the Baseline with a 2030 carbon reduction of 59.7% compared to 57.3%.

The overall approach to the modelling was to test mature energy technologies within accepted cost projections. The small number of residual emissions in our final scenario could be removed with a greater role for these speculative technologies such as DACC or bioenergy with carbon capture and storage. In addition, the industrial sector is notable for its difficulty to decarbonise in the modelling; there is room to extend the existing levels of afforestation in the scenarios to offset emissions from heavy industry.

Carbon Budgets

The research was approached with the UK's existing carbon budgets in mind. At the time work started this meant the 5th carbon budget, which set a 2032 target to reduce emissions by 57% on 1990 levels. The modelling achieves this target with a 60% reduction in comparative emissions by 2030. However, the Government has since published its 6th carbon budget which raises ambition significantly, targeting a 78% reduction by 2035. The impact will be to frontload decarbonisation efforts to the short and medium term.

The research outcomes have clear implications for the increased ambition of the 6th carbon budget. One of the key findings of the results is the potential for creating a zero-emissions power sector by 2030. The SFM modelling does not have sufficient granularity to show emissions for 2035, however it does show the importance of the ZCB scenario which decarbonises faster by 2030, an important factor is the reduction in emissions due to replacing gas with low-carbon alternatives, and the faster build time of renewables compared to nuclear.

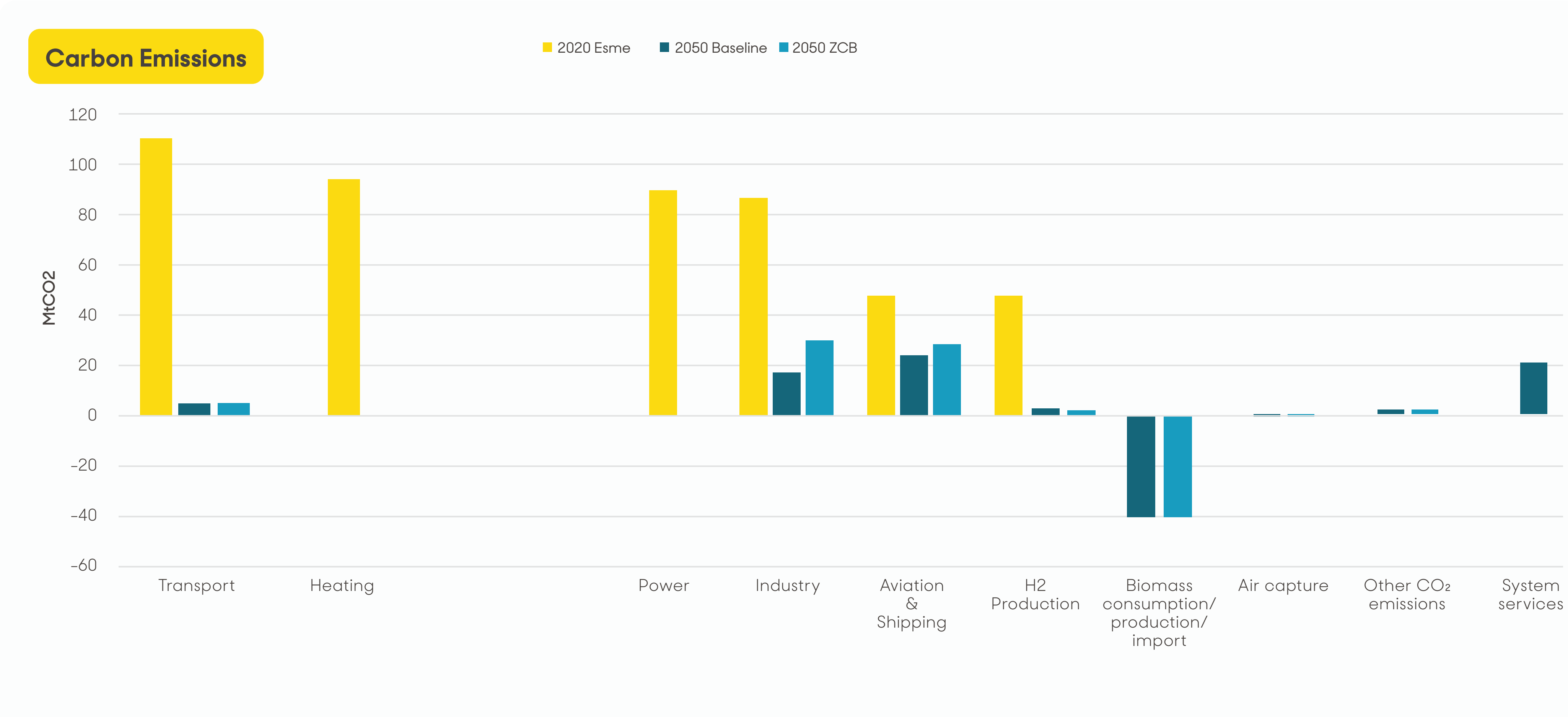
The transport sector sees slower rates of decarbonisation. High rates of emissions exist in 2030 due to a transition from hybrid vehicles to battery electric vehicles by 2050. The implications of the 6th carbon budget mean acting sooner on the shift to zero emission vehicles. Furthermore, the modelling anticipates offshore wind power to increase significantly from 2030 onwards. The new emissions trajectory could mean a stronger impetus to bring more offshore wind projects forward in the 2020s.

> **The implications of the 6th carbon budget mean acting sooner on the shift to zero emission vehicles.**

Industry and aviation

Industry aviation and shipping are very difficult to completely decarbonise although large reductions are present. The ZCB scenario has higher emissions for these hard to decarbonise sectors than Baseline, in effect, the modelling is using the 20mtCO2e saving from using storage for system services rather than fossil fuels to avoid very expensive changes to industry.

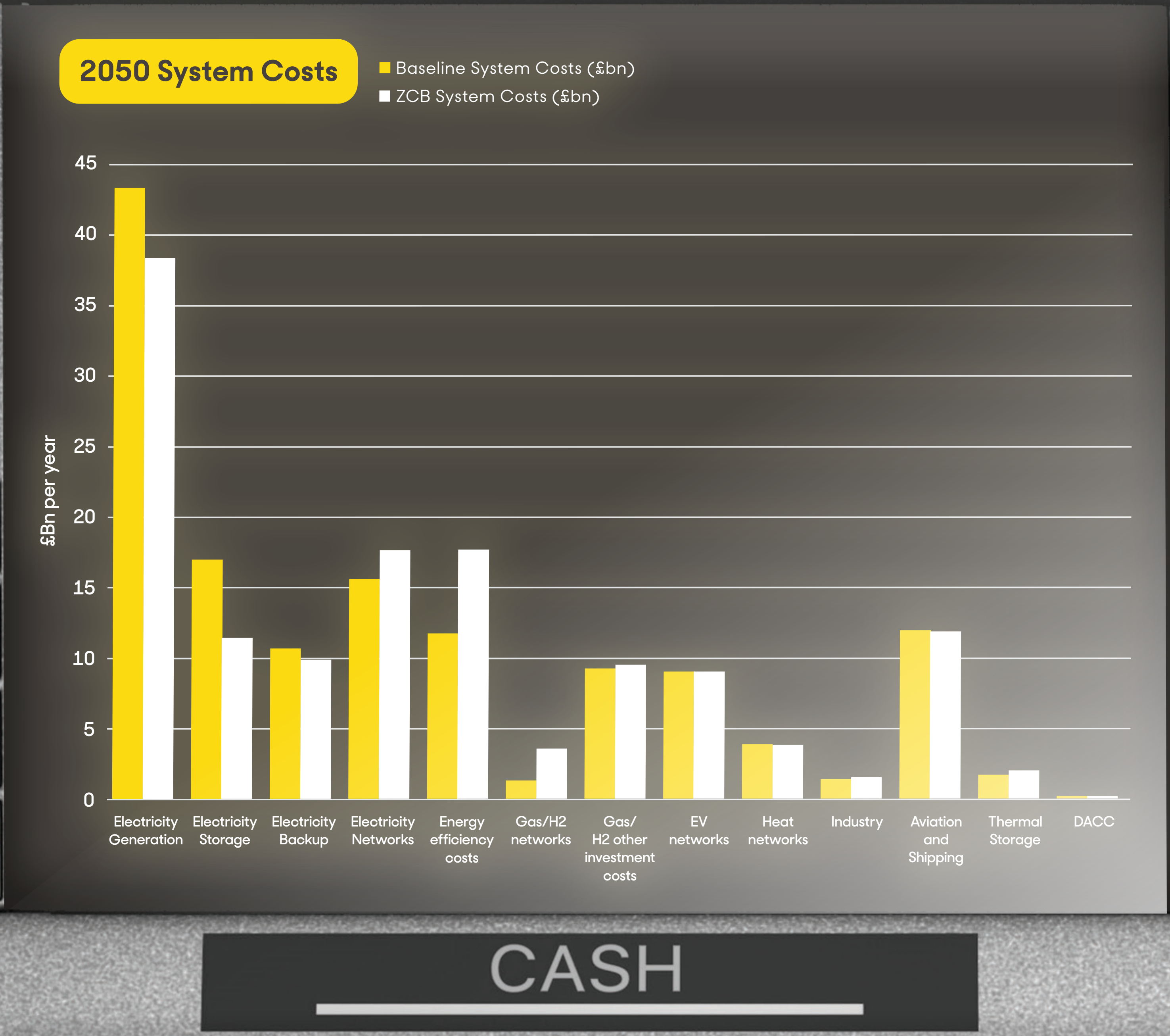
Fig 15
Carbon Emissions
↓



Costs and Benefits of Net Zero

The annual total system costs for the Baseline and ZCB scenarios are virtually the same at £126 billion and £126.4 billion per year, respectively.

Fig 16
2050 System Costs



[29] https://www.ofgem.gov.uk/system/files/docs/2019/11/20191030_state_of_energy_market_revised.pdf and https://www.ukpra.co.uk/en/about/facts-and-figures#:~:text=The%20UK%20Retail%20Road%20Fuels%20Market%202019&text=Petrol%20%2D%2016.2bn%20litres%20(Retail,%2D%20 9.5bn%20litres%20(Commercial)

[30] Ministry of Defence (2020), Finance and economics annual statistical bulletin: https://www.gov.uk/government/publications/international-defence-expenditure-2020/finance-and-economics-annual-statistical-bulletin-international-defence-2020

This system provides all energy for heating, transportation, electricity, and industry. For comparison, the UK currently spends roughly £55 billion per year on gas and electricity; and £62 billion on transportation fuels, such as petrol and diesel, equating to around £117 billion per year.[29] Expanding for the increased population modelling in 2050 this shows that a transition to net zero comes at a very manageable additional cost, or possibly a slight reduction to current costs.

The greater energy efficiency and flexibility of the ZCB scenario means it is able to reduce the size of the electricity system and, therefore, the amount of electricity generation and storage needed. This can be seen in costs in Fig. 16; an increase in energy efficiency costs is offset by a reduction in energy generation and storage costs.

Table 1

2050 system cost	£126 billion / year
Total 2050 including vehicle premium	£161 billion / year
2019 comparative costs	£97 billion / year
2019 comparative costs scaled to 2050 population	£112 billion / year
Net cost of decarbonisation	**£14 - 49 billion / year**

Estimating net costs

One large cost not incorporated in the results are the impact of buying EVs and other low carbon vehicles. Over the next 30 years the vast majority of vehicles on the road will have to be replaced anyway; the modelling has calculated the cost of replacing all of these vehicles with low carbon alternatives at £175 billion per year. It is not clear what the counterfactual costs would have been to replace all these vehicles if vehicle emissions were not considered. We have assumed that the change to zero emissions vehicles will add 20% to the cost of vehicles and therefore should be considered a true cost in our results.

Because the Baseline and ZCB costs are so similar, only the ZCB figures will be shown in the headline figures:

The net costs of decarbonisation are estimated to be between £14 – £49 billion a year, which is fully manageable. The range depends on assumptions around the future costs of electric vehicles, and the possibility of reaching price parity with petrol and diesel. To put this into context the annual increase in costs could be slightly higher than what we currently spend on building and maintaining the road network (£11 billion) and around the same as the UK's current defence budget (£42 billion).[30]

Financial Benefits:

There are many financial benefits of the modelled energy transition which may offset increased net energy costs, but which are out of the scope of this report to estimate. Three benefits include: a reduction in paying for imported fuel; a significant increase in new jobs and growth industries, especially in energy efficiency; and a large public health saving due to improved air quality.

The modelling focusses on accepted cost trajectories for mature technologies, many of which are conservative, and increased spending on innovation may reduce these costs even further. A good example of this is in energy storage: new technology could improve the efficacy of energy storage and negate the need for a large proportion of the energy generation and energy backup costs. Additionally, storage costs themselves may drop significantly, especially if improvements in recycling and renovating old batteries are made. A large proportion of the required grid-scale batteries could come from end-of-life EV batteries, which again could reduce costs significantly.

The cost results show that decarbonisation is challenging, but very much achievable. We should investigate ways to reduce the environmental and economic cost of the net zero transition, but the scenarios show that including nuclear and gas in the energy mix does not lead to reduced costs.

Conclusions and Recommendations

This report offers a new clean energy vision for the UK. The results show that net zero emissions can be achieved by maximising the use of renewable power, energy storage, increased flexibility, and energy efficiency.

This new vision for the future sets out an energy system which provides good security of supply and low total system costs, which are not improved by allowing the modelling to build out new gas and nuclear plants. A key conclusion of the report is that these technologies are not a necessary component to reach net zero.

The UK's carbon targets are challenging but possible by 2050, with a strong reduction in emissions by 2030. Total energy costs are similar to what we face today, with overall costs increasing between 0% - 1.5% of GDP per year.

We found that the electricity sector continues to decarbonise rapidly with around 100 GW of solar power and 70 GW of wind capacity installed by 2030. This will dramatically change the wholesale market and the volatility created will provide many opportunities for battery storage and other flexible technologies.

The heat and transport industries follow the lead by electrifying rather than switching to hydrogen. The impact is to create very high demands on supplying electricity during peak periods, which will require new and existing tools to increase system flexibility and energy efficiency.

The electrification of everything will allow consumers to actively participate in providing flexibility to the grid. Another visible societal change will be the mass retrofitting of Britain's deeply inefficient housing stock.

Net Zero Opportunities

The transition to net zero will have many positive economic implications for the UK economy. These include reduced costs due to a dramatic reduction in imported fuel; more stable fuel costs and, therefore, more predictable inflation figures; and reductions in healthcare costs due to improved air quality.[31]

To provide power when wind speeds and solar radiation is low the model has oversized the renewables fleet significantly. If a new form of low-carbon backup generation or flexible demand becomes available this could bring considerable cost savings by reducing the required size of the wind and solar fleet. The ZCB scenario allows for flexibility for future developments, and we envisage other innovations will support an expanded renewables grid when wind speeds or solar radiation is low.

Finally, the large number of lithium-ion batteries are costed as brand new, but there is real potential for electric vehicle batteries to be used for grid scale storage as millions of clean cars replace petrol and diesel.

Net Zero Risks

The results highlight the danger in choosing certain technologies to support the transition which go on to block progress.

Using blue hydrogen or micro combined heat and power may offer short-term benefits, but it will prove very difficult, and unrealistic, to dismantle these industries in 10-20 years' time after high levels of investment have been made. Their development will also come at the expense of zero-carbon alternatives, such as green hydrogen.

A key risk the modelling has highlighted are overambitious capture rates for CCS. Even at high, 95% capture rates, the modelling chose other technologies because emissions remained too high. Developing an energy system which is reliant on CCS, will lead to higher emissions and security of supply issues. However, the modelling regularly chose to replace CCS with bioenergy as it provided a reliable source of negative emissions.

In addition, the modelling tended to install electric resistive heating instead of heat pumps. This is due to their lower capital costs and the availability of very cheap electricity for large portions of the year. This causes real issues during the 'stress test' where temperatures are very low and resistive heating leads to very high (possibly undeliverable) evening peak demand.

[31] EnergyREV (2020): Post-pandemic recovery: How smart local energy systems can contribute: https://www.energyrev.org.uk/media/1490/energyrev_postpandemic_report_final.pdf (p.5)

Five Principles for Net Zero

This report has shown the potential to decarbonise the UK economy with very high levels of renewable power at low cost.

Our analysis relied on a number of policy and cost assumptions. These included conservative assumptions around the future costs of renewable power; the availability of smart electric vehicle charging; and high levels of energy efficiency in buildings.

Building on the findings of the Zero Carbon Britain scenario, we developed five principles to guide policy decisions. The outcomes of the scenario and its assumptions can be achieved by following the key recommendations within each principle.

01 Doing the known now

Some of the solutions to net zero are already known and can be deployed immediately. Acting now will greatly affect the ease and speed with which the transition can be made.

- **Invest a minimum of 1.5% of GDP into net zero research and development. This recommendation works across principles and is designed to redress the low levels of innovation funding within the energy sector.**
- **Accelerate the uptake of wind and solar power by holding yearly Contracts for Difference auctions and remove barriers to onshore wind in the planning process.**
- **A substantial fiscal and policy package is needed to replace the Green Homes Grant, and new legislation to ensure minimum efficiency standards for all buildings.**
- **Raise the ambition on heat pump installations to 900,000 per year by 2028, in line with the Climate Change Committee's target.**
- **Develop a stable and wide-ranging carbon price which can deliver long term signals to decarbonise.**

02 Unleashing people power

Net zero offers the potential for long lasting, positive impacts to the way people live their lives. Policy decisions need to be made with consumer support and protections built in from the outset. All communities and households need to participate in the energy transition, especially those from deprived areas and low incomes.

- **Incentivise the installation of solar panels on every appropriate new home and building.**
- **Provide access to interest free financing for home retrofit, low carbon heat, self-generation, storage, and EV charging. This includes removing VAT on energy-saving materials.**
- **Ensure consumers are protected by establishing a 'net zero watchdog' to combat greenwashing across all sectors.**
- **Bring forward the digitalisation of the energy sector to put households in control of their data and support flexibility services, such as vehicle-to-grid and half hourly settlement.**

03 Embrace diversity

The energy system will need as many clean technologies working on different parts of the economy to be successful. Net zero markets and R&D funding will be needed to usher in the full range of these technologies. We should focus on those technologies with the potential to integrate with wind and solar power.

- **Ringfence capacity for new technologies such as wave, tidal and geothermal in future Contracts for Difference auctions.**
- **Change the role of the Capacity Market and balancing mechanism to meet the demands of net zero. Energy storage needs to replace fossil fuels in providing back-up power.**
- **Increase research and development into new clean technologies, including EV smart charging; different forms of energy storage (liquid salt, thermal storage); and end-of-life uses for renewable technologies.**

04 Making the best of Britain

Britain is ideally placed to develop renewable technologies and spread the economic benefits across the country. Applying Britain's strong academic and research capabilities to net zero problems will be essential.

- **Scale-up innovation funding within industries where Britain has a natural advantage: wave, tidal and geothermal energy.**
- **Link government financial support to the creation of strong UK-based supply chains.**
- **Introduce a zero emissions mandate on car manufacturers. This will increase production of electric vehicles in the UK prior to the 2030 ban on new ICE vehicles.**
- **Create incentives to utilise surplus renewable power, for example, in the production of green hydrogen, or to build utility-scale battery sites.**

05 To 2050 and beyond

The decisions we make now will have a lasting impact on the makeup of the energy system and the opportunities of future generations. Our decision making should not be confined, or constrained, by the 2050 target date. Not only could parts of the economy decarbonise before this date, but we need a plan for how emissions will be subdued long into the future.

- **Legislate a decarbonisation mandate for Ofgem which will protect future consumers.**
- **Legislate for a Future Generations Bill which puts net zero and the Sustainable Development Goals at the heart of future policymaking.**
- **Create a mandatory net zero clause for all private and public investment. This will ensure financial decisions are aligned with cutting emissions and prevent stranded assets.**

Appendix

List of acronyms:

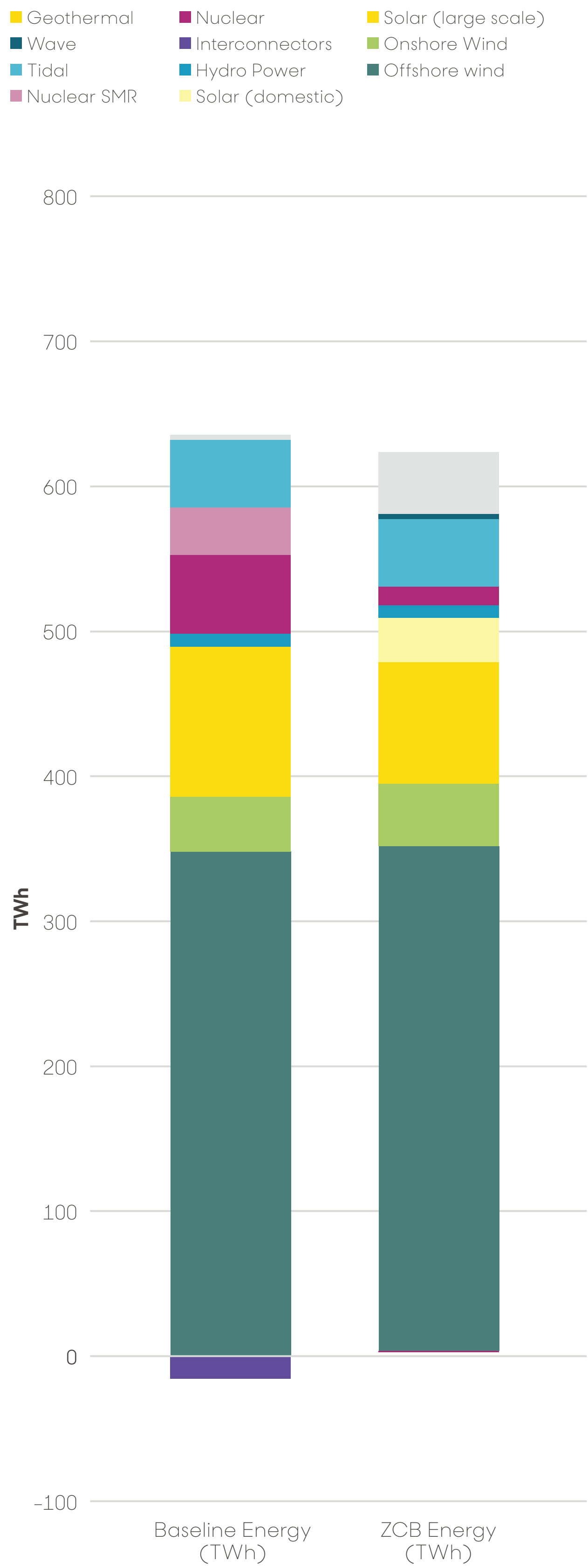
ASHP	Air Source Heat Pump
BECCS	Bio Energy Carbon Capture and Storage
BEIS	Department of Business, Energy and Industrial Strategy
BEV	Battery Electric Vehicle
CAES	Compressed Air Energy Storage
CAPEX	Capital Expenditure (Investment cost)
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
CO2	Carbon Dioxide
DACC	Direct Air Carbon Capture
DSR	Demand Side Response
ESC	Energy Systems Catapult
ESME	Energy Systems Modelling Environment
EV	Electric Vehicle
GDP	Gross Domestic Product
GHSP	Ground Source Heat Pumps
GW/GWh	Gigawatt / Gigawatt-hour
H2	Hydrogen
ICE	Internal Combustion Engine
IGCC	Integrated Gasification Combined Cycle
LSHP	Large Scale Heat Pump
OCGT	Open Cycle Gas Turbine
PV	Photovoltaics
SFM	Storage and Flexibility Model
SMR	Small Modular Reactor
TW/TWh	Terawatt / Terawatt-hour
VAT	Value-Added Tax
ZCB	Zero Carbon Britain

Appendix A: Table of Scenarios

Scenario	Cost assumptions	Flexibility	Hydrogen availability	Heat supply	Nuclear power availability	CCS availability	DACC availability
Baseline	As ESC Patchwork plus: BEIS Mid wind and solar costs Conservatism on nuclear power	As ESME Patchwork	Grey, blue, green and bio-derived all available	As ESC Patchwork	As ESC Patchwork	As ESC Patchwork	As ESC Patchwork (1 Mt)
Renewables to 11	As Baseline except: BEIS Low wind and solar costs	As ESME Patchwork Fossil fuel phase-out	Grey, green and bioderived	As ESC Patchwork	Hinkley Point C only	Industry, H2 roduction and BECCS	As ESC Patchwork
Customer Flexibility Revolution	As Baseline except: BEIS Low wind and solar costs Hurdle rate reduction for domestic technologies	Greater scope for smart EV charging (50% of demand assumed shiftable)	Grey, green and bioderived	As ESC Patchwork	As ESC Patchwork	As ESC Patchwork	As ESC Patchwork
Hydrogen Economy	As Baseline	As ESME standard	Grey, blue, green and bio-derived	Slower deployment of ASHPs	As ESC Patchwork	As ESC Patchwork plus 99% capture rate blue H2	As ESC Patchwork
No Unicorns	As Baseline	As ESME standard	Grey and green	Slower deployment of ASHPs	As ESC Patchwork	Industry and biomass postcombustion	Up to 25 Mt, artificially high costs
Zero Carbon Britain	As Customer Flexibility Revolution plus: BEIS Low costs for wave and geothermal energy	Greater scope for smart EV charging (60% of demand assumed shiftable) Fossil fuel phase-out	As Customer Flexibility Revolution	Greater ASHP COP	As Renewables to 11		

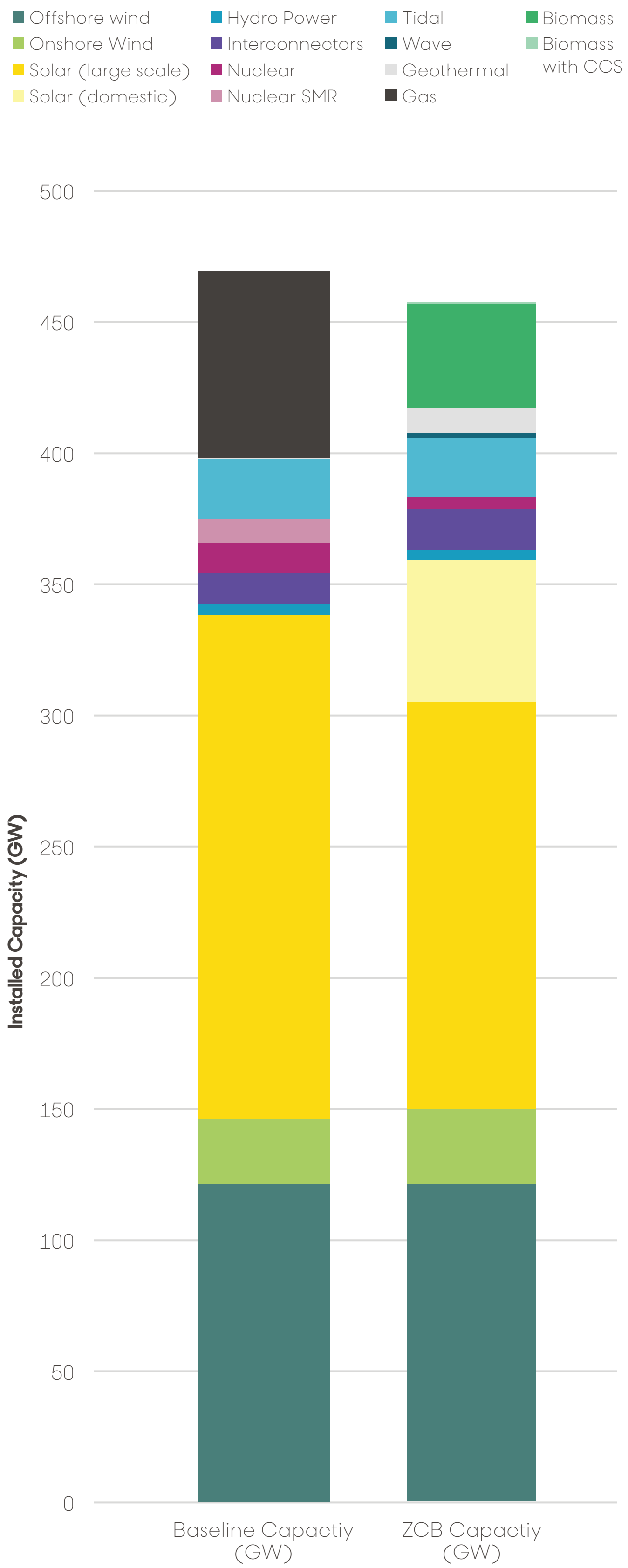
Appendix B: 2050 Energy Generation Across Baseline and Zero Carbon Britain Scenarios

2050 Energy generation



Appendix C: 2050 Electricity Installed Capacity – SFM Model

ZCB Energy



Appendix D: Building Heat Production – ESME Model