Imperial College London

Delivering Our Future Power System

Accelerating the UK's Progress Towards Decarbonising Electricity

An Energy Futures Lab Briefing Paper

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Acknowledgments

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Table of Contents

Acronyms & Abbreviations

AR	Allocation Round (for CfD auctions)
ASP	Administrative Strike Price
ASTI	Accelerated Strategic Transmission Investment
BECCS	Biomass with Carbon Capture and Storage
BEIS	Department for Business, Energy & Industrial Strategy (responsible for energy policy before DESNZ)
BESS	British Energy Security Strategy
BEV	Battery Electric Vehicle
CB6	The 6th Carbon Budget
CCC	Climate Change Committee
CCS	Carbon Capture & Storage
CCGT	Combined Cycle Gas Turbine
CCUS	Carbon Capture Usage & Storage
CES	Crown Estate Scotland
CfD	Contract for Difference
CHP	Combined Heat & Power
CPS	Carbon Price Support
CSNP	Centralised Strategic Network Plan
DESNZ	Department of Energy Security & Net Zero
DEFRA	Department for Environment, Food and Rural Affairs
DLUHC	Department for Levelling Up, Housing and Communities
DNO	Distribution Network Operator
DofE	Department of Education
DSIT	Department for Science, Innovation and Technology
DSR	Demand Side Response
DSO	Distribution System Operator
EIA	Environmental Impact Assessment
ENA	Electricity Networks Association
ETS	Emissions Trading Scheme
EV	Electric Vehicle
FES	Future Energy Scenarios
FiT	Feed-in Tariffs
FSO	Future System Operator
FTE	Full-Time Equivalent
GB	Great Britain
GHG	Greenhouse Gas
GT	Gas Turbine
HND	Holistic Network Design
HVDC	High Voltage DC
IPCC	Intergovernmental Panel on Climate Change
LDES	Long Duration Energy Storage
LLES	Large-scale Long-duration Energy Storage
LW	Leading the Way – one of the FES Pathways
$MtCO_2e$	Million tonnes CO_2 equivalent
NAO	National Audit Office
NGESO	National Grid Electricity System Operator
NIC	National Infrastructure Commission
NPPF	National Planning Policy Framework
NPS	National Policy Statement
NSIP	Nationally Significant Infrastructure Project
ONS	Office for National Statistics
PPS	Planning Policy Statements
PPW	Planning Policy Wales
RAG	Red-Amber-Green
REMA	Review of Electricity Market Arrangements
SPP	Scottish Planning Policy
T&S	Transport & Storage
TCE	The Crown Estate
TNO	Transmission Network Operator
TOs	Transmission Owners
TSO	Transmission System Operator
UKRI	UK Research & Innovation

Acronyms & Abbreviations

Executive Summary

The UK has been a leader in setting out ambitious and legally binding targets to meet its obligations under the Paris Agreement, and in 2019 was the first major economy to pass a net zero emission law. The UK remains one the few countries with emissions targets in line with the long-term temperature goal of the Paris Agreement. A core part of its emissions reduction roadmap is the decarbonisation of the electricity power system. Whilst emissions from electricity generation have declined by 73% since 1990, approximately 40% of electricity generation still comes from greenhouse gas (GHG)-emitting sources, primarily natural gas. Decarbonising the electricity power system will require a significant ramp-up of low-carbon generation capacity, primarily variable renewable generation via wind and solar, and other firm low-carbon generation sources such as nuclear and biomass with carbon capture and storage (BECCS).

As well as replacing the current GHG-emitting forms, low carbon sources of electricity generation will need to fulfil a large increase in demand, driven by the electrification of energy use across transport, industry and domestic settings. Compared to today, DESNZ and CCC expect 2035 electricity demand to increase by around 50%. As well as significant increases in low-carbon generation capacity, there will be additional requirements for increases in the capacity to move this generated electricity throughout the GB grid spatially and temporally. As a result, meeting the 2035 target will also require significant increases in network and flexibility capacity driven by i) the requirement to meet the significant increase in electricity demand, ii) the broad and increasing geographical dispersion of generation capacity, iii) the spatial mismatch between where generation is located versus demand, and iv) the larger share of generation that relies on variable renewables. All told, meeting the 2035 power system decarbonisation target could require over £500 billion of investment over the next 12 years across generation, networks and flexibility, in what will be one of the largest and most rapid deployments of national infrastructure in the UK's history, analogous to the delivery of ten HS2 projects in that period, on time and on budget.

Despite the unprecedented scale of the undertaking required to deliver our future decarbonised power system, there remains a distinct gap in frameworks that can be used to meaningfully track progress and systematically inform efforts to accelerate it. This Briefing Paper provides a means to do that, showcasing a novel, codified framework that defines the objective of delivering a decarbonised power system, a means of tracking progress and an assessment of the UK's progress to date. This analysis highlights opportunities to accelerate progress towards the target.

This proposed framework – the "landscape" – incorporates a taxonomy of 28 segments that together make up the objective of decarbonising a power system. These 28 segments are grouped under two main sections, "Infrastructure" and "Enablers for Infrastructure Delivery". The segments in the infrastructure section are further grouped under three sub-sections, "Generation & Networks", "Grid Scale Flexibility" and "Demand". This sub-section grouping is an important feature of the framework which helps highlight some important real-world dynamics including i) the importance of increasing the capacity of grid-scale flexibility, and ii) the important facilitating role played by the enablers section, which underpins all infrastructure delivery that surround and underpin the segments of infrastructure.

Using this landscape, progress to date within each segment is assessed, comparing rates of delivery required versus what is currently achieved, and identifying key opportunities to accelerate rates of delivery. The analysis is grounded in a systematic review of existing published material and semi-structured interview input across a wide range of stakeholders. The findings from this analysis

Executive Summary

are summarised using a qualitative five-step rating based on a "Red-Amber-Green" (RAG) designation, where, for example, dark green segments indicate delivery at the rate required to meet the target, while red segments indicate that delivery remains well below the rates required *and* we find insufficient efforts to change the status quo. The culminating output, shown in Figure 1, is a gap analysis of current policy and levels of activity across public and private sector participation. It presents a heat map of opportunities to accelerate the delivery of a decarbonised power system in the UK. Using the landscape and resulting gap analysis, the Briefing Paper makes recommendations targeted at the segments with the most significant opportunities to accelerate delivery (red and amber) towards achieving a decarbonised power system by 2035.

Across the 28 individual segments considered, seven segments present the most significant opportunities to accelerate delivery. These require urgent attention to deploy infrastructure at the rates required to achieve a decarbonised power system by 2035.

Within infrastructure the highest priority segments are:

i) Distribution
ii) Energy Efficiency

Within enablers, the highest priority segments are:

iii) Strategy, Coordination & Governance
iv) Public Engagement & Advocacy
v) Financing & Investment
vi) Planning & Permitting
vii) Workforce & Supply Chains

Other segments within the landscape, most notably Connections and Transmission, have been the subject of substantial recent coverage, emphasising their impacts on slowing down rates of progress in decarbonising the power system. Our analysis has found concerted and systematic efforts aimed at addressing the issues identified within these segments, with credible roadmaps that aim to seize opportunities to accelerate progress. Similarly, Planning & Permitting, included in the shortlist above, has been the subject of a substantial set of very recent reforms (in particular with the passing of the Levelling Up Act in October 2023) with the aim of accelerating delivery. As a result, these segments have not been included in the list of recommendations. The recommendations aim to bring attention to other areas that present similar, important opportunities to accelerate delivery, and where the attention to date has been insufficient and/or inconsistent.

The ten, highest priority recommendations are included below. A full list of recommendations across the priority segments outlined above are provided within the assessments for each segment, and are collated at the end of the paper.

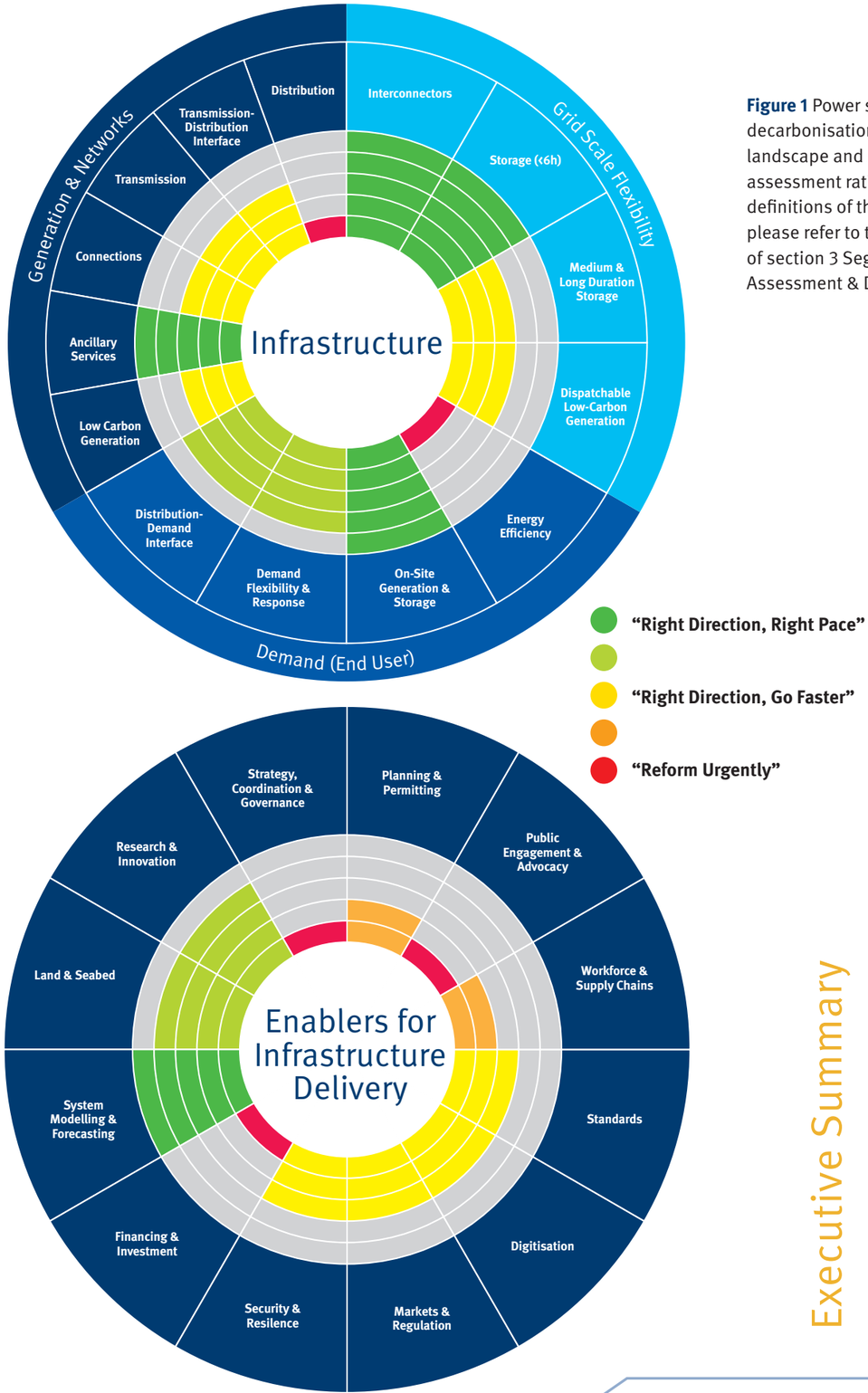


Figure 1 Power system decarbonisation landscape and segment assessment ratings - for definitions of the ratings, please refer to the start of section 3 Segment Assessment & Discussion

Executive Summary

Ten Key Recommendations

1) Accelerate the Roll-Out of Energy Efficiency

Launch a nationally coordinated energy efficiency and home retrofit programme without delay. Develop tailored solutions that address regional needs and encourage participation and, in parallel, promote energy-saving actions for both businesses and households through widespread public engagement initiatives. Guarantee consumer and supply chain certainty by integrating support for heat pump installation, energy efficiency measures, and incentives for upgrading blocks of flats.

2) Publish a Long-Term Delivery Plan

For the Future System Operator (FSO), Department for Energy Security & Net Zero (DESNZ) or other capable organisation, to publish as soon as possible, in order to enable effective strategic planning, a comprehensive long-term strategy for the delivery of a decarbonised, resilient power system by 2035. This strategy should incorporate the portfolio of investments required for the electricity power system but also other energy vectors that interface with this such as hydrogen, Carbon Capture Usage & Storage (CCUS) and heat networks infrastructure and how these key interactions will be managed.

3) Create a Cross-Government Delivery Body

Appoint or create a minister-led infrastructure delivery body with responsibility to deliver this plan, and coordinate actions across the FSO; Ofgem; DESNZ; Department for Environment, Food and Rural Affairs (DEFRA); Department for Levelling Up, Housing and Communities (DLUHC); Department of Education (DofE); Devolved Administrations; Local Governments; and other relevant government departments and bodies.

4) Update Our Social Contract

Involve the public in the decision making required on key trade-offs, potentially through further deliberative forums such as follow-ups to the UK Climate Assembly, to build a social contract around the actions required for delivery and to enable community buy-in.

5) Build Public Advocacy

Rapidly publish a comprehensive public communication strategy and plan, with the aim of establishing a broad base of support for the overarching goal of net zero and power system decarbonisation in the interim.

6) Compensate Disrupted Communities

Rapidly conclude and implement a generous community compensation scheme for those communities that will bear more of the burden of hosting critical power system infrastructure (and the significant disruptions during their construction), exploring all avenues including part community ownership, discounted services, investment in local services and infrastructure and direct cash compensation.

7) Recognise and Plan for Inflexion in Investment

Rapidly publish a plan for how the UK can increase levels of investment in power system decarbonisation infrastructure by 2-3 times relative to the previous 12-year period, including the likely sources of this increase in capital (i.e. how much of this can come from domestic vs international sources) and lay out a clear and credible plan for how the UK will compete for and secure international sources of capital in the face of significant incentives being put into place by other jurisdictions (such as the EU and USA).

8) Revamp and Recalibrate the Flagship Subsidy Regime

As well as incorporating relevant non-price factors in to Contracts for Difference (CfD) auctions as appropriate coming out of the consultation, reconsider the approach to CfD auctions, and recalibrate these to once again be tools for price discovery for the delivery of the levels of capacity increase required at that time, rather than a tool to drive prices down for each successive auction round.

9) Accelerate Workforce Actions

Collaborate with devolved administrations, local authorities, businesses, trade bodies, and accrediting organisations to create a comprehensive Net Zero and Nature Workforce Action Plan by 2024. In alignment with net zero objectives, this plan must outline strategies to address workforce priorities, assessment of skills gaps and shortages, address barriers to inclusive labour market entry into essential occupations for the transition, and provide a clear roadmap for addressing these gaps through the education system.

10) Build a Supply Chain Plan Beyond Critical Materials

Rapidly undertake and publish a comprehensive analysis of the supply chain requirements critical to the net zero transition and the interim target of power system decarbonisation.

Executive Summary

1. Introduction

Following the UN Climate Change Conference (COP21) in Paris in 2015, 194 parties signed up to a legally binding international treaty ("Paris Agreement") to substantially reduce greenhouse gas (GHG) emissions (United Nations, 2015), and over 100 countries have already set or are planning to set GHG emission reduction targets that would see them achieve net zero GHG emissions to combat global climate change (van Soest, den Elzen and van Vuuren, 2021). The UK has been a leader in setting out ambitious and legally binding targets to meet its obligations under the Paris Agreement and in 2019 was the first major economy to pass a net zero emission law (BEIS, 2021c). The UK remains one the few countries with emissions targets in line with the long-term temperature goal of the Paris Agreement (CCC, 2022).

The Climate Change Act 2008 (UK Parliament, 2008a) sets the UK's framework for reducing GHG emissions and adapting to climate risks. It created the Climate Change Committee (CCC), an independent body that advises the government on emissions targets and independently assesses progress (CCC, 2023b). The government must set legally binding Carbon Budgets for five-year periods, 12 years ahead of time. The latest, the Sixth Carbon Budget (CB6), covers 2033-2037 (CCC, 2020b). The UK has cut its GHG emissions by c.50% since 1990 and decoupled them from economic growth, as shown in Figure 2. The historical emissions reduction pathway and the expected range of future emissions outcomes based on current policies, relative to the respective carbon budgets, is also shown in Figure 3.

In March 2023, the United Nations Intergovernmental Panel on Climate Change (IPCC) released the synthesis of its Sixth Assessment Report (AR6 Synthesis Report) (IPCC, 2023) as a further warning to the world on climate change. This report highlighted the lack of progress made in the decade following the release of the AR5 report (IPCC, 2014), and emphasised the need to accelerate decarbonisation to try to limit warming to the levels set in the Paris Agreement. In order for western economies to reach net-zero emissions in time, the electricity power system ("power system") will need to be fully and rapidly decarbonised, and to offset other sectors which cannot decarbonise in time, in many cases it will need to reach a point of negative emissions (National Grid ESO, 2023i).

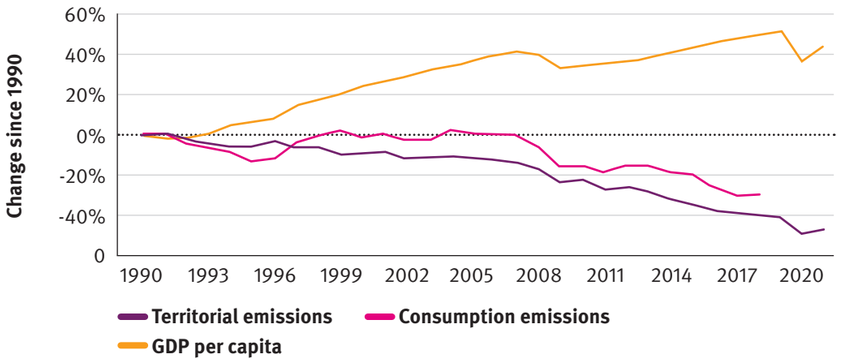


Figure 2 *UK's Historical Emissions vs per capita GDP - 1990-2020* (CCC, 2022)

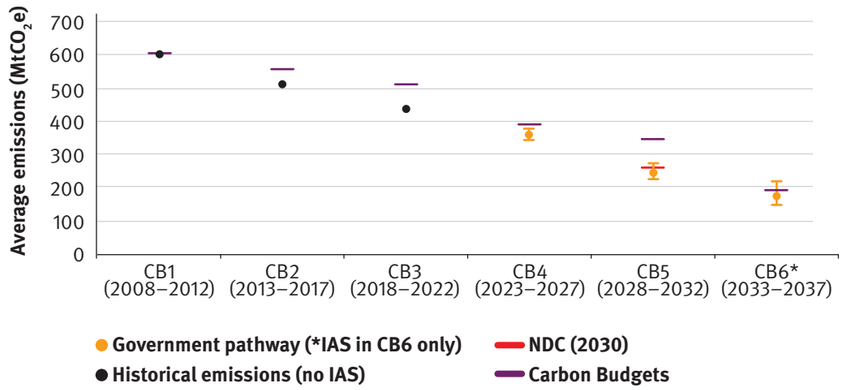


Figure 3 *Government Pathway and Historical Emissions Compare to Legislated Targets* (CCC, 2022)
**IAS: International Aviation & Shipping*

Power system decarbonisation is a key component of the UK's future emissions reduction ambitions. In 2021, the UK committed to decarbonising its power system by 2035 subject to security of supply (the "target"). This brought forward the target by 15 years compared to the original delivery timeline of 2050, which was set as part of the UK's original commitment to net zero (BEIS, 2021b). This accelerated timeline brought government policy in line with the CCC's recommendations in the CB6 (CCC, 2020b). This is a highly ambitious target requiring a rapid, deep decarbonisation of the power system.

Electricity generation made up about 13% of the UK's 2021 GHG emissions, representing approximately 54 million tonnes CO_2 equivalent ($MtCO_2e$) – this is a 73% reduction on its 1990 emissions, which were approximately 200 $MtCO_2e$. These historical reductions in emissions have been driven in part by a reduction in electricity usage owing to industrial production moving overseas, and the phase out of coal and ramp-up in renewables, as shown in Figure 4. Figure 5 shows the historical GHG emissions reduction in the context of the target for power system GHG emissions through to 2050.

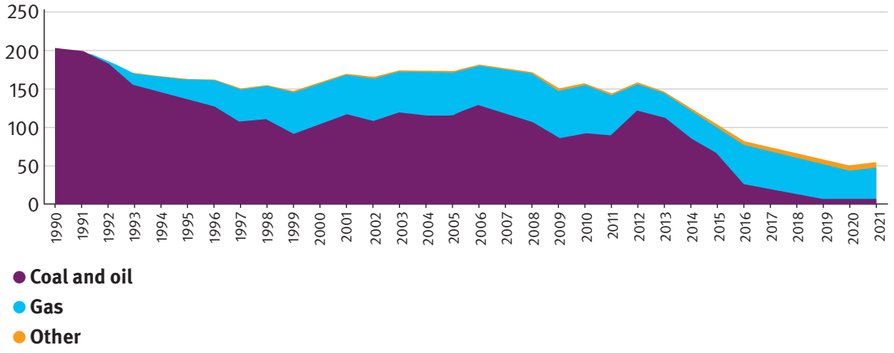


Figure 4 *UK Electricity Generation GHG Emissions by Fuel Type, 1990-2021. Taken from NAO report on Power System Decarbonisation* (NAO, 2023a)

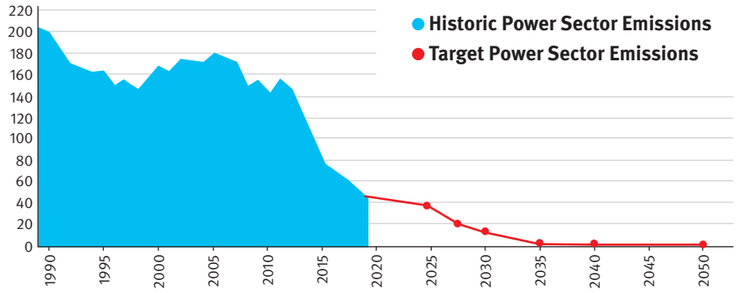


Figure 5 *UK Power System Gross GHG Emissions ($MtCO_2e$) - historic values & future targets. Taken from AFRY analysis on power system decarbonisation for CCC* (CCC and AFRY, 2023)

The government has backed up its power system decarbonisation target with a series of policy commitments laid out across a broad range of publications over the past two years (NAO, 2023a). Assessment of these publications by the CCC in 2022 showed that the decarbonisation of electricity supply was the most credible component of the government's legally binding emissions reduction plans by 2035 (Figure 6). However, updated analysis by the CCC in 2023, shown in Figure 7, identified increases in delivery risk across the UK's decarbonisation targets (CCC, 2023a), including for delivering the decarbonisation of the power system (referred to as 'Electricity Supply' in the Figures). The CCC's updated analysis has found that the majority of required emissions reductions do not have a credible delivery plan.

For the UK to meets its power system decarbonisation target, a substantial programme of delivery is required to make tangible progress and deliver on policy commitments. Meeting this ambitious power system decarbonisation target will require the deployment of new energy infrastructure at a scale and pace never achieved before in the UK (Industrial Strategy Committee, 2023). Encouraging private investment in low-carbon infrastructure will continue to be crucial for achieving the desired level, pace, and scale of ambitions. As will be highlighted throughout this paper, there are many instances within many segments where delivery is already encountering significant bottlenecks. There are therefore significant opportunities to accelerate delivery and help meet, or exceed, this ambitious target.

Purpose & Structure of the paper

The motivation for this paper stems from the focus of the existing corpus of material on either i) high-level coverage ii) detailed coverage focused on specific technical or policy aspects or iii) assessments of progress by organisations with mandates to advise and/or hold government to account (e.g., CCC, National Audit Office (NAO), National Infrastructure Commission (NIC) etc.), often focused on specific aspects of delivery. There is therefore a gap of material providing a single, comprehensive summary of progress made towards the delivery of the target, the source and nature of blockers that may be impeding progress, and potential solutions to accelerate progress. We have endeavoured to fill this gap by first providing a framework that codifies the objective of delivering a decarbonised power system in Great Britain (GB) and to further provide an assessment of progress to date and provide recommendations for accelerating progress, cutting through what Professor Dieter Helm recently referred to as the "*dense mass of overlapping aspirations, strategies and targets published over more than 10,000 pages of reports, consultations and white papers*" that currently makes up the policy landscape (Helm, 2023).

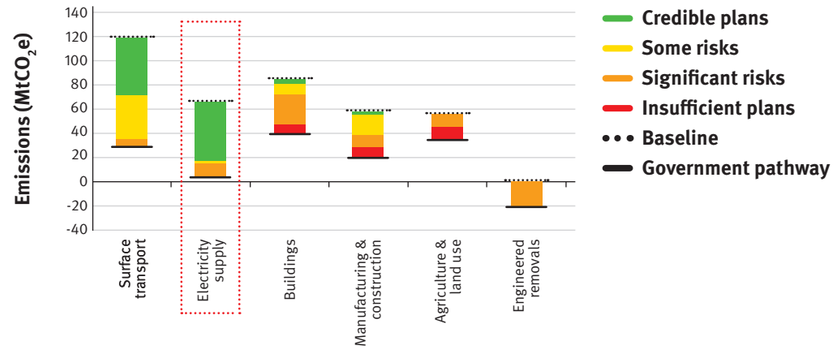


Figure 6 *CCC Analysis of the Credibility of Government Plans to Meet its 2035 Pathway Targets, by Sector. Taken from CCC 2022 Update Report to Parliament* (CCC, 2022)

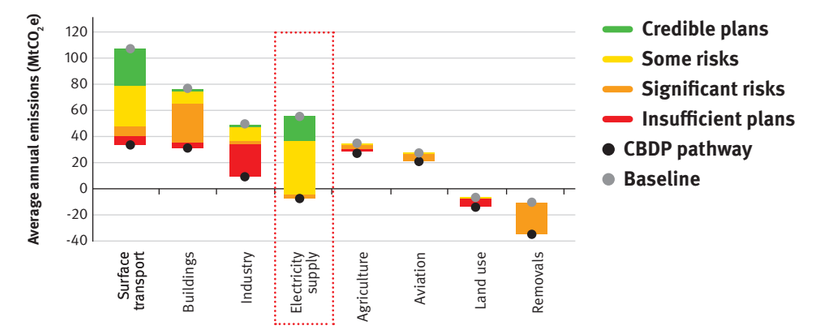


Figure 7 *Updated CCC Analysis of the Credibility of Government Decarbonisation Plans, by Sector. Taken from CCC 2023 Update Report to Parliament* (CCC, 2023a)

Recognising the complex, multi-faceted nature of transforming a nation's power system, the research first aims to codify the delivery landscape, providing a novel and comprehensive framework for a systematic assessment. This landscape is then used to provide a summary assessment of progress made across the segments that it encompasses, and to highlight key risks to delivery and opportunities to accelerate progress using a visual and intuitive Red-Amber-Green (RAG) rating system. Where possible, the report also provides recommendations for unlocking the identified opportunities to accelerate progress, leveraging research already conducted by stakeholders across the landscape as well as those flagged during the semi-structured interviews conducted as part of the research.

The next chapter, Taxonomy & Framework – the Delivery Landscape, presents the framework and taxonomy used to define the objective and assess progress, which is followed by the segment-by-segment assessment incorporating relevant discussions in the chapter on Segment Assessment & Discussion. Key conclusions and recommendations are then summarised in the following chapter on Conclusions and Recommendations.

2. Taxonomy & Framework – the Delivery Landscape

The framework developed as part of the analysis presented here – the "landscape" – is presented in Figure 8. This landscape incorporates a taxonomy of 28 segments that make up the objective of decarbonising the power system by 2035. Definitions for these segments are also provided in Figure 10. These 28 segments are grouped under two main sections, "Infrastructure", which includes 16 of the segments, and "Enablers for Infrastructure Delivery", which includes 12.

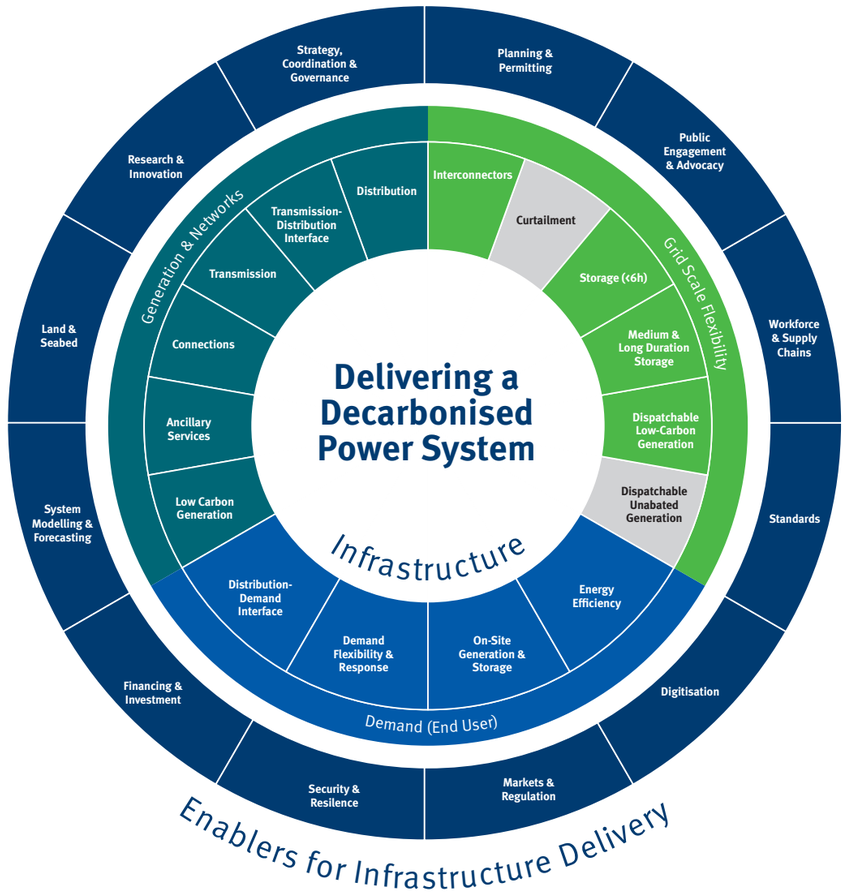


Figure 8 *Power System Decarbonisation Delivery Landscape - a novel framework proposed by the authors* (Ersöz and Rhodes, 2023)

The segments in the Infrastructure section are further grouped under three sub-sections, "Generation & Networks", "Grid Scale Flexibility" and "Demand". This grouping is outlined in Figure 9, and is an important feature of the framework which helps unpack some important real-world dynamics. First is the importance of increasing the capacity of grid scale storage – this is covered in more detail in section 3.2.1 Flexibility in a Decarbonised Power System. Second is the important facilitating role played by the enablers section, which underpins all infrastructure delivery that sits 'on top'.

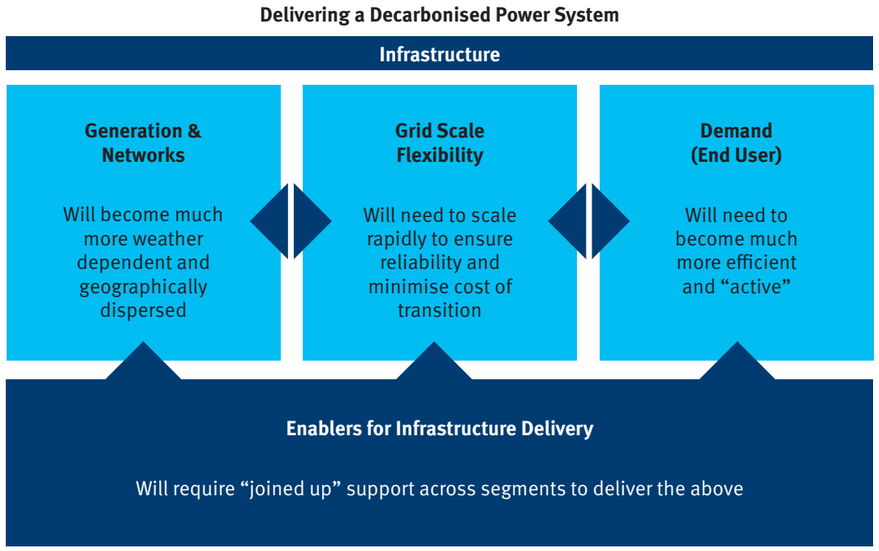


Figure 9 *Sections within the Delivery Landscape, outlining two important dynamics; i) central role of grid scale flexibility to deal with variability in generation and demand, and ii) the foundational role of Enablers* (Ersöz and Rhodes, 2023)

2. Taxonomy & Framework – the Delivery Landscape

Segment Group	Segment	Definition
Generation & Networks	Low Carbon Generation	Low carbon generation capacity that can replace current natural gas and other GHG emitting generation types. Includes renewables (e.g., wind and solar) and nuclear
Generation & Networks	Ancillary Services	Also referred to as "balancing" services – these keep the grid stable to smaller scale and shorter duration fluctuations until reserve / dispatchable capacity can be brought online if required
Generation & Networks	Connections	The infrastructure that allows new generation, storage, and demand assets to connect to the electricity network, across transmission and distribution
Generation & Networks	Transmission	This is the infrastructure for the high voltage (›132 kV) part of the electricity network, excluding interconnectors which are covered separately
Generation & Networks	Transmission-Distribution Interface	This is the physical and digital infrastructure that forms the connections between the transmission and distribution networks
Generation & Networks	Distribution	This is the infrastructure for the low voltage (‹132 kV) part of the electricity network
Grid Scale Flexibility	Interconnectors	This is large capacity High Voltage DC (HVDC) connections between the electricity networks in Great Britain (GB) and other grids (e.g., Ireland, Norway, France, Belgium, Holland etc)
Grid Scale Flexibility	Curtailment	This is the potential for excess renewable generation to be treated a supply-side response, presenting an alternative to dispatchable generation
Grid Scale Flexibility	Storage (‹ 6h)	Grid scale short duration storage capacity, primarily Li-Ion batteries but other options are included as well – see section for more details
Grid Scale Flexibility	Medium & Long Duration Storage	Grid scale flexibility assets that can provide storage and discharge at longer time frames e.g., days/weeks/months
Grid Scale Flexibility	Dispatchable Low Carbon Generation	The infrastructure underpinning the generation, transport and storage of hydrogen, and the capture, transport, and sequestration infrastructure for Carbon Capture Usage & Storage (CCUS)
Grid Scale Flexibility	Dispatchable Unabated Generation	The infrastructure underpinning the generation, transport and storage of natural gas, for use in dispatchable electricity generation in unabated plants
Demand (End User)	Distribution-Demand Interface	This is the physical and digital infrastructure that forms the connections between distribution network and the end user
Demand (End User)	Demand Flexibility & Response	This is the infrastructure that underpins Demand Side Response (DSR), allowing demand to shift temporally based on variations in generation and provide flexibility capacity to the grid – in this sense, it is a subset of ancillary services but is considered separately in this review as the infrastructure is spatially distributed vs the bulk gird connected capacity considered earlier
Demand (End User)	On-Site Generation & Storage	This is the distributed, on-site, "behind the meter" generation and storage infrastructure on domestic, commercial and industrial sites.
Demand (End User)	Energy Efficiency	This refers to the broad range of infrastructure that allows for the efficient use of energy resources across domestic, commercial and industrial end users
Enablers for Delivery	Strategy, Coordination & Governance	This refers to the degree of strategic direction, centralised coordination, and governance underpinning accountability for delivery across the broad range of activities required to deliver the target.
Enablers for Delivery	Public Engagement & Advocacy	This is the extent to which the public are engaged, aware and supportive of the rapid build out of infrastructure required to deliver the target, and the suitability of initiatives that are being deployed to achieve it.
Enablers for Delivery	Standards	This covers a broad range of policies that provide the standards that need to be complied with across the landscape, and the extent to which these are suitable for, and compatible with, delivering the target
Enablers for Delivery	Markets & Regulation	This refers to the market and regulatory arrangements that govern the landscape, including the structure of support mechanisms such as Contracts for Differences (CfDs)
Enablers for Delivery	Financing & Investment	This is the public and private finance available to fund the projects that will be required across the landscape to meet the target.
Enablers for Delivery	Land & Seabed	This refers to the space required (on land or out at sea) for the infrastructure that will be needed to deliver the target.
Enablers for Delivery	Planning & Permitting	This refers to the wide range of processes associated with obtaining permission to build a given project at a given location – with terms such as siting, planning, permitting, consenting, and others often used interchangeably to refer to the different parts of this process.
Enablers for Delivery	Workforce & Supply Chains	This is the process with which relevant infrastructure projects are developed and built, and the supporting infrastructure required to do so such as workforce and supply chains
Enablers for Delivery	Digitisation	These are the frameworks and infrastructure that underpin the digital parts of the landscape
Enablers for Delivery	Security & Resilience	This refers to the security and resilience of the landscape, including cybersecurity, and the extent to which these are suitable to delivering the target
Enablers for Delivery	System Modelling & Forecasting	This refers the modelling capabilities required to accurately simulate and forecast the complex spatial and temporally interactions between supply and demand, across different types of networks (e.g., transmission & distribution) and across different energy vectors (e.g., electricity, natural gas, hydrogen)
Enablers for Delivery	Research & Innovation	This refers to the research and innovation capabilities available to develop, test and scale the technologies, business models and other key components required to meet the target

Figure 10 *Segment definitions*.

2. Taxonomy & Framework – the Delivery Landscape

3.Segment Assessment & Discussion

As well as providing a holistic framework for defining the delivery a decarbonised power system – the landscape introduced above – our paper also aims to provide a method for tracking progress, and a stock-take of the progress to date with a focus on areas of most significant opportunity to accelerate it.

The qualitative assessment used for this analysis is based on a visual and intuitive "Red-Amber-Green" (RAG) scale. The rating for any given segment is arrived at using the set of questions outlined in Figure 11. In order to answer these questions and arrive at the segment ratings, our analysis considered a systematic review of a broad corpus of published material, referenced throughout, validating and refining these findings with experts covering a broad range of relevant stakeholders across over a dozen semi-structured interviews (Ersöz and Rhodes, 2023). The primary aim of this rating is to provide an intuitive way to bring attention to those that are most ripe for exploitation to accelerate the pace of delivery.

The culminating assessment, outlined in this section, is a "gap analysis" of the existing policy and actions across public and private sector participation, presenting a heat-map of opportunities to accelerate power system decarbonisation delivery.

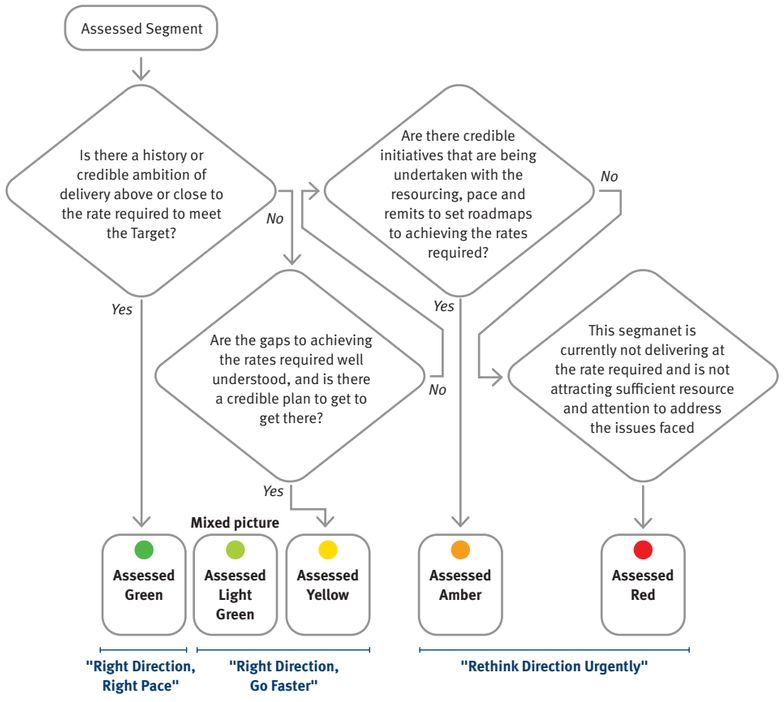


Figure 11 Qualitative Segment Assessment Approach for Generating Red-Amber-Green Rating

3.1 Infrastructure: Generation & Networks

3.1.1 Low Carbon Generation [Yellow]

In 2022, the UK used 273 TWh of electricity, more than half of which came from low carbon sources. Renewable sources, especially wind, also increased their share of electricity generation (DESNZ, 2023i). As well as displacing the approximately 44% of demand met by fossil-fuel generation today, more electricity will be needed in the future to supply the increased demand from the electrification of transport, heating and industry. The government's 2021 Net Zero Strategy estimated that the UK will need between about 40-60% more electricity by 2035 than in 2019 (HM Government, 2021). The CCC's Balanced Pathway for the Sixth Carbon Budget also projected a similar increase, with most of it coming from electrifying heating, transport and industry (Figure 12). This would mean that by 2035, almost half of the total energy demand for heating, transport and industry would be met by electricity (CCC, 2023a).

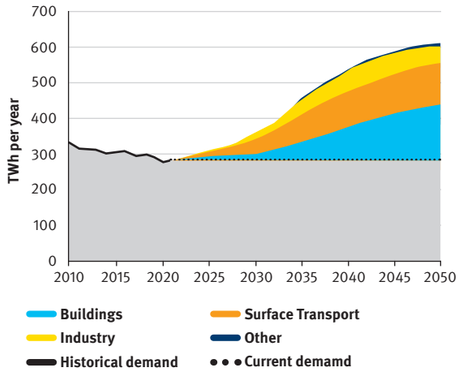


Figure 12 *Expected Growth in Electricity Demand under CCC's Balanced Pathway* (CCC, 2023c)

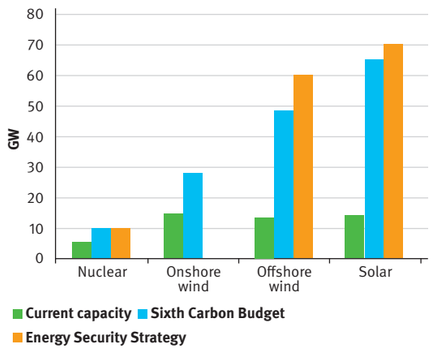


Figure 13 *Low Carbon Generation Capacity in 2035 Under Different Scenarios* (CCC, 2023c)

There is the possibility of further expansion of the use of decarbonised electricity beyond these projections. For instance, large-scale production of electrolytic hydrogen, powering direct air capture of CO_2, and synthetic aviation fuel production are potential areas where decarbonised electricity could also be utilised. However, the feasibility of these use cases is likely contingent upon a significant reduction in the cost of zero-carbon electricity. The CCC's analysis suggests a further halving of the costs of wind and solar power compared to current costs would make these opportunities more feasible (CCC, 2023c). For the purposes of this analysis, the demand profile for the Balanced Pathway is used as the requirement for low carbon generation capacity.

This demand is expected to be met primarily through a significant expansion of bulk zero-carbon generation at scale, with cheap but variable renewables (offshore & onshore wind and solar) making up the backbone, offshore wind in particular, alongside nuclear and biomass with carbon capture and storage (BECCS) providing firm generation that is not weather dependent. In the British Energy Security Strategy (BESS) policy published in 2022 (HM Government, 2022a), the government outlined an ambitious target to deploy 50 GW of offshore wind by 2030 (increasing to 60 GW by 2035), 70 GW of solar generation and 10 GW nuclear by 2035 as part of a target to get to 25 GW capacity by 2050 (Figure 13). This plan has been widely scrutinised across several reports including those by the CCC in their 2022 and 2023 progress reports to parliament and their

3.Segment Assessment & Discussion

Delivering a Decarbonised Power System report in 2023 (CCC, 2022, 2023c, 2023a), NIC in their 2023 Infrastructure Progress Review (NIC, 2023b), the NAO in their 2023 Decarbonising the Power Sector report (NAO, 2023a), and the 2022 Independent Review of Net Zero (Skidmore, 2022), and has been found to be appropriate and sufficient to deliver the generation capacity needed to meet the 2035 target.

There are other scenarios that have been proposed through academic and third-sector literature (Zeyringer *et al.*, 2018; Aunedi *et al.*, 2021; Dixon, Bell and Brush, 2022; Masoud Sajjadian, 2023; Price, Keppo and Dodds, 2023) that may be able to deliver similar power system decarbonisation outcomes by 2035 using a different mix of generation capacity and/or a focus on other interventions such as higher demand reduction through energy efficiency. Whilst these alternative paths are available and may allow for different trade-offs (e.g., lower system deployment costs, less reliance on low maturity technologies, better energy security, etc), it is clear that there is sufficient and credible policy ambition in the targets and pathway set by the BESS, and therefore a key question for meeting the target is whether this strategy can be credibly executed.

The ability to deliver this bulk renewable generation capacity is a foundational component of hitting the target. Figure 13 shows the significant gap between current capacity and what is required to meet the target. Progress in delivering this segment of the landscape and the status of the enablers required constitutes the core focus of our research. We have come across two primary lenses in existing published assessments that consider the progress of deployment, i) the rate of deployment currently achieved versus what is required (NIC, 2023b), and ii) the pipeline of projects across different generation sources versus what is required to achieve the target (National Grid ESO, 2022d).

For the first, as shown in Figure 14, the historical (2010-2022) rate of deployment of renewable generation capacity appears to be on track to deliver on the NIC's interim 2030 target for low carbon generation, with annual historical increase in renewable share of generation slightly below but close to what is needed going forward to meet this interim target. However, an important downside of looking at deployment rate in this way is the use of a % share – as electricity usage is expected to increase (see above), continuing a given rate of increase in generation penetration will become incrementally more difficult – therefore, closeness in the required rate of deployment today vs the future years is likely an over-estimation of the progress being made today relative to what is required.

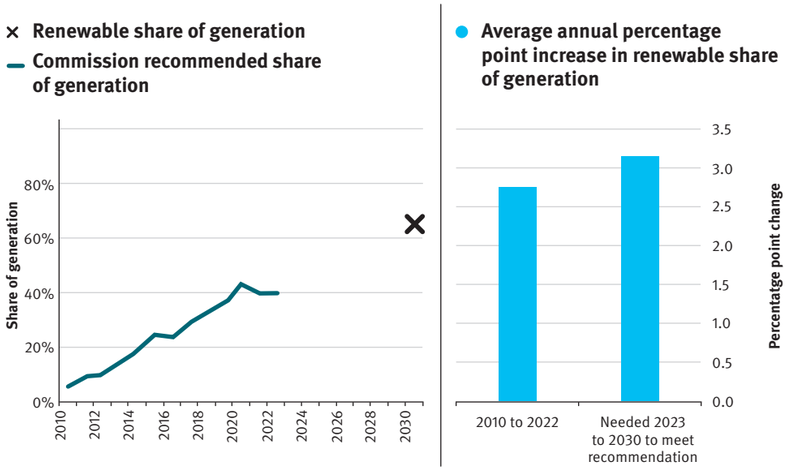
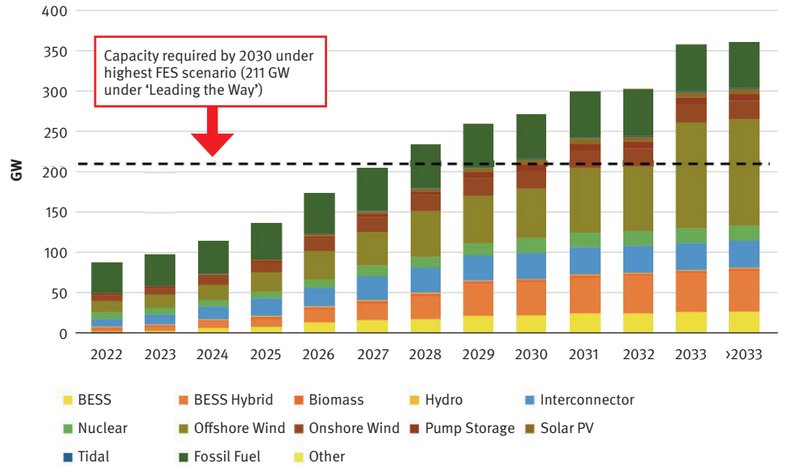


Figure 14 *Historical Renewable Deployment relative to NIC's 2030 Recommendation* (NIC, 2023b)

As part of its Future Energy Scenarios (FES) analysis, the National Grid Electricity System Operator (NGESO) publishes 4 different pathways for reaching the 2050 net zero targets, the most ambitious, Leading the Way (LW) delivers a net *negative* emission grid by 2035, exceeding the ambition of the target (National Grid ESO, 2022c, 2023i). For the second lens, Figure 15 shows how the existing connection offers to the grid compare to the LW scenario outlined in this analysis. The status of connections will be covered in more detail in section 3.1.3 below, however NGESO's 2023 report published as part of bringing forward a case for change in deploying connections (National Grid ESO, 2022d), shows that the demand for bringing generation projects on to the grid *already* far exceeds what is required to meet an even more ambitious pathway than what is needed to deliver the target. Whilst not all the projects associated with these connection requests will go ahead, this pipeline shows a clear ambition to invest in low carbon generation capacity in the UK, at or above the levels needed to meet the target.

However, neither of these "top down" perspectives provide enough confidence about the rate of physical infrastructure deployment. Indeed, the reports cited above highlight a number of risks that may hinder progress in delivering this ambitious pipeline of projects including the lack of an overarching delivery plan (considered further in 3.4.1), the connections backlog (considered further in 3.1.3), problems in planning & permitting (considered further in 3.4.7), and under-investments in workforce and supply



Source: TEC Register (as of 5th December 2022)

Figure 15 *Cumulative Contracted Generation Capacity by Type and Year, Relative to FES LW Pathway. NGESO Connections Analysis* (National Grid ESO, 2022d)

Segment Assessment & Discussion

chains (considered further in 3.4.8). In order to better assess progress in achieving the physical deployment required versus what is being achieved, key low carbon generation technologies are considered separately below.

Offshore Wind – Fixed Bottom & Floating [Yellow]
The UK is a global leader in deploying both fixed bottom and floating offshore wind, with 13.8 GW of operational fixed bottom offshore wind capacity and 78 MW of floating capacity already deployed – it is home to the world's first, second, third and fourth largest offshore wind farms (Tim Pick, 2023). In order to deliver the target, the government will need to hit its 50 GW of offshore wind deployment by 2030, and this will need to increase to 50-85 GW by 2035 (CCC, 2020b; National Grid ESO, 2023i). The Department of Energy Security and Net Zero (DESNZ) is tracking c.80 GW of fixed bottom offshore wind project pipeline today, with a further c.19 GW of existing floating pipeline and up to 10 GW which may be added via the Celtic Sea leasing rounds (4 GW of which is expected in the first round later this year) (Industrial Strategy Committee, 2023; The Crown Estate, 2023; Tim Pick, 2023).

As part of the offshore wind champion Tim Pick's analysis to accelerate offshore wind deployment (Tim Pick, 2023), RenewableUK analysed the pipeline of wind projects and showed that close to 100 GW of offshore wind capacity could be deployed by 2035, exceeding the required capacity range across the scenarios considered that would meet the target. This analysis assumed project progression and dropout rates would be in line with historical averages. However, as highlighted elsewhere in the same report, project progression has slowed, with timescales increasing from c.5 years in the early 2000s to over 10 years taken to deploy current projects. A significant contributor to this slowdown is the planning & permitting process. Testimony given to a recent parliamentary committee report (Industrial Strategy Committee, 2023) stated that of all projects that had received approval since 2017, 6 GW in total, none had been recommended for approval by the Planning Inspectorate who instead had to refer them to the secretary of state for approval, significantly prolonging the time taken. The government opened a consultation in July 2023 to amend planning rules and enable the fast-tracking of the process for offshore wind farms with a view to half the time taken for these projects to gain planning approval (Current News, 2023h; DLUHC, 2023a).

Measures to accelerate grid connections, and the transmission reinforcement investments required to enable this, were singled out by Tim Pick as the main enabler to meet deployment targets (Industrial Strategy Committee, 2023; Tim Pick, 2023). RenewableUK highlighted that all offshore wind sites leased in the past two years had received connection offers for after 2032 (Industrial Strategy Committee, 2023). Tim Pick, across both his report and his testimony to the parliamentary committee, emphasised that in the absence of measures to accelerate connections, offshore wind capacity deployment by 2030 would likely be capped at c.40 GW, missing the 50 GW BESS ambition, and undershooting the deployment needed by 2035 to meet the target (Industrial Strategy Committee, 2023; Tim Pick, 2023).

Supply Chains are also considered at length in publications assessing offshore capacity deployment (CCC, 2022, 2023a; Industrial Strategy Committee, 2023; RenewableUK, 2023; Tim Pick, 2023). In particular, port capacity is called out as requiring significant investments in order to meet UK's deployment requirements – with turbines expected to reach heights of over 300 metres, the capacity of ports which will act as manufacturing and assembly sites for these structures will be a key bottleneck for overall capacity of generation deployment (Industrial Strategy Committee, 2023; RenewableUK, 2023; Tim Pick, 2023). The reports call on c.£4 billion of investment in ports, which is considerably higher than the £160 million in support announced by the government in March 2023 (HM Government, 2023d). The structure of Contracts for Difference (CfD) auctions, which remain driven primarily by lowest price and discussed in further detail later in the paper (see 3.4.4 and 3.4.5), are also highlighted as being a barrier to investment in expanding capacity, instead driving bidders to use ports outside of the UK that have already expanded, and transport manufactured / assembled components to sites in the UK (Industrial Strategy Committee, 2023).

Planning & Permitting (3.4.7), Connections (3.1.3) and Workforce & Supply Chains (3.4.8) make up key segments of the landscape and are discussed at further length in the relevant section of the report, however, given the importance of offshore wind capacity in meeting the target, these cross-cut relationships were highlighted here to emphasise the impact they are having in overall deployment rates.

As well as time taken to progress projects, driven by planning, connections, and supply chains, dropout rates have seen recent increases, with cost increases driving late stage exits such as the high-profile scrapping of a >1 GW capacity site by Vattenfall, a project with planning permission and a timely connection date, and a decision by Vattenfall to further review another 3.2 GW of UK offshore wind development in the pipeline (Offshore Wind, 2023a, 2023b). One of the main drivers of these dropouts, and for those where there is concern for further pipeline exits, is the structure of government subsidies, the CfD programme in particular, which has not adapted to the changing cost environment (this is considered in more detail in the Markets & Regulations (3.4.4), and Financing & Investment (3.4.5) segment discussions) (Current News, 2023b, 2023e; DESNZ and BEIS, 2023e; Financial Times, 2023e, 2023k, 2023l). Increases in dropout rates in the pipeline puts additional pressure on the rate of progression of remaining projects to ensure the required rate of delivery can be achieved. Indeed, as was widely publicised, the latest CfD round (AR5) did not attract any bids from offshore wind developers (DESNZ and BEIS, 2023e) – unless corrective action is taken, this could drive a potentially significant chasm in the actual vs required deployment of generating capacity.

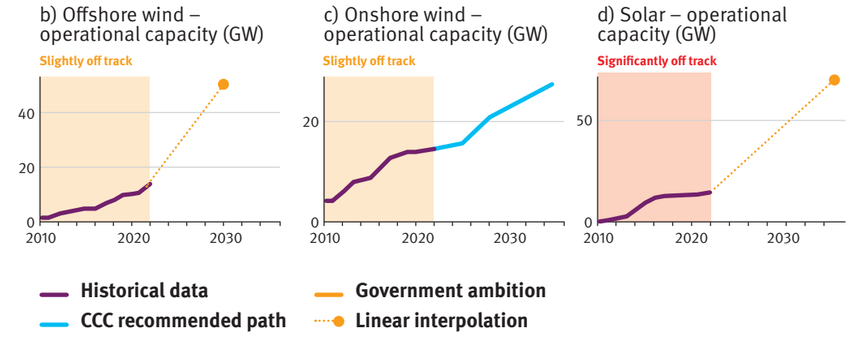


Figure 16 *CCC's assessment of delivery progress vs government targets for offshore wind (b), solar (d) and CCC's recommended path for onshore wind (c)* (CCC, 2023a)

Segment Assessment & Discussion

Overall, the BESS target to reach 50 GW of offshore wind generation capacity by 2030, a prerequisite for achieving the overall power system decarbonisation target by 2035, will require an average annual deployment rate of 4.5 GW between 2023-30 – in 2022, a total of 2.7 GW of capacity was deployed, a significant acceleration is therefore needed to meet the target (Figure 16). Whilst there appears to be a healthy pipeline of projects that could see deployment exceed this ambitious target, the prolonged planning timelines, limited capacity for connections, significant supply chain investment requirement which is not yet sufficiently seeded, and recent high-profile dropouts undermining the government's cornerstone investment subsidy scheme, appear to be driving significant risk to the downside. Many of these risks are the subject of concerted efforts to build credible roadmaps that would aim to bring deployment rates on track to meet targets – the assessment rating is therefore Yellow.

Onshore Wind [Amber]

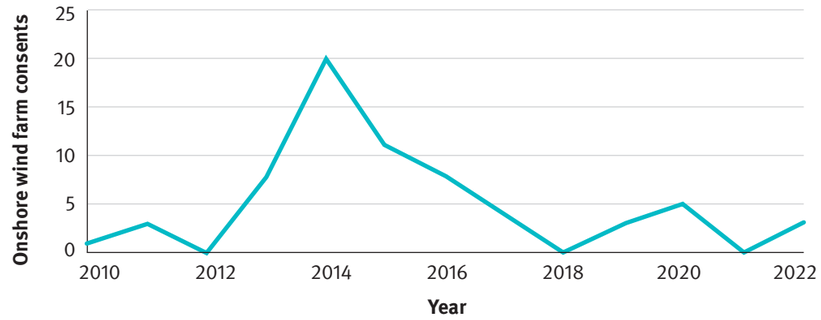
Despite being one of the cheapest forms of electricity generation (DESNZ, 2023f), onshore wind deployment in the UK is progressing very slowly – only 0.3 GW of capacity came online in 2022 (versus. around 1GW per annum needed to make the target), and only 1 MW of this capacity came online in England (CCC, 2023a). There were several headlines in the summer of 2023 highlighting that Ukraine had brought online over 100 times more onshore wind capacity (114 MW) than England in the same period, despite the ongoing armed conflict engulfing the country (The Guardian, 2023b).

The primary driver of this slow deployment is planning laws in England, which in 2015 were modified to make onshore wind development prohibitively difficult – planning applications could be rejected by the local authority on the basis of an objection by a single local resident, causing a significant decline in onshore wind development approvals from their peak in 2014 as shown in Figure 17 (Hobbs *et al*., 2023; Industrial Strategy Committee, 2023). Research conducted by RenewableUK has shown that 80% of the public in England believe that onshore wind developments should be permitted if the majority of the local community support it, with only 9% supporting the current planning arrangements (Industrial Strategy Committee, 2023). The Department for Levelling Up, Housing and Communities (DLUHC) undertook a consultation to reform planning rules for onshore wind development in December 2022 (DLUHC, 2022) as part of the Levelling-up and Regeneration Bill. The government released its responses to the consultation in September 2023 (DLUHC, 2023c), and a number of amendments aimed at easing onshore wind development were passed as part of the Bill, which gained royal assent in October 2023 (UK Parliament, 2023a). In their report analysing the changes and their testimony to the parliamentary committee, Regen stated that these reforms would not go far enough to accelerate the deployment of onshore wind capacity, and that onshore wind would still be subject to "*stricter rules than any other project requiring planning permission [.] or even fossil fuel generators such as diesel or gas*" (Industrial Strategy Committee, 2023; Regen, 2023b).

As a result, deployment rates of onshore wind are below what would be required to meet CCC's Sixth Carbon budget (Figure 16) and meet the target. The impact of recent planning changes remains unclear, but given the low-cost of deploying generation capacity (relative to most other low carbon technologies), if successful reforms are enacted, there is potential to accelerate the pace of deployment. Until there is further policy certainty around the lifting of the "de facto" ban on onshore wind deployment (National Grid Group, 2023a; Octopus Energy, 2023a), the achievable rate of deployment will remain unclear, the assessment rating is therefore Amber.

Solar [Yellow]

Similar to onshore wind, solar generation is one of the cheapest forms of generating electricity (DESNZ, 2023f), and similar to onshore wind,



Source: IPPR analysis of Renewable UK Wind Energy Projects data (Renewable UK 2023).

Figure 17 *Planning consents for onshore wind farms, 2010-22 (Hobbs et al., 2023)*

is being deployed at a slow rate in the UK – 0.7 GW of capacity came online in 2022. However, unlike onshore wind, government has ambitious targets to deploy solar, targeting 70 GW of capacity deployment by 2035 as highlighted above. The UK currently has 14 GW of solar generation capacity across a mix of rooftop and ground mounted installations, therefore to meet the BESS target, deployment would need to increase to an average of c.4.3 GW per year between now and 2035 (CCC, 2023a), meaning current deployment rates are significantly off track vs the BESS target (Figure 16). It should be noted that both the Sixth Carbon Budget and the FES LW scenarios achieve the target with less solar capacity deployed vs the BESS, at 65 GW (requiring an average 3.9 GW deployment per annum) and 60 GW (3.5 GW deployment per annum) respectively – although both make up for this shortfall with increased onshore wind generation, where the BESS does not put forward a target (see Figure 13). The UK has achieved a previous peak solar deployment rate of 4.1 GW which gives a good indication of the potential to reach the required deployment rate with the right policies in place (CCC, 2023c).

There are two main barriers to increasing solar deployment rates, planning and grid connection queues. There is currently c. 40 GW of utility scale solar projects in the pipeline, and only 7 GW has obtained local planning permission, with over 20 GW in the planning pipeline (Industrial Strategy Committee, 2023), and similar to offshore wind, many solar projects are receiving connection dates for 2032 and beyond, which is deterring investment and slowing rates of deployment. As highlighted above, both Planning & Permitting (3.4.7) & Connections (3.1.3) are considered in more detail below. Solar capacity deployment is a high priority area for government policy and following its announcement in March 2023 (HM Government, 2023d), the solar task force was appointed in May 2023 (DESNZ, 2023x) to oversee the delivery of the 70 GW deployment target by 2035. Given the concerted policy focus to increase deployment rates, this sub-segment is rated Yellow.

Nuclear [Light Green]

As highlighted above, the BESS is targeting 24 GW of nuclear generation capacity, of which 10 GW is expected to come online by 2035, with the CCC incorporating this into their Sixth Carbon Budget and their pathway to achieving the 2035 decarbonised power system target. The FES 2023 analysis assumes much less nuclear capacity being online, approximately 5GW, whilst still meeting the target (National Grid ESO, 2023i). As highlighted by their analysis, all but one of the reactors in the UK's current fleet are currently scheduled to be shut down by 2030 and only one plant is under construction in Hinkley Point C, which is expected to leave nuclear capacity at c. 4.6

Segment Assessment & Discussion

GW by 2030 (National Grid ESO, 2023i). NGESO are not expecting Small Modular Reactors (SMRs) to come online before 2033 and for their deployment rate to not increase until later into the 2030s (after the target). The Government has undertaken a number of initiatives to accelerate nuclear deployment beyond what is included in the FES; seeding construction funding at the Sizewell C site to accelerate site preparations (DESNZ, 2023q), launching Great British Nuclear to oversee the acceleration in deployment (DESNZ, 2023j), launching the Future Nuclear Enabling Fund (DESNZ and BEIS, 2023g) and the Advanced Modular Reactor R&D programme (DESNZ and BEIS, 2023a). The parliamentary committee on science and innovation recently released a comprehensive assessment of the government's nuclear power deployment outlook (Financial Times, 2023j; Technology Committee, 2023), with the main findings around a lack of strategy plan to deliver the 2050 target, and a shortfall in the skilled workforce and supply chains required to deliver the capacity targeted. Overall, given the ability of the power system to meet its decarbonisation target by 2035 without a significant increase in nuclear generation capacity, and any increase to this being more of an upside or contingency for under delivery elsewhere, the assessment rating for this sub-segment is Light Green.

Other Low Carbon Generation (e.g., BECCS, Tidal)

In addition to the bulk of the low carbon generation which is expected to come from wind, solar and nuclear, there are a number of other technologies such as BECCS and tidal generation which could make contributions to UK's low carbon generation mix through to 2050, but are unlikely to play a significant role in meeting the 2035 target.

There have been a number of BECCS generation project announcements as part of the Carbon Capture Usage & Storage (CCUS) industrial cluster selections (covered in more detail in section 3.2.6). However, these are not expected to be delivered before 2030, and BECCS generation capacity is not expected to scale until CCUS technologies have started to scale themselves (National Grid ESO, 2023i). Given the important crossovers of bioenergy with other forms of land use (discussed further in section 3.4.6), its use for electricity generation must be considered alongside other potential uses – the UK's Bioenergy Strategy, and Land Use Strategy publications have been expected since 2022 but are yet to be published. It is therefore unclear to what extent BECSS is expected to play a role in power system decarbonisation, and UK's longer term net zero pathways.

The UK has an estimated 30-50 GW of potential tidal generation capacity (National Grid ESO, 2023i), and the BESS committed to £20 million of funding annually to seed the supply chains, bring costs down and scale this industry (HM Government, 2022a). The Offshore Renewable Energy Catapult estimated that tidal stream generation could become cost competitive with nuclear (at around £90 / MWh) if it reached c.1 GW of deployed capacity, with the potential to halve it further by 2047 (Industrial Strategy Committee, 2023). However, despite its potential, tidal generation is unlikely to play a significant role in decarbonising the UK power system due to its early maturity and lack of existing scale.

Overall

It will be important to revisit the assessments outlined in this report throughout 2024 to see if there has been an acceleration vs 2022 deployment performance and to take stock of any further policy announcements in autumn 2023 and early 2024.

3.1.2 Ancillary Services [Green]

Ancillary services are essential for maintaining grid stability and are provided through various markets, including Frequency Response, Reserve, Reactive Power, and others (National Grid ESO, 2023h, 2023b).

Our assessment did not identify significant concerns regarding the delivery of ancillary services as the power system transitions toward decarbonisation. NGESO are actively adapting these services to work as part of a zero-carbon system. They aim to achieve a zero-carbon compatible grid by 2025, a decade ahead of the 2035 power system decarbonisation target (National Grid ESO, 2023r). This proactive approach is reflected in initiatives like the Stability Pathfinder program and the MW Dispatch Service (National Grid ESO, 2023p, 2023o).

However, as discussed further in the Financing & Investment section (3.4.5), CfD schemes have not been set up to support the delivery of these services and the current structure discourages the installation of equipment necessary for ancillary services (DESNZ and BEIS, 2023h). The impact of this concern on service provision is currently deemed not significant but this may evolve.

As a result of the proactive approach taken by NGESO, continued progress and ambitious timelines that would deliver compatibility well ahead of the target, this segment of the landscape is assessed as Green.

3.1.3 Connections [Yellow]

Overview

Connections, in the context of power system decarbonisation, refers primarily to the process undergone by large scale users of the power system (including power generation & storage) to connect to the electricity transmission system – this is the part of the system that transports electricity across the country (progress in the transmission system is discussed further in the next section (3.1.4)). When a customer applies for a contract to connect or to make use of the transmission system, the application comes to the ESO (operated by National Grid), who progress it with the relevant electricity Transmission Network Owner (TNO/TO) depending on where the connection is. For smaller scale users of the power system, the application for a connection may be at the level of the distribution grid (discussed in section 3.1.6) – this is the part of the system that transports electricity across a region, and is managed by a Distribution Network Operator (DNO). In both instances, the scale of connection required is substantially larger than domestic scale connections, and can therefore require work to be carried out to upgrade the transmission or distribution infrastructure to make the connection possible. The process of figuring out what, if any, additional work needs to be done for a given large scale customer to connect, and giving them a date by which they can connect to the network, is referred to as the "connections" process.

There is broad recognition across government (HM Government, 2022a, 2023e, 2023d, 2023h), industry actors (Ofgem, 2021a, 2022c; CCC, 2022, 2023c; National Grid ESO, 2022d, 2023c; Skidmore, 2022; DESNZ and BEIS, 2023h; Regen, 2023c), the broader trade and news press (E&T, 2023; Financial Times, 2023h, 2023f; The Economist, 2023d, 2023a), and the experts interviewed, that timely connections of new infrastructure to the grid plays a vital role in delivering a decarbonised power system. National Grid's FES publications (National Grid ESO, 2022c, 2023i) outline how the UK's energy transition towards Net Zero and the interim target of delivering a decarbonised power system by 2035 will require connecting new capacity and new types of customers more quickly than at any time since the current process was established. Figure 18 shows how the pathways outlined for the future energy system will be markedly different from today, with a near doubling of electricity demand by 2050, changing customer types with new and evolving energy needs, changing demand patterns from the electrification of transport

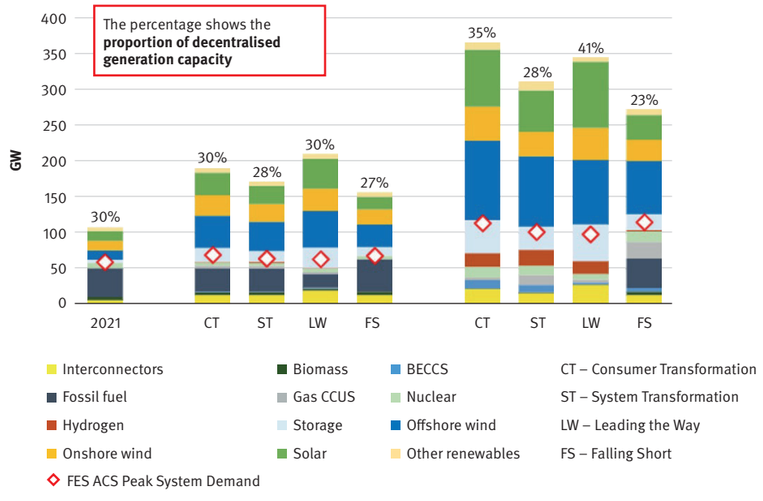


Figure 18 *Installed Generation Capacity, Peak Demand and % of Decentralised Generation (GW) - NGESO Connections Analysis* (National Grid ESO, 2022d)

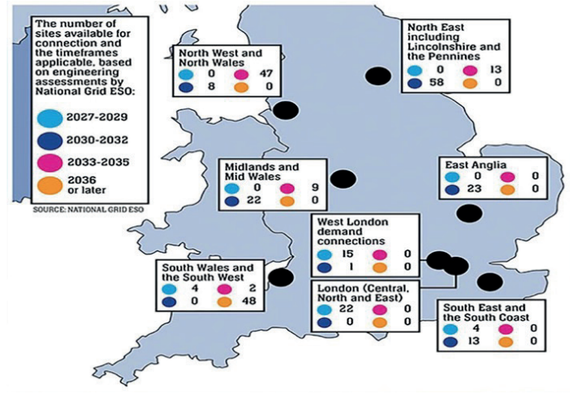


Figure 19 *Number of Sites by Connection Date & Region - E&T Analysis of NGESO Data (E&T, 2023)*

and heat, the decentralisation of generation, and the establishment of new technologies such as hydrogen and Long Duration Energy Storage (LDES). Incorporating this new generation and demand will give rise to an increasing volume of connections.

Challenges

At the end of 2022, there were almost 1000 projects with a combined capacity of c.280 GW that were in the queue to connect to the GB transmission grid (i.e., they had connection offers from the ESO and were on the Transmission Entry Capacity (TEC) register), compared to c.80 GW of existing connected capacity (Climate Change Committee, 2023a; Regen, 2023a). In addition to this, there was a further c.100 GW of capacity with accepted offers to connect directly to the distribution grid (Regen, 2023a). The Connections Action Plan, published in November 2023, showed that the queue across transmission and distribution had increased to around 500 GW (DESNZ and Ofgem, 2023). BNEF analysis of both the TEC register and the distribution connection queue showed that at the end of 2022, there was already c.220 GW of solar and wind generation capacity with connection offers across the GB grid (Financial Times, 2023g). If deployed in full, this would exceed the LW scenario in the 2023 FES publication, which delivers a decarbonised power system ahead of the target, by almost 25%, and would *already* deliver almost 90% of the solar and wind capacity needed by 2050 (National Grid ESO, 2023i).

The current grid connections process in Great Britain is facing a number of issues that are impeding the power system transition to net zero. Across several recent industry press reports, renewable energy and battery storage site developers have warned that wait times of up to 13 years to connect to the grid is threatening investment and undermining the power system transition (E&T, 2023; Financial Times, 2023f; The Economist, 2023a). Some sites that would be suitable for renewable projects cannot progress because of the grid connection issue, and where a connection date of 2025 would have been possible, this has been pushed back in some cases to 2040 (Skidmore, 2022). Figure 19 shows the number of projects that have been given a connection date across England and Wales by region, and the date given in their connection offer (E&T, 2023). As shown on the figure, there are already 48 projects with connection dates that are 2036 or later, after the target date of 2035. Across the GB grid, 70% of applicants who received an offer in the past last year had connection dates that were over five years away, and over 25% had dates that were beyond 2032 (CCC, 2023a).

NGESO's assessment of the drivers leading to these significant wait times to connect (National Grid ESO, 2022d) found significant challenges driven by, i) increasing application volumes and related increases to the timescales for connection, ii) significant changes to the mix of technologies, iii) greater interaction between Transmission and Distribution networks, iv) greater complexity and uncertainty over network investment planning, v) and the urgent need for a holistic, whole systems approach to planning network investment.

Figure 20 shows the growth in connection requests since 2018, with the number of new requests in 2022 almost 10 times the number in 2018, and Q1 2023 higher than the 2022 total. NGESO also states that much of this capacity is allocated to projects that may not progress, holding back those that can. Additionally, many applications fall out of or repeat the process, and 57% of the applications contracted between 2018-22 have been modified so far, some multiple times, with uncertainty around how many more will be modified and how many times.

NGESO estimate that "paper projects", speculative connections requests filed with the intention to flip them at a later date, may make up as much as 80% of the queue; many of these do not have any designs prepared or engineers on staff who may carry them out. However, under the existing regulations, NGESO was obliged to treat all applications the same, regardless of their likelihood of progressing to actually connect, which leads to customers making more speculative applications to secure their place. NGESO had stated that the existing regulatory regime did not give them the tools with which to discriminate between "builders and flippers" (National Grid ESO, 2022d; E&T, 2023).

The lack of investment in the transmission and distribution network to increase capacity ahead of need – requiring strategic planning and investment – has led to 'grid congestion' and exacerbated the wait times as projects will in many instances need to wait for reinforcement works to be completed before being able to connect. Indeed, until recently, the regulatory

Segment Assessment & Discussion

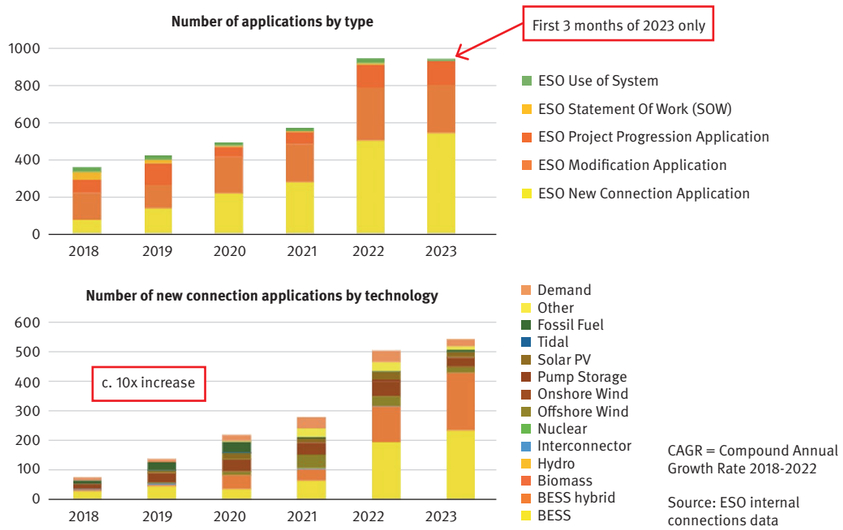


Figure 20 *Number of Connection Requests, by Request and Connection Type, 2018-Q1 2023 - NGESO Connections Report* (National Grid ESO, 2022d)

regime prohibited any strategic planning for the grid and instead allowed renewable developers to request connection to the network from any site. Additionally, network providers could only invest in building capacity based on connection requests they had received. The regulatory regime also incentivised the networks to focus on minimising costs, and therefore consumer bills, rather than setting a path to delivering a power system decarbonisation target (Ofgem, 2021a, 2022c; National Grid ESO, 2022d; Financial Times, 2023f).

NGESO has acknowledged that their current internal connections process and staffing is also not fit for purpose, originally focused on connecting a small number of large fossil fuel plants every year, and has not kept pace with the rapid changes occurring in the energy sector. This can be seen in Figure 21, with a rapid increase in number of applications per full-time equivalent (FTE) employee in the connections team (National Grid ESO, 2022d). There is an added challenge of skills competition, investment, and materials with many countries also facing similar issues and looking to rapidly grow their connections teams. In parallel the industry expects a quarter of all current UK connection staff in DNOs to retire in the next two to five years, potentially further exacerbating the issues faced (E&T, 2023).

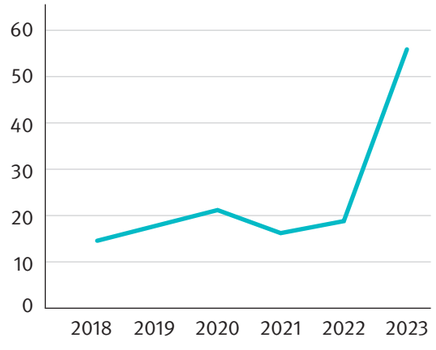


Figure 21 *Number of Connection Applications per ESO Full-Time Equivalent (FTE) in the Connections Team* (National Grid ESO, 2022d)

What is Being Done

To help overcome some of these issues, several recommendations have been made focusing on changes to the governance and institutional structure of the segment. These include updating the Ofgem's mandate to include delivering net zero, alongside their consumer obligations, and the creation of the Future System Operator (FSO), which is crucial for a comprehensive approach to solving the challenges of the UK's future multi-fuel energy system (Skidmore, 2022). Both recommendations have been actioned by the government with the passing of the Energy Act into law in October 2023 (DESNZ, 2023p).

Following the end of the first consultation as part of the Connections Reform process, NGESO published a 'Five Point Plan' outlining several initial actions to help overcome the issues identified and progress on the recommendations (National Grid ESO, 2023c). NGESO applied for license changes with Ofgem to bring forward projects that have planning permission and are ready to proceed, rather than managing connection requests on a "first come, first served" basis (National Grid ESO, 2023m). This change in approach proposed by NGESO was approved by Ofgem in November 2023 (Ofgem, 2023h). NGESO & Ofgem have further announced £9 billion in investments to accelerate connections for projects in the five years to 2026, as well as approving an amnesty that allowed customers to leave the register at no cost to make way for projects that are getting developed, freeing up over 8 GW of connection capacity (Ofgem, 2023e).

NGESO are also updating their background modelling assumptions to reflect current connection rates and reducing the assumption that all projects in the queue will connect. The FES 2023 publication highlighted that NGESO had completed this action and was working through existing connection offers with TOs to update them with revised connection timings (National Grid ESO, 2023i). NGESO are also changing the treatment of storage on the network, which makes up c.95 GW of the queue, to allow them to connect faster and free up capacity for other projects (National Grid ESO, 2023a). As a result, an interim, non-firm connection option for Battery Energy Storage System (BESS) projects is also being offered, allowing them to connect to the transmission network sooner, with the caveat that they may be required to turn off more frequently when the system is under stress without initially being paid to do so (National Grid ESO, 2023c, 2023d). To date, these revised modelling assumptions have allowed the acceleration of 20 GW of connections, with 10 GW across renewable generation (Current News, 2023j) and 10 GW across 19 BESS projects (Current News, 2023k).

As part of this initial phase of reforms, Ofgem has in parallel published new rules that allow NGESO to go ahead and expand in advance of grid connection requests. It is also reforming its procedures so that projects in the queue can be required to hit milestones or lose their place, though it has been cautious about making the rule retroactive (Ofgem, 2022c). NGESO is putting into place a range of measures to improve the connections process, including accelerating the Business Plan 2 (BP2) plans to undertake a strategic review of connections. The GB Connections Reform programme and other workstreams should enable quicker connections and a more diverse range of connectees (National Grid ESO, 2023c, 2023d).

NGESO have also been undertaking consultations around a second phase of longer-term reforms to adopt a "future proofed" connections process, going beyond the more tactical reforms put forward in the Five Point Plan considered above. They published their proposed longer-term strategy in June 2023 for further consultation, outlining their proposed holistic reforms to connections (National Grid ESO, 2023g, 2023k, 2023e, 2023l, 2023f), with the aim of completing the implementation of all proposed solutions and closing out the project within the next two years, by Q2 2025 (National Grid ESO, 2023d).

Segment Assessment & Discussion

It should be noted however, any changes that are made to the connections process as part of this consultation will not apply to the existing (and growing) transmission connection queue of over 300 GW of capacity, and are therefore not likely to be relevant to projects that will deliver low carbon generation / storage capacity between now and the target, and instead most likely play a role in delivering further growth in the power system to meet increasing low carbon electricity demand after 2035 as the UK continues to electrify energy demand through to 2050 and beyond.

In response to the growing need, Ofgem's Accelerated Strategic Transmission Investment (ASTI) framework has approved £20 billion in transmission network investment for 2030 delivery, with future regular strategic planning due to take place as part of the Centralised Strategic Network Plan (CSNP) process being introduced – these initiatives are covered in more detail in the next section on Transmission. Whilst the ASTI presents a significant investment in the transmission network that is expected to be delivered for 2030, all investments are still subject to planning permission, and it currently takes an average of 12-14 years to deliver new transmission infrastructure (Energy Systems Catapult, 2023a). This provides an indication of the likely long lead times between investment decision and impact in accelerating connection timelines. As a result, it remains unclear if these investment initiatives will increase the rate of connections for projects contributing to delivering the target.

As well as NGESO's connections reform initiatives focusing on connections to the transmission network, the Energy Networks Association (ENA) released their three-point plan to accelerate connections to the distribution network (ENA, 2023). Alongside the announcements from ENA, NGESO and Ofgem's open letter outlining the actions being taken across the different stakeholders (Ofgem, 2023j), in November 2023 DESNZ and Ofgem published their anticipated Connections Action Plan (DESNZ and Ofgem, 2023) which was initially expected to be delivered over the summer (HM Government, 2023e). The action plan sets out an ambitious target to reduce connections times from an average of 5 years today to less than 6 months – with "substantial progress at latest by 2025" – and has received a positive reception from a wide range of stakeholders (Current News, 2023i). This acceleration in connections timelines is enabled primarily by an overhaul in the governance around the delivery of reform, creating an Ofgem-chaired Connections Delivery Board to provide accountability, track progress and mandate further actions where required. The plan makes clear that existing initiatives being undertaken by NGESO, ENA and Ofgem have the potential to free up 100 GW of connection capacity in transmission, and up to 50 GW of connection capacity in Distribution. Provided these initiatives are undertaken in a timely manner and to their full potential, this would account for a substantial majority of the generation and storage capacity that needs to come online to deliver the 2035 power system decarbonisation target (DESNZ and BEIS, 2023f).

Overall

Across NGESO, ENA, Ofgem and the Government, there is clear a recognition of the challenges faced and the concerted, centrally coordinated efforts to overcome these over the next two years. Whilst delays in connections presents a central issue to the delivery of decarbonisation of the power systems and the UK as a whole, the recent publication of the action plan provides more clarity of the potential for the proposed initiatives to address them as well as updated governance mechanisms to bolster their delivery. As a result, on balance, the assessment of this segment applies an Yellow rating, as a result of concerted efforts currently being undertaken to overcome the challenges. For the moment, it remains unclear how effective these initiatives will be, therefore continued research closely tracking progress in accelerating connection queues is warranted to better understand their impact. Ofgem expects the majority of existing projects in the queue to receive updated connection offers from NGESO by March 2024, with connection dates being brought forward by 2-10 years for most offers, incorporating the impact of updated modelling assumptions and the exit of some projects from the TEC amnesty and updated modelling assumptions (Ofgem, 2023j) – this therefore presents an important milestone where another stock-take on progress should take place.

3.1.4 Transmission [Yellow]

When the Climate Change Act was passed in 2008 (CCC, 2023b), there were 56 centralised electricity generation plants and 500 renewables sites; by 2018, this had increased to 3,000 large renewables sites and 800,000 smaller sites (Tim Pick, 2023). As the UK continues to move towards a decarbonised and geographically dispersed generation mix with the bulk generation coming from renewables, upgrading the transmission and distribution networks will be essential to ensure that the electricity generated by these low carbon sources can be delivered to where it is needed.

In addition, as outlined in the CCC power system decarbonisation report (CCC, 2023c), the network will need to handle a significant increase in demand from new sources such as electric vehicles and heat pumps, and connect new low carbon generation to meet this demand. Without this infrastructure, NGESO's analysis (National Grid ESO, 2022g) shows that zero carbon wind energy would be constrained off, and higher carbon, fossil-fuelled generation would be needed instead. This would have additional energy security impacts beyond delaying the achievement of the target. As the report also points out, it is essential that the costs of these upgrades are kept as low as possible, while also protecting vulnerable consumers.

Overall, the UK's transmission network requires an average doubling of capacity between 2025 and 2035 to support the transition. Historically, two key issues impeded progress: offshore wind farms were treated as standalone connections, and Ofgem's regulatory license prevented strategic transmission investments. The historical lack of strategic transmission planning and slow pace of historical transmission investment now means that the UK has to deliver the required investments at a pace that has not been achieved since privatisation. Over the next seven years around four times as much new transmission network will need to be delivered in GB as was built since 1990 (Energy Systems Catapult, 2023a), and six times as much in the next 12 years to meet the target (Octopus Energy, 2023a). Whilst the investment planning process has been undergoing a recent overhaul to enable the commencement of the required expansion, delivery of capacity is expected to come up against significant bottlenecks; the lack of an overarching institution responsible for delivery, delays in getting projects through Planning & Permitting and constrained capacity across Workforce & Supply Chains are called out across the assessments compiled by Nick Winser (Energy Systems Catapult, 2023a), Tim Pick (Tim Pick, 2023), the Industrial Strategy Parliamentary Committee (Industrial Strategy Committee, 2023) and by many of the experts interviewed.

Recent initiatives, including the Holistic Network Design (HND) and Electricity Networks Strategic Framework (ENSF), are reforming the transmission planning process. The CSNP will replace existing planning and facilitate anticipatory investments. The HND focuses on efficient offshore-to-onshore connections, optimising landing points, reducing project timelines, and creating a regulatory framework for anticipatory investment.

Further, a number of initiatives have been undertaken to tackle the historically slow pace of transmission network delivery. The government have now responded to Nick Winser's recommendations to expedite infrastructure projects (DESNZ, 2023g), accepting them in full, and aiming to halve the end-to-end project process to seven years by the mid-2020s. Ofgem has approved £20 billion of HND-identified transmission projects is expected to expedite low-carbon technology upgrades. Consultations on revised National

Segment Assessment & Discussion

Policy Statements will designate HND-identified infrastructure as strategic, although challenges with planning permissions remain.

Overall, as with the Connections segment, Transmission is an area that is critical to the delivery of the target, and taking in to account the significant challenges faced, on balance this assessment considers that there is substantial effort on the part of NGESO, Ofgem, the government, and a very clear roadmap to deliver acceleration in the recently published review by the Network Commissioner, to ensure that sufficient levels of transmission network capacity can be deployed to be compatible with meeting the target. As such, the assessment rates this segment at Yellow.

3.1.5 Transmission-Distribution Interface [Yellow]

The coordination between Transmission System Operators (TSOs) and Distribution System Operators (DSOs) holds significant importance for the effective implementation of a decarbonised power system. The summary responses to the Review of Electricity Market Arrangements (REMA) consultation report underscored the need for improved collaboration, formalised governance arrangements, and enhanced digitisation for better decision-making (DESNZ and BEIS, 2023h). The visibility of assets across the network, along with digitisation efforts, remains an active consideration. Ofgem's approval of £116 million investment by DNOs for monitoring equipment installation across various voltage levels, including the transmission-distribution interface, demonstrates a commitment to improving network visibility and constraint management (Ofgem, 2023j). While progress is underway, further efforts are needed to ensure a smooth and efficient transition, resulting in an Yellow rating for this segment.

3.1.6 Distribution [Red]

Distribution infrastructure is an important consideration when assessing potential barriers to the transition towards a decarbonised power system. Conducting a bottom-up evaluation of the investment plans across the 6 individual DNO/DSOs operating across 14 licenced regions is beyond the scope of this research. The CCC report on power system decarbonisation makes some references to the upgrades required (CCC, 2023c). Further, this was a segment that was mentioned a number of the expert interviews conducted as posing potential challenges to delivering the target, driven by similar concerns to those discussed in the assessment on Transmission networks – namely the lack of historical strategic planning, as well as Workforce and Supply Chain constraints.

According to the CCC report the growth in demand driven by the electrification of transport and heat will necessitate significant investment in distribution networks – although they point out that the scale of this investment remains uncertain due to data limitations, uncertainties around the path that is expected to be taken around home heating, and lack of a centrally coordinated plan (CCC, 2023c). This is further evident in the large range of investment requirement coming out of modelling completed by BEIS (now DESNZ, see discussion in section 3.4.1 additional detail), setting out an investment requirement of between £60-180 billion across the distribution networks by 2050 as part of the power system decarbonisation and broader net zero transition (BEIS, 2022a). This highlights both the substantial scale of investment needed to deliver the target and the coordination that will be required across the multiple operators that operate in this segment. The CCC report emphasises that the network upgrades should be designed and built anticipating major new sources of generation and demand up to 2050, pointing out that the cost of upgrading distribution networks is relatively insensitive to the size of the capacity increase, as most of the cost is in civil works rather than equipment. Therefore, wherever possible, grid capacity should be increased to a level sufficient to avoid having to upgrade capacity again before 2050. So far, Ofgem have approved £22 billion worth of investment by DNOs as part of the most recent price control framework – a doubling of investment compared to the previous five year period (Industrial Strategy Committee, 2023), although given the opacity around total requirements, it is unclear if this would achieve the levels of infrastructure deployment required to be on track for delivering the target.

CCC's report also highlights that given the scale of network build required, mitigation and adaptation needs should be considered holistically in strategic planning and investment, although in their analysis they were unable to ascertain which, if any of the DNO's plans are compatible with this approach. In their work assessing UK's progress towards meeting the target, the Industrial Strategy Parliamentary Committee found that the strong consensus on the levels of investment required in the Transmission Network was not applicable to investment in Distribution, with divergent views on the scale and nature of investment need (Industrial Strategy Committee, 2023). Regen, in their testimony to the committee cautioned that "*it is highly likely that, under these plans, distribution network capacity will be a major barrier to government targets for low-carbon technologies such as EVs electric vehicles, heat pumps and renewables*".

Overall, due to the lack of clarity on what the required scale and nature of investments are, lack of an overall, coordinated plan to deliver on the investments required, the potential challenges that may be faced when delivering the required upgrades e.g. difficulties in timely upgrades of infrastructure in densely populated urban areas, and the crucial role that distribution networks will play in delivering the decarbonised power system, the assessment for Distribution is rated at Red.

3.2 Infrastructure: Grid Scale Flexibility

Explainer: Flexibility in a Decarbonised Power System

As well as the roll-out of bulk low carbon generation discussed above, net zero compatible sources of dispatchable generation will also need to be deployed to replace today's gas turbine generation. These low carbon dispatchable sources of electricity will need to smooth out variability in generation outputs across days, seasons and years (see weather variability in Figure 22). This is acknowledged

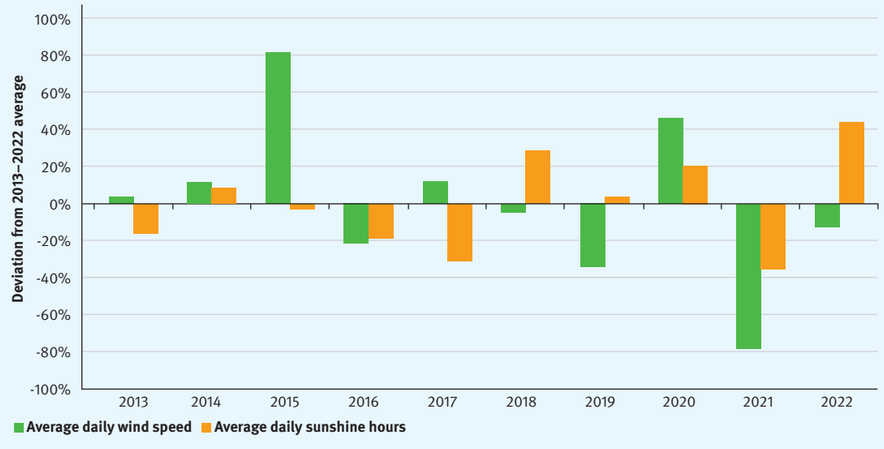


Figure 22 *Weather variability, 2013-22, using data from DESNZ Energy Trends* (CCC, 2023a)

Segment Assessment & Discussion

in the BESS (HM Government, 2022a), the CCC decarbonised power system report (CCC, 2023c), and in the review by the government and Ofgem in their Smart Systems and Flexibility Plan report (BEIS and Ofgem, 2021).

There have not as of publication been specific targets outlined by the government for how this gap will be filled across clean dispatchable generation (e.g., gas turbines with Carbon Capture & Storage (CCS)), short term storage (e.g., grid scale batteries), medium / long term storage (e.g., thermal storage, hydrogen) or demand response. The CCC sees the 10% demand not being met by wind, solar, nuclear and BECCS coming from these "flexible low carbon" solutions, with a role for hydrogen and/or gas with CCS to cover gaps in renewable generation lasting days to weeks at a time. The CCC also endorses a small remaining role for unabated gas power in 2035, meeting "up to around 2%" of annual demand, down from 40% today (CCC, 2023c).

Due to the variability in generation output from renewable sources, it is important to understand and plan for periods of supply and demand mismatches on an at-least hourly basis, and under different weather conditions (as discussed in section 3.4.11). This allows for the forecasting of the magnitude of 'residual demand' which will need to be covered on an hourly basis under these conditions.

The volume and shape of residual demand are crucial determinants of the capacity and combination of flexible solutions required to balance an electricity system. The CCC commissioned AFRY to do a detailed analysis of the distribution of residual demand under different weather conditions as part of its decarbonised power system report (CCC, 2023c; CCC and AFRY, 2023); Figure 22 shows the expected distribution of residual demand for a 'typical' weather year (taken as 2012 by AFRY) for the generation mix shown in section 3.1.1 in Figure 13.

Figure 23 shows the expected distribution of residual demand in 2035, defined as the difference between demand at a particular hour in the year and the power available at that time from renewable (wind & solar) and firm (BECCS & nuclear) generation. This distribution therefore represents, when it is a positive value, the demand to be met from flexible, dispatchable sources or, when it is negative, the power available for use by flexible demand, export, or storage (CCC, 2023c). When taking this perspective, sources of "flexibility" will need to discharge c.45% of the hours of the year and charge the remaining c.55% of the hours in a typical weather year. This surplus of 'charging' hours is one of the drivers of the likely shift in the UK electricity trade, where it is expected to become a net electricity exporter through its interconnectors between 2030-35 (CCC, 2023c; CCC and AFRY, 2023).

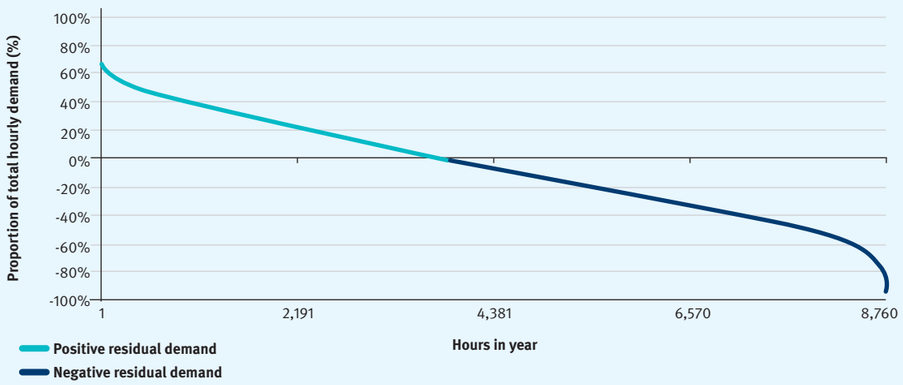
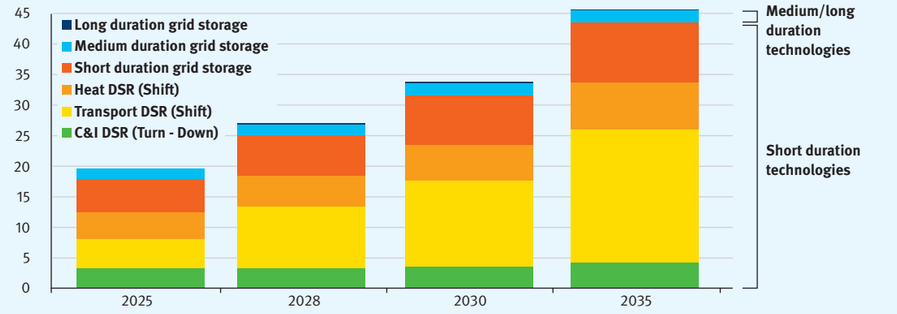
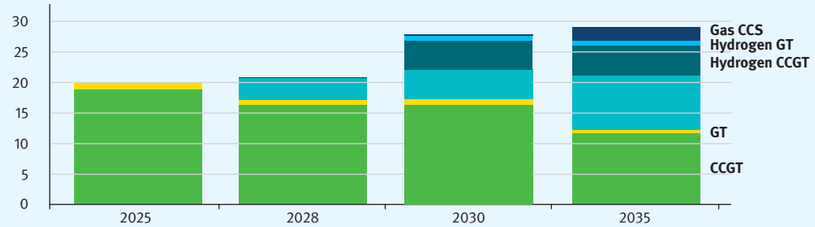


Figure 23 *Residual Demand Distribution & Volume (% of total demand) - CCC Analysis & Definition using AFRY data* (CCC, 2023c)



Short duration technologies include DSR and ≤4hr grid storage (eg. short-duration Batteries and short-duration Pumped Storager)
Medium duration technologies include grid storage ranging from over 4hr to 12hr (er. 6hr Batteries and medium-duration Pumped Storage)
Long duration technologies include ≤12hr grid storage (eg. CAES)

Figure 24 *Output Capacity Requirement (GW) by Dispatchable Generation Option by Year - AFRY Analysis* (CCC and AFRY, 2023)



Notes: This excludes CCGT capacity that is mothballed in 2025 ahead of anticipated conversion to Hydrogen CCGT (Retrofit).

Figure 25 *Output Capacity Requirement (GW) by Flexibility Option by Year - AFRY Analysis* (CCCand AFRY, 2023)

In contrast, grid storage and demand side response (DSR) are better equipped to handle extreme ramps and within-day variability. Grid storage and DSR are well-suited to enhancing short-duration system stability and are capable of providing similar flexibility services, responding rapidly to extreme fluctuations in supply and demand, shifting load to periods of surplus generation, and balancing intra-day volatility.

Figure 24 and Figure 25 show the mix and capacities of flexibility technologies that are expected by CCC & AFRY to provide the necessary flexibility by 2035 at the lowest cost (CCC, 2023c; CCC and AFRY, 2023). The bulk of the days/hours response duration is provided by DSR output capacity alongside

Segment Assessment & Discussion

some grid storage in the form of batteries. The role of medium- and long-duration grid storage solutions is expected to be limited by 2035. Instead, alternative sources of flexibility such as hydrogen storage and low-carbon dispatchable capacity are found to be more cost-effective given the base technology cost & availability assumptions used and the patterns of residual demand coming out of their hourly modelling.

In summary, the low carbon generation backbone in the 2035 power system as envisioned in the government targets delivers a certain residual demand distribution, with its volume and shape determining the flexibility requirements for the power system to reliably deliver electricity throughout the year.

Given performance, cost and deployment rate constraints, CCC and AFRY's analysis finds the following mix of technologies in 2035 deliver sufficient flexibility to meet the corresponding residual demand profile (CCC, 2023c; CCC and AFRY, 2023):

- 11 GW of grid storage output capacity (with a range of 10-19 GW),
- 32 GW of DSR across heat, transport (EV charging) demand shift and Commercial & Industry (C&I) "turn-down",
- 17 GW of dispatchable low-carbon capacity (made up of gas CCS, hydrogen GTs & CCGTs)
- 11 GW of dispatchable unabated gas

3.2.1 Interconnectors [Green]

Interconnectors are expected to play a crucial role in the decarbonisation of the GB power system, as highlighted across several of the reports reviewed (Carbon Trust and Imperial College Consultants, 2021; Ofgem, 2021b, 2023d; National Grid ESO, 2022b; CCC, 2023c; CCC and AFRY, 2023). These reports highlight how Interconnectors can help balance the GB grid by importing and exporting electricity to and from neighbouring countries, which in turn reduces the need for domestic backup generation capacity. The expansion of interconnectors is expected to improve the overall efficiency of the power system and reduce costs. Moreover, it can help reduce the overall system cost by enabling access to low-cost renewable energy sources. However, they also point out that interconnectors may increase the dependency on foreign electricity sources, thereby impacting energy security and resilience. As explored in the Security & Resilience section of this thesis, events that stress UK's generation capacity are also likely to impact the renewable generation capacities of interconnected grids.

The FES scenarios that would meet the target suggest that interconnection capacity should be increased to 19-25 GW by 2035 and 22-27 GW by 2050 to achieve decarbonisation and net-zero emissions targets in the UK (National Grid ESO, 2022b). The government has committed to delivering 18 GW of interconnectors by 2030 (HM Government, 2021), which is in line with these scenarios. At present, the UK has 8.5 GW of interconnector capacity, with Ofgem approving a further c.10 GW capacity to be built (Ofgem, 2021b, 2023d, 2023g, 2023f; CCC, 2023c). Furthermore, as outlined in the REMA summary of responses report, the cap and floor market model used for interconnectors is working well (DESNZ and BEIS, 2023h), incentivising investment in this space, with Ofgem looking through a healthy pipeline of projects for future approvals. Figure 26 shows the expected trajectory of interconnector capacity development through to 2035 (CCC and AFRY, 2023). It should also be noted that this outlook excludes fully privately funded (i.e. have not asked for a cap and floor market scheme support) interconnection projects, such as Xlinks, which is proposing to connect a further 3.6 GW of capacity to bring solar and wind generated electricity from Morocco to the UK market (Xlinks, 2023) – investments such as this would allow the UK to significantly out-deliver the requirements to meet the target in this segment.

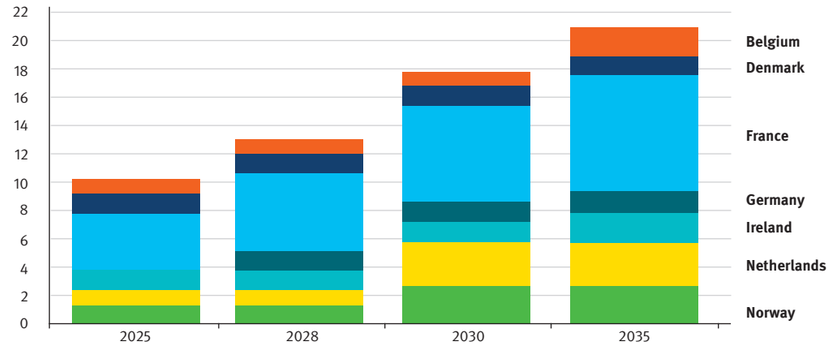


Figure 26 *Outlook for GB Interconnector Capacity (GW) - AFRY Analysis* (CCC and AFRY, 2023)

The government is also bringing forward proposals for Multi-Purpose Interconnectors (MPI) which would integrate the interconnectors with offshore transmission infrastructure being built to bring offshore wind generated electricity to the UK grid and vice versa (BEIS, 2021a; DESNZ, 2022b; HM Government, 2023h). This could help unlock significant cost advantages and may also help accelerate the delivery of required infrastructure.

Overall, the research shows that interconnectors are being delivered at or above the rate required to be compatible with the target, with a supportive regulatory and market environment that is enabling significant and rapid expansion. As a result, this segment is assessed with a rating of Green.

Explainer: Curtailment

As discussed in the Flexibility primer section above, the UK's decarbonised power system is expected to have negative residual demand for approximately 55% of the year by 2035. This excess generation can be used to charge various forms of storage or export excess electricity via growing interconnector capacity to other power systems. However, NGESO, the system operator, still expect there to be periods where supply of low carbon electricity significantly exceeds demand across all the remaining flexibility options and where curtailment – or turndown of generating capacity – cannot be avoided. As a result of the rapid increase in renewable generation which will be required to achieve the target, curtailment resulting from excess generation is expected to rise rapidly through to 2035. Figure 27 shows the expected growth in curtailment across the different FES scenarios (National Grid ESO, 2023i) – it should be noted that FES' system modelling assumes an unconstrained network (National Grid ESO, 2023j), therefore the profile shown in this figure is likely to be an underestimate of curtailment as transmission constraints are expected to continue to add to this. These constraints are the main driver of curtailment today (Industrial Strategy Committee, 2023; NAO, 2023a).

Curtailment is often referred to as an issue and a cost for the system – however, as highlighted by some of the experts interviewed, given the likely future availability of very cheap electricity generation from renewable sources such as wind and solar, this excess generation capacity could be treated as supply-side flexibility. Indeed, there may be instances where it is cheaper on a whole system basis to build more generation and curtail more in times of excess, as opposed to building and maintaining low utilisation dispatchable generation. The Industrial Strategy Parliamentary Committee report noted that turn-up action to bring dispatchable generation online is often significantly more expensive than the turn-down of a renewable generator, with the average cost of turn down action for a

Segment Assessment & Discussion

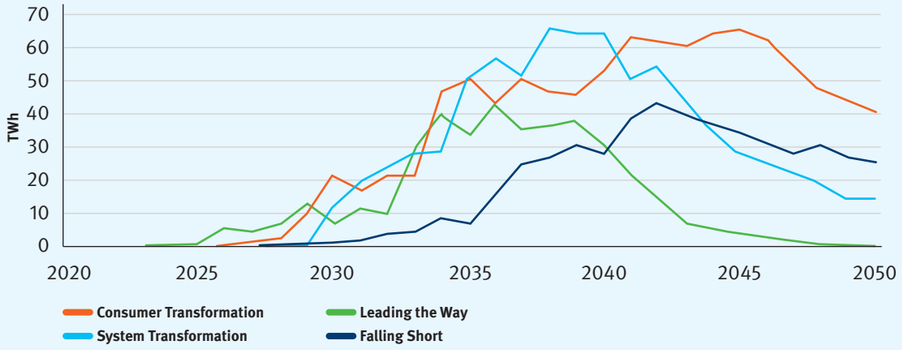


Figure 27 *Annual curtailment in TWh across FES 2023 scenarios, excluding curtailment from transmission constraints, 2022-2050* (National Grid ESO, 2023i)

windfarm at around £50 per MWh vs £200 per MWh for turn-up of a CCGT (Industrial Strategy Committee, 2023). The assessment of the system cost trade-offs between these different approaches is beyond the scope of this paper, and as such an explicit assessment rating of this Segment is not provided.

3.2.2 Storage (‹ 6h) [Green]

As outlined above, a decarbonised power system will likely need 10-19 GW of grid scale short duration storage capacity online by 2035. This compares to around 3 GW of grid connected battery storage already operational today (National Grid ESO, 2023i). A further 7.3 GW of new build battery capacity has won contracts in recent capacity market auctions, with 2.3 GW due to come online for 2023/24 and 5 GW in in 2026/27 (CCC, 2023c) – successful delivery of these projects would bring grid connected battery storage capacity to over 10 GW, already at the lower end of the required range 9 years "ahead of schedule". NGESO stated that they expected around 18 GW of storage (across battery and pumped hydro storage) to be connected to the system by 2028 (National Grid ESO, 2023i), which would already be at the upper end of the range of likely requirements, 7 years ahead of the target. It is also worth noting that there is a total c.95 GW of grid connected battery storage capacity in the pipeline (CCC, 2023c; National Grid ESO, 2023k; Ofgem, 2023j). If delivered, this would far exceed the need identified in CCC's analysis but may allow the grid to increase levels of resilience and reduce delivery risk around DSR capacity across heat pumps & vehicle charging.

To aid the deployment of grid-scale storage projects, the Planning Act 2008 was reformed in 2020 to streamline the planning process in England & Wales for certain types of storage projects (notably excluding pumped hydro) (UK Parliament, 2020). These projects have subsequently not been subject to local planning procedures and are instead considered under the Nationally Significant Infrastructure Projects regime. The primary bottleneck for the deployment of grid-scale storage projects are multi-year delays in securing grid connections (UK Parliament, 2022), although as discussed in section 3.1.3 on Connections, this constraint may start to ease with the implementation of the 'five point plan' (National Grid ESO, 2023c, 2023a). Overall, it is clear that the technology maturity and deployment ambition and actual rates of deployment are at or above what is needed to support the deployment of low carbon generation and achieve the target. Short duration grid-connected storage is therefore assessed with a rating of Green.

3.2.3 Medium & Long Duration Storage (days/weeks/seasons) [Light Green]

The development and deployment of medium and long-term storage technologies, crucial for storing energy over days and weeks, are not yet mature in the UK, apart from the existing 2.5 GW of pumped hydro capacity. These storage capabilities are expected to be essential for de-risking current decarbonisation strategies, particularly in addressing long-duration energy requirements dependent on emerging low-carbon dispatchable generation technologies supported by hydrogen and CCUS infrastructure (CCC, 2023c; CCC and AFRY, 2023). Challenges to the acceleration of these technologies include market constraints, lack of government guidance, and limited revenue prospects for assets offering longer duration flexibility services (BEIS, 2022c; Skidmore, 2022; UK Parliament, 2022).

To facilitate their development, the government has initiated various measures, including funding demonstration projects and consultations aimed at removing barriers for low-carbon technologies in the Capacity Market (DESNZ, 2023o, 2023n; DESNZ and BEIS, 2023b, 2023c). The government's commitment to establishing an appropriate policy framework by 2024 to enable investment in these projects, as outlined in the updated energy security strategy, demonstrates their recognition of the importance of these technologies in achieving the 2035 target (HM Government, 2023e). While not currently considered a significant barrier to a decarbonized power system by 2035, ongoing government support is crucial for accelerating the development and deployment of medium and long-term storage technologies.

As this is not an area that is seen as presenting significant barriers to achieving a decarbonised power system by 2035, and the assessment for the segment is Light Green.

3.2.4 Dispatchable Low-Carbon Generation [Light Green]

As outlined in the Flexibility in a Decarbonised Power System section above, the grid will likely require c.40 TWh of dispatchable low carbon generation from gas with CCUS and hydrogen-based generation plants, and an additional 11 TWh from dispatchable unabated gas turbine plants. It is envisaged that this generation comes from c.17 GW of dispatchable low carbon capacity and c.11 GW of dispatchable unabated capacity (with a range of 10-12 GW).

In the CCC's central case, the 40 TWh of dispatchable low carbon generation is made up of 30 TWh of hydrogen generation (with a range of 15-45 TWh) and 10 TWh of gas CCS (with a range of 0-20 TWh) (CCC, 2023c). The report highlights the interchangeable nature of this dispatchable generation capacity and that given the uncertainty over the appropriate mix of hydrogen and gas CCS generation, they can be thought of together as "low-carbon dispatchable generation". In other words, over-delivery in the development of the infrastructure supporting one of these technologies can help counter any under-delivery in the other. Similar to the development efforts for alternative long duration storage technologies (LDES/LLES), this cross-technology compatibility provides a useful hedge for meeting the target, as both of these options are in their early stages of development and deployment (CCC and AFRY, 2023).

As shown in Figure 28, the existing fleet of gas turbine generation plants and their associated likely decommissioning timelines would already provide an expected fleet capacity that exceeds the high end of the required need under the CCC's scenario analysis (CCC, 2023c; CCC and AFRY, 2023) – therefore no further investment in unabated gas generation capacity should be required to provide the flexibility capacity needed to meet the target. It is worth noting that the need for some unabated gas to remain online was found to be robust in terms of cost-effectiveness even when considered with CCC's expected high value of carbon in 2035, around £300/tonne CO_2.

Segment Assessment & Discussion

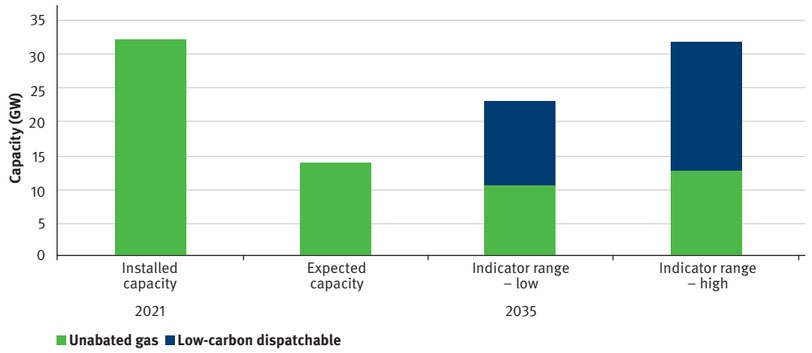


Figure 28 *Unabated Dispatchable Gas Generation Capacity in 2035 - CCC Analysis* (Climate Change Committee, 2023b)

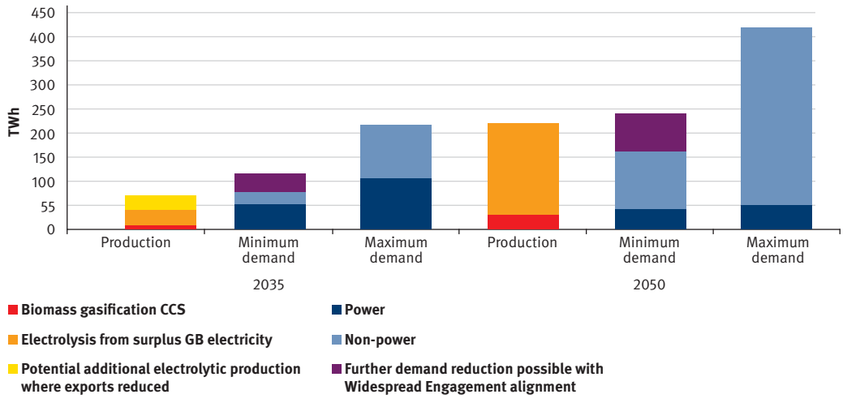


Figure 29 *Gap Between Annual non-fossil Based Domestic Hydrogen Production vs Demand - CCC Analysis* (Climate Change Committee, 2023b)

Figure 29, from the CCC's analysis (CCC, 2023c), illustrates the possible gap between overall hydrogen demand and the modelled domestic non-fossil hydrogen supply (from electrolysis using surplus electricity and with a small contribution from biomass gasification with CCS) in 2035 and 2050. This shows that even the likely minimum hydrogen demand in 2035 would substantially exceed domestic non-fossil fuel production. Considering the already ambitious levels of low carbon generation build assumed in the modelling (in line with the BESS), it is very likely that there will be continued reliance on hydrogen production from fossil fuel-based sources to at least meet part of the demand in 2035. This may scale down as low carbon electricity generation continues to ramp through to 2050 and outstrips growth in non-electrolysis electricity demand.

A comprehensive analysis of the corpus of material covering the range of scenarios for UK's hydrogen and CCUS demand, both within and beyond the power generation sector, and the potential pathways to fulfilling these range of outcomes, is beyond the scope of this

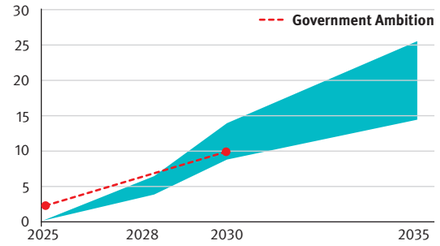


Figure 30 *Low-Carbon Hydrogen Production Capacity (GW) - Range of Requirement vs Current Government Ambition - AFRY Analysis* (CCC and AFRY, 2023)

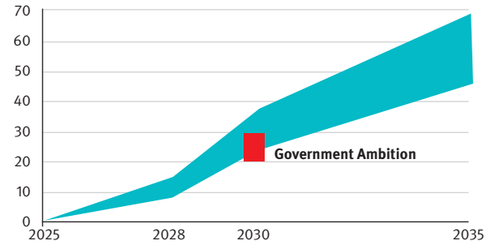


Figure 31 *Volume of Captured CO_2 per annum ($MtCO_2$) - Range of Requirement vs Current Government Ambition - AFRY Analysis* (CCC and AFRY, 2023)

research. For the interested reader this review would recommend the CCC's 6th Carbon Budget (CCC, 2020b) and their 2022 & 2023 update to parliament reports (CCC, 2022, 2023a) for a detailed overview of the likely range of demand across the UK economy, and the CCC report on power system decarbonisation (CCC, 2023c) for the range of scenarios considered for the power sector through to 2050 (also incorporating likely non-power demand across both technologies), alongside the accompanying AFRY report providing further detail on their analysis (CCC and AFRY, 2023), as good grounding for a more detailed exploration.

Figure 30 and Figure 31 show the current stated policy ambitions relative to the range of annual hydrogen production capacity and annual volume of CO_2 capture and storage respectively, through to 2035. The former shows that the stated policy aim of delivering 10 GW of hydrogen production capacity by 2030 is on the low end of the range of likely required capacity by 2030. It is worth noting that the current pipeline of production projects, compiled by the Hydrogen Investment Roadmap (DESNZ, 2023l), if all built, would deliver 20 GW of production capacity by 2030. This is double the government's target and is well above the top end of the range of likely requirements, indicating high levels of commercial interest. For CCUS, the government's stated ambition is to capture and store 20-30 $MtCO_2$ by 2030 – if delivered towards the top end of the range, this would satisfy demand in the middle of the expected range, whereas if delivered towards the bottom end, would fall below what is expected to be the lower end of the range of demand by 2030. As stated in the introduction however, this may be less important for the grid if for example hydrogen production or other LDES technologies have over-delivered vs their current expected pathways.

The CCC analysis also provides a comparison of the required build-rate of dispatchable low carbon generation capacity from the late-2020s until 2035. The central case used here requires the deployment of 1.1 GW per year on average and a peak annual build rate of 3.3 GW per year across the different sensitivities analysed. This is within the historical peak annual build rate for unabated gas CCGTs of 3.7 GW per year (CCC, 2023c).

There are a number of operational challenges that are faced when deploying and operating the transport and storage infrastructure associated with hydrogen and CCUS. These include potential borehole infrastructure compromise, hazardous unintended reactions leading to methane and corrosive gas production, induced seismic activity, and natural seismic activity affecting storage structures. Careful planning and risk mitigation will therefore be crucial when deploying this infrastructure at scale.

The deployment of both CCUS and hydrogen infrastructure require a streamlined policy framework, coordination of infrastructure, and clear roadmaps. Recent government announcements include substantial financial backing for CCUS (£20 billion), initial projects in clusters, and plans for expansion across additional clusters. Hydrogen faces similar challenges related to infrastructure, coordination, and business models. Initiatives include funding for hydrogen projects and a shortlist of projects for due diligence, supporting up to 750 MW of new hydrogen production capacity. Recommendations to accelerate include fast-tracking hydrogen transmission support frameworks and business model development.

Overall, recent government initiatives match well with the gaps identified across the sources reviewed, with the announcement of significant financial backing and progress in giving go ahead to a broad range of projects across clusters to start deploying the infrastructure and projects required to meet the target. However, some of the recent announcements by the government undermine efforts to seed these industries, in particular those around the Emissions Trading Scheme, where the UK has increased the allowances available to emitters, thereby reducing the cost emitting, hence undermining the revenue model for capturing and sequestering (Financial Times, 2023b, 2023d). The assessment here acknowledges that there are areas where significant challenges remain, in particular around the coordinating of infrastructure such as networks and storage infrastructure across both hydrogen and CO_2 capture technologies, and that it will be crucial to closely monitor the implementation and effectiveness of these policies. However, given the level and scope of support announced, the assessment for this segment is given as Light Green.

Explainer: Dispatchable Unabated Generation

As highlighted by the FES 2023 publication, recent new build gas generation capacity has been awarded 15-year capacity market contracts, which means this capacity will still likely be online in 2035 (National Grid ESO, 2023i). As highlighted above, CCC expects the share of electricity generation from unabated gas capacity to decline rapidly, approximately halving between 2022 and 2025 (CCC, 2023c). They also expect 10-12 GW of unabated dispatchable gas capacity to still be online in 2035 – these plants are expected to operate at very low capacity factors, likely under 10% depending on weather conditions (CCC and AFRY, 2023).

As highlighted across some of the expert interviews, these low capacity factors and broader declining usage of the underlying infrastructure will have significant impacts on the economics of power plant and T&S operators. The approaches required to keep these low capacity factor assets operable was highlighted as being an area that is not well understood or explored. Due to the timing of the input of these discussions, it has also remained beyond the scope of this research to explore this further and is something that should be taken up as part of potential further research in this area. As a result, whilst included as a segment in the framework, an assessment rating is not provided.

3.3 Infrastructure: Demand (End User)

3.3.1 Distribution-Demand Interface [Light Green]

As the GB power system decarbonises with more bulk generation coming from renewable sources, the variability of generation will continue to increase – as highlighted across a broad corpus of relevant literature. One of the balancing mechanisms for this variation in generation will be demand response & flexibility (BEIS and Ofgem, 2021; BEIS, Ofgem and UKRI, 2021; Carbon Trust and Imperial College Consultants, 2021; Barrett *et al*., 2022; Dixon, Bell and Brush, 2022; Jing, Zhou and Wu, 2022; National Grid ESO, 2022a, 2023r; CCC, 2023c; Chaudry *et al*., 2023; DESNZ, 2023e; HM Government, 2023e, 2023f, 2023d; NAO, 2023a; The Economist, 2023c). A key enabler for demand response and distributed flexibility is the presence of a digital interface between networked & variable supply and end user demand that allows for real time exchange of price and usage information – i.e., smart metering. This digital interface allows for the roll-out of time-of-use tariffs and the incentivisation of end users to shift their usage.

The smart meter rollout, initiated in 2008, has faced delays, with targets first extended due to the pandemic and later reintroduced in 2022 (BEIS, 2020; DESNZ, 2023v; Smartme, 2023). The pace of the rollout has raised concerns about achieving the 2025 target, despite the majority of households being suitable for installation (Cornwall Insight, 2023; Electrical Review, 2023). The Independent Review of Net Zero emphasized the importance of continued focus on smart meter adoption and half-hourly settlement, enabling the provision of time-of-use tariffs and generating substantial bill savings for consumers (Skidmore, 2022). The NAO's recent analysis confirmed steady progress in the smart meter rollout, with DESNZ effectively managing challenges and engaging stakeholders to ensure program success. Ofgem's MHHS implementation aims to bring net benefits of £1.6 billion to £4.5 billion for consumers, supporting various market reforms vital for the transition to net zero. Government has committed to expeditiously complete MHHS, reflecting the priority of this initiative for enhancing demand flexibility and response (NAO, 2023b).

Overall, given the targets set around the roll out of smart metering and MHHS, findings from NAO's recently published progress on the smart meter rollout, and the timeframes that would see the required levels of adoption around a decade before the target, this segment is assessed with a rating of Light Green. However, this outlook may change if there are continued and significant delays to the smart meter roll out, and it would therefore be prudent for continued tacking of progress, given its importance as a precursor to implementing MHHS and broader demand flexibility and response initiatives.

3.3.2 Demand Flexibility & Response [Light Green]

As stated in the Flexibility in a Decarbonised Power System primer section, a significant portion of the short-term flexibility capacity, 32 GW of the approximately 43 GW total, will need to come from demand flexibility and response – DSR. This would shift 18 TWh of demand annually by 2035 to accommodate for different durations of gaps in bulk low carbon generation and residual demand (CCC, 2023c; CCC and AFRY, 2023). As AFRY states in their analysis, this is equivalent to 8.3 GW of 4-hour batteries operating at 1.5 cycles per day or 12.5 GW of 2-hour batteries operating at 2 cycles per day (CCC and AFRY, 2023). When compared to the approximately 3 GW of current grid scale battery capacity and 0.5 GW of commercial demand response contracted through the capacity market in the UK today (CCC, 2023c; National Grid ESO, 2023i), the requirement to build significant additional capacity becomes apparent. The successful scale-up of this capacity will therefore be highly contingent on the adoption rates of heat pumps, electric vehicles and business models that allow consumers, businesses, and

Segment Assessment & Discussion

industry to engage in providing these services. In the future, additional large-scale electricity demands such as electrolysers (for producing electrolytic 'green' hydrogen), DACC and the growing demand from data centres could also join this mix.

Of the 32 GW of DSR requirement identified by the AFRY analysis (CCC and AFRY, 2023), 80% is expected to come from the combination shifting electrified domestic heat and smart charging of battery electric vehicles (BEVs, and commonly referred to as EVs), with the majority coming from smart charging. The UK has over 1 million BEVs on the roads and BEV purchases made up nearly 23% of cars sold in the in 2022, indicative of progress made to date (National Grid ESO, 2023i). The pace of rollout of BEVs and the associated charging infrastructure are included in the delivery metrics tracked by the CCC and included in their update report to parliament. The 2023 report shows that BEV sales are on track vs CCC's modelling, and charging infrastructure rollout has remained line with their recommended pathway – although charging infrastructure rollout will need to accelerate over the next few years to remain in line with the pathway (sections b) and d) in Figure 32 (CCC, 2023a)). BEV charging infrastructure, in particular for those with on-street parking, has been an area of focus for a number of local council and private charge point operator initiatives, with several roll-out schemes announced recently to improve access to on street charging (Current News, 2023f, 2023n, 2023p, 2023d). Whilst not included in the AFRY analysis, Vehicle-to-Grid trials, where distributed battery storage from BEVs is used to feed electricity back to the grid, are starting to be rolled out more widely and could present a significant upside to the DSR capacity offered by BEVs – Octopus and NGESO announced their Powerloop V2G partnership in June 2023 (National Grid ESO, 2023q), and Ev.Energy set out their V2G market roll-out road map in the same month (Current News, 2023g).

Progress on the rollout of electrified heating to enable DSR from domestic energy demand has been much slower. CCC have assessed the current pace of heat pump roll out and the growth of the trained workforce required to carry installations to both be significantly off-track vs government targets and their recommended pathway (sections h) and j) in Figure 32 (CCC, 2023a)). MCS's report published in July 2023 analysing the comparative performance of the heat pump roll out in the UK and France found that France had deployed heat pumps at ten times the pace of the UK (MCS, 2023). Similar comparative analysis by the ECIU in their December 2022 Cost of Not Zero report, found that heat pumps were being rolled out 25 times faster in Estonia vs the UK – and had the UK matched Estonia's pace of roll out, domestic gas use in the UK would have been reduced by more than 33% in 2022 (ECIU, 2022). Undeterred by the slow rollout of the underlying hardware components of domestic heating DSR, industry participants have in parallel announced a number of business model innovations that could help seed the industry and scale capacity. Octopus and UK Power Networks (UKPN, a DNO) in August 2023 announced that they will be providing 'free energy periods' as part of their revamped 'Agile Tariff' when there is excess generation on the network to encourage households to electrify their energy demand and shift their demand to these periods (Current News, 2023m). Octopus in July 2023 also announced a partnership with Vertol to deliver 'Zero Bills' homes, making full use of energy efficiency and demand flexibility services to the grid (which could in future allow the energy provider to make money from the 'grid'), and offer 'energy as a service' at no cost to the end user (Current news, 2023). Further 'heat and energy as a service' business model innovations were announced in August 2023 through a partnership between E.On and Energy Systems Catapult (Energy Systems Catapult, 2023c).

Overall, this is an area where Ofgem, the government, and private sector participants are investing in innovation for technical and business model solutions and building out roadmaps for their implementations. However, the key bottleneck for the roll out demand flexibility will be the availability of the fundamental "hardware" components that make this possible, i.e., broad adoption of smart-meters, flexible heating (e.g., heat pumps with forms of storing heat such as hot water tanks), BEVs and the associated charging infrastructure that would allow vehicles to be kept plugged in for long periods. On balance, given the success of the current BEV rollout, innovations in underlying business model and policies that align with the goal of delivering the required flexibility to meet the target, this segment is assessed with a rating of Light Green. If BEV and charging infrastructure roll-out slows, or there the pace of heat pump / electrified heating rollout does not accelerate, the assessment may need to be downgraded further, warranting further policy interventions.

3.3.3 On-Site Generation & Storage [Green]

On-Site Generation & Storage, often referred to as decentralised generation & storage, is an important aspect of power system decarbonisation that involves the deployment of renewable energy sources within the vicinity of end-users – "behind the meter". Local low carbon generation has a number of benefits including, an increase of the overall capacity of low carbon generation on the grid, a reduction in transmission and distribution costs due to its vicinity to demand, an increase in the overall resilience of generation as well as other benefits to local communities (Bauknecht, Funcke and Vogel, 2020; Wagner, Venjakob and Schröder, 2021). However, increasing the share of local intermittent resources often results in higher costs vs larger grid-scale generation projects for the same generation capacity, and could also reduce the stability of the overall grid (Veldhuis, Leach and Yang,

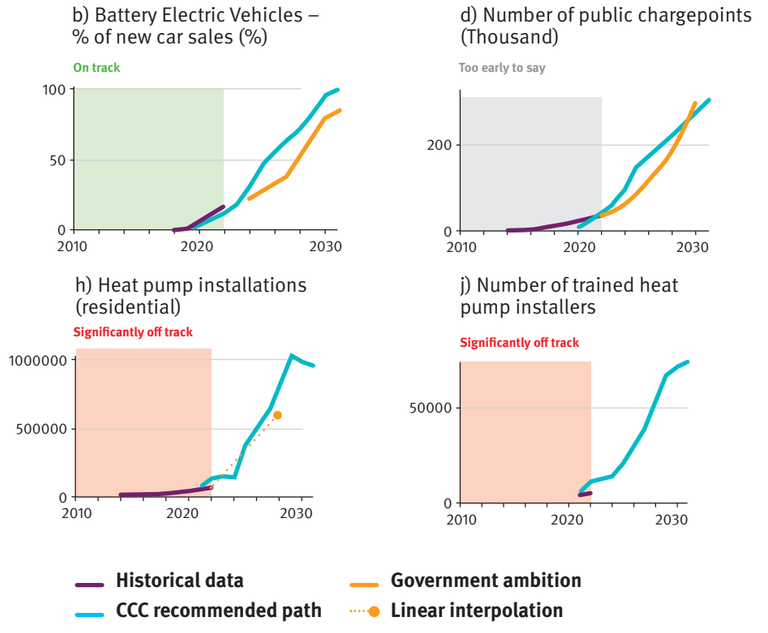


Figure 32 *Key delivery metrics for components underpinning DSR using smart charging of BEVs and shifting domestic heating demand* (CCC, 2023a)

Segment Assessment & Discussion

2018; Bauknecht, Funcke and Vogel, 2020). As discussed in the Storage and Demand Response segments, there are further significant cost and resilience benefits from the adoption of flexibility, including decentralised flexibility e.g., decentralised battery and hot water tanks for electricity and heat storage (Aunedi *et al*., 2021; Carbon Trust and Imperial College Consultants, 2021; Jing, Zhou and Wu, 2022).

The primary support mechanism for the roll-out of decentralised generation in the UK was the Feed-in Tariff (FiT) scheme, which was launched by Ofgem in April 2010 and continued until 2019 (Ofgem, 2020). The scheme incentivised the installation of on-site generation facilities by requiring suppliers to make payments for electricity generated and exported by qualifying installations. The scheme resulted in a sizeable uptake in local low carbon generation, with almost a million installations of solar PV, and a further ten thousand installations of the remaining technologies that qualified such as anaerobic digestion, hydro, micro combined heat and power (CHP), and Wind (Ofgem, 2022d). However, uptake has slowed following the termination of the scheme (DESNZ, 2023w).

Further incentivising the deployment of On-Site Generation & Storage could help accelerate the transition to a decarbonised power system and historical investments and schemes have enabled large-scale adoption of decentralised low carbon generation, solar PV in particular. Introducing additional incentives, financing schemes, standards that integrate these technologies by default, and increasing public awareness could accelerate further adoption and play a role in meeting the 70 GW solar generation target by 2035, whilst also helping ease pressures elsewhere e.g., the various trade-offs faced when considering land-use (covered in more detail in the relevant section below).

The government has proposed several initiatives that could drive the required adoption, but have not provided any specific targets, timelines, or responsibilities for achieving it – it is therefore unclear to what extent decentralised generation can help deliver further low carbon capacity. However, as covered earlier in this review, the pipeline of grid scale low carbon projects (across generation and storage) already exceeds what will likely be necessary to achieve the target. Deployment of low carbon generation at grid scale would provide the capacity at a lower overall cost and therefore should be prioritised. The lack of clear roadmap for the scaling of decentralised generation is therefore not seen as an impediment to delivering the target – as such, the assessment gives this segment a rating of Green.

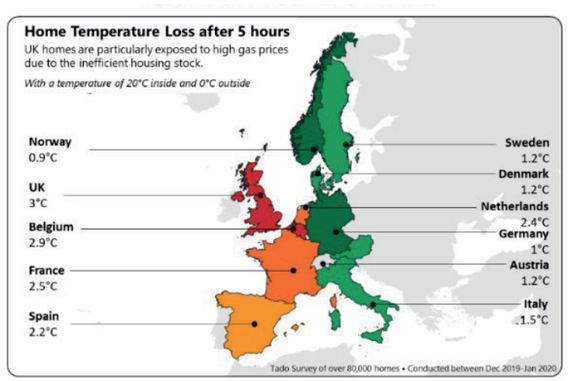


Figure 33 *Comparison of Home Temperature Loss - Independent Review of Net Zero* (Skidmore, 2022)

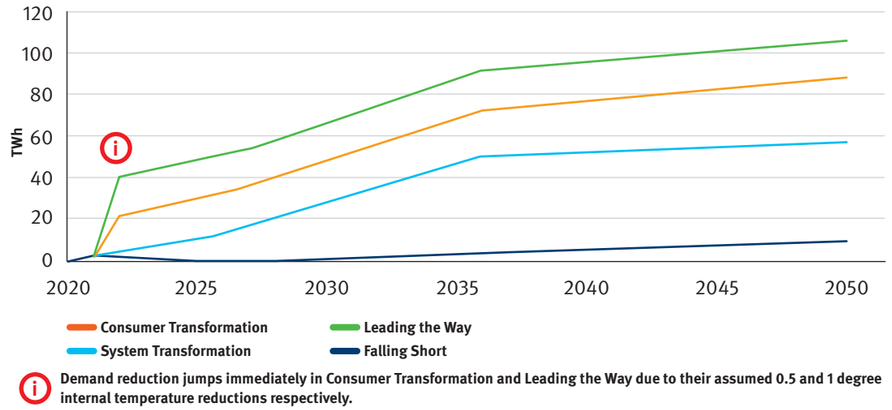


Figure 34 *Cumulative savings in underlying thermal energy demand from applying fabric insulation measures to buildings, and behaviour change* (National Grid ESO, 2023i)

3.3.4 Energy Efficiency [Red]

Energy efficiency is a critical and under-invested segment of the energy infrastructure in the UK, which has one of the least thermally efficient housing stocks across Europe as shown in Figure 33 (Skidmore, 2022). A comprehensive review of energy efficiency and the suitability of the current trajectory of the UK across domestic, commercial, industrial, and public sector energy use is beyond the scope of this research which is focusing on the generation, networks and flexibility sections of the landscape (and the enablers underpinning them) – instead, an assessment of recent policy announcement and targets, focused primarily on domestic energy efficiency, is provided as an indication of progress in this space.

Whilst it is possible to deliver a decarbonised power system without delivering significant improvements in energy efficiency, it becomes much more costly to do so (CCC, 2022; National Grid ESO, 2022c; Skidmore, 2022). This impact is further amplified as pathways to net zero see electrification as an important enabler for achieving decarbonisation in parts of the economy that use other sources of primary energy (e.g., industry, surface transport etc). Indeed, all three pathways that met the government's power system decarbonisation and overall net zero targets in the FES 2023 analysis required significant improvements to thermal envelopes of buildings (Figure 34). Therefore, a focused effort to improve energy efficiency allows for the faster and more cost-effective delivery of decarbonised power system, and also allows other energy services demands being met through electrification.

Despite the significant potential from energy efficiency to accelerate decarbonisation it remains an area that has suffered from inconsistent approaches to policy – one of the experts interviewed summarised the approach as "piecemeal, and the worst designed policy space across energy". This sentiment is echoed in ECUI's Cost of Not Zero report, which shows inconsistent implementations of and changes to domestic new build energy efficiency standards and schemes that were designed to encourage retrofits (ECIU, 2022).

The no-regrets nature of improving energy efficiency, in particular home insulation, is called out across many of the publications analysed for this research, as it reduces investment requirements elsewhere, and improves affordability and energy security (CCC, 2022; National Grid ESO, 2022c; Skidmore, 2022). However, the challenges in rolling this out at scale are also acknowledged, e.g.,

Segment Assessment & Discussion

increasing the rate of deployment of energy efficiency measures in domestic settings would require the scaling up of a comparatively nascent home retrofit workforce to between 200,00-300,000 before 2030 (CCC, 2022). The high upfront costs of home retrofits, which also lead to those who would most benefit from the affordability gains to find it most difficult to access these benefits, are also called out as a major barrier, requiring a mix of public funding and business model innovation to overcome (Skidmore, 2022).

The government has made a number of announcements in support of energy efficiency, including the expansion of the Energy Company Obligation to insulate a further 300,000 of the worst performing homes, the launch of an Energy Efficiency Taskforce, the target to ramp up to 600,000 heat pump installations per year, and an overall 15% improvement in energy efficiency across the country by 2030 (BEIS, 2022b; HM Government, 2023e). Although the overall 15% target is ambitious, and comparable to the 2nd most ambitious credible demand reduction scenario outlined in recent research that looked at different demand reduction pathways for the UK (Barrett *et al.*, 2022), there was no detail or roadmap for how the various measures announced would contribute to achieving it. Further, the Energy Efficiency Taskforce was scrapped in September 2023, less than a year after its announcement (BBC, 2023c). Indeed, it is unclear if the government's own Carbon Budget Delivery Plan would meet this target (CCC, 2023a; HM Government, 2023a). For their analysis of the UK's power system decarbonisation target, and in reaction to the above policy announcement, The Public Accounts Parliamentary Select Committee released an assessment in June 2023 stating that "*government's track record in implementing energy efficiency schemes is patchy at best*" and that "*such schemes were often fragmented, and that stop-start policy was an obstacle to long-term progress towards government's energy efficiency ambitions*", and further that "*government has too often pursued stop-start strategies which undermine confidence for business, investors and consumers*" (Public Accounts Committee, 2023). This segment therefore has significant opportunities to accelerate progress towards the target, across Strategy & Coordination (3.4.1), Standards (3.4.3), Markets & Regulations (3.4.4), Financing & Investment (3.4.5), Workforce (3.4.8) and other enablers.

Overall, despite the high-level exploration of this segment of the landscape, the status of energy efficiency today, the significant potential from improving it, and the gaps in the roadmap for delivery are evident and as a result the segment is given a rating of Red. We would recommend substantial further work in this segment to firm up these views and create a more comprehensive gap analysis and accompanying mitigation pathways for this segment, if not already available.

3.4 Enablers for Infrastructure Delivery

3.4.1 Strategy, Coordination & Governance [Red]

Overview

Delivering GB power system decarbonisation requires a co-ordinated and strategic approach. Clear institutional responsibilities, well-targeted investments, and contingency plans need to be developed to ensure delivery of the decarbonisation target within the ambitious timeline that has been set. Long-term, sector-specific plans communicated clearly to the public are essential to ensure buy-in and provide a stable investment environment (Public Engagement & Advocacy is another enabler that is discussed further in the next section).

In July 2022, the UK government's approach to delivering its decarbonisation targets was found to be illegal by the High Court (BBC, 2022; UK High Court of Justice, 2022). Following this judgement, as well as the publication of a more quantitative assessment of the impacts of the broad set of policy assessments on the UK's decarbonisation targets, the government has taken some important actions to improve strategy, coordination, and governance to accelerate delivery of the target. These actions are primarily aimed at mitigating delivery risks and reducing barriers to deployment in several discreet areas, focusing on workforce actions, and increasing coordination across the power sector.

To tackle delivery risks and barriers to deployment of low-carbon generation technologies, DESNZ has taken several measures, including the appointment of offshore wind and hydrogen champions (BEIS, 2022g, 2022e) and an Electricity Networks Commissioner, and the establishment of the Offshore Wind Acceleration Taskforce (OWAT) (BEIS, 2022g), Great British Nuclear (GBN) (DESNZ, 2023j), and the Solar Task Force (DESNZ, 2023x). The aim of these various initiatives is to bring industry experts together to work with the government, including Ofgem, National Grid and others, to accelerate the deployment of the respective technologies and projects.

There is, however, no clear mechanism for managing the different priorities across these various champions' and delivery groups' respective roadmaps, or the competing priorities of other departments, such as DLUHC and Department for Education, that may be in tension with those of DESNZ. This, and other gaps in the current approach to this segment have been the subject of several extensive assessments published following the high court judgement (Skidmore, 2022; CCC, 2023c, 2023a; Energy Systems Catapult, 2023a; Industrial Strategy Committee, 2023; NAO, 2023a; Public Accounts Committee, 2023; Tim Pick, 2023). These assessments have all identified important gaps around strategy, coordination, and governance for the delivery of GB's power system decarbonisation, which will need to be addressed rapidly to accelerate the pace of delivery. The opportunities identified can be grouped under three main categories – i) Institutional Coordination & Oversight, ii) Planning & Progress Tracking, and iii) Communication.

Institutional Coordination & Oversight

The opportunities identified in the first of these, the current approach to institutional coordination and oversight of delivery, include a current lack of clear institutional responsibilities and central coordination, significant risks posed by policy incoherence across different departments and bodies, and the absence of a long-term strategy and delivery plan.

Delivering decarbonisation requires an all-of-government effort to drive increased and well-targeted investments across innovation, infrastructure, and skills. Central coordination and oversight of the transition can ensure that every government department is contributing towards achieving the target while preventing any policies that would unintentionally undermine the transition (Skidmore, 2022). As highlighted by the NAO, despite the acute need for planning and coordination to bring together the various public and private organisations involved, there is no government delivery plan that brings together all aspects required for successfully meeting the target (NAO, 2023a). As well as providing central coordination, government can also empower the agency of regions, local communities, and individuals to play a greater role in their own net zero journey. This requires a collaborative effort from all stakeholders to ensure that the UK's power system decarbonisation efforts are successful (Skidmore, 2022). There do not appear to be established mechanisms through which these goals can be achieved today.

Figure 35, adapted from the NAO report, shows the complex array of public and private sector organisations that are involved in delivering the target, further emphasising the need for central coordination (NAO, 2023a). Of particular importance is the formalisation of the institutional responsibilities of the FSO, Ofgem, and Ministers to ensure a clear delineation of respective roles in the strategic planning and delivery of a decarbonised, resilient system (CCC, 2023c).

Segment Assessment & Discussion

Organisation type/organisation(s)	Role in decarbonising electricity supply
Central government departments	
Department for Energy Security & Net Zero	Responsible for developing and implementing policies to achieve net zero in the power sector and developing policy for innovation.
HM Treasury	Responsible for allocating budgets to government departments.
Department for Environment, Food & Rural Affairs (Defra)	A priority outcome for Defra is protecting and improving the environment. Inputs into how power-generating activities (for example, offshore wind) impact the environment, such as biodiversity.
Department for Transport	Has a priority outcome to tackle climate change and improve air quality by decarbonising transport. This could affect overall electricity demand, and advances in new technologies could be relevant for the power sector.
Department for Levelling Up, Housing & Communities	Responsible for reforming the planning system, which impacts decisions relating to the development of power-generating infrastructure.
Department for Business & Trade	Responsible for encouraging foreign investment and export trade. The Net Zero Strategy emphasises the need for private investment both from within the UK and abroad.
Ministry of Defence	Ensures interference caused by offshore wind farms on military radar is mitigated.
Other Central Government Organisations	
Ofgem	Protects the interests of consumers relating to gas conveyed through pipes and electricity conveyed by transmission or distribution systems.
The Crown Estate & Crown Estate Scotland	Manage the UK's seabed and approximately half of the foreshore. Responsible for permitting the installation of renewable technologies in these locations.
North Sea Transition Authority	Regulates and influences the oil, gas and carbon storage industries including approving and issuing storage permits.
UK Research & Innovation (UKRI)	Invests in national and international research and innovation across multiple disciplines and sectors. This includes funding research into experimental low-carbon technologies.
Low Carbon Contracts Company	Manages Contracts for Difference (CfD) with low-carbon electricity generators under the CfD scheme.
Planning Inspectorate	Purpose includes dealing with planning appeals, national infrastructure planning applications (such as for power-generating stations) and examining local plans.
Local Government	
Local Authorities	Responsible for decisions on planning proposals including power-generating infrastructure.
Private Sector	
National Grid	Investing in the electricity transmission network to connect and transport electricity from generators to consumers. Owns the National Grid Electricity System Operator (ESO), which is responsible for matching electricity supply and demand to keep them in balance at all times; loss of balance can cause power cuts.
Transmission System Operators	Manage the networks that carry large amounts of electricity across the country at high voltage.
Distribution System Operators	Distribution networks take electricity from the transmission networks and distribute it locally at lower voltages.

Figure 35 *Roles and Responsibilities Across Public and Private Sector Organisations with Responsibilities Relating to the Power System - NAO Analysis* (NAO, 2023a)

DESNZ will establish the FSO in 2024 (now a statutory obligation following the passing of the Energy Act in October 2023 (DESNZ and BEIS, 2022)) to increase coordination across the power sector. The remit of the FSO has not been finalised and remains under consultation (DESNZ, 2023y) but it is expected to have a key role in advising the government to inform key policy decisions and facilitate net zero while maintaining security of supply, and an efficient, coordinated, and economical system (HM Government, 2023e). Several of the publications considered and the experts interviewed cautioned against over-burdening the FSO without giving it a clear mandate to deliver on its various priorities e.g. the government's current plan for the FSO includes the delivery of a medium range gas supply security assessment and to consider gas supplies against a five to ten year time horizon (Industrial Strategy Committee, 2023) – given the expected continued reliance on imports for at least part of securing supplies to cover UK gas demand (CCC, 2023c), this would require the FSO to make political judgements related to foreign policy, for which it may not be in a good position to do so, potentially distracting it from delivering on its other core objectives.

To further improve the levels of institutional accountability and central coordination, recommendations include i) the creation of a "Minister-led infrastructure delivery group", advised by the new Electricity Networks Commissioner (CCC, 2023c; Energy Systems Catapult, 2023a) ii) the creation of a new forum to coordinate across all regulators, iii) a new Office for Net Zero to drive overall delivery and ensure a joined-up approach across government and iv) the introduction of a new set of 'Net Zero select committees' in both Houses of Parliament to ensure consistent and detailed scrutiny of the net zero agenda.

Reducing policy incoherence across stakeholders is also highlighted as a lever to accelerate progress. Examples of this potential to accelerate progress include the rollout of BEVs and decarbonising domestic energy use, with the former undermined by unsupportive tax policies and stop-start subsidies, and the latter slowed by weak building standards and lack of investment in energy efficiency (Skidmore, 2022).

One of the most significant gaps in the current approach to delivery is the absence of a long-term strategy and plan to achieving the target. A co-ordinated and strategic approach to delivery is essential due to the scale and complexity of the task and the inherent interdependencies (CCC, 2023c, 2023a). As highlighted throughout the assessments examined, it will not be possible to achieve this coordinated and strategic approach to delivery without an overarching plan. The NAO in particular note that DESNZ does not yet know if their ambition to meet the target is achievable due to the lack of a delivery plan, and that industry stakeholders are increasingly concerned about the lack of a government delivery plan that brings different aspects of the power system decarbonisation roadmap together (NAO, 2023a).

The CCC refers to a "comprehensive long-term strategy", the Independent Review calls it a "long-term delivery framework" and the NAO report asks for a "clear delivery plan" – all three referring to a common need for greater certainty and consistency, and clear delivery plans to decarbonise the UK's power system. The reports all recommend that the government take a more active role in designing the overall system or delegate it clearly to another body with the powers and capacity to do so, reiterating the recommendation that the CCC has made annually since 2020 (CCC, 2020a, 2022, 2023c, 2023a; Skidmore, 2022; NAO, 2023a). In their response to the Industrial Strategy Parliamentary Committee report calling on the government to publish their delivery plan by the end of 2023 (Industrial Strategy Committee, 2023), DESNZ committed to publish one in autumn 2023 – as at the time of writing, this had not yet been published and it remains unclear what it would include.

Planning & Progress Tracking

As well as the publication of an overarching strategic plan, there is significant potential to accelerate delivery through an improved approach to planning and progress tracking. In particular, assessments emphasise the need for i) contingency planning, to tackle risks to delivery that cannot be credibly tackled without further reliance on greenhouse gas removal technologies (CCC, 2023a), ii) whole-system, asset-level infrastructure planning to ensure required investments are made in time and money is not wasted on unnecessary infrastructure, and that the infrastructure that is delivered is reliable and resilient even with higher degrees of weather-dependence (CCC, 2023c; E3G, 2023), and iii) establishment of a set of system-wide measures to track progress and costs, which would enable DESNZ to identify when it is off-track against expectations (CCC, 2023c; NAO, 2023a).

Segment Assessment & Discussion

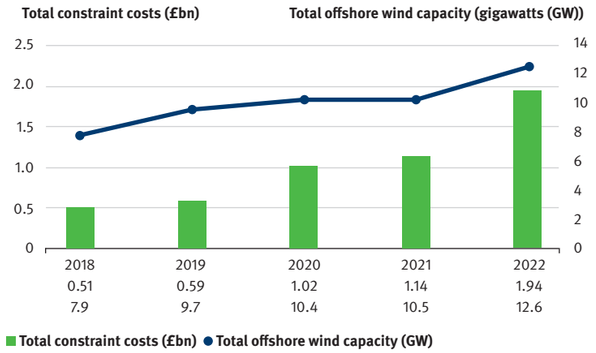


Figure 36 *Transmission Constraint Costs & Offshore Wind Capacity (2018-22) - NAO Analysis* (NAO, 2023a)

The second of these improvements would also help identify areas with high risk of disruption to progress as a result of interdependencies upon a given program's success e.g. the roll-out of BEV charging infrastructure with the reinforcement of a particular part of the transmission & distribution grid. Given the timelines, the government has limited means to compensate for significant setbacks in delivering on its current commitments, making active management of delivery crucial. NAO's report provides the case study of increasing constraint costs, shown in Figure 36, as a result of "poor sequencing", highlighting a lack of historical coordination between new generating capacity and expansion of electricity networks that connect them to the grid. The report notes that while constraint costs typically vary, total annual costs have recently increased, alongside growth in offshore wind capacity (NAO, 2023a). A planning approach that takes better account of interdependencies as different segments of infrastructure are delivered in parallel, will help avoid similar setbacks going forward.

Communication

All of the above recommendations point to the overarching benefits of enhancing the levels of communication around the delivery of the target. As highlighted by the Independent Review of Net Zero, the 2021 Net Zero Strategy (HM Government, 2021) and other recent government publications do not provide adequate certainty to business and investors. The publication of a government strategy with clear plans that were focused on individual sectors, set out over the long-term, and communicated clearly to the public, is essential to ensure buy-in and provide a stable investment environment. Their assessment found that the broad range of stakeholders engaged across the review had concerns that this was not happening (Skidmore, 2022).

Overall

Whilst there have been several initiatives by government to improve the coordination of the delivery of power system decarbonisation, there are a number of important gaps that remain, and these may present significant barriers to the achievement of the target. It will be important to review the overarching plan for delivery once released by DESNZ as well as the FSO's remit once this is finalised. On balance, given the fundamental role of a coordinated roadmap of delivery, the importance of mechanisms for ensuring cross department coordination and prioritisation in achieving the target, and the lack of both of these core mechanisms in the UK's current approach to delivery, the assessment for this segment is rated as Red. This assessment should be reviewed upon the planned release of the delivery roadmap by DESNZ as this may provide some of the policy direction required to overcome some of the issues highlighted in this segment.

3.4.2 Public Engagement & Advocacy [Red]

In order to achieve the GB power system decarbonisation target, over the next 12 years the UK will need to embark on one of the most extensive infrastructure build-out programmes in its history, delivering projects at or close to its maximum capacity every year over this period (NAO, 2023a) – this will involve the construction of projects potentially worth over £500 billion across low carbon generation, transmission, distribution and storage (HM Government, 2023f). This is around 10 times the current budget for HS2, itself a major infrastructure undertaking (DfT and HS2 Limited, 2023). Whilst this presents a "once in a generation" opportunity to invest in communities across the country (Skidmore, 2022), the extent and pace of infrastructure build out will inevitably cause disruptions to people's lives across communities throughout the country.

The unprecedented scale of investment required to finance the transition will inevitably have to be paid for by savings – either savings through foregone consumption domestically in the UK, or via savings from elsewhere being imported to the UK (i.e. Foreign Direct Investment, or Foreign Lending) – given the global competition for sustainability transition investments (discussed in further detail in the Financing & Investment section), a significant proportion of the investments required to achieve the target may have to be funded via savings imposed on the UK population (Helm, 2023).

As a result, there is risk of a potential build-up of a negative narrative around the transition, whereby the public start to question why they are being asked to "foot the bill" when global fossil fuel demand continues to rise, as does concentrations of GHGs in the atmosphere, and where as Prof. D Helm outlined, "*the UK's unilateral commitment to territorial net zero will neither stop it causing further climate change, nor make any discernible difference to climate change*", leading to significant reduction in public enthusiasm (Helm, 2023).

Therefore, the unprecedented scale of build out for the decarbonisation of the power system, and the associated financial investments required to deliver it, require a similarly ambitious campaign of public engagement and the updating of the social contract to encompass these delivery ambitions. Studies of previous public reactions (and backlashes) to significant changes in energy policy that impact the day-to-day lives of citizens, and in particular those that impose financial costs on them, highlight the importance of building social acceptability and cultural legitimacy in the context of sustainability transitions, and how its absence can become a fundamental and entrenched blocker preventing the actions needed to decarbonise the economy (Martin and Islar, 2021). Despite its importance, there remains insufficient attention paid to this segment and our assessment has identified significant potential to improve the approach, aiding the potential acceleration of delivery progress – these can be grouped under three main headings i) data & understanding of current position, ii) recognition of importance and iii) government policy attention.

Data & Understanding of Current Public Position

There is a mixed picture regarding the understanding of current public attitudes towards the transition – the CCC notes (CCC, 2023a) that there is very limited data on public support for current or planned government policies around climate change. There is ad-hoc public polling which provides snap shots of public attitudes, such as the August 2023 RenewableUK public opinion poll, showing strong support for important infrastructure investments such as network upgrades to enable the decarbonisation of the UK economy, with 64% of those surveyed supporting the investments and only 5% opposing (Current News, 2023a). However, it has also been shown that whilst the broader net zero transition has widespread public support, this support

Segment Assessment & Discussion

is often hindered or undermined by a lack of information, associated costs, and limited access to opportunities. Crucially, while general support for net zero policies is strong, support drops when people are presented with potential implications for them personally (Skidmore, 2022).

Improving the understanding of current public attitudes towards both net zero and the initiatives that need to be taken to decarbonise the power grid, and tracking these consistently over time, will play a vital role in accelerating delivery. This should be pursued in line with the efforts to undertake a major expansion of the government's public reporting on net zero, potentially through the Office for National Statistics (ONS)'s climate change statistics as recommended by the Independent Review of Net Zero (Skidmore, 2022).

Recognition of Importance

Our research has come across a number of recent publications from sources with a broader readership outside of the power sector, with popular press coverage about power system decarbonisation, and the entailed significant roll out of infrastructure required (The Guardian, 2021; Financial Times, 2023f, 2023h; The Economist, 2023d, 2023c, 2023f, 2023a, 2023b, 2023e), including a recent five-part special in the Economist (The Economist, 2023e, 2023b, 2023a, 2023f, 2023c). However, whilst there are a small number of exceptions (CCC, 2022, 2023a; Skidmore, 2022; IEA, 2023), it is notable that across the dozens of sources and publications studied as part of this assessment, there exists a distinct gap in coverage and emphasis around the importance of building public awareness and advocacy. This is a key and necessary enabler for the adoption of the solutions needed to drive the delivery of the target and should be given more prominence as part of the policy discussion and debate.

There have been some key players in the industry who have made concerted efforts to build public outreach programmes and increase levels of public advocacy for power system infrastructure investments. These include the National Grid's "Great Grid Upgrade" outreach programme engaging the public around the need to make significant upgrades to the networks (Current News, 2023l; National Grid Group, 2023b), and Octopus Energy's "Let's Build More Wind" publicity campaign (Octopus Energy, 2023b), which also saw Octopus install a temporary wind turbine to power the 2023 Glastonbury festival and use this as a platform to engage communities who could ask the turbine to be installed in their community to "trial" the energy source and receive discounted electricity (Octopus Energy, 2023c). Whilst these initiatives give an indication of the weight given to public engagement by some industry actors, this remains the exception.

Government Policy Attention

Despite the foundational role played by this enabler in unlocking acceleration of progress, and indeed its potential to significantly hinder progress if neglected, there remains insufficient government attention directed to this topic. Whilst the government committed to construct a guiding framework to amplify "net zero messaging" as part of their latest net zero policy framework in March 2023 (HM Government, 2023f), the Communications Plan for 2023-24, also published March 2023 (HM Government, 2023c), did not include any substantive plans to engage the public to build a base of support for net zero policies and delivery actions. Further, the government have to date been reluctant to take onboard recommendations to create and publish a public engagement strategy (Skidmore, 2022; CCC, 2023a; HM Government, 2023h).

To ensure that the public understands the benefits, trade-offs, and challenges of net zero, the government should provide authoritative, trustworthy, and engaging official data (Skidmore, 2022). It will be important for the government to engage the public in an "open and honest discussion" that outlines the benefits, trade-offs, and challenges associated with the transition (Skidmore, 2022). By doing so, the government can help build trust and understanding, which are essential for driving collective action towards achieving net zero (Skidmore, 2022). As stated above, it will be important to have robust tracking of how these perceptions and attitudes are trending over time as well (CCC, 2023a).To achieve the scale of change needed, the government should involve communities directly in local net zero action and encourage communities across the UK to lead their own net zero and climate projects (Skidmore, 2022).

Finally, government should publish a public engagement plan by end of 2023, and outline its strategy to build public advocacy around the pathways to achieving decarbonisation targets for the power system and the country as a whole (Skidmore, 2022; CCC, 2023a). Providing clear, honest, and positive messaging about what changes people will see during the transition, and where and why action from them is necessary. As part of this engagement plan, the government should demonstrate the many benefits that net zero will offer the public while being frank about the challenges (Skidmore, 2022). It is essential for the government to help develop more positive visions of the future that engage people and sell the benefits of net zero (Skidmore, 2022).

Overall

Recent events highlight the pertinence of sound public backing and provide cautionary views of the barriers that decarbonisation efforts may face in its absence. These include the protests by local communities that will host a new 180km transmission line (Financial Times, 2023a) which is required as part of the HND and accelerated under the ASTI frameworks (as outlined in the Connections and Transmissions sections above), backlash against the expansion of the charges levied on heavily polluting vehicles in London (Financial Times, 2023c), green parties in the EU resisting the increases to EU ETS costs in April 2023 (Helm, 2023), and the success of the political party representing farmers who are protesting emissions reductions measures seeing successes in the March 2023 election in the Netherlands (BBC, 2023b).

Given the critical role that will be played by public engagement and advocacy in the adoption and delivery of the infrastructure needed to meet the target, the significant gaps in policy and government initiatives around how to achieve this, and the significant risks to delivery that would result from the loss of public support, the assessment for this segment is rated as Red. Substantial efforts should be made to translate the successes of engagements such as the 2020 UK Climate Assembly (Climate Assembly UK, 2023) and the extensive corpus of academic research in this space (Chilvers *et al.*, 2017, 2023; UKERC, 2020; Bellamy *et al.*, 2022; Otto, Chilvers and Trdlicova, 2023) into public policy to ensure that cultural legitimacy and advocacy can precede the many asks that will be levelled at the public in the transition of the power system and the broader economy.

3.4.3 Standards [Yellow]

Standards are an important consideration for rolling out a decarbonised power system as they provide the necessary framework for equipment and technology to work seamlessly and safely within the system, and govern the actions and behaviour of a broad range of stakeholders, from DNOs to equipment manufacturers through to house builders. The transition to decarbonised power system requires a massive transformation, incorporating new technologies, equipment, and infrastructure. Ensuring that these elements meet a common set of standards is critical in enabling efficient and reliable operation of the power system.

Standards provide policymakers and regulators with a tool to create a level playing field for stakeholders and galvanize actions toward a decarbonized power system. Specific mentions of standards in other segments of the landscape include the need for resilience standards for infrastructure equipment (CCC, 2023c), cybersecurity standards for micro-generation/ storage assets (The Economist, 2023f), and changes to industry codes and standards to enable the delivery of the HND (National Grid ESO, 2022e). Lack of standards can hinder

Segment Assessment & Discussion

progress in areas such as DNO/DSO product standardization and the adoption of a Green Homes/Net Zero Homes Standard (Skidmore, 2022; DESNZ and BEIS, 2023h).

We would suggest that additional work is done to highlight emerging and potential standards, in the context of further analysis of a specific area of infrastructure where standards may play a role in accelerating progress (e.g., Transmission-Distribution Interface). This may be an area that others explore in more depth through a primarily standards lens. Overall, the assessment for this segment is given as Yellow.

3.4.4 Market Design & Regulation [Yellow]

As set out in the consultation document that marked the start of the REMA process – electricity markets will form the "backbone of the future electricity system" (BEIS, 2022h). As the consultation highlights, the last significant reform programme for electricity markets was a decade ago, leaving some market structures untouched from the time when fossil fuels were the dominant energy source. Thus, it is essential to reassess the current market arrangements to ensure they are fit for purpose and deliver a clean, secure, and affordable energy system for consumers.

Another important market that impacts power generation today is the Emissions Trading Scheme (ETS) and the accompanying Carbon Price Support (CPS) mechanism. Carbon pricing affects investment and operational decisions by raising the operating cost of fossil fuel plants, making them less competitive, and sending a long-term market signal to decarbonise. However, as stated in the consultation, UK's ETS extends to a broad range of sectors beyond the power sector, all with varying degrees of abatement potential, and therefore changes to this market are not being considered as part of the REMA process (BEIS, 2022h). It should be noted that in response to a recommendation by the Independent Review of Net Zero (Skidmore, 2022), the government announced that it will be looking to set out a long-term pathway for the UK ETS and will work with the ETS Authority to set this out in 2023 (HM Government, 2023h).

Alongside the importance of markets, the Independent Review of Net Zero (Skidmore, 2022) also highlights that to make the best long-term investments, businesses require a suitable regulatory framework, and failure to update the regulatory and policy framework could hinder the investments needed to achieve power system decarbonisation and broader net zero goals. The importance of suitable regulatory frameworks is highlighted throughout this paper, in particular as part of the discussion in the Connections, Transmission and the Strategy, Coordination & Governance segments. As noted previously, the government is undertaking consultations with Ofgem around its regulatory mandate (Ofgem, 2022b, 2022a, 2022c, 2023b, 2023i, 2023a; DESNZ, 2023y), its working remit with the FSO once formed (DESNZ, 2023y; HM Government, 2023e; Ofgem, 2023i), and is implementing the recommendations coming out of the Regulation of Technologies Review: Green Industries report (HM Treasury, 2023a, 2023b).

The REMA consultation period ran between July and October 2022, receiving 225 responses from a range of electricity market participants and wider range of stakeholders including academia and private individuals. A summary of the result of the first phase of the consultation is outlined in Figure 37, where a number of options were ruled out and will not be taken forward (shaded in red) or will be discounted as standalone options (shaded in brown/orange) but are being considered in conjunction with other options. The review has since been through a further phase of consultation to consider the feasibility of these options alongside their potential benefits, stating that "*decisions will be driven by whole system considerations which account for the needs of all energy market participants, with a high weighting for future considerations*". A timeline for when the outcome of this next phase will be published has not been released – in their response to the Independent Review

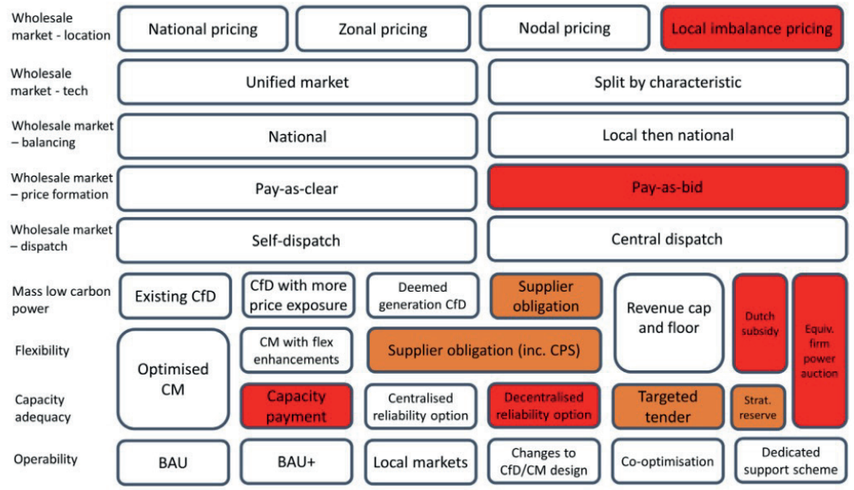


Figure 37 *Map of options space with those ruled out (shaded in red) and only being considered in combination with other options (shaded in orange) highlighted. (DESNZ and BEIS, 2023h)*

of Net Zero the government indicated that this would be done by Autumn 2023 (HM Government, 2023h).

Outside of the REMA review process, the Independent Review on Net Zero's stakeholder engagement also highlighted a request from market participants for CfDs to incorporate non-price factors, as the current arrangements were driving developer procurement activities to "*seek lowest cost supply markets to enable projects to remain economically viable at such low electricity pricing [...] the current model thus misses the opportunity of helping foster the UK supply chain*". In response, the government launched a call for evidence on non-price factors in CfD auctions such as system integration and supply chain development, which ran between April and May 2023 – they are still analysing the feedback received, and have not given a timeframe to expect completion (DESNZ, 2023m).

As discussed in this section, market design is a critical enabler in the pathway to achieving the target, and there is a significant case for change. REMA provides a robust mechanism for this change to be consulted, and this segment is therefore given an assessment rating of Yellow. It should be noted that the decision on reform from government had not been released and so does not feature here – this is an area where future work could be considered.

3.4.5 Financing & Investment [Red]

Appropriate regulatory frameworks, market design and project deliverability are key to galvanising the levels of investment flows needed to achieve power system decarbonisation (CCC, 2023c) – once again highlighting the interlinkages between the enablers considered in this assessment. These have been discussed in more detail throughout this report, however it is important to note that achieving the levels of investment required will be contingent on progress across these other enablers, equally if not more so than the status of financing standalone – this section explores the scale of investment necessary to achieve

Segment Assessment & Discussion

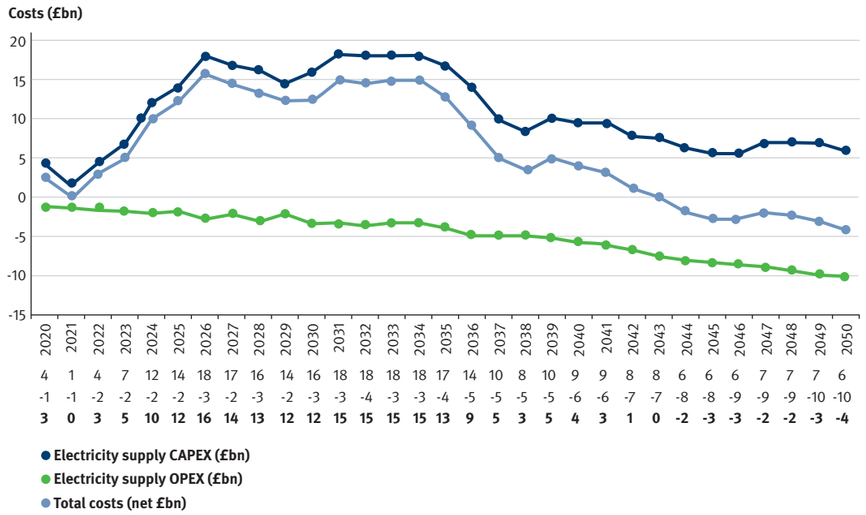


Figure 38 *Annual Capital Investment Costs in Low Carbon Generation & Operational Cost Savings from Electricity Supply, 2020 to 2050 - NAO Analysis* (NAO, 2023a)

the target, and the capacity for the UK to secure this investment.

Financing is a critical enabler of delivering the decarbonisation of the power system. The NAO estimates that £280-400 billion is required in generation and flexibility assets alone by 2037 – the end of the CB6 period (NAO, 2023a). In the latest Carbon Budget Delivery Plan published in March 2023 the government estimated that £325-525 billion of investment would be needed across generation, flexibility and networks, to decarbonise the power system by 2035 (HM Government, 2023a). In its 2021 Net Zero Strategy, the government estimated that annual investment flows into UK's decarbonisation across all sectors would need to reach £50-60 billion throughout the late 2020s and early 2030s to meet the UK's net zero targets (HM Government, 2021). The government's estimate for realised decarbonisation related investments in 2022 was £23 billion (HM Treasury, DESNZ and DEFRA, 2023), indicating the need to rapidly ramp up investment flows, by around 2.5-3 times, over the coming years to facilitate the pace of delivery required to deliver the target. Figure 38 shows the profile of expected annual capital investments in low carbon generation (excluding the investments needed in broader infrastructure such as transmission, distribution, storage and CCUS) and the resulting cost savings in electricity supply, through to 2050.

The material examined as part of this research suggests that the UK remains an attractive market for investment and enjoys a comparative advantage over other advanced economies in several key areas - notably offshore wind, CCUS, and green finance (Skidmore, 2022). The government noted that the UK attracted the second-highest inflows of low-carbon investment in Europe over the past five years and that cumulatively since 2010, the UK has seen £198 billion of investment into low carbon energy, through a mix of government funding, private investment, and levies on consumer bills (HM Government, 2023h). In the recently published Green Finance Strategy, the government also noted that the UK remains the top-ranking country on the Global Green Finance Index for the third consecutive year (HM Treasury, DESNZ and DEFRA, 2023), indicating a strong base with which to attract and deploy investment capital.

The government is using different funding models to support low-carbon nuclear power stations, which are vital for the future power system (target of 25 GW by 2050 (HM Government, 2022a)). For example, the Hinkley Point C plant has a guaranteed price through a CfD scheme, and the proposed Sizewell C plant will use a Regulated Asset Base (RAB) model, which allows a regulated charge to consumers during construction (NAO, 2023a). This way, the government hopes to lower the cost of capital and attract private investment in the nuclear industry, indicative of the willingness to innovate and find different financing models.

As part of the March 2023 set of policy publications, the government launched a "comprehensive green finance strategy" (HM Government, 2023b), and also announced that i) they have moved to annual CfD auctions to increase the pace of investment in renewable generation (BEIS, 2022d; HM Government, 2023h), ii) throughout 2023, the government announced a series of net zero investment roadmaps that detail investment needs by sector and provide information on relevant policies and investment opportunities, including offshore wind (published March 2023 (DESNZ, 2023s)), heat pumps (published April 2023 (DESNZ, 2023k)), CCUS (published April 2023 (DESNZ, 2023a)), hydrogen (published April 2023 (DESNZ, 2023l)), and nature positive investment (not published at of November 2023) (HM Government, 2023h), and iii) the government is launched a review led by Lord Harrington of Watford to increase foreign direct investment across five growth areas, including green industries (HM Treasury, 2023c). The latter report and the government response to it were published in November 2023 as part of the Autumn Statement (HM Treasury, 2023d).

Whilst these announcements and publications provide a positive backdrop, the UK faces significant headwinds in achieving the required ramp up in investments to deliver power system decarbonisation by 2035. Firstly, the numbers used by HM Treasury (in the Carbon Budget Delivery Plan), CCC, NAO and others assume efficient implementation of projects, and even so the £325-525 billion in capital requirements for the next 12 year period to deliver power system decarbonisation (HM Government, 2023a) represents a 1.6-2.7 times increase relative to the £198 billion in low carbon energy investments realised in the previous 12 (HM Government, 2023h). Taking HS2 as an example of another significant national infrastructure investment spanning over a decade, analysis by the Institute for Government published in 2020 (Institute for Government, 2020) found that, relative to what was budgeted in the original plan, expected costs rose by approximately 2.4 times in real terms, from £45 billion to £110 billion between 2011 and the 2019 independent review. It would therefore be prudent to assume that the ramp in investment requirements is at the upper end of the ranges considered, if not higher, and plan for this scenario to ensure that delivery of the target remains feasible. To date the government have not published, or announced a plan to publish, a strategy for how the level of investment over the next 12 years would scale to the over £500 billion that may be required vs. the £200 billion achieved in the last 12 years.

Sourcing the Ramp Up in Investment

As highlighted above, the UK will need to significantly ramp up its investment in power system decarbonisation to meet its 2035 delivery target. This ramp up in investment must be sourced somehow – it can be sourced domestically from household savings (foregone consumption), from businesses via retained earnings, or from the issuance of debt (and whilst this spreads the cost over time, it will need to be paid back, with interest, using domestic savings), or via investments and debt from other countries.

Segment Assessment & Discussion

Current levels of UK household savings and retained earnings from businesses are however, "grossly inadequate" for funding this ramp up (Helm, 2023). Further, recent rapid increases in UK inflation, and subsequently interest rates, have left the country with the largest government debt interest bill in the developed world (Financial Times, 2023i), which is likely to be a significant limiting factor in ramping up investment via government debt. Increasing domestic contributions to investments is therefore likely to require the imposition of increased savings rates on the public and businesses, either through increases in taxation or via increases in cost of consumption which are then used for investments (i.e. energy bills) – as discussed in the Public Engagement & Advocacy section above, the lack of a concerted effort to build broad public buy in for such policies, and the current backdrop of significantly higher energy bills vs 2021 levels and other general cost of living pressures being faced by the UK public (Institute for Government, 2022; BBC, 2023a; ONS, 2023a; The Guardian, 2023a), means that the scope for doing this is likely to be severely limited. This would mean that the UK would require significant increases flows of capital from overseas to fund its power system decarbonisation investments.

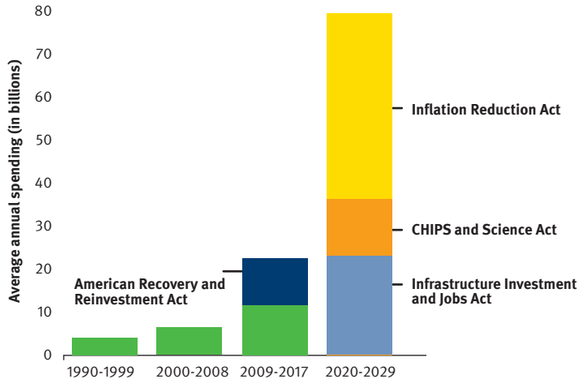
Competing for International Investment

Whilst the UK has a strong history in attracting significant levels of investment from overseas, bringing forward innovative regulations, market designs and government support models, there is increasing global competition to attract investments towards the net zero transition (Skidmore, 2022). We have come across widespread caution and scepticism around the adequacy of the scale and ambition of the UK's policy response to those of the US, EU, China (CCC, 2023a; Industrial Strategy Committee, 2023). The CCC points out that "neither *the Strategy nor Investment Roadmaps published to date go far enough in setting out how the investment needed to deliver Net Zero will be secured, and a mechanism to track this is yet to be established*". Similarly, while developers of renewable energy projects in the UK face significant cost increases, the windfall tax exemptions applied to them are less generous than those given to the oil and gas sector. Further, despite significant investment programmes announced by others, such as the Inflation Reduction Act in the USA, the UK government has continued to show an unwillingness to undertake similar investment support programmes.

Given the UK will need to compete for globally mobile pools of international investment and debt capital, it is important to put this approach into perspective relative to other jurisdictions that are also competing for this pool of capital – for example, the US government. Across three substantial infrastructure investment laws enacted since 2021, the US government is expected to spend c.$80 billion per annum between 2020-2029, up from c.$20 billion per annum 2009-2017 and less than c.$10 billion per annum in the preceding 20 year period (see Figure 39) (The Atlantic, 2022). This scale of increase in public expenditure is expected to crowd in private capital at multiples of the expenditure itself, with companies already investing over $270 billion in US based clean energy projects within the first year of the passing of the Inflation Reduction Act (Time, 2023). It remains unclear how the UK plans to attract the levels of international capital required to ramp up the levels of investment needed.

Contracts for Difference Scheme & Its Future Success

Notwithstanding the 2023 round, CfD schemes have been a major success story for crowding in investment to expand low carbon generation capacity, providing a highly creditworthy, 15-year, inflation-indexed, guaranteed price route-to-market (Tim Pick, 2023). This has been a driver of significant innovation, rapidly bringing down costs of low carbon generation, at a pace that was much faster than initially expected by the designers of the scheme – as seen for offshore wind with both the rapid declines in clearing bids through successive allocation rounds (ARs) and the clearing prices coming in below the Administrative Strike Prices (ASPs) for each round (see Figure 40) (Tim Pick, 2023).



Source: RMI

Figure 39 *Average annual investment spending on clean energy related projects by the US government, in USD billions* (The Atlantic, 2022)

However, this flagship scheme has come up against a number of issues – reforms to the scheme are currently under consultation (DESNZ, 2023m) as the current focus on price as the only evaluation metric for auctions has been found to narrowly favour incumbency and existing capacity over investment in local supply chains and capacity (which is another important barrier as discussed in further detail in the section on Workforce & Supply Chains 3.4.8). Further, renewables developers who had won contracts under the last AR4 round (which ran in November 2021) have faced cost increases of 20-30% since their bids, with some developers reporting cost increases of up to 50% (Industrial Strategy Committee, 2023).

As highlighted in the earlier section on Low Carbon Generation, this has led to some high profile project cancellations from developers and others putting final investment decisions "on-hold". These cost pressures and the lack of accommodation for them in the most recent ASPs lead to the lack of any bids coming in for the offshore wind part of the latest AR5 round of subsidies (Current News, 2023b, 2023e; DESNZ and BEIS, 2023e; Financial Times, 2023e, 2023k, 2023l). This presents a major red flag for this flagship programme, which may need urgent modifications in other ways to ensure that it remains viable as a way to continue attracting investment in low carbon generation capacity. As emphasised by Energy UK, "*the main purpose of CfDs should be to deliver the largest volume of renewable capacity possible at lowest available cost, not to keep driving prices down beyond what is realistic given market conditions*" (Industrial Strategy Committee, 2023).

Other Policies to Crowd in Investment

Further, there are a number of policy developments which may slow growth in levels of investment vs. what is achievable. First, the Public Procurement Bill (UK Parliament, 2023b) that is being considered by parliament was amended to no longer include references to meeting UK's decarbonisation targets (CCC, 2023a) – government procurement is a highly effective tool to increase investment in local supply chains and scaling technologies required for decarbonisation (Regulatory Assistance Project, 2023), as such, this should be seen a significant missed opportunity. Secondly, as discussed in the previous section on Market Design & Regulation, the UK is considering a number of potentially significant changes to market design as part of the REMA process – it is important to note, as highlighted by

Segment Assessment & Discussion

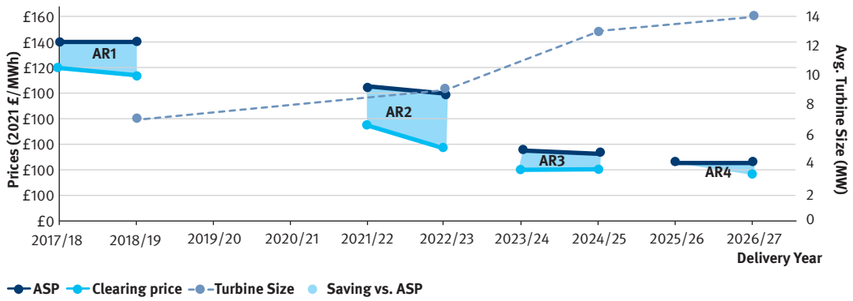


Figure 40 *Historic offshore wind allocation rounds, showing Administrative Strike Prices vs auction clearing strike prices, as well as average turbine size for each round* (Tim Pick, 2023)

several of the experts interviewed, that whilst market reforms are necessary in many ways, these should be considered in the context of the overall priority of increasing investment in generation, network and flexibility capacity and drive the power system decarbonisation. Substantial changes to market design that do not also come with suitable lead times and clear communications around implementation could have negative impacts on levels of investment between policy announcements and clarity around their impacts.

Overall

In summary, whilst the UK has seen significant successes in attracting investments in low carbon generation historically, there will need to be a substantial increase in investments relative to what has been achieved in order to deliver the power system decarbonisation target. There remains a lack of a policy strategy for how this increase in investment will be achieved, and there has been no announced plan to create one. In the context of limited domestic capacity to drive increases in investment, significant and growing competition internationally for globally mobile pools of capital, a number of issues being encountered with existing subsidy regimes (notably the CfD scheme), insufficient consideration of other policy mechanisms such as public procurement for driving investment, and a number of fundamental reforms to market design that may impact levels of investment following their implementation, the outlook for achieving the rapid growth in levels of investment required appears negative. As a result, the assessment for this segment is rated as Red. In order to drive an improvement in the investment outlook, the government should urgently consider publishing a coordinated strategy for how they plan to facilitate the required rapid growth in investment, urgently look to reform the CfD design to address concerns, and consider other policy options for crowding in further investment.

3.4.6 Land & Seabed [Light Green]

Siting and land / seabed use are critical considerations for the roll-out of a decarbonised power system. Developing renewable energy infrastructure requires significant amounts of land and seabed, whether it be for solar farms, wind turbines or new transmission infrastructure. This presents challenges in terms of land-use competition, where various sectors, including industry, agriculture, housing, and biodiversity, compete for the same limited land resources. DSIT's Finding Common Ground land use policy paper published in June 2023 outlined several of these competing 'transformations' that make up important policy goals of the government, all competing for land use, summarising them as follows (DSIT, 2023):

i. Energy: Accelerate the transition from fossil fuels to renewables, such as increasing solar capacity from 14 GW to 70 GW by 2035.

ii. Housing: Meet the government's aspiration of 300,000 homes per year in England.

iii. Biodiversity: Protect 30% of the UK's land for nature by 2030. Restore or create more than 500,000ha of a range of wildlife-rich habitat in England by 2042.

iv. Forestry: Increase tree canopy and woodland cover to 16.5% of England's total land area by 2050 (increase of around 250,000 ha, equivalent to an area the size of Cheshire)

v. Food: Broadly maintain current levels of domestic food production in England.

vi. Infrastructure: Significant public investment in strategic road and rail, UK-wide gigabit broadband roll-out, EV charge points, water resilience and flood defence.

vii. Net Zero: Emissions in agriculture. forestry and other land use sectors could need to fall by 17-30% by 2030 and 24-30% by 2035, relative to 2019 levels.

viii. Water: Restore 75% of our water bodies to good ecological status.

Without proper planning and coordination, development of renewable energy infrastructure can lead to conflicts over land use, which can delay or even prevent project implementation. Effective siting and land-use policies are essential to minimise these potential conflicts, ensure efficient use of land, and enable the rapid deployment of renewable energy infrastructure needed to meet the target.

The Independent Review of Net Zero highlighted the complications arising from the interactions between different policies related to net zero are, including trade-offs on land use (Skidmore, 2022). To help tackle this issue, one of the key recommendations of the Review was for the government to publish a Land Use framework as soon as possible, and by mid-2023. The review also made references to The Council for Science and Technology recommendations from 2020 regarding the strengthening of the government's central oversight of net zero, to understand how different policies interact and influence the transition of the whole economy towards net zero, including with respect to land use trade-offs, between mitigation, adaptation, and resilience, including the need to protect biodiversity and wider sustainability initiatives (Council for Science and Technology, 2020).

In their response to the review (HM Government, 2023h), the government announced the Department for Environment, Food and Rural Affairs (DEFRA) will publish a Land Use Framework for England in 2023 (originally due in 2022), as part of the Food Strategy. As of the time of this writing (November 2023), the framework had still not been published. Delays to the publication of the framework could potentially hinder progress given the critical nature of these trade-offs; timely publication of this framework will be important for the delivery of the target.

The seabed resource around the British Isles has been managed in a much more proactive and centrally coordinated way when compared to the management of land use. As outlined in Tim Pick's report on expanding UK's offshore wind industry (Tim Pick, 2023), The Crown Estate (TCE, in England, Wales and Northern Ireland) and Crown Estate Scotland (CES) both have authority to grant seabed leases for Offshore Wind Farms; in the case of TCE, pursuant to the Energy Act 2004 (UK Parliament, 2004); and in the case of CES, pursuant to the Scotland Act 1998 (UK Parliament, 1998) and The Crown Estate Transfer Scheme 2017 (UK Parliament, 2017). TCE and CES both also go beyond a simple seabed landlord or asset manager function, acting as delivery partner with government and the private sector to take an active, long-term approach

Segment Assessment & Discussion

to maximising usage of the seabed, including offshore wind (Tim Pick, 2023). The report highlights that whilst UK's historical approach to try and balance competing needs for a given area of seabed has worked well to date, it will be difficult to go forward without establishing an agreed hierarchy of needs and a holistic long-term vision and plan. This is another area where DEFRA are leading a cross-government programme to map out the competing needs and build out the required hierarchies.

Overall, whilst the increase in premiums being paid by land-based developers are not currently providing a barrier for renewable project development, regulatory and policy guidance on where these projects sit relative to other land use priorities will be important to clarify as soon as possible. The assessment acknowledges the success of the historical approach to managing the seabed resources in seeding the offshore wind industry and recognises the initiatives being taken by government across both the development of the Land Use Framework in 2023 and the holistic approach to future seabed use. As a result, this segment is assessed with a rating of Light Green.

3.4.7 Planning & Permitting [Amber]

Planning, siting, and the permitting and consenting process associated with it have been cited, almost without exception, across the reports and publications that were studied, as a major blocker to the acceleration of infrastructure deployment necessary (across generation, storage & flexibility, and networks, etc as outlined in previous sections of this review) for meeting the target.

Alongside setting out the ambitions for its net zero targets, the UK government has acknowledged the need to make the infrastructure consenting process better, faster, and greener. This need for reform is explicitly called out in its 2020 National Infrastructure Strategy (HM Treasury, 2020) and the 2022 British Energy Security Strategy (HM Government, 2022a). The Nationally Significant Infrastructure Project (NSIP) planning regime, which was enacted as part of the Planning Act 2008, was set out to provide more certainty on the process for nationally significant projects, where the government set out the need through National Policy Statements (UK Parliament, 2008b). Where projects do not fall under the NSIP regime, they must go through local planning consent processes, and these must take into account the planning policies outlined in the National Planning Policy Framework (NPPF) in England, Planning Policy Statements (PPSs) in Northern Ireland, Scottish Planning Policy (SPP) in Scotland, and Planning Policy Wales (PPW) in Wales.

The NSIP regime has been successful in reducing the time taken for major infrastructure projects to achieve development consent to an average of around 4 years in 2021 – Heathrow Terminal 5 took 8 years to go through the local planning process, prior to the introduction of NSIPs – although the average time has increased from 2.6 years in 2012 (DLUHC, 2023b).

There is broad acknowledgement that the system needs to be more agile and move with the focus and speed required to meet urgent challenges across UK's infrastructure including decarbonising power. NIC in their analysis (NIC, 2023a) found that for the UK to meet its 50 GW offshore wind capacity target by 2030, it would need to consent offshore wind farms at over double the historic rate (i.e., in half the time) over the next six years. There would also need to be at least 17 new transmission line consents to support this capacity, which would need to be approved within the next four years, requiring consenting of these new lines at four times the rates achieved historically (NIC, 2023a). In its March 2023 energy policy announcement, the government committed to delivering more effective planning regimes, including changes to the NPPF (for local planning in England), the energy National Policy Statements (for NSIPs), and Electricity Act planning (HM Government, 2023d). As highlighted in the discussion on Low Carbon Generation (3.1.1), the government also opened a consultation in July 2023 to amend planning rules and enable the fast-tracking of the process for offshore wind farms with a view to half the time taken for these projects to gain planning approval (Current News, 2023h; DLUHC, 2023a).

Planning is a complex and specific field, and an exhaustive analysis is beyond the scope of this research. We outline some of the issues highlighted and the case for change, some of the recommendations set out to address them, and the actions being taken or proposed to date. The opportunities in this segment are in five overall groups, i) mandates for planning bodies, ii) approach to environmental assessments, iii) regulatory capacity, iv) community benefits, and v) combined spatial planning.

Mandates for Planning Bodies

As outlined above, National Policy Statements (NPSs) determine the criteria for qualifying under the NSIP regime, and many of these have not been updated for over a decade, and are therefore not aligned to many of the decarbonisation targets announced since, including the power system decarbonisation target. One of the key opportunities would therefore be to update the National Policy Statement to recognise critical infrastructure identified by the Holistic Network Design (Skidmore, 2022), to include onshore wind, and for the government to introduce legislation to make five-yearly reviews of these to ensure they remain relevant and up to date (NIC, 2023a).

The government have recently published five revised National Policy Statements for consultation, including three that cover Renewables (DESNZ, 2023r), Electricity Networks (DESNZ, 2023h) and an overarching Energy statement (DESNZ, 2023t), including a new requirement for offshore wind and all associated offshore and onshore transmission reinforcement identified in the HND to be designated as "critical national infrastructure". The government also announced that they would release an NPS covering nuclear in due course (HM Government, 2023e). In their response to the NIC report (DLUHC and HM Treasury, 2023), the government have not outlined any plans for bringing legislation to ensure regular updates to the NPS', however they have re-committed to reviews within a 5 year time frame, following their 2021 guidance on updating NPS documents (DLUHC, 2021).

For projects that do not qualify for the NSIP regime, local planning rules, administered by local planning bodies, must be followed. As outlined above the relevant planning policy varies by region and in England this is set out by the NPPF - in the current NPPF the Climate Change Act is only referenced once in a footnote, and net zero is not mentioned at all (CCC, 2023a). As a result, even where there is desire to develop projects that are net zero compatible, there is reluctance among local authorities to exceed national planning standards given the lack of impetus provided by the legislation (Skidmore, 2022). This is exacerbated by the litigious nature of the system, with stricter standards like Net Zero compatible developments as getting struck down in planning tribunals (Skidmore, 2022). There has been a significant increase in judicial review of consents, with c.58% of approved schemes in recent years being judicially reviewed, up from a long-term average of c.10% (NIC, 2023a). As noted by the NIC "the increase in legal challenges suggests that public trust in the system may be reducing, potentially because of the increase in the volume of schemes required" – given the requirement to increase deployment rates still further, the number of schemes that will be going through planning is only going to increase, exacerbating this dynamic in the absence of broader public buy-in (highlighting the importance of the discussion in section Public Engagement and Advocacy (3.4.2)). Reforming the local planning system and updating the NPPF to explicitly include net zero as a planning objective and to give clarity on when local authorities can exceed national standards therefore represents a significant opportunity to accelerate progress (Skidmore, 2022). The government have recently undertaken a consultation process for

Segment Assessment & Discussion

the NPPF but have not indicated a time frame for responding and amending the policies (HM Government, 2023e), it therefore remains unclear if this will deliver what is required against this recommendation.

Approach to Environmental Assessments

Another significant opportunity to accelerate consenting times is through updating the approach to conducting Environmental Impact Assessments (EIAs). Today, these take place at a scheme level in the UK, involving developers gathering up to three years of environmental data from their proposed site - this is "often duplicated by other developers gathering the same data in the same area" (NIC, 2023a). The requirement to conduct environmental impact assessments are derived from UN treaties, and are therefore legal requirements under international law. However, there can be significant gains from conducting these assessments at ecosystem level rather than scheme level, and for government to build a centralised data platform that allows ecosystem & species and mitigations data to be added and accessed in standardised way (NIC, 2023a). The requirement for EIA data to be made publicly available is already included as part of the Levelling Up and Regeneration Bill (UK Parliament, 2023a), which has recently become law. Related to his would be the centralised environmental data gathering and mitigation design for designated development zones, initially applied to target critical infrastructure such as offshore wind and transmission infrastructure (NIC, 2023a). Similar site level, pre-lease, centralised strategic EIA's have been used in offshore wind development in Brazil (Orestes *et al*., 2020) and Holland (NIC, 2023a), and are currently being trialled in the UK as part of the Celtic Sea floating offshore wind seabed leasing rounds (Current News, 2023c; Tim Pick, 2023). Further, the centralised and standardised data sharing is being trialled in offshore wind developments under OWEC's Planning Offshore Wind Strategic Environmental Data and Information Network (POSEIDON) initiative (Tim Pick, 2023).

Regulatory Capacity

Increasing regulatory capacity and reforming the processes by which consenting applications are handled also present important opportunities to accelerate rates of deployment. Indeed, DESNZ and other stakeholders have repeatedly flagged capacity issues at the Planning Inspectorate, which is responsible for considering NSIP applications (Skidmore, 2022; NAO, 2023a; National Grid Group, 2023a; NIC, 2023a). As an example, it currently takes three to five years for an offshore wind farm to move through the consenting phase, driven mainly by "under-resourcing within planning authorities and environmental regulators, [...] and a lack of streamlining within the process" (Skidmore, 2022). The expected increase in the number of applications will make this more pressing – twice as many planning applications were submitted in 2021 compared to 2020, and this trend is expected to continue (Skidmore, 2022). Therefore, a key recommendation is to build additional capacity and support for regulators and local authorities to expedite processes, including more innovative approaches within existing frameworks and clearer guidance for local authorities (Skidmore, 2022; NIC, 2023a).

In February 2023, the government released an action plan for reforming the NSIP regime to speed up consenting for a number of projects including those related to the energy grid – the primary reform proposed here is the introduction of a fast-track regime available for projects that defined quality standards (and in parallel launched a consultation process to determine what these standards should be) (DLUHC, 2023b). The fast-track regime once implemented, would set a maximum formal examination period of 12 months and for the Secretary of State to have powers to shorten this maximum time frame where required (HM Government, 2023e). If implemented this would be a significant acceleration for the planning stage of qualifying projects. In their July 2023 consultation on planning reforms, DLUHC also committed to increased funding for additional resources at the Planning Inspectorate, to support investments in digital transformation to reduce processing times, and to bring in reforms to allow for full cost recovery from applicants, which would enabler further investment in resources (Current News, 2023h; DLUHC, 2023a, 2023b, 2023e).

Community Benefits

The current approach to community benefits has been identified as an important barrier to progress, making it hard to make the case for local communities to host energy infrastructure for the benefit of the wider society (Skidmore, 2022; NIC, 2023a). Setting out a consistent framework for community benefits is therefore an important recommendation to help accelerate deployment of the infrastructure required. The government launched a consultation on community benefits for network infrastructure in March 2023 (DESNZ, 2023c). The resulting framework was published as part of the 2023 Autumn statement, introduce consistent guidelines on appropriate levels and forms of benefits for communities, and the flexibility to choose benefits in consultation with project developers (DESNZ, 2023d). This is a positive step towards increasing the rate of infrastructure deployment, however It is unclear if this framework will be sufficient in building broad local support for network infrastructure to increase rates to those required. Further, it does not fully address the need for a broader community benefits framework that encompasses other relevant power system infrastructure (e.g. generation, storage etc).

Combined Spatial Planning

Finally, a combined spatial plan for all of the expected upcoming infrastructure development plans for a given local community could also aid in streamlining the process and increase rates of consenting. Indeed, the lack of a spatial plan is increasingly becoming an issue for communities that are being exposed to multiple NSIP applications that are disjointed from each other – for example some local authorities have been receiving 12 to 14 NSIP applications per year (NIC, 2023a), and the lack of spatial pipeline makes this hard to plan for. This also makes it difficult to bring associated economic benefits to the local communities by planning associated developments, and better understand cumulative impacts of these schemes such that they can be mitigated effectively (NIC, 2023a). In their response to some of the NIC recommendations released as part of the Autumn Statement, the government committed to producing a Strategic Spatial Energy Plan which would be informed by other initiatives such as the CSNP process discussed earlier in our assessment (DLUHC and HM Treasury, 2023). Further, the government is aiming to come to a conclusion by summer 2024 on the merits of adopting a combined spatial planning approach across multiple segments of infrastructure (e.g. transport, water, energy etc), and to lay out next steps (DLUHC and HM Treasury, 2023).

Overall

Overall, planning & permitting remains a significant barrier to the delivery of the target. Recent announcements by government have proposed a number of reforms that aim to address some of the recommendations coming out of recent reviews that have identified a substantial case for change. It remains unclear whether these proposed reforms will have the intended impact. Given the critical nature of this enabler tying into almost all aspects of delivering the infrastructure needed to meet the target and its central role in being an enabler of other enablers (e.g., ability to secure planning is a key part of securing project financing), and the uncertainty around the impact of recently announced reforms, the assessment for this segment is given a rating of Amber.

3.4.8 Workforce & Supply Chains [Amber]

An important enabler for delivering power system decarbonisation will be the ability to translate targets, plans and capital into tangible infrastructure that can then be built, requiring ready access to the workforce and supply chain resources required to do so. The NGESO analysis on connection queues shown in Figure 15 and the levels of interest in the government CCUS cluster and hydrogen

Segment Assessment & Discussion

capacity schemes outlined earlier in this review provide a strong indicator of interest in developing the scale of physical infrastructure needed to meet the target. Ensuring that these projects can obtain access to existing resources and infrastructure (e.g., land and connections), financing, and planning consent are other key enablers of delivery considered in more detail earlier in the assessment. As discussed, some of these enablers have seen recent progress but significant bottlenecks remain. What is then needed are, i) the people with the right skillsets, and ii) supply chains with the capacity to serve this unprecedented pipeline of projects. The ability for these projects to readily access these two core components is the subject considered in this section of the assessment.

Workforce

In 2020 there were already an estimated 430,000 UK jobs in "low carbon" businesses and their supply chains - 208,000 direct and 222,000 in the supply chain (Skidmore, 2022). It is expected that the workforce involved in delivering decarbonisation will grow to an estimated 780,000 direct jobs and a further 905,000 in the supply chain by 2035 – i.e., an addition of 1,255,000 jobs between 2020 and 2035 (Skidmore, 2022). This presents a unique opportunity to build a skilled and well-paid workforce, but the pace and scale of job creation required also presents a significant challenge. Indeed, skills challenges are being highlighted across all sectors involved with the net zero transition, with a 5-30% decline in skilled workforce over the past three years, and in construction, where 50% of Federation of Master Builders members reported challenges recruiting for key trades (Skidmore, 2022).

Workforce was one of the most frequently mentioned segments by experts during interviews when discussing barriers to the delivery of the target. Experts mentioned a broad range of ways in which workforce challenges were impacting the decarbonisation of the power system including:

i. The cascading impacts of not having enough people for some specialist roles that end up causing delays across a chain of actions,

"For a number of our projects, we have been waiting behind a 400 kV upgrade to take place and there are only a certain number of engineers certified to do this work, you could have dozens of different follow up actions that are held up as a result"

ii. Needing to expand the overall workforce across the board,

"Workforce does not get enough attention – the core problem we are having in getting connections progressed is having the people in place – project managers, planning engineers, boots on the ground installing this stuff… haven't invested in training these people, desperately needs doing"

iii. The need for organisations to integrate very different profiles of people vs what they have historically had to recruit and train and,

"The nature of the workforce is going to change a lot – our organisation alone will need 200 data scientists, we have never had to recruit and develop this sort of workforce before, have historically all been power engineers. This will be a big challenge for us"

iv. That there was a huge increase in demand globally for the talent needed to deliver power system decarbonisation, particularly around network infrastructure.

"Power system engineers are getting offers everywhere in the world – our own grid lead left 3-4 months ago to work in Saudi Arabia and they are throwing hundreds of thousands of pounds at them […] we are losing talent in this country, and we really should be trying to hold on to them"

To try and tackle the overall workforce challenge faced across decarbonisation, the government have undertaken a number of initiatives over the past 3 years. The first substantial undertaking was the establishment of the Green Jobs Taskforce in 2020, comprising of a diverse group from industry, academia, unions and the education and skills community (DESNZ, DBT and BEIS, 2021), which published its recommendations in July 2021. This led to the ONS starting to track workforce statistics in this sector more closely through its Low Carbon and Renewable Energy Economy Survey (ONS, 2023b). In order to facilitate the roll out of the recommendations coming out of the taskforce, a Green Jobs Delivery Group was set up (HM Government, 2022b). The primary deliverable for this group is the Net Zero and Nature Workforce Action Plan due in 2024, with an initial prioritisation of the Net Zero Power and Networks working groups, who were due to publish these sections of the plan by summer 2023 (HM Government, 2023d, 2023h) – as at the time of writing in November 2023, this had not yet been published.

The contents or intended coverage of these action plans are not clear, and it will be important for them to include detail on how actions will be coordinated across devolved administrations (Scotland and Wales have published their own workforce action plans (Scottish Government, 2023; Welsh Government, 2023)), local authorities, businesses, trade bodies and organisations responsible for accrediting courses and qualifications to ensure priorities can be addressed effectively, as well as a comprehensive assessment of when, where, and in which sectors there will be skills gaps specific to Net Zero (CCC, 2023a).

Ahead of the publication of the plan, the government has also announced an additional £3.8 billion funding for skills by 2024-25 (HM Government, 2023d, 2023h). However, assessments of this funding have been critical of its short-term nature and that the current funding landscape "*does not provide the certainty for businesses and education providers to invest in the training and skills required to decarbonise energy*" (Public Accounts Committee, 2023). Given the lack of further detail on the government announcement, it is unclear what impact the additional funding announced would have on the issues currently faced.

Workforce readiness in the decarbonisation of the power system covers a very broad range of issues and is a highly complex issue to try and address. Whilst there have been many announcements and reports published advising on some important actions, a comprehensive and appropriate workforce plan is yet to be published – this could be delivered as part of the anticipated Net Zero and Nature Workforce Action Plan in 2024 mentioned above. The continued uncertainty means that progress is slowed, exacerbating delays in delivering infrastructure needed to meet the target.

Supply Chains

To date, the UK's approach to understanding supply chains and related bottlenecks has primarily been on a sector-by-sector basis, and there has not yet been a similar overarching assessment for supply chains similar to that conducted for workforce assessment by the Green Jobs Taskforce. Government has completed (and recently updated) an overarching assessment focused on critical materials (BEIS and DBT, 2022; DBT and BEIS, 2023), and has commissioned detailed work on sector-specific supply chains such as offshore wind (Tim Pick, 2023) and electricity networks (BEIS, 2022f). Similar efforts are being undertaken for Nuclear via the Great British Nuclear body (DESNZ, 2023u), and for solar via the recently commissioned solar task force (HM Government, 2023h). This assessment will focus on the findings on offshore wind to date as this is the area with the most policy attention to date – the absence of this level of scrutiny and planning for other sectors not mentioned above, and the lack of an overarching power system transition supply chain assessment constitutes an important gap, which given further attention, would present a significant opportunity to accelerate progress.

The Offshore Wind Sector Deal, published in March 2019 (BEIS and DESNZ, 2019) has been

Segment Assessment & Discussion

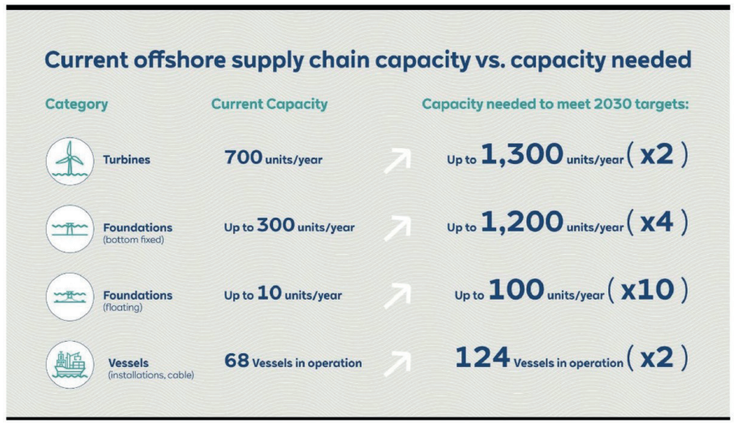


Figure 41 *RWE Analysis on current supply chain capacity vs what is required to deliver 2030 offshore wind deployment targets for EU, UK and Norway (165 GW)* (Tim Pick, 2023)

widely cited a good example of coordination between industry and government to identify and address key supply chain and delivery issues and there have been recommendations to set up similar task forces and roadmaps for other low carbon generation technologies and for the electricity networks required to deliver power system decarbonisation (Skidmore, 2022). A number of these have been referenced above and further to these, the government has since set up the Offshore Wind Acceleration Taskforce (OWAT) (BEIS, 2022g) with a mandate that includes identifying and addressing workforce and supply chain issues.

In assessments of supply chains for offshore wind, the need for enabling infrastructure has been highlighted (Skidmore, 2022). In particular, port infrastructure and vessel capacity in the UK are found to be insufficient to support the assembly of offshore wind turbines, with significant investment required in infrastructure and supply chains for the industry to meet its growth targets to deliver on the broader aims of power system decarbonisation and net zero (Skidmore, 2022; Tim Pick, 2023). Rapid and significant investment in this infrastructure is a key recommendation - e.g. the Floating Offshore Wind Taskforce report who have called for £4 billion in additional investment in ports which was seen as a requirement in order for the industry meet its 5 GW deployment target by 2030 (RenewableUK, 2023). In its March 2023 net zero strategy policy (HM Government, 2023d), the government announced £160 million of funding for "pilots of the Floating Offshore Wind Manufacturing Investment Scheme" aimed at increasing UK port infrastructure capacity and to further reduce the cost of delivering offshore wind – whilst this is aimed at overcoming a significant bottleneck, the quantum falls significantly short of the scale of investment required.

Further, analysis of the broader supply chain capacity for offshore wind has shown that combined targets for offshore wind deployment across the EU, UK and Norway, totalling 165 GW by 2030, exceed current supply chain capacity by 2-10 times (Figure 41). This looks particularly acute as the rapid historical growth in supply chain capacity does not appear to have fully consolidated, with important suppliers such as Vestas & Siemens facing supply chain issues, constraining their capacity to invest in further growth before these issues are resolved (Financial Times, 2023k; Reuters, 2023). The Global Wind Energy Council has in parallel warned that "*spare capacity in wind manufacturing is likely to disappear by 2026*" (Financial Times, 2023m). It is therefore very unlikely that the industry will be able to deliver capacity at the pace required without a significant increase in supply chain investments.

As noted in the discussion on Market Design & Regulations (3.4.4) segment earlier in this assessment, there is an important opportunity to link supply chain action to key decision points in the offshore project development timeline, such as the seabed leasing and CfD auctions (Skidmore, 2022; CCC, 2023c). This would help align investments in the supply chain with the growing pipeline of offshore wind generation projects and help de-risk delivery. It should be noted that this would most likely increase the "clearing price" for CfD support and increase the effective subsidy spend by government.

Overall

Overall, the analysis of publicly available assessments and input from industry experts shows that there is a significant and complex challenge around workforce readiness and the government is taking the ramp-up opportunity and challenge seriously and looking to address bottlenecks with urgency and in coordination with a broad base of stakeholders. However, progress on the broader supply chain appears more limited. Given its critical role in delivering the target, and the current gap in a comprehensive approach to ensure its adequacy, this is an area that needs timely and broad intervention. As a result, the assessment for this segment is rated as Amber.

3.4.9 Digitisation [Yellow]

Digitisation and data infrastructure have become increasingly important in the energy sector, with stakeholders looking to leverage digital technologies to achieve decarbonisation goals, improve efficiency, and enhance energy security.

Responses to the REMA consultation expressed concerns over NGESO's digital infrastructure, transparency, and decision-making processes, and many stressed the importance of ensuring equitable access to smart technologies and safeguarding users from price spikes while emphasizing the need for cybersecurity (DESNZ and BEIS, 2023h; E3G, 2023; Industrial Strategy Committee, 2023; Regen, 2023a). The Independent Review of Net Zero recommended a campaign to promote digital technologies in industry, highlighting underinvestment in digitalization in the UK (Skidmore, 2022).

Government have undertaken a number of initiatives to accelerate the digitisation of the power system. DESNZ and Energy Systems Catapult initiated the Energy Digitalisation Taskforce, focusing on digital transformation and the development of a 'digital twin' for the power system (BEIS, Ofgem and UKRI, 2021; Ofgem, 2022b; Current News, 2023o; DESNZ, 2023e). In parallel, the UK government, Ofgem, and Innovate UK are actively collaborating to drive digitisation in the energy sector, with a focus on improving data availability and exchange (Energy Systems Catapult, 2021, 2023b; Ofgem, 2022e, 2023c).

Overall, our assessment found that there are areas of digital infrastructure where the UK is not currently delivering at the pace required, in particular through the ways in which it remains a blocker to reforms around market design, which are on the critical path to infrastructure delivery. However, this also appears to be an issue at the forefront of government policy action indicated by Ofgem's various initiatives in this space, as well as the continued work of the Energy Digital Taskforce. This segment is therefore given an assessment rating of Yellow.

3.4.10 Security & Resilience [Yellow]

Security and Resilience considerations have been evaluated and recommendations made across several recent publications, including those by the CCC (CCC, 2023c, 2023a) and NGESO in their Resource Adequacy, Net Zero Market Reform and FES 2023 reports (National Grid ESO, 2022f, 2023i, 2023n).

Segment Assessment & Discussion

The material covered as part of this research emphasise the importance of ensuring that the UK's decarbonised power system is built with sufficient resilience to future climate conditions, citing that much of the system is yet to be built and that current resilience specifications may not be fit for purpose going forward (CCC, 2023c).

A key concern which is repeatedly highlighted is that governments and industry may be significantly underestimating the vulnerability of interconnected systems, with energy, water, and IT infrastructure often located together (National Grid ESO, 2022f; CCC, 2023c, 2023a). As mentioned in the Digitalisation & Data Infrastructure section, steps are being taken to try and identify these vulnerabilities with the Digital Twin initiatives.

A key recommendation is for the government to develop a pathway to "minimum resilience standards" for the electricity system, with a regular review and revision process (CCC, 2023a, 2023c). The reports also suggest boosting the geographical diversity in the spread of offshore wind capacity between the east and west coasts of the UK, which would reduce the impact of wind droughts by making wind generation more consistent (National Grid ESO, 2022f; CCC and AFRY, 2023).

National Grid's Resource Adequacy report similarly emphasises the importance of better understanding and modelling weather patterns as a key part of security and resilience (National Grid ESO, 2022f). The report suggests that weather patterns will be the dominant driver of stress periods in a fully decarbonised power system, representing a change for the GB system, as tight periods have traditionally been driven by plant availability and high demand. The most challenging situations found by their analysis are weather patterns extending across North-West Europe that result in prolonged periods of low wind during winter.

Across the published material analysed and the expert interviews, it was emphasised that there will be greater inter-dependence with neighbouring countries who may be experiencing similar weather conditions at the same time as the UK, and as the volumes of interconnection grows, the understanding of these flows during times of system stress – from both under capacity but also over supply – becomes increasingly important, and that this is not at a sufficient level today.

Grid standards and the approach to resilience will need to adapt to new forms of generation. There will need to be a shift from a plant & infrastructure-based failure modes and timelines to a more systemic approach that emphasises and better understands impacts of large weather systems on generation, impacting multiple countries, and building models and understanding of how other grids will also respond to these weather systems (National Grid ESO, 2022f; CCC, 2023c).

This is an area where key industry actors such as NGESO are conducting substantial work, and whilst concerns raised by the CCC and others do not appear to be a bottleneck for deploying the infrastructure needed to achieve the target, there is likely to be substantial benefits from front loading more of this thinking and modelling before most of the infrastructure is deployed, in particular around standards. It should also be noted that the documentation released as part of government's updated net zero policies in late March 2023 (DESNZ, 2022a, 2023b, 2023h, 2023t; DESNZ and BEIS, 2023d; HM Government, 2023f, 2023d, 2023g, 2023a, 2023e, 2023h; HM Treasury, 2023a) included very little (if any) detail on the approach to integrate these concerns, highlighting a potential gap in thinking.

Overall, the pace of progress on establishing revised standards to ensure a resilient decarbonised power system will need to accelerate, but the work already being carried out in this space appears well aligned to deliver what is required to meet the target – the segment is therefore given an assessment rating of Yellow.

3.4.11 System Modelling & Forecasting [Green]

Accurate, spatially and temporally granular system modelling is a critical aspect of delivering a decarbonised power system, as it enables simulations and forecasting of load and generation under different weather and load conditions.

In July 2022, the UKERC published independent research (Chaudry *et al*., 2022) into the modelling capabilities of existing power system models used for simulations and forecasts, finding that gaps were primarily around research areas that were non-technical and around values related research questions such as the impacts of different scenarios on access to energy. The UKERC review also highlighted that as of July 2022, there were no models that were able to represent multiple energy vectors (e.g., electricity, hydrogen, heat) across scales (e.g., across transmission and distribution). We did not come across any updates to this, suggesting a gap in current whole system modelling capabilities.

The "digital twin", highlighted above, should further allow for very granular representation and modelling of the power system infrastructure across generation, distribution, transmission, storage, and load, further increasing the accuracy and utility of forecasts (Current News, 2023o; National Grid ESO, 2023s).

Overall, whilst ongoing research in non-technical areas and addressing of gaps in whole system modelling capabilities could lead to further improvements in system modelling and forecasting, modelling capabilities were not highlighted as a bottleneck to the delivery of the target across the materials reviewed. The current state of modelling is aligned with the delivery of the target and there is continuous research effort to ensure continued alignment, therefore this segment is assessed with a rating of Green.

3.4.12 Research & Innovation [Light Green]

The UK Innovation Strategy, published October 2021, defines innovation as "the creation and application of new knowledge to improve the world" (DSIT and BEIS, 2021). Research & Innovation is a key enabler of achieving power system decarbonisation and the net zero 2050 targets for the UK – indeed many of the technologies, processes and business models required to achieve it are yet to be invented and scaled (CCC, 2022, 2023a). The UK has a world class research and innovation infrastructure, ranked fifth on the Global Innovation Index and is the highest ranking G7 and G20 economy (DBT, 2023).

The government has undertaken a systematic approach to understand and support innovation needs for achieving net zero, including power system decarbonization. This includes the Energy Innovation Needs Assessment (EINA) in 2019, the UK Innovation Strategy, the Net Zero Innovation Framework, and the Net Zero Innovation Portfolio. The Net Zero Innovation Portfolio, with a £1 billion innovation fund, has been established to address the ten focus areas identified in the Net Zero Innovation Framework.

Additional funding for research and innovation, exceeding £4 billion, was allocated under the "Delivery Plan 2022 to 2025," with contributions from Ofgem and the aim of providing private sector clarity on priority areas for investment. However, recent announcements have not been accompanied by updated sectoral gap analyses to align funding with current priority areas. The CCC has recommended updated, evidence-based roadmaps for new technologies and accelerated demand-pull initiatives.

Overall, the UK has a well-funded, whole system approach to supporting Research & Innovation for net zero, including power system decarbonisation, and has world-class institutions that are able to conduct cutting edge research. There remains a continued need to ensure policy priorities are aligned with the latest gaps that are arising across different sectors, and to continue to support innovations as they look to scale beyond primary research. As a result, the segment is given an assessment rating Light Green.

3. Segment Assessment & Discussion

4. Conclusions & Recommendations

The net-zero decarbonisation target for the power system in 2035 is ambitious, requiring both a substantial increase in low-carbon generation and an unprecedented rollout of network infrastructure. This rollout has been estimated to cost over £500 billion and if achieved would be one of the largest and most rapid deployments of national infrastructure in the UK's history. The rollout is complicated further by the broad geographical distribution of new variable renewable generation and the locational mismatch between generation sites and demand centres. This Briefing Paper has explored the progress in delivering the net-zero target utilising a framework assessment dividing the delivery process into 28 segments, consisting of both infrastructure delivery segments and enablers, such as governance, planning and financing. In this concluding section, summary ratings of the segment assessments are presented as part of the framework and a set of collated key recommendations for segments rated Red or Amber are presented. The recommendations are primarily sourced from the corpus of material examined as part of the research, but do not present an exhaustive list of potential actions that could be considered in each segment.

Across the 28 individual segments considered, two infrastructure segments and five enabling segments require urgent reform to deploy infrastructure at the rates required to achieve a decarbonised power system by 2035 (Figure 42). One of these segments is already the subject and focus of extensive reform efforts to accelerate deployment, namely Planning & Permitting, but this review finds that the six remaining segments – Distribution, Energy Efficiency, Strategy, Coordination & Governance, Public Engagement & Advocacy, Financing & Investment and Workforce & Supply Chains – require concerted policy effort with a level of ambition that is aligned with delivering the net-zero target, which remains absent today.

Up until the latest announcements as part of the 2023 Autumn Statement, Connections was also rated Amber but the culmination of policy focus has lead us to upgrade the assessment of this segment to Yellow.

Several findings stand out in particular, many relating to industry and government leadership and coordination. Strategy, coordination and governance measures need to be taken to provide certainty in delivery and to reassure private-sector investors and stakeholders – these should include the publication of a comprehensive long-term strategy for the delivery of a decarbonised, resilient, power system by 2035 as well as the creation of a minister-led infrastructure delivery body with responsibility to deliver this plan and to coordinate actions across governmental and regulatory bodies. Public understanding and engagement as to the scale of the task is currently limited – the public should be informed through a comprehensive communication strategy and involved in decision making around key trade-offs. Generous community compensation schemes for those communities that will bear more of the burden in hosting critical infrastructure should be agreed and implemented. Levels of financing and investment will need to substantially increase to fund the transition, and the government should set out a clear, credible strategy for attracting private investment, especially given the international environment and the significant incentives being offered by the US and EU. Workforce and supply chains similarly need attention, and central government should aim to produce a net-zero and nature workforce plan by 2024 in conjunction with devolved administrations, local authorities, businesses and trade bodies. Likewise, supply chains need to be comprehensively analysed and understood. Finally, in order for the net-zero target to be met in an economic and secure way, a nationally coordinated energy efficiency programme should be launched without delay.

Near-term developments, in particular around the impact of revised modelling which should result in accelerated connections offers by March 2024, and the pace with which planning reforms which are out for consultation are implemented, should be tracked closely to ensure alignment with delivery of the target and continued timeline implementation.

Overall, while substantial challenges remain in deployment, the UK's endeavour to have a net-zero power system by 2035 is ambitious, necessary, and forward-thinking, building on a history of world-leading climate and energy policies. It has the potential to position the country as a leader in this field, with the subsequent stimulation of export opportunities in design, deployment and expert advice as well as new business and job-creation opportunities across many sectors in the UK.

4. Conclusions & Recommendations

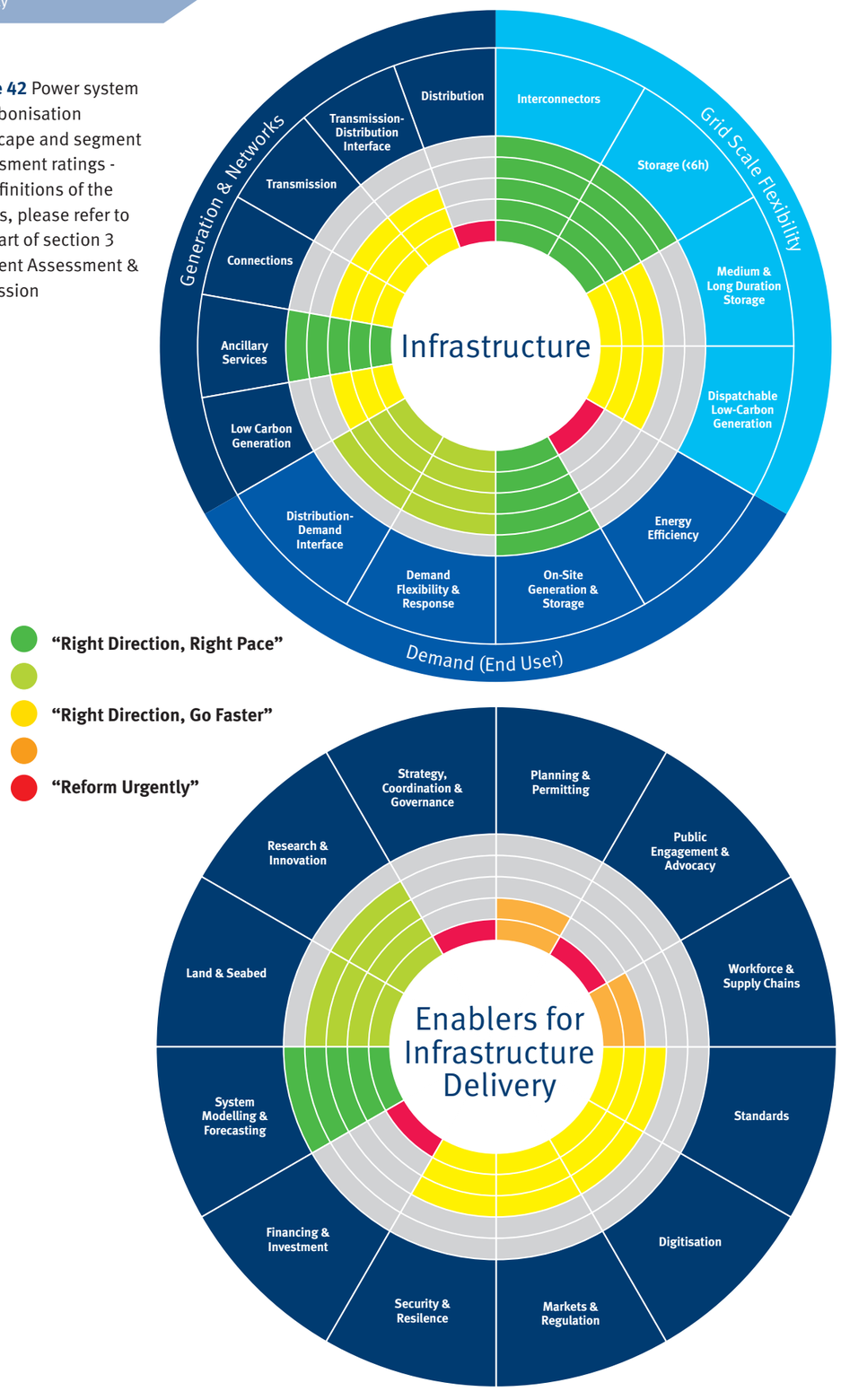


Figure 42 Power system decarbonisation landscape and segment assessment ratings - for definitions of the ratings, please refer to the start of section 3 Segment Assessment & Discussion

Collated Recommendations

Segments Rated Red:

i) Distribution

a. For all DNOs to publish costed upgrade plans that are compatible with the increases in usage consistent with the Sixth Carbon Budget, and that are also compatible with future mitigation and adaptation needs,

b. Use the ENA body to publish a coordinated and holistic network upgrade plan across all DNOs that are compatible with the delivery of the target,

c. Ahead of the 2026 decision on use of hydrogen for domestic heating, and by 2024, for the FSO or other relevant body to identify which areas of the UK are unlikely to be suitable for hydrogen, and progress immediately with low regret infrastructure upgrades to distribution networks (CCC, 2023a).

ii) Energy Efficiency

a. Implement the commitment made in autumn 2021 by implementing plans to elevate privately rented homes in England and Wales to an EPC C rating by 2028 (CCC, 2023a),

b. Extend energy efficiency standards beyond the private rented sector. Establish net zero compatible minimum standards for new and existing housing. Align these with the Future Home Standard from 2025 to ensure elevated energy efficiency in all new build properties (National Grid ESO, 2023i),

c. Allocate the additional £6 billion funding for energy efficiency measures immediately. Implement strong, long term financial incentives, grants, and subsidies to ensure widespread access to energy efficiency improvements. Prioritise low-income households to eliminate disparities in accessing energy-saving upgrades (Industrial Strategy Committee, 2023),

d. Launch a nationally coordinated energy efficiency and home retrofit programme without delay. Develop tailored solutions that address regional needs and encourage participation and, in parallel, promote energy-saving actions for both businesses and households through widespread public engagement initiatives. Guarantee consumer and supply chain certainty by integrating support for heat pump installation, energy efficiency measures, and incentives for upgrading blocks of flats (CCC, 2023a),

e. Fast-track the implementation of low-carbon heat networks and electrification. Drive emissions reduction and minimise fossil fuel dependency, enhancing public confidence for the transition to electrified heating solutions (CCC, 2023a),

f. Directly adapt successful international policies such as France's Marime Rénov' and Sobriété Énergétique, Canada's Greener Homes Initiative and Strategic Energy Management programs, and others (CCC, 2023a).

iii) Strategy, Coordination & Governance

a. Rapidly implement the updated Strategy and Policy Statement clarifying the objectives Ofgem, FSO and ministers following the completion of the consultation and provide a very clear sense of direction to the regulator and system operator on how to manage the political and distributional trade-offs intrinsic to their responsibilities (CCC, 2023a; DESNZ, 2023y; Industrial Strategy Committee, 2023; Ofgem, 2023i),

b. For the FSO, DESNZ or other capable organisation, to publish as soon as possible, in order to enable effective strategic planning, a comprehensive long-term strategy for the delivery of a decarbonised, resilient power system by 2035. This strategy should incorporate the portfolio of investments required for the electricity power system but also other energy vectors that interface with this such as hydrogen, CCUS and heat networks infrastructure and

Conclusions & Recommendations

how these key interactions will be managed (Skidmore, 2022; CCC, 2023a, 2023c; Energy Systems Catapult, 2023a; Helm, 2023; Industrial Strategy Committee, 2023; NAO, 2023a; Public Accounts Committee, 2023),

c. Appoint or create a minister-led infrastructure delivery body with responsibility to deliver this plan, and coordinate actions across the FSO; Ofgem; DESNZ; DEFRA; DLUHC; DofE; Devolved Administrations; Local Governments; and other relevant government departments and bodies (Skidmore, 2022; CCC, 2023a, 2023c; Energy Systems Catapult, 2023a; Helm, 2023; NAO, 2023a).

iv) Public Engagement & Advocacy

a. Involve the public in the decision making required on key trade-offs, potentially through further deliberative forums such as follow-ups to the UK Climate Assembly, to build a social contract around the actions required for delivery and to enable community buy-in,

b. Rapidly publish a comprehensive public communication strategy and plan, with the aim of establishing a broad base of support for the overarching goal of net zero and power system decarbonisation in the interim,

c. Rapidly conclude and implement a generous community compensation scheme for those communities that will bear more of the burden of hosting critical power system infrastructure (and the significant disruptions during their construction), exploring all avenues including part community ownership, discounted services, investment in local services and infrastructure and direct cash compensation (RenewableUK, 2011; DESNZ, 2023c; NIC, 2023a).

v) Financing & Investment

a. Rapidly publish a plan for how the UK can increase levels of investment in power system decarbonisation infrastructure by 2-3 times relative to the previous 12-year period, including the likely sources of this increase in capital (i.e. how much of this can come from domestic vs international sources) and lay out a clear and credible plan for how the UK will compete for and secure international sources of capital in the face of significant incentives being put into place by other jurisdictions (such as the EU and USA) (CCC, 2023a; Helm, 2023; Industrial Strategy Committee, 2023),

b. As well as incorporating relevant non-price factors in to CfD auctions as appropriate coming out of the consultation, for the government to reconsider their approach to CfD auctions, and recalibrate these to once again be tools for price discovery for the delivery of the levels of capacity increase required at that time, rather than a tool to drive prices down for each successive auction round (Industrial Strategy Committee, 2023),

c. For the government, TES and CES to consider funding EIAs and determine mitigations upfront for seabed that is allocated for offshore wind development ahead of auctions, to provide certainty and reduce cost for developers and reduce the time it takes to secure permitting once seabed leases have been secured, making these auctions overall more attractive for investors and developers (Industrial Strategy Committee, 2023; NIC, 2023a),

d. For the government to consider other forms of crowding in private investment, e.g., through incentivising public procurement to procure low carbon, helping fund the 'green premium' paid and bringing these costs down (CCC, 2023a; Regulatory Assistance Project, 2023).

Segments Rated Amber, & Priority Segment:

i) Workforce & Supply Chains

a. Collaborate with devolved administrations, local authorities, businesses, trade bodies, and accrediting organisations to create a comprehensive Net Zero and Nature Workforce Action Plan by 2024. In alignment with net zero objectives, this plan must outline strategies to address workforce priorities, assessment of skills gaps and shortages, address barriers to inclusive labour market entry into essential occupations for the transition, and provide a clear roadmap for addressing these gaps through the education system (Skidmore, 2022; CCC, 2023a),

b. Rapidly undertake and publish a comprehensive analysis of the supply chain requirements critical to the net zero transition and the interim target of power system decarbonisation (Skidmore, 2022),

c. Drive investment in world-class port infrastructure at a scale that matches the £4 billion need identified, crucial for project delivery and securing a significant portion of supply chain jobs, growth, and expertise within the offshore wind industry (Tim Pick, 2023)

d. Identify plan to co-develop offshore wind's demand for steel and efforts to decarbonise the UK steel sector. Foster a mutually beneficial relationship that supports both industries' growth (Tim Pick, 2023)

Segments Rated Amber, but not Priority Segment:

i) Planning & Permitting – this is a segment that is currently undergoing consultation to accelerated projects through planning, aiming to halve the time taken to get consent across a number of key infrastructure investments including new transmission lines, offshore wind and solar (DLUHC, 2022, 2023a, 2023e, 2023d, 2023b). The government have already started to implement a number of the recommendations from the April 2023 report from the NIC, however they should respond to these recommendations in full (NIC, 2023a).

Conclusions & Recommendations

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Energy Futures Lab

Energy Futures Lab is one of seven Global Institutes at Imperial College London. The institute was established to address global energy challenges by identifying and leading new opportunities to serve industry, government and society at large through high quality research, evidence and advocacy for positive change. The institute aims to promote energy innovation and advance systemic solutions for a sustainable energy future by bringing together the science, engineering and policy expertise at Imperial and fostering collaboration with a wide variety of external partners. The Energy Futures Lab Briefing Papers are periodic reports aimed at all stakeholders in the energy sector. They bring together expertise from across Imperial College London to provide clarity on a wide range of energy topics.

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