ENGINEERING NET ZERO

SUMMARY REPORT
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ATKINS
Member of the SNC-Lavalin Group

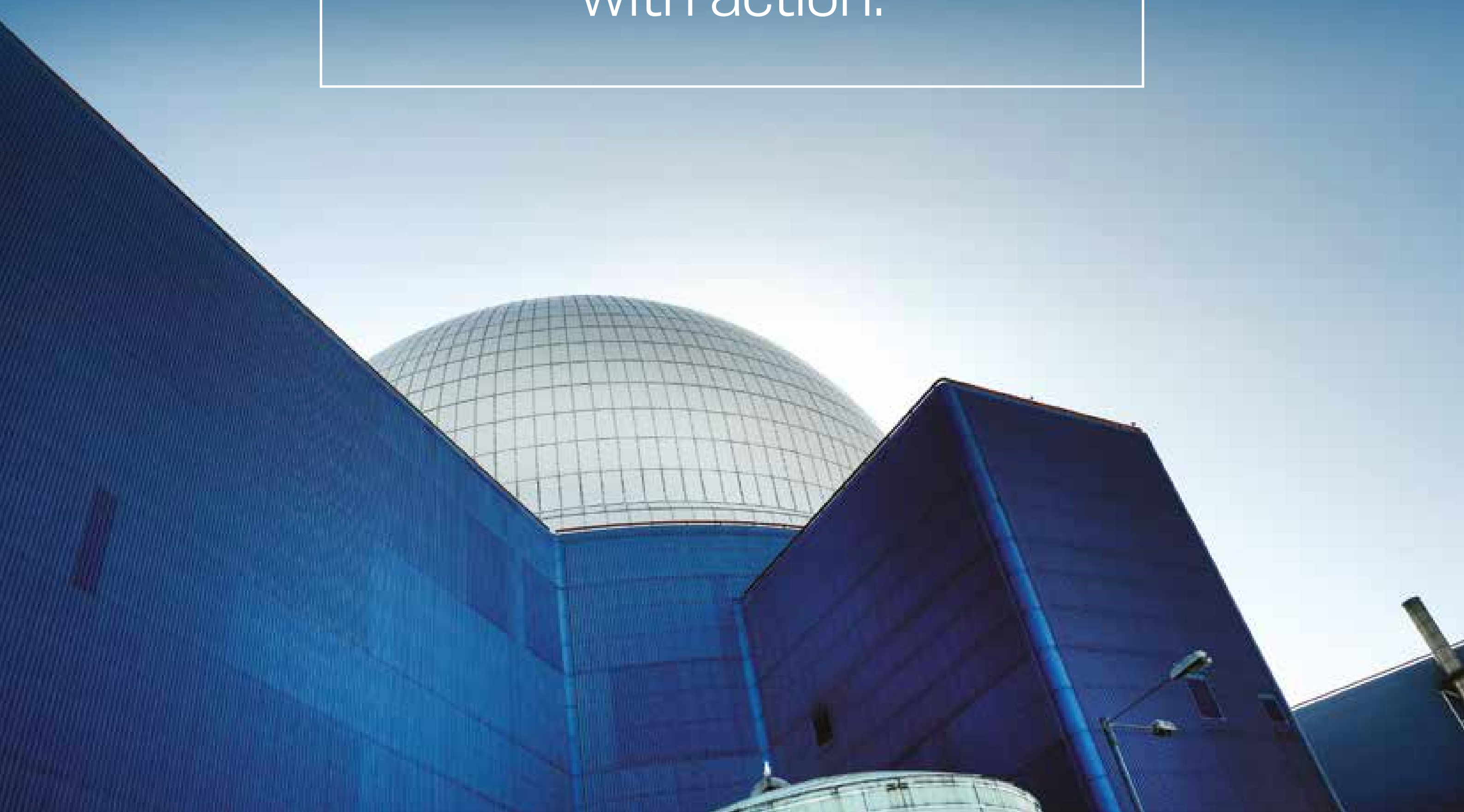
Meeting the UK's 2050 Net Zero target is achievable, but the risk of falling short is very high.

Contents

Tables

Figures

As the urgency around climate change intensifies, decisions across Government must accelerate if the UK is to match ambition with action.



Introduction

Understanding the Net Zero risks, challenges and opportunities.

As the urgency around climate change intensifies, decisions across Government must accelerate if the UK is to match ambition with action.

The Net Zero Challenge

In October 2018, Atkins published a paper titled The Road to Decarbonisation [REF 1]. The paper evaluated potential changes in our key energy markets in light of several reports published by advisors and commentators since the release of the UK Government's Clean Growth Strategy [REF 2] in October 2017.

Almost one year later, the pressure for action on climate change has increased. In May 2019, the Committee on Climate Change (CCC) published its report advising that the UK should accelerate its decarbonisation programme, targeting Net Zero (i.e. net zero greenhouse gas emissions) by 2050 REF 3, REF 4].

In June 2019, the Government accepted CCC's recommendation, taking the significant step of becoming the world's first major economy to pass laws to end its contribution to global warming by mid-century. The target now is for the UK to bring all greenhouse gas emissions to Net Zero by 2050, surpassing its previous target of an 80% reduction from 1990 levels.

CCC's Net Zero report provides a 'proof of concept' scenario for a future energy system. This scenario shows that Net Zero by 2050 is theoretically possible but recognises that further work is required to develop the pathways to achieve this goal.

Our Capability & Experience

Atkins, a member of the SNC-Lavalin Group, is a leading engineering, design and project management organisation with capability and experience in delivering major capital projects and programmes that span the energy, transportation and infrastructure sectors.

We have an extensive portfolio covering Carbon Capture and Storage (CCS) design and delivery, energy storage and system integration/resilience. We also have considerable experience in the offshore wind, nuclear and oil and gas sectors. Above all, we maintain a 'technology agnostic' stance across the industry.

These credentials, coupled with our expertise in transportation and infrastructure, give us a unique perspective on the challenges of achieving Net Zero.

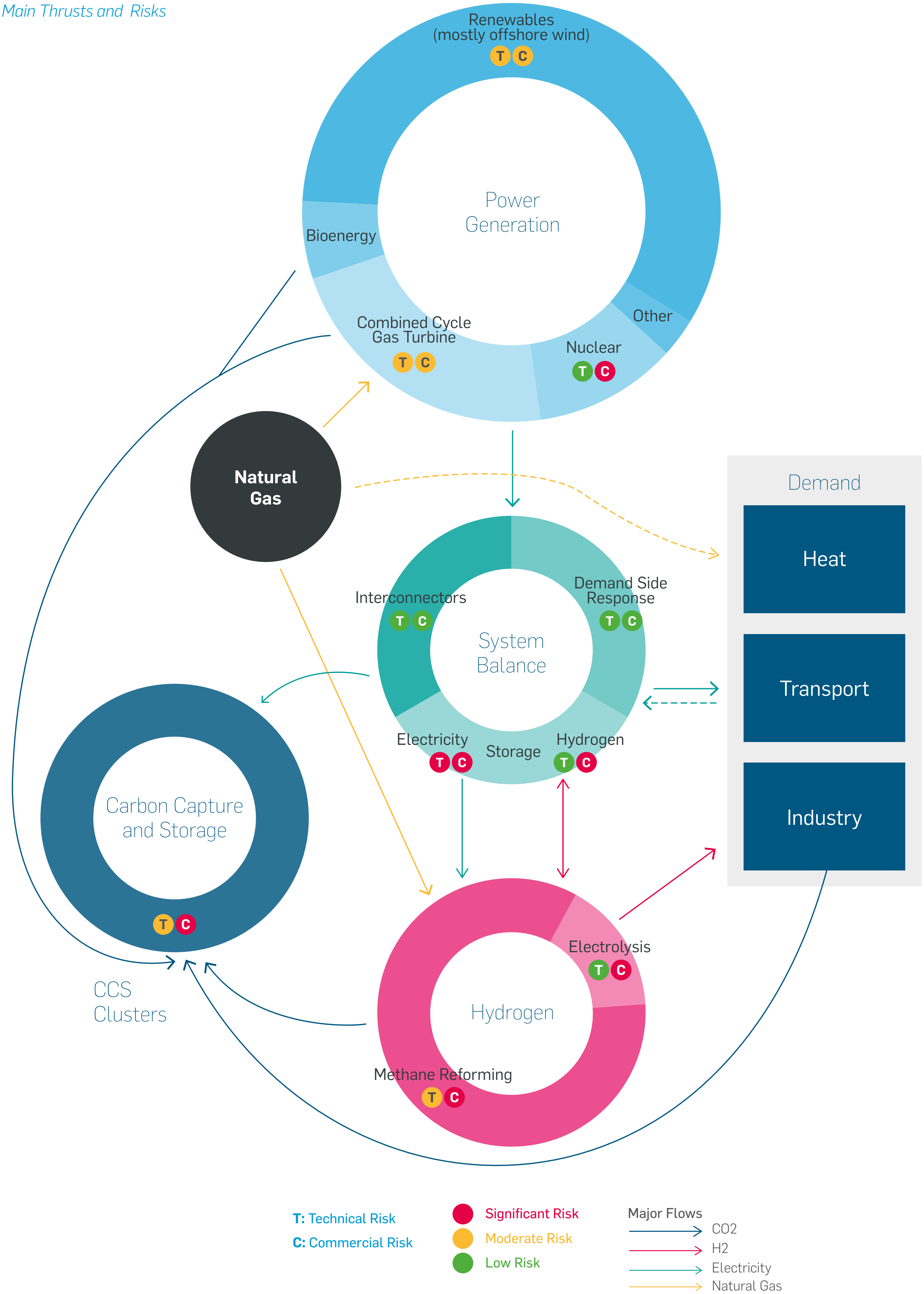
The year 2050 may seem a long way off, but for major energy projects the journey from initiation to commissioning can take ten years or more. Many such projects depend on difficult policy decisions, which can only be properly made on a 'whole system' basis. As the urgency around climate change intensifies, decisions across Government must accelerate if the UK is to match ambition with action. Inevitably, such a wide-ranging programme of change in a complex and highly interdependent system will entail significant risks that need to be carefully assessed.

Our Approach: A toolkit for policy makers

This paper provides a summary of the detailed engineering assessments carried out by Atkins to understand the risk, challenges and opportunities associated with the Net Zero target. It builds on the work from The Road to Decarbonisation [REF 1] to identify the range of major capital projects that will be required to achieve Net Zero by 2050. It also assesses the engineering implications of Net Zero; this includes project delivery risks that will need to be managed, alongside non-technical risks that will need to be addressed through Government policy decisions.

Net Zero will not be achieved by major projects alone: millions of homes must be better insulated, millions of gas and oil fired domestic boilers must be changed, thousands of electric vehicle charging points must be installed. These are huge programmes of work with challenges of their own, and we do not underestimate their significance. We will address these topics in separate publications.

Figure 1 – Net Zero System - Main Thrusts and Risks



Biofuels may be able to address difficult sectors such as aviation, but it will be important to ensure that biomass is used where it can have most impact, which may not be in power generation.

For such a complex challenge, we recognise that we do not have all the answers. Frankly, no single organisation does. However, we believe our approach provides a basis for further discussions with Government and industry on the key issues that will shape the UK's journey to 2050.

This summary report is underpinned by more detailed assessments in our Engineering Net Zero Technical Report, which can be accessed at www.atkinsglobal.com/engineeringnetzero.

In Figure 1, we illustrate the main thrusts and risks within the Net Zero System, with the varying levels of risk indicated.

Our approach provides a 'toolkit for policy makers'. This toolkit is made up of:

1. A diagnostic approach to analyse the Net Zero system interdependencies

The system components on the supply and demand side of the Net Zero system are interconnected, as described in greater detail in the sections that follow.

A change to any one of these components will have a knock-on effect within the overall system.

For example, if CCS is slower to deploy at scale than planned, more low-carbon generating sources would be required. In turn, hydrogen production would be impacted or would need to switch to electrolysis, which is more costly and electricity intensive.

Our diagnostic approach helps to analyse the impacts and implications of these system interdependencies.

> The components of Net Zero are interconnected. A change to any one of these components will have a knock-on effect within the overall system.

2. Our engineering assessment

Focusing on the Net Zero capital project components, system interconnection and optimisation, we have considered the following questions:

- What are the technologies that need to be engineered and deployed to meet the Net Zero target?
- Are these technologies well established and proven? If not, what technology development is required?
- Can the technologies be deployed in sufficient quantity and at pace to achieve the target? How will they be financed?
- What are the principal risks, both technical and commercial, that could derail efforts to achieve the target?

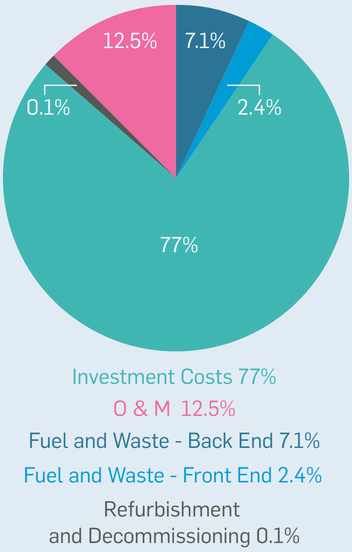
3. A risk framework

To help identify, manage and mitigate the key Net Zero risks, we have developed a comprehensive risk framework, which is presented in summary in this document.

Seven Key Conclusions

From our analysis of Net Zero, we have arrived at seven key conclusions. These are set out briefly here, along with the underlying evidence and our core recommendations.

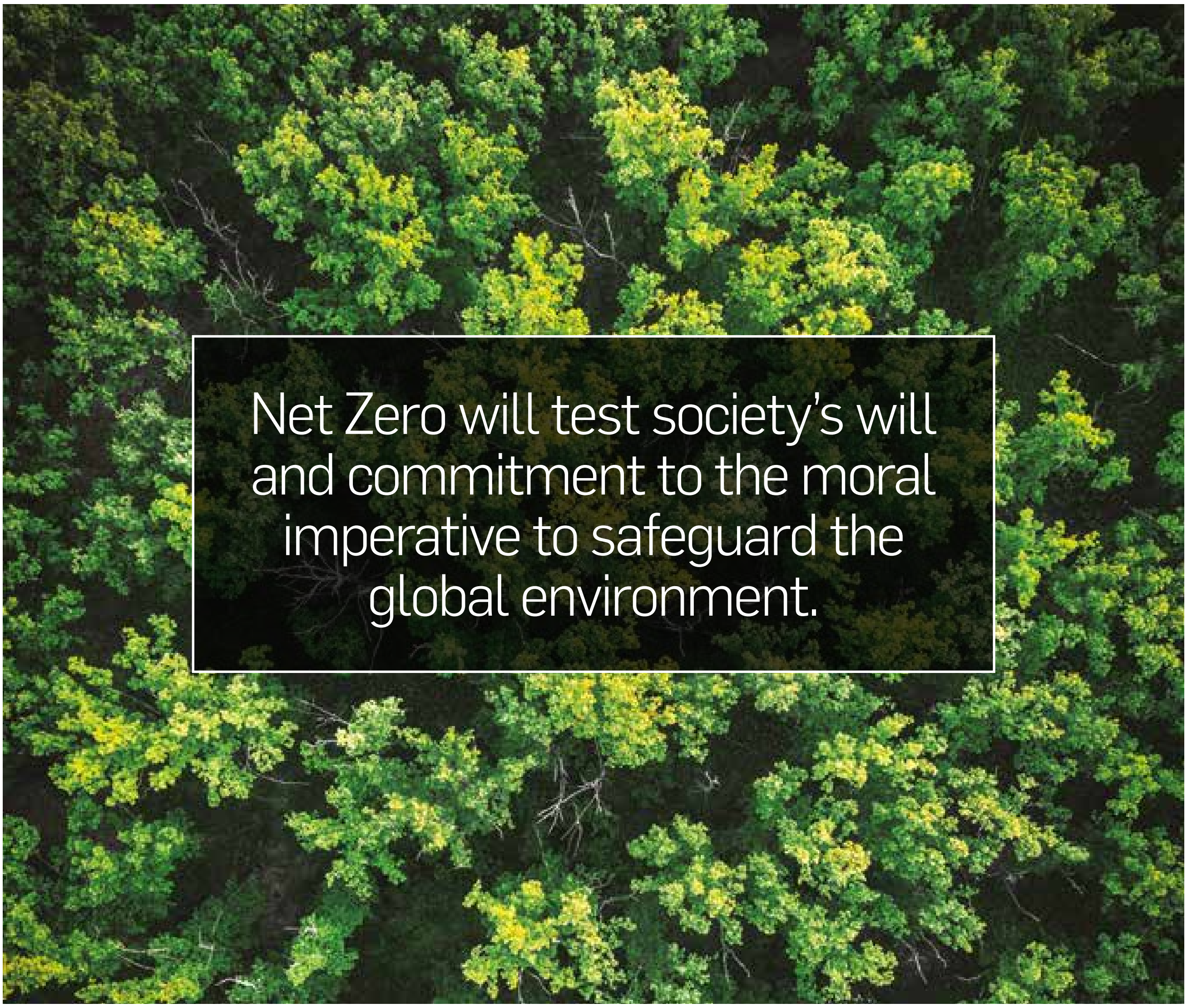
Conclusion	Evidence	Recommendation
1. The Committee on Climate Change's (CCC) Net Zero scenario is theoretically achievable but the risk of failure is high. This 30-year programme demands an evolving and flexible approach to ultimate system configuration.	The potential generating capacity build rate of up to 9-12 GW per annum is higher than anything achieved in the UK in the previous 50 years. Implementation of multiple technologies in an integrated system further complicates this challenge.	Focus on early build projects for all strands of Net Zero to: › de-risk design and construction; › prove technologies at scale; and › identify necessary policy and market triggers. This process will reduce time and cost in subsequent construction, enabling delivery at the least whole system cost and minimising bills for the consumer.
2. The 2050 Net Zero Energy System will be highly complex with interdependencies between subsystems. These sub-systems will be managed by 'smart' algorithms to minimise required operating margins. It is highly unlikely that an optimal system will be delivered by pure market forces or Darwinian selection. Government intervention is inevitable and is already the major determining factor in what gets built. Such intervention must be set against a strategic view of the 'system architecture' and based on evaluation of 'whole system' cost. The creation of an Energy System Architect (ESA) is critical.	Technology selection and comparison are challenging. In power generation, for example, selection on the basis of Levelised Cost of Energy (LCOE) between nuclear, Combined Cycle Gas Turbines (CCGT) with CCS and offshore wind would neglect the following: › The value of nuclear in underpinning stability › Potential CCGT/CCS synergies with wider CCS needs (e.g. hydrogen generation) › The integration costs required to manage offshore wind's intermittency Least cost to the consumer can only be assured by developing robust whole system cost analyses. And this can only be achieved within a defined framework of system architecture.	Develop and implement an ESA, with a view to: › achieving the 2050 Net Zero goal, demonstrating least cost to the consumer; › maintaining system architecture, including system requirements, subsystem interfaces and technology diversity; › balancing strategies for national, high density systems (e.g. cities), decentralised systems and their interaction as a whole; › defining and optimising 'smart system management' and energy storage strategies and quantification; › developing a strategy for national infrastructure, such as gas transmission and networks, that may be necessary for whole system operability but at much reduced utilisation levels; and › ensuring strategic energy security and resilience.

Conclusion	Evidence	Recommendation
3. Nuclear presents a low technological risk but is significantly challenged by the current financial model. Net Zero assumes that nuclear will contribute only 11% of electricity generation, down from 18% today. Only nuclear and CCGT/CCS can offer firm low carbon power, an essential component for a stable, least cost energy system. With UK gas production declining, nuclear offers the only source of firm power with assured security of supply. With considerable risk linked to the Net Zero reliance on CCS (see below), nuclear is a critical yet currently undervalued element within the system. Although Net Zero references work by ETI suggesting that up to 35GW of new nuclear could be required by 2050, it appears that only 3 new stations are factored into Net Zero (Hinkley C, Sizewell C and Bradwell B) which total 8.6GW. Government policy has been to build 15GW of new nuclear, replacing our retiring fleet.	The breakdown for nuclear LCOE in OECD countries has been estimated as follows [REF 5]: As this chart indicates, the upfront and ongoing financing costs (i.e. CAPEX and cost of capital) dominate the total. This highlights the key challenges facing those who seek to continue the UK's nuclear programme. 	Urgently prioritise current Government consultation on alternative financing models (RAB) for nuclear and develop innovative approaches to construction risk. The operation of the electricity market also needs to be reviewed to evaluate the impact of intermittent renewables on firm power pricing. The nuclear industry must focus on: › Innovation to reduce design and construction times and risk › Implementation of the Nuclear Sector Deal › Greater collaboration with the renewables industry to develop approaches to whole system optimisation (this could be facilitated by the ESA). Critically review the potential consequences of effectively eliminating nuclear beyond those projects that are currently being developed. Model alternative scenarios with substantially reduced CCS and energy storage, reflecting the technical and commercial risks to both.
4. CCS is critical to the proposed Net Zero scenario. This constitutes the biggest risk to achieving Net Zero, even if the final required capacity of CCS is reduced.	The Net Zero scenario calls for176Mt/yr of CCS, which is four times current global capacity. Today, the UK has zero CCS and no firm plan for a demonstration-scale project. The Department for Business, Energy & Industrial Strategy (BEIS) would like the option of deploying CCS from the mid-2030s, subject to costs coming down. BEIS's proposed plans and the Net Zero ambition are not aligned. Net Zero assumes that over 40% of our energy in 2050 will depend on CCS.	Accelerate pilot projects but be sure to treat them as pilot projects. Previous attempts to launch demonstration projects in which sponsors/contractors were expected to carry significant 'performance risk' met with predictable failure. Develop alternative 'Plan B' scenarios for varying reductions in available CCS, including reduction to 25% of the proposed capacity (45Mt/yr) – equivalent to today's total global capacity.

Conclusion	Evidence	Recommendation
5. The anticipated rapid growth of offshore wind is achievable in terms of build rate, but there are uncertainties regarding assumed capacity factors. There are also challenges around integration, system balancing and stability. Global supply chain pressure and the shift to floating systems may arrest or reverse the recent reduction of LCOE. The UK has opportunities to lead in floating wind, but it must increase UK supply content and capture IP.	Offshore wind has prospered by being the only power generation technology that has benefited from clear and consistent UK policy (for 20 years) and funding appropriate to the industry. As a result of this, by late 2019, industry learning curves and technological developments in deploying the 8.4GW of installed offshore wind capacity have been significant. Contracts for Difference (CfD) strike prices have reduced significantly but are likely to 'bottom out'. The average 'fleet wide' LCOE of offshore wind farms currently operating under CfDs is approximately £148/MWh (with a capacity factor of around 40%). This LCOE will continue to fall as the 2017 CfD and 2019 CfD projects come online to an average circa £75/MWh and will further improve in the long term as older fields retire and future fixed foundation fields start up (although floating offshore wind farms will have higher LCOEs to begin with).	Ensure the offshore wind and renewables industry: › implements measures to address the 'hidden costs' of system balancing and stability; › develops UK floating wind technology and IP; › increases UK supply content; and › increases collaboration with the nuclear industry to develop approaches to whole system optimisation such as hydrogen production using nuclear waste heat and surplus renewable power (this could be facilitated by the ESA).

6. Hydrogen may serve as both an energy vector and an energy store. Hydrogen can contribute to industry decarbonisation, domestic heating and transportation. It has great potential flexibility but also some fundamental challenges to be addressed.
Net Zero assumes 30% of UK Energy will be delivered through hydrogen, of which 80% is produced by methane reformation (MR). But MR depends on CCS, thereby significantly increasing the risks associated with the potential role of hydrogen.
	Globally, hydrogen hybrid trains are expected to be the fastest growing sector within the rail industry.
	Domestic heating companies are beginning to develop hydrogen compatible boilers and hybrid heat pump systems.
	TfL has ordered 20 hydrogen-powered double-decker buses.
		Pursue with vigour the current research programme and at least two demonstration projects. Other recommendations include:
		› Technology triggers, such as optimising hydrogen electrolysis at scale, should be prioritised
		› Industries with a key role to play in Net Zero should collaborate on optimal hydrogen system development (i.e. OSW and nuclear taking a whole system view on process heat use and variable generation management)
		› A holistic assessment and solution development programme for the hydrogen lifecycle should be overseen by the ESA. This should encompass:
		  › Hydrogen uses;
		  › Manufacture;
		  › Storage;
		  › Distribution;
		  › Conversion efficiencies and losses.

Conclusion	Evidence	Recommendation
7. With high renewable penetration, system balancing depends on firm power, interconnectors, demand-side response and energy storage. Energy storage is widely misconstrued. There is currently no battery technology capable of gridscale balancing storage – and there is no such technology on the horizon. In addition to the system storage potential of hydrogen, we must be clear about what current electrical storage systems can do. For example, many do not support gridscale fluctuations in generation that last more than minutes.	Battery storage is used for fast response over short periods (seconds to minutes) to maintain system stability. See Figure 19 in [REF 6]. Larger-scale grid balancing over extended periods (minutes to hours) cannot be achieved with batteries. Even smart grid aggregation of multiple small batteries, as proposed in Vehicle-to-Grid scenarios, would not be sufficient. See Figure 5.6 in [REF 1].	Ensure the energy storage debate is grounded in current technology. It should also be clearly structured on both the power achievable (MW to GW) and the duration, which depends on how much energy is stored (MWh).



Net Zero will test society's will and commitment to the moral imperative to safeguard the global environment.

The policy goal of reaching Net Zero by 2050 has been set. Government must lead the way to ensure the UK achieves this landmark target.

Engineering Assessment Overview

In 2050, the Net Zero system will be underpinned by five key components: Increased Electricity Generation; Hydrogen as an Energy Vector; CCS; System Integration; and System Optimisation.

In this section, we introduce these key components and Net Zero as a whole. We also provide an overview of our engineering assessment of the Net Zero system and its implications.

The Net Zero System

2050 Low Carbon Technology Penetration by Sector

- Power Generation 100%
- Heating Existing Homes 90%
- Heating Non-Residential 100%
- Light Vehicles 100%
- Heavy Vehicles 91%
- Industry Processes 100%
- Industry Heat 85%

The policy goal of reaching Net Zero by 2050 has been set. Government must lead the way to ensure the UK achieves this landmark target.

The Net Zero goal is extremely ambitious. It will require coordinated use of what we call the 'four levers of control' across Government departments and through central, devolved and local administrations.

The four levers of control are:

- Exhortation – the societal impact will be significant, public acceptance is critical.
- Taxation – notionally free markets can be directed, for example by the Carbon Tax.
- Spending – Government can lead by supporting research and high-risk development.
- Legislation/Regulation – new laws can aid progress, for example through the banning of petrol and diesel vehicle sales.

Net Zero can only be achieved through a dramatic increase in the rate of change across our entire energy system, incorporating electricity generation, heating, transportation and industry. It also requires changes in how we use our land and live our lives. It even extends to changes in our diet.

Net Zero is a fundamental challenge that will reach into people's homes, their daily travel and workplaces. It will test society's will and commitment to the moral imperative to safeguard the global environment.

It will also test our financial resolve; HM Treasury has suggested that the cost of these changes may exceed £1Tn and has implicitly questioned its affordability [REF 7]. The high cost of achieving 'Net Zero' must be compared with the cost of 'Do Nothing'.

Reaching Net Zero following the path described by CCC [REF 3] will require, over a period of 30 years:

- a four-fold increase in low-carbon electricity generation;
- a ten-fold increase in hydrogen production and infrastructure for its use; and
- the creation of an entirely new industry to capture 176Mt CO_2 per annum, where currently the UK has zero capacity.

In addition to these headline changes, there will need to be substantial changes to the supporting infrastructure. A sophisticated smart grid will also be required to integrate, interface and match supply and demand on a real-time basis at user, regional and national level.

In residential heating, a sector with large seasonal demand variation, Net Zero anticipates extensive use of hybrid heat pumps. These pumps will use both hydrogen and electricity, optimising their energy source to provide least cost heating. In the UK, the impact of climate change may itself mitigate some seasonal demand variation; milder winters could reduce heating requirements, while hotter summers could generate greater air conditioning loads.

The rollout of electric vehicles will also impact electricity demand. At the same time, it might provide an opportunity for energy storage through vehicle-to-grid arrangements supported by smart grid infrastructure. Charging infrastructure will require significant investment and presents challenges in the urban environment, particularly where only on-street parking is available.

Although heating and vehicle charging are major areas of change, we do not consider them in detail in this paper. Instead, we focus on the major projects required to deliver the headline changes referenced above.

Somewhat inevitably, modelling such a complex system is an uncertain process, as the stability of model output can be sensitive to changes in input assumptions. For example, a modest increase in the assumed cost of one form of electricity generation, and a similarly modest decrease in the assumed cost of another, may substantially alter the optimal balance between the two. It might also significantly impact the system's operational characteristics, such as grid stability and storage requirements. Modelling results should therefore be taken as an indication of the direction of travel. This approach recognises that technological developments, changes in gas prices, international market developments and policy decisions could all impact the UK's ability to deliver Net Zero and the mix of investments required. With this cautionary proviso, we have identified what we believe to be the main thrusts of the Net Zero report and considered their feasibility and engineering implications.

Increased Electricity Generation

Net Zero Headlines
By 2050:

- Power generated will double (300 TWhr/yr to 645 TWhr/yr)
- Low carbon energy will increase four-fold (155 TWhr/yr to 645TWhr/yr)
- Peak demand will rise to 150GW
- There will be a sustained build rate of 9-12GW/yr, including the replacement of existing assets

By 2050, Net Zero shows intermittent renewables contributing 58% of power generation, with the remainder being CCGT with CCS (22%), nuclear (11%), bioenergy with CCS (6%) and others (3%).

CCGTs are proven technology and present little technical risk. CCGTs have flexibility that enables rapid response to renewable intermittency. The addition of carbon capture is well understood when operating on a firm basis, but technical issues increase if carbon capture is required on peaking plants with frequent start-stop cycles. In the Net Zero scenario, 28% of generation (CCGT and bioenergy) is dependent on CCS; this is a significant risk which we address below.

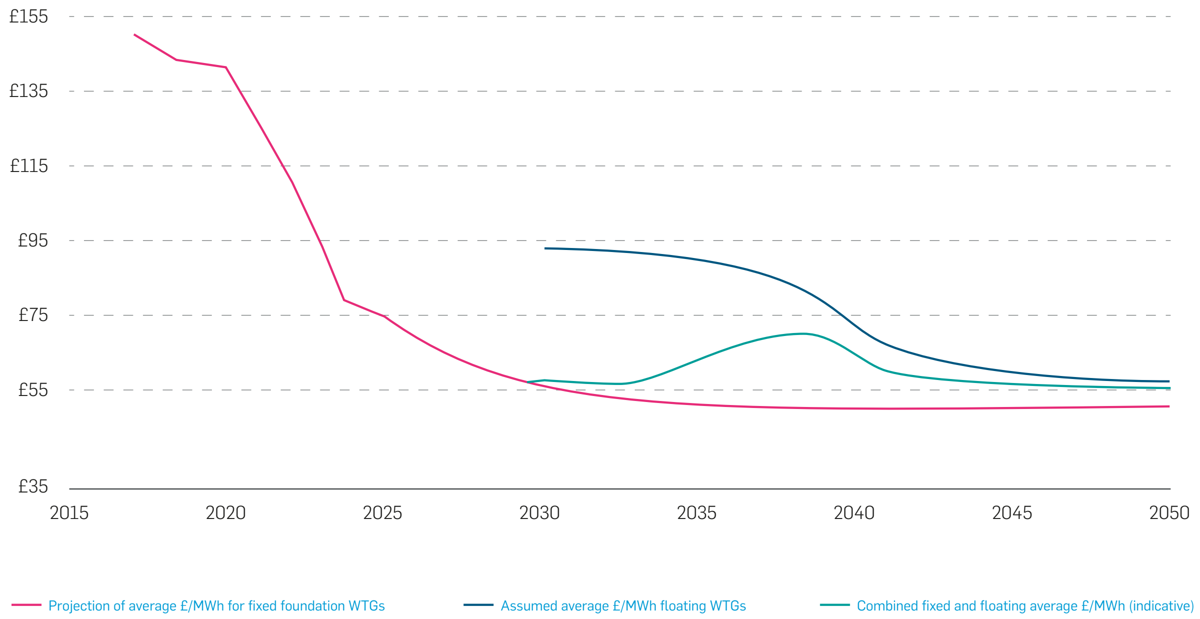
Renewable Energy

In our opinion, the very substantial increase in offshore wind generation, which is central to the Net Zero scenario, is achievable. The rate of technological advancement in this sector has been rapid but is now slowing. Turbines will approach a limiting size and floating units will be needed to achieve the higher availability assumed by Net Zero. We believe that LCOE, which has fallen dramatically in recent years from £150/MWh to £40/MWh, must be nearing its low point due to increasing technical challenges and the bottoming out of many unit costs within projects. It should also be noted that the low price of £40/MWh achieved in the most recent CfD auction is, as yet, a promise that remains to be delivered. The bid prices in the 2019 auction were as low as £39.65/MWh, a drop of 30% since the last auction only 12 months earlier.

This notable strike-price reduction may be feasible due to expected economies and efficiencies, specifically in relation to the wind farms in question. However, our opinion still remains that we are likely to see offshore wind LCOE 'bottoming out', especially once floating wind farms start to be commissioned (see Figure 2).

Furthermore, we do not yet know the actual costs of operating in deeper waters in more exposed conditions.

Figure 2 – Indicative average LCOE £/MWh for both fixed and floating offshore wind farms to 2050



The growing international market may also put pressure on supply chains, which in turn will limit further cost reduction. From a technical feasibility perspective, the scenario is considered relatively low risk with respect to turbines, but moderate risk regarding the shift into deeper waters and the use of floating technology. And while the cost assumptions may be optimistic, prices may soon rebound.

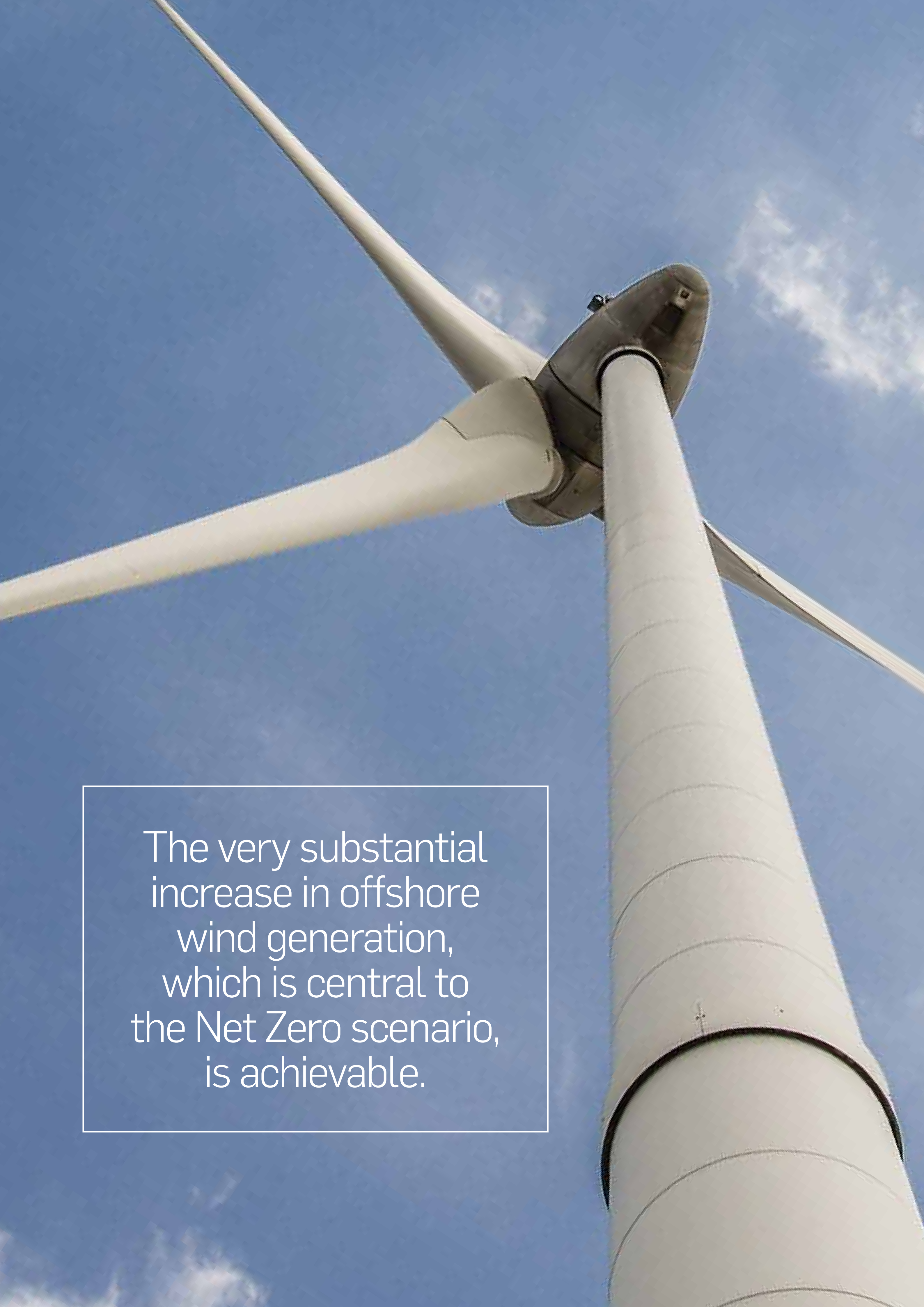
> At the levels suggested in Net Zero, nuclear new build will effectively be shut down on completion of currently developing projects (early 2030s). This would eliminate the only technically proven alternative to CCS for providing firm power.

Whilst we recognise Net Zero has included solar as part of the renewable energy mix, we have not considered this component within our assessment. Two key characteristics of solar that have knock on effects to its effective contribution to the Net Zero system are that it is:

1. highly intermittent – leading to increased system integration costs which need to be factored in to system optimisation considerations;
2. seasonal – solar generation peaks through the summer months at the point where electricity demand is lowest. Credible large-scale, long-term electricity storage would need to be available and implemented to allow the system demands to benefit from solar at the appropriate times.

The overall benefit to the system of deploying tens of gigawatts of solar by 2050 is not clear to us based on the above, but we also recognise that the majority of this capacity would be deployed on a distributed basis and thus falls outside of the major programmes scope of our assessment.

The combination of these points form the basis for our exclusion of solar in the renewable energy mix in our engineering assessment.



The very substantial increase in offshore wind generation, which is central to the Net Zero scenario, is achievable.

New nuclear

Large-scale nuclear is a proven technology with a 60-year operational track record. As such, it presents a low technical risk. However, the recent suspension of the Wylfa project shows that the current UK market model does not support large nuclear project development. Despite existing Government policy commitments to build 15GW of new nuclear, it was not possible to agree a deal structure that would enable Wylfa to proceed. We believe the LCOE of Wylfa was approximately £75/MWh, but to achieve this required the Government to invest equity and carry a share of the project risk. The collapse of the project brings into focus the tension between climate policy goals and the Government's risk appetite. It puts in doubt the UK's deployment of new nuclear, which is the only viable alternative to CCGT with CCS for providing firm low-carbon power.

At the levels suggested in Net Zero, nuclear new build will effectively be shut down on completion of currently developing projects (early 2030s). This would eliminate the only technically proven alternative to CCS for providing firm power.

Neither CCGT with CCS nor new nuclear will be forthcoming without determined policy changes which are sustained over the long term. Therefore, while technically feasible, the increase in electricity generation to meet CCC's target is at risk. Our high-level analysis of the technical and commercial risks to each of Net Zero's main thrusts are summarised in Figure 1 on page 6.

The assigned risk assessments in such a broad range of technologies and applications are, of necessity, somewhat subjective. We have based the assessment on the current technical status of each technology, its dependence on other technologies and the current and anticipated commercial arrangements for deployment. These are given in more detail in the technical report.

Hydrogen

Net Zero Headlines
By 2050:

- There is likely to be a ten-fold increase in UK hydrogen production from today's output
- Extensive storage and transmission rebuilding will be required
- Repurposing of existing natural gas distribution infrastructure will be needed to accommodate the physical properties of hydrogen

Net Zero includes a substantial role for hydrogen (30% of UK's energy) as fuel for heating, industry and transport. Hydrogen has the potential to act as both an energy store and an energy vector. However, while its use presents few fundamental engineering problems, there are numerous issues which, cumulatively, raise doubts about the extent of this use and associated costs.

Hydrogen can be a substitute for natural gas but has a significantly lower energy density on a volume basis (in gaseous form it is approximately one tenth the density of methane).

The transport of hydrogen also presents issues relating to its small molecular size and ability to penetrate other materials. Our national natural gas transmission grid is built from steel pipe, which would be unsuitable to carry hydrogen. As noted in the BEIS hydrogen supply chain study [REF 9], it is assumed that an entirely new high-pressure transmission pipeline network would be needed to transport hydrogen to local distribution networks. While this programme of works does not represent a major technical risk, its undertaking would be significant in scale. There are also regulatory issues relating to the use of hydrogen in the current gas distribution system.

Table 1. Physical properties of hydrogen

Property	Hydrogen	Comparison
Density (gaseous)	0.089kg/m^3 (0 °C, 1 bar)	1/10 of natural gas
Density (liquid)	70.79kg/m^3 (-253°C, 1 bar)	1/6 of natural gas
Boiling point	-252, 76°C (1 bar)	90°C below LNG
Energy per unit of mass (LHV)	120.1 MJ/kg	3x that of gasoline
Energy density (Ambient cond, LHV)	0,01 MJ/L	1/3 of natural gas
Specific energy (liquefied, LHV)	8.5 MJ/L	1/3 of LNG
Flame Velocity	346 cm/s	8x methane
Ignition range	4-77% in air volume	6x wider than methane
Autoignition temperature	585°C	220°C for gasoline
Ignition energy	0.02 MJ	1/10 of methane

Notes: cm/s = centimetre per sound; kg/m^3 = kilograms per cubic metre, LHV = lower heating value; MJ = megajoule; MJ/kg = megajoules per kilogram; MJ/L = megajoules per litre.

Repurposing the infrastructure

At distribution level, most gas pipes are now plastic and better suited to carrying hydrogen, depending on the pressure. Substitution of natural gas by hydrogen to decarbonise domestic heating is clearly a very attractive proposition, so long as existing infrastructure can be repurposed cost effectively. Government has initiated a series of research projects to further identify and assess the opportunities and technical issues associated with hydrogen use. As part of these efforts, the Hy4Heat programme [REF 10] is paving the way for a large-scale community trial to fully evaluate the option to replace natural gas with hydrogen, resolve technical issues and demonstrate safety.

Methane Reforming

Currently, the least cost production method for hydrogen is Methane Reforming (MR). MR is effectively pre-combustion carbon removal from methane, with the disposal of the resulting CO2 through CCS. The Net Zero scenario depends on hydrogen from MR (specifically advanced-gas reforming). As such, the technical risks specific to the production, storage and distribution of hydrogen are compounded by the risks of dependency on CCS, as noted below.

Hydrogen's dependency on CCS can be eliminated by using alternative production methods such as electrolysis, which are currently more costly than the projected cost of MR with CCS. Technical evaluation should prioritise the potential for hydrogen production through means other than MR, thereby partially de-risking the hydrogen option.

Large-scale hydrogen production through electrolysis would have a significant impact on the optimal power generation mix and could help smooth peak power demand. However, this option is currently considered unaffordable. As electrolysis becomes more efficient at higher temperatures, one potential route is to link hydrogen production to nuclear generation by leveraging the waste heat from nuclear plants. At the higher temperatures reached in gas-cooled reactors, production of hydrogen by thermochemical processes is feasible, but the required technology is far from mature.

In terms of energy efficiency, the round-trip efficiency of hydrogen formed through MR with CCS, storage and reuse in gas turbines would be less than 30% [Figure 6, REF 11]. Therefore, hydrogen as an energy store in a power-to-power cycle is not immediately attractive.

Net Zero Headlines
By 2050:

- There will be up to 176Mt/yr of CCS – more than four times today's global capacity
- Several 'clusters' of multiple and diverse CO2 sources sharing infrastructure (e.g. CCGT with CCS for electricity production, industrial plants with CCS, hydrogen production) will need to be developed – note, no such clusters with end-to-end CO2 management and CCS exist today

CCS has the potential to manage CO2 from almost any source and offers a route to negative emissions (removing CO2 from the atmosphere) through bioenergy with CCS. Net Zero relies heavily on large-scale CCS, which is needed to capture carbon from hydrogen production through MR and to sequester CO2 from industry. It is also required to enable low-carbon power generation by CCGT and bioenergy plants, which are assumed to contribute 28% of electricity in 2050 [REF 3].

CO_2 injection for enhanced oil recovery is a very well established technology and many internationally respected experts have concluded that large-scale CCS is essential for decarbonisation. However, the progress of CCS has been slow. We believe this is because CCS has been viewed through the lens of decarbonising electricity production from coal or gas plants, where its deployment isn't necessary for commercial operation and its application results in a significant energy penalty.

Inevitably, CCS adds to the cost of electricity produced, which means no utility will deploy CCS at scale until mandated by regulation, or until the price of carbon emissions exceeds the cost of CCS. In rapidly changing energy markets, where the intermittency of subsidised renewables is driving price instability, the economics of CCS become even more problematic.

> Many internationally respected experts have concluded that large-scale CCS is essential for decarbonisation.

The concept of clustering

For many industrial carbon sources, the implementation of CCS at individual site level is likely to be uneconomic, hence the concept of clustering industrial sources to share the costs of infrastructure. Even with such clusters, it is difficult to structure economic projects without an 'anchor' user. As a result, clusters tend to be structured around a power generator. The idea is that the generator's need will ease the infrastructure cost burden on the industrial users. However, as noted above, CCS is not attractive for power generators and is becoming even less attractive as markets change, resulting in a catch-22 situation.

CCS system and technology

A typical post-combustion CCS system involves three main elements: CO_2 capture, CO_2 transport and geological storage. Different processes are available for CO_2 capture and the specific engineering maturity depends on both the emission source (for example a CCGT, a biomass burner or an industrial process) and the chosen CO_2 capture technology. As a general statement, CO_2 capture processes vary from technically proven to requiring significant development.

CO_2 transport is well developed, as is geological injection, while most CCS experience is currently linked to enhanced oil recovery. In power applications, the cost of CO_2 capture may be up to 80% of the cost of the CCS chain, with transport and storage being relatively small cost components.

Although much of the technology is well understood, the integration of capture from multiple diverse sources to create a viable end-to-end system presents an engineering risk. However, this risk is far outweighed by the contractual/deal-structuring risk which was well characterised in the Oxburgh report, which set out many of the obstacles to CCS deployment [REF 12].

Unprecedented development

CCS development at the scale envisaged by Net Zero is unprecedented, with estimates suggesting the UK will need to sequester up to 176Mt CO2/year. It is reported that current global CCS capacity of 18 large plants store almost 40MtCO2/yr, much of which is single source for enhanced oil recovery [REF 13]. In the BEIS CCS Action Plan [REF 14], a large-scale CCS facility is defined as one that can capture, transport and store 400kt CO2/yr. The Net Zero scenario therefore requires the equivalent of 440 large-scale plants to be operational in 2050, storing more than four times the current total global capacity. To date, despite two attempts over ten years, the UK has failed to deploy a single CCS demonstrator project. The programme risk is obvious.

The current BEIS Action Plan for CCS has been heavily criticised by the BEIS select committee, whose report is aptly titled CCS – Third Time Lucky? [REF 15]. We have no doubt that CCS remains a very significant risk to the Net Zero scenario. BEIS intends that UK should have the option of deploying CCS at scale in the 2030s, subject to costs falling sufficiently. If the decision on CCS deployment is delayed until after 2030, reaching 176MT/yr by 2050 will be extremely challenging. If, after 2030, it becomes clear that CCS is uneconomic for power generation or hydrogen production, then alternative firm low-carbon power will be needed. And the only firm low-carbon power alternative is nuclear.

The cost of CCS, meanwhile, depends on system specific attributes: the size of the system, the sources of CO2, location and proximity to transport pipelines, and proximity to suitable storage sites. Cost estimates vary considerably. Frequently, the cost of CCS has been characterised by reference to the estimated LCOE for electricity generated from a baseload thermal (coal or gas) power plant fitted with CCS. For a CCGT with CCS, estimates are in the range of £80-100/MWh, but often with provisos regarding access to and re-use of pre-existing oil/gas infrastructure and liability for long-term storage security.

The Wood report [REF 16], which has been widely quoted, provided a comparison of costs of CCS applied to various sources of CO2 in power generation. For a CCGT with post-combustion CCS, Wood estimated an LCOE of £70/MWh. However, the purpose of the Wood report was to compare the costs of different technical options, assuming plant availability of 90% and a load factor of 100%. This does not provide an estimate of the cost of power generated using CCS within the integrated UK electricity system. The Net Zero report refers to modelling by Imperial College, suggesting mid-merit gas plants will be operating at 25% load factor, which would greatly increase the LCOE. It also raises technical issues regarding CCS design for highly variable loading.

The risk of CCS dependency

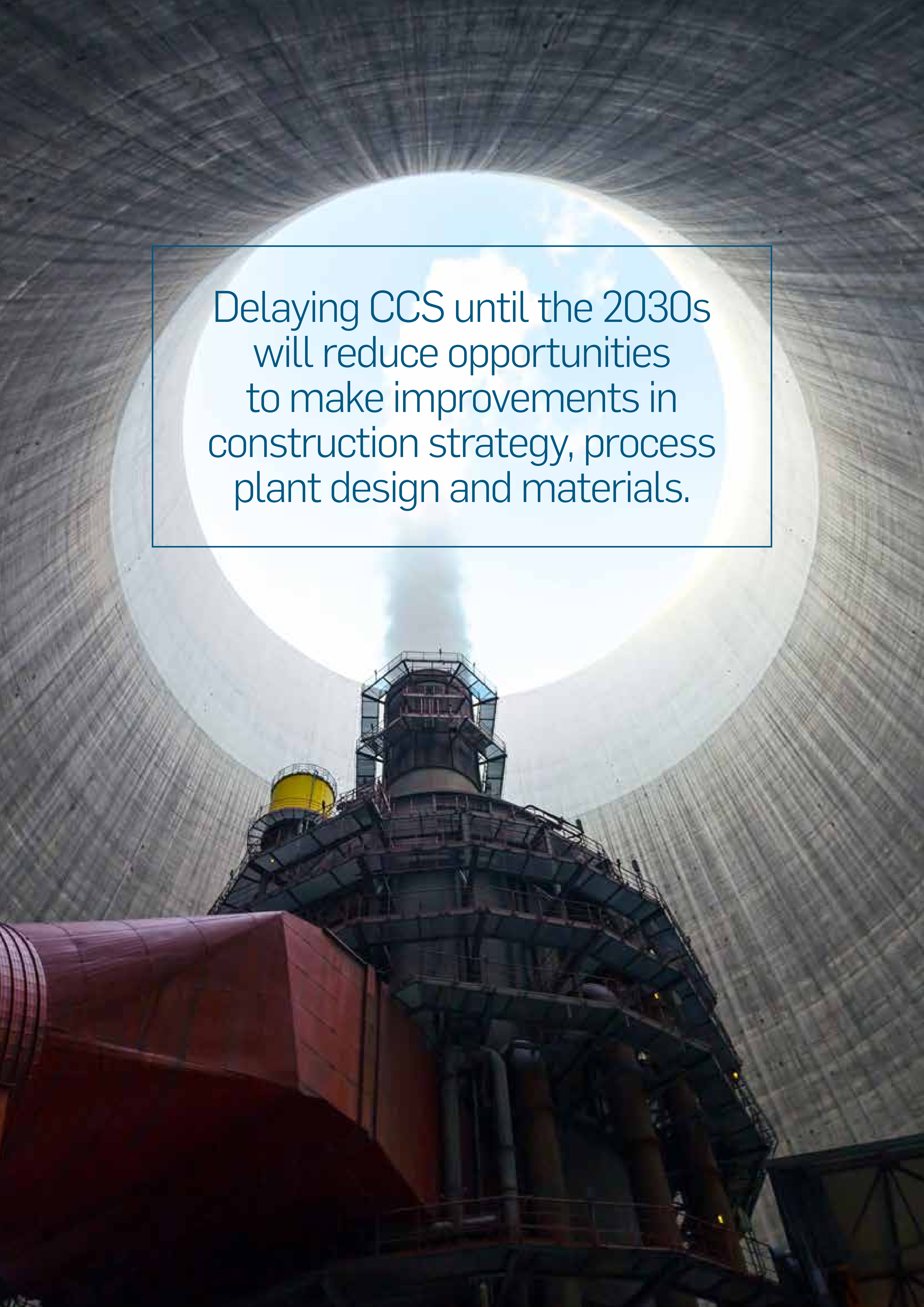
In our opinion, the dependency of Net Zero on extensive CCS is the biggest risk to the scenario. Engineering uncertainties are significant and commercial obstacles to deployment will be very difficult to overcome. The outlook will only improve if the Government is prepared to intervene, effectively mandate CCS and accept significant commercial risk for the carbon transport system and long-term storage liability.

Even then, costs are very uncertain and cannot be estimated without detailed analysis at both the whole system and individual project levels.

Furthermore, there is a significant mismatch between Net Zero's dependency on large-scale CCS and the BEIS ambition to create an option for CCS deployment at scale in the 2030s, subject to price reductions. Without successive projects the industry cannot learn by doing. Delaying CCS until the 2030s will reduce opportunities to make improvements in construction strategy, process plant design and materials.

It will also limit the chances of improving the efficiency of the carbon capture process.

Cost reduction can be achieved, but it requires the experience that only comes from full-scale development and operation. Demonstration projects in the 2020s will therefore be necessary to move this industry forward.



Delaying CCS until the 2030s will reduce opportunities to make improvements in construction strategy, process plant design and materials.

System Integration

Net Zero Headlines

- Net Zero suggests that improvements in system flexibility can come from increased deployment of battery storage, interconnection and fast-response gas plant as well as demand-side management and improvements in system operation, but these are not modelled in detail
- Regulatory frameworks may need to evolve as new vectors emerge and with an increasing integration between systems
- Policy and regulatory frameworks should also encourage flexibility (e.g. demand response, storage and interconnection)

The modelling of systems with high renewable dependency usually demonstrates a need for balancing intermittency through a range of mechanisms. These include demand side response (effectively compensating customers for reduced supply), imports from interconnectors and energy storage.

The modelling of systems with high renewable dependency usually demonstrates a need for balancing intermittency through a range of mechanisms. These include demand side response (effectively compensating customers for reduced supply), imports from interconnectors and energy storage.

Demand-side response presents few technical issues and interconnectors are well established, However, largescale storage presents considerable uncertainty and the Net Zero report does not appear to account for storage requirements. Proven energy storage systems, such as pumped-storage hydro, require suitable sites which are not easy to find. Other large-scale physical systems such as flywheels, dropping weights and compressed air caverns may offer some storage potential but require development. Hydrogen produced from electrolysis can act as an energy store, but power-to-power round trip efficiency is low.

Furthermore, no currently available battery technology is capable of grid-scale storage. Large amounts of storage might be achieved through the aggregation of multiple small-storage volumes, such as electric vehicle batteries and user-owned batteries.

However, this would require the implementation of a very sophisticated smart grid and the development of a market mechanism to compensate owners. All of which tell us that a system dependent on large energy storage to maintain supply carries a high degree of technical risk.

We believe that optimal energy system design must be based on system integration, which balances interdependencies between power generation, heat, transport and industry, both strategically and within each subsector. System design is similar to the function of an architect. System architecture ensures overall balance and provides the framework within which detailed specification and the engineering of individual elements can be performed.

Modelling systems and scenarios

At present, there are a number of respected modelling groups analysing the energy system. Some have different objectives, but all are attempting to identify future system architectures. National Grid's Future Energy Scenarios (FES) modelling [REF 20] seeks to identify a range of plausible scenarios that 'bracket' likely outcomes, although does not attempt to define the future system design. Similarly, CCC uses modelling to assess the feasibility of decarbonisation but does not present this as the system design.

National Grid's FES modelling includes scenarios with varying degrees of decentralisation. From an engineering perspective, the degree of decentralisation is absolutely critical. Historically, the UK's system has been one of large centralised plants and a transmission system feeding distribution networks. The move to more decentralised power generation (which is already occurring) has many implications, with reverse flows in the existing power networks affecting both control and cost.

The challenges of financing multi-billion pound projects, social acceptance, site availability and economies of scale all impact the balance between large centralised facilities and smaller distributed facilities.

In the case of hydrogen, there are two very different paths. Reliance on MR with CCS would take us towards large centralised production plants, storage and distribution. Alternatively, if hydrogen is produced by electrolysis, we would see a shift towards smaller distributed production facilities closer to users and smaller local storage facilities.

As we move closer to 2050 and investment levels increase, investors will need assurance that their investments will not become stranded by system change. While stable system architecture will help to provide such assurance, Government-backed financial assurance mechanisms, such as long-term CfDs, could also come into play.

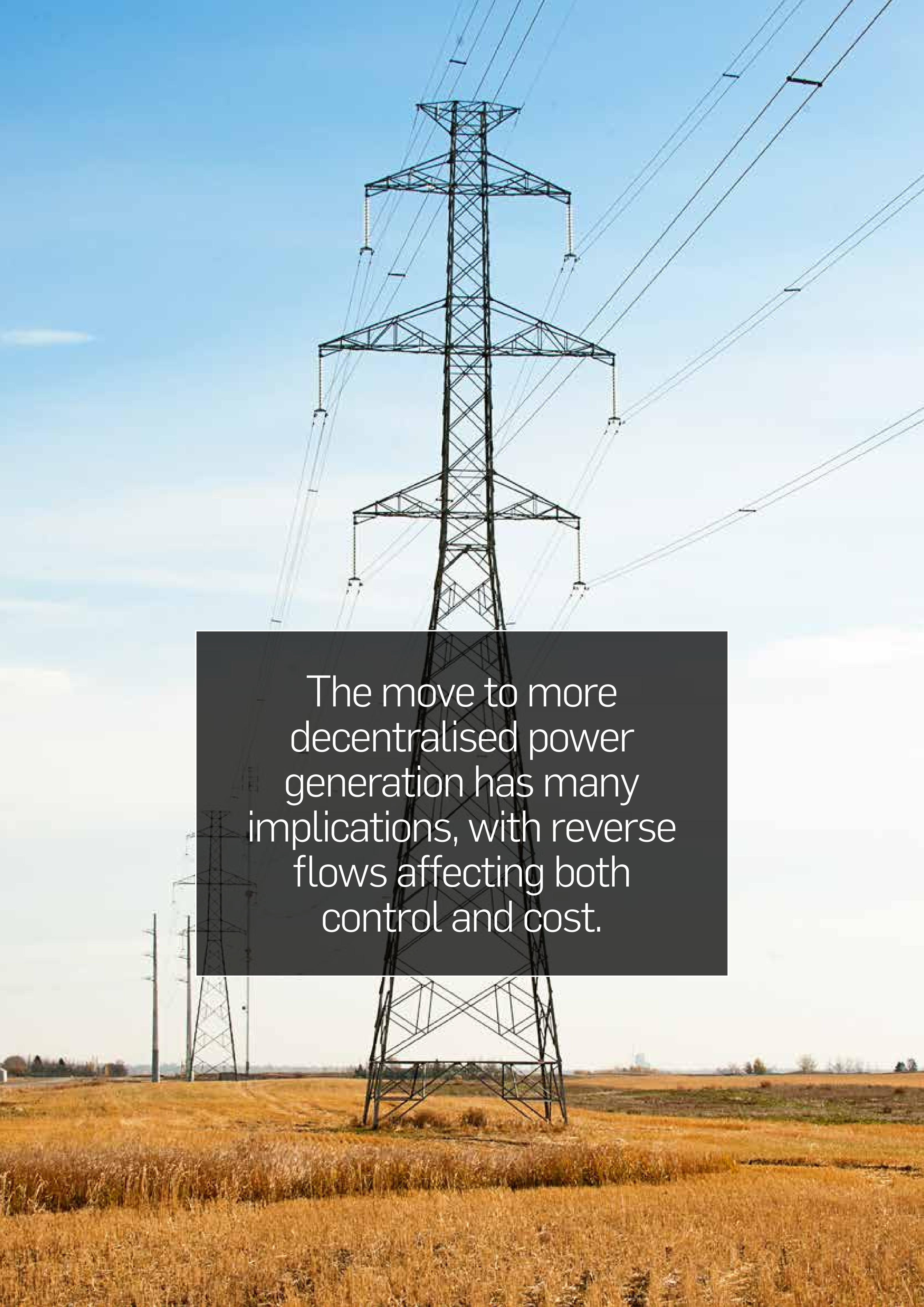
System Optimisation

Net Zero Headlines

- An additional £20/MWh (or more) could be incurred as system integration costs when intermittent renewables achieve greater than 50% penetration.
- Offshore wind and nuclear are projected to be comparable in cost to users when whole-system costs are taken into account.
- Gas with CCS will be considerably more expensive

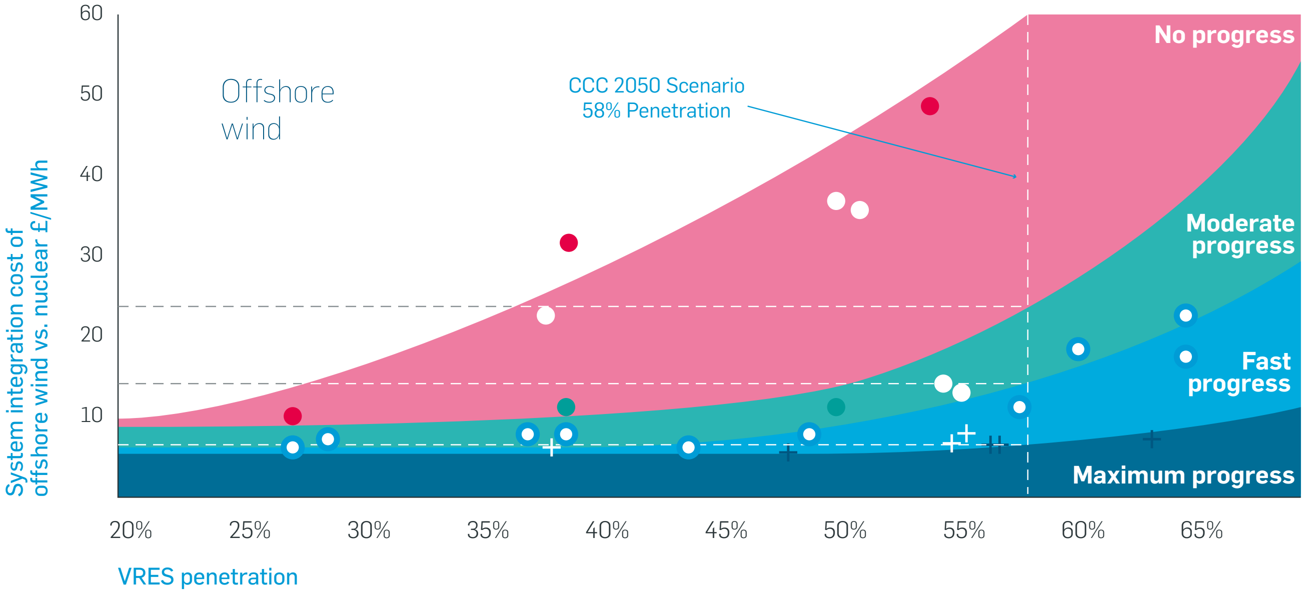
Much of the published energy system modelling attempts to describe an optimal system delivering energy at least cost. CCC endeavours to identify least cost pathways to achieve the UK's carbon reduction goals. Modelling therefore relies on input assumptions regarding costs for each element within the system.

The Net Zero scenario shows intermittent renewables contributing 58% of electricity in 2050. The remaining 42% comprises mostly CCGT and bioenergy (both with CCS) and nuclear. The system-wide requirements and costs of supporting high levels of intermittent generation are the subject of much academic debate. CCC suggests that up to 40% intermittent power will incur system integration costs of about £10/MWh. At 50% penetration, the cost may be £20/MWh or more, rising as the proportion of intermittent generation increases. The frequently quoted LCOE figures for different types of generation do not include these system integration costs, therefore they do not provide a valid basis of comparison. Modelling of system integration costs for offshore wind shows a wide range of outcomes, as presented in Figure 3 below, based on data from CCC technical annex [REF 21].



The move to more decentralised power generation has many implications, with reverse flows affecting both control and cost.

Figure 3 – Modelling of system integration costs for Offshore Wind. Based on Fig B2.1 [Ref 21]



In Table 2 we have taken Net Zero's assumed cost of the major electricity generation sources in 2025 and 2050 [REF 4], which we assume to be LCOE, and added the system integration costs presented in the Net Zero Technical Annex [REF 21]. This shows that by 2050, with renewables exceeding 50% of generation, the incremental cost (on a system wide basis) of nuclear and offshore wind are equal and both less than gas with CCS.

Figure 3 Notes. Integration costs are expected to be similar for onshore wind, but will differ for solar as it has a different seasonal generation profile. Estimates of system integration costs for a system with a carbon intensity of 100gCO2/ kWh. 'No progress' has no added system flexibility. 'Moderate progress' includes 5 GW of new storage, 25% DSR uptake and 10 GW of interconnection. 'Maximum progress' includes 15 GW of interconnection capacity (15 GW) and 100% uptake of DSR.

Table 2 - Comparison of costs for different generation sources in 2025 and 2050, including potential system integration costs [REF 3]

Technology	LCOE at the Point of Generation in 2025 (£/MWh)	System Integration Costs for Intermittency (£/MWh)	2025 Cost of Electricity (£/MWh)	LCOE at the Point of Generation in 2050 (£/MWh)	System Integration Costs for Intermittency (£/MWh)	2050 Cost of Electricity (£/MWh)
Offshore Wind	69	10	79	51	20	71
Solar PV	47	10	57	41	20	61
Nuclear	98	0	98	71	0	71
Gas CCS	79	0	79	79	0	79

** Lower percentage of renewables penetration in 2020s*
*** Over 50% intermittent renewables penetration in 2050*

Uncertain predictions

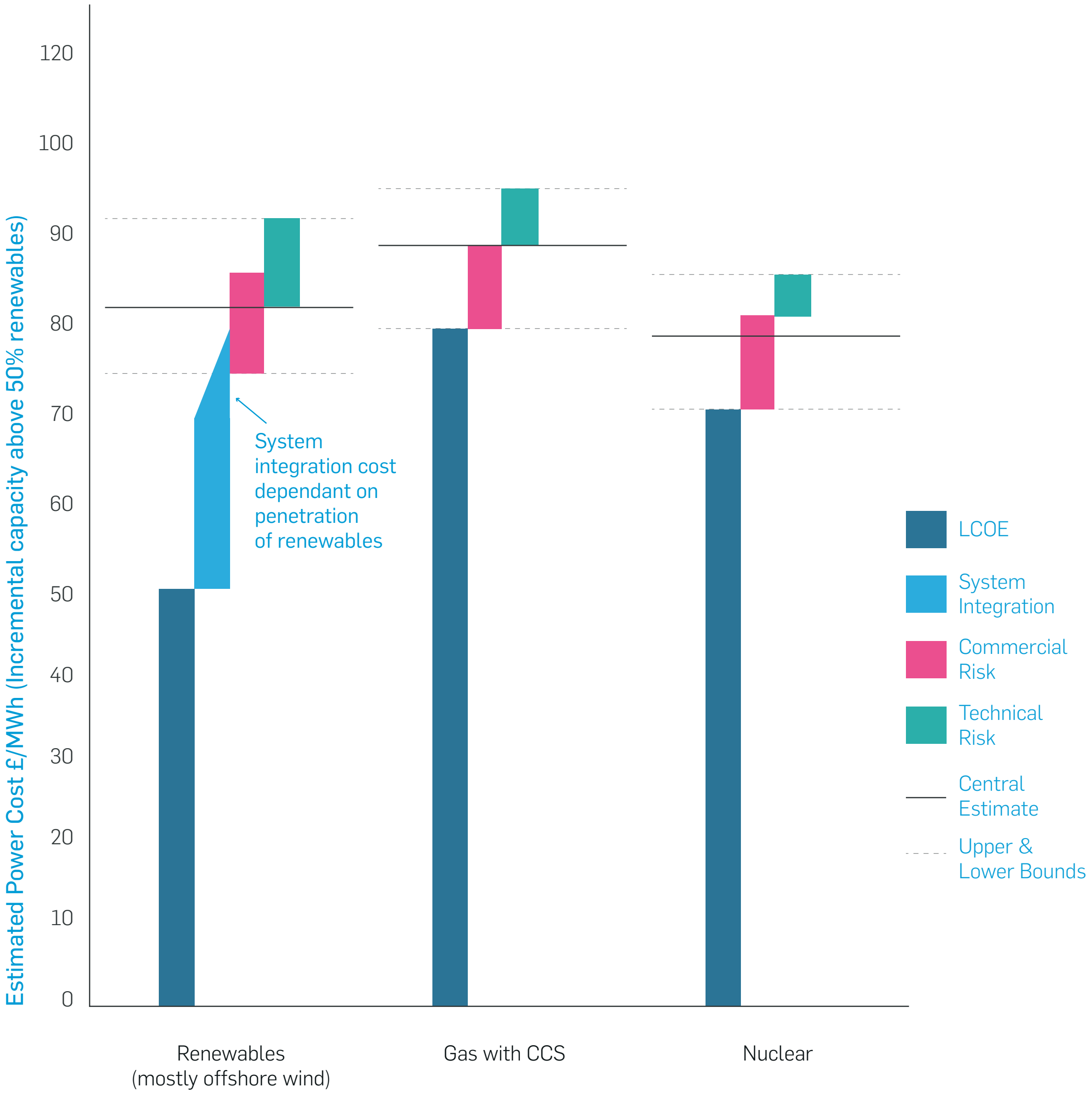
There is significant uncertainty in predicting these costs. It is clear that modelling to achieve system optimisation must take account of whole system costs. Furthermore, in order to achieve an optimal balance between different forms of generation, system costs should be allocated to the technology that requires their support. The sensitivity of the results to changes in input assumptions must also be clearly stated.

Based on the LCOE figures for 2050 and making pragmatic allowance for technical and commercial risk, we find that beyond 50% renewables the incremental cost per MWh for offshore wind, CCGT with CCS and nuclear are in the same range. These results are presented in Figure 4.

The historic focus on LCOE at the point of generation as a measure of competitiveness in electricity generation is outdated by the complexities of the modern integrated energy system. It is also potentially grossly misleading. LCOE comparisons, though simple to understand, should be avoided in discussions of energy policy.

We also believe that system architecture needs to be developed based on whole system costs and designed to minimise the cost of energy to the customer.

Figure 4 – Incremental cost of Power Generation beyond 50% Renewable Penetration (LCOE figures from [REF 3])



Risks

In assessing the high level risks for Net Zero, we have considered both the major technical and commercial/policy risks. In many cases, we see the commercial/policy risks as more significant at this time.

We believe that the requirement to implement CCS on an unprecedented scale is by far the most significant risk to the UK's Net Zero target. Failure to implement CCS would impact 28% of the proposed electricity generation, over 80% of the proposed hydrogen production (combined, this represents over 40% of total energy) and all of the non-substitutable industrial emissions.

If CCS is non-deliverable or prohibitively expensive at the scale proposed, then a Plan B would be needed. Logically, this would focus a lesser volume of CCS on the non-substitutable industrial emissions, while substituting other non-carbon generating power and hydrogen production technologies. For power, the options are increasing renewables or increasing nuclear. For hydrogen, the option is to increase the proportion of electrolysis, which in turn will further increase power generation requirements.

Expanding renewables will incur increasing system-wide costs. Within currently known technology, there is no practical or available storage mechanism for large grid scale seasonal demand/supply imbalances. Pumped storage is the only well-established technology and suitable sites are limited in number. Surplus power can also be applied to electrolysis, which would act as an energy store. However, high dependency on hydrogen for heating would entail very large hydrogen storage capacity to meet seasonal variation.

Nuclear may be the most cost-effective means of addressing the generation shortfall. It also has the added advantage that heat may be used to increase the efficiency of electrolysis. In the later part of the forecast period, high-temperature advanced nuclear may offer further improvement in hydrogen generation efficiency. However, nuclear projects have long timescales and currently, following the demise of Wylfa, the UK does not have a credible path forward for nuclear project development.

The pathways for the three main thrusts of the Net Zero scenario are summarised in Figure 5, with the dependency on CCS clearly demonstrated. In our view, the current BEIS intention to have a CCS demonstration project in place by the mid-2020s, and the option for deployment at scale in the 2030s is, quite simply, too little too late.

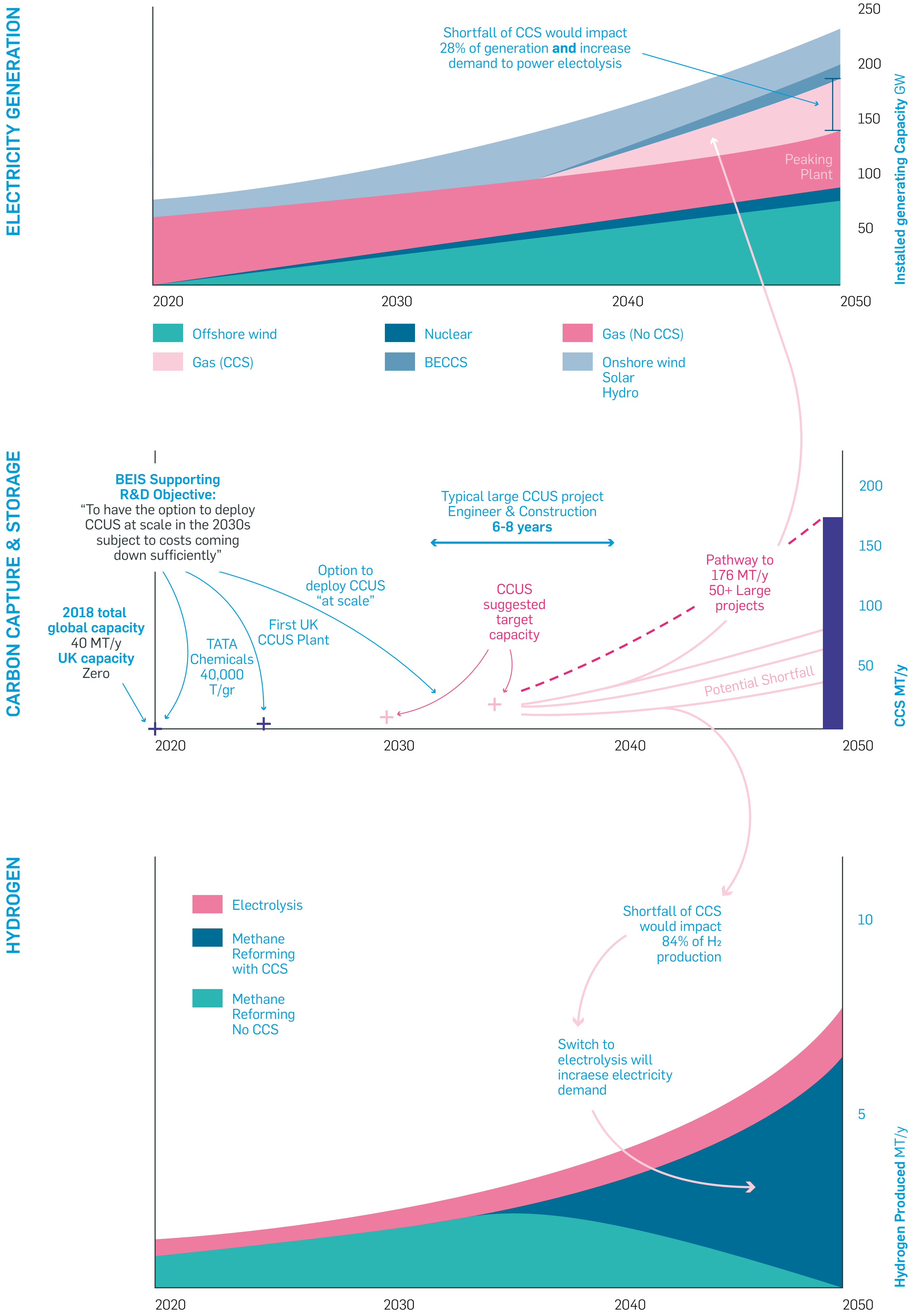
If nuclear new build is curtailed as implied by Net Zero and the extent of CCS deployment is also curtailed due to technical or commercial risks, then the UK risks being boxed in to a dependency on offshore wind at a level that poses serious questions about system reliability and affordability. To mitigate this risk, high priority should be placed on the earliest possible CCS demonstration project at significant scale (500,000t CO2 per year). Investments to increase system flexibility and the development of an alternative financing model to bring forward nuclear power are also critical.

Keeping options open

In a system with so many uncertainties, it is essential to keep as many options open as possible. We should only close down options when they have been shown to be impractical or uneconomic in all likely future scenarios. The role of the ESA in making these judgements will be essential. While achieving the 2050 goal would be the ESA's main objective, we should not overlook the near-term inadequacy of the system. Our coal fleet will very soon be completely off-line. Our nuclear fleet is rapidly approaching end of life. Many of our CCGTs are nearing their expected life span, with no forthcoming investments in CCGT under current market conditions. Keeping other options open is therefore essential.

> Failure to implement CCS would impact 28% of the proposed electricity generation, over 80% of the proposed hydrogen production and all of the non-substitutable industrial emissions.

Figure 5 – Timeline and Potential Pathways of Principal Net Zero Systems



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