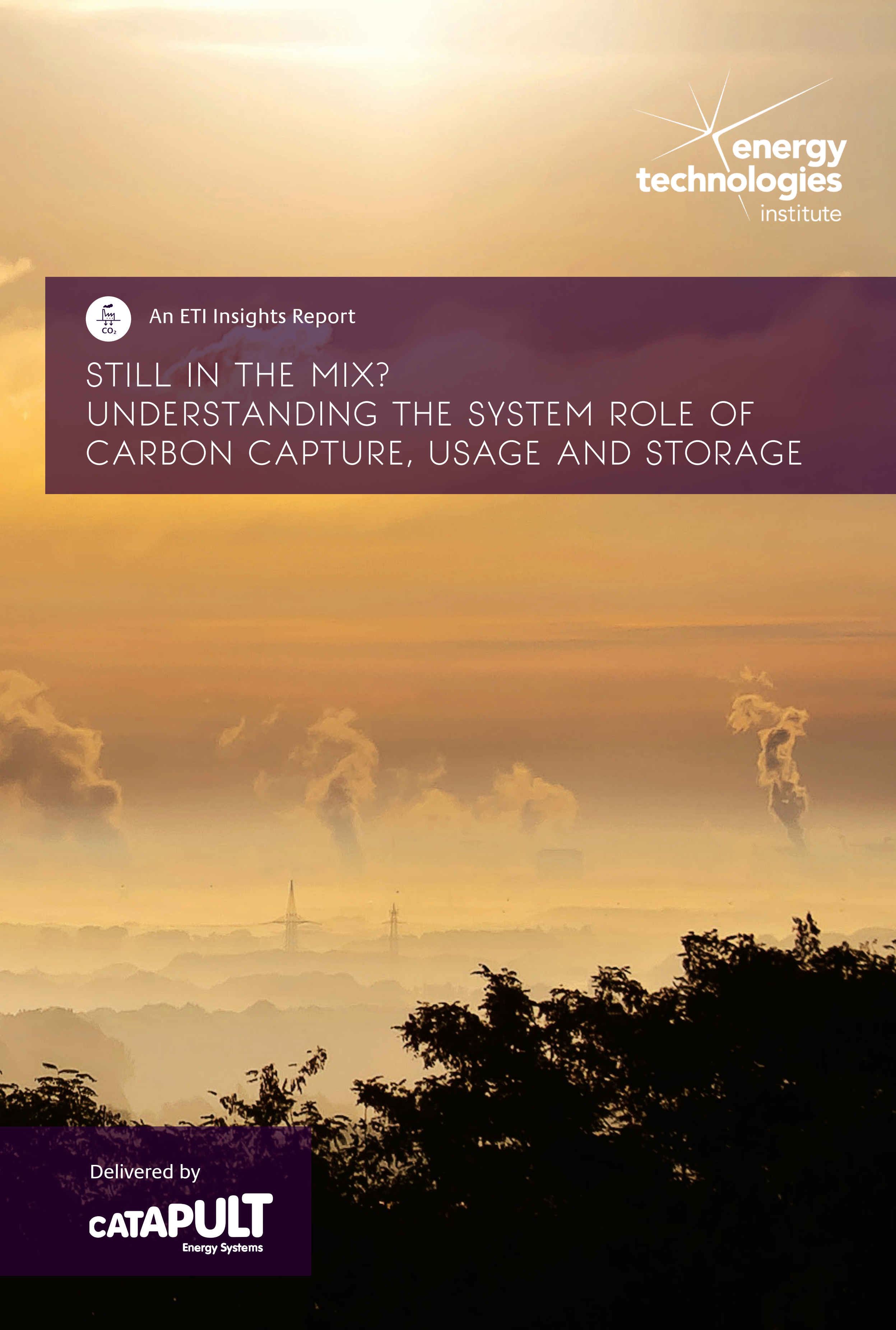


energy technologies institute

An ETI Insights Report

STILL IN THE MIX? UNDERSTANDING THE SYSTEM ROLE OF CARBON CAPTURE, USAGE AND STORAGE

Delivered by

CATAPULT Energy Systems

Contents

Despite startling cost **reductions** in **renewables** and storage, there is still a case for investment in **low carbon** baseload **electricity** generation options – to include **CCUS**

Gas power **CCUS** can be deployed **cost-efficiently** before **2030** within an electricity generation mix that meets the fifth carbon budget

The **Committee** on **Climate Change** stated that **CCUS** is 'part of the **cost-effective** pathway for an emissions **reduction** of 80% by 2050'

STILL IN THE MIX?

UNDERSTANDING THE SYSTEM ROLE OF CARBON CAPTURE, USAGE AND STORAGE

If **CCUS** is not deployed by **2030**, abatement costs will increase by circa **£1billion** a **year**, and could double if there is no **CCUS** before 2050

£1bn

If **CCUS** is not developed before **2050**, then the 'national bill' for **low carbon** energy in the year **2050** itself would be circa £35bn higher

2050

Analysis has consistently shown that CCUS is a key component in minimising costs for **whole system decarbonisation**

The **'least cost'** pathway in ESME includes **4GW** of **gas** with CCUS by 2040, rising to **6GW** by **2050**

CCUS will increase the **portfolio** of low carbon options for electricity and **decarbonisation**, reducing deployment risks for other low carbon technologies

CO_2

CCUS could potentially support **hydrogen production** before 2030, with biomass gasification enabling negative emissions in the medium term

EXECUTIVE SUMMARY

- Analysis by the Committee on Climate Change (CCC) and the Energy Technologies Institute (ETI) has for several years indicated that carbon capture, usage and storage (CCUS) is indispensable to a cost effective low carbon transition for the UK.

- This report presents three new pieces of analysis that support the case for **investing in up to 3GW of gas power CCUS before 2030, as part of a cost-effective pathway to 2050.**

- Firstly, updated whole energy system analysis shows how delaying commercial scale deployment of CCUS will increase the risks and probably increase the costs of energy sector transition.

- Secondly, new electricity system analysis shows that we are still likely to need low carbon baseload generation to complement renewables. We should continue investing in options for low carbon baseload electricity generation, even though the costs of renewables and storage are falling fast. Both gas power with CCUS ('gas power CCUS') and new nuclear are worthy of comparable effort.

- Electricity modelling shows that early gas power CCUS capacity (i.e. up to 3GW) is part of a cost-effective pre-2030 electricity generation mix that meets the fifth carbon budget. The modelling takes full account of cost reductions in renewables and the latest ETI evidence on the cost premium required for early gas power CCUS projects.

- Thirdly, new analysis of the value for money of electricity technologies shows how gas power CCUS is cost effective because it delivers both low carbon electricity and capacity at peak. Current market arrangements do not fully reflect its system value. A 'level playing field' comparison significantly improves the competitive ranking of gas power CCUS compared to other low carbon options.

- In summary, gas power CCUS has low exposure to trade risk and can be developed at scale under existing support mechanisms. It can provide anchor loads for CO_2 pipelines and stores that serve emerging CCUS clusters, with wider decarbonisation benefits for low carbon industry and hydrogen.

- Developing gas power CCUS in a favourable location for a CCUS industrial cluster represents the most straightforward, deliverable and best value approach to early deployment. The government should not risk failing to realise the future benefits and cost savings associated with CCUS, by failing to test the potential for cost reduction through deployment at scale.

The Committee on Climate Change continues to support early action to deploy CCUS.

Steady deployment of low carbon technologies has the potential for significant cost reduction, with limited downside risk. As demonstrated through the price reductions for offshore wind, there may be significant cost savings to be made from deployment of many low carbon technologies in the UK. Evidence suggests that cost reductions could be achieved for carbon capture and storage, if support for deployment is made available.
(CCC Progress report 2018)

The power sector is likely to be an important element in a credible strategy for developing UK CCS infrastructure (see CCC Progress report 2018 Chapter 1).

INTRODUCTION

The CCUS Taskforce delivered its report in July 2018, and the government has committed to publishing a revised deployment pathway for CCUS by the end of 2018.

This insight aims to inform debate about how best to progress CCUS in the UK, including its potential for low carbon electricity generation. The paper sets out the latest evidence from ETI analysis of the role of CCUS, comprising:

- Updated evidence on the potential role of CCUS across the whole energy system, and the consequences of delaying deployment. This is based on new whole energy system modelling using ESME the ETI's national whole energy system planning capability (now maintained and managed by the Energy Systems Catapult) and fully reflects recent cost reductions in renewables.

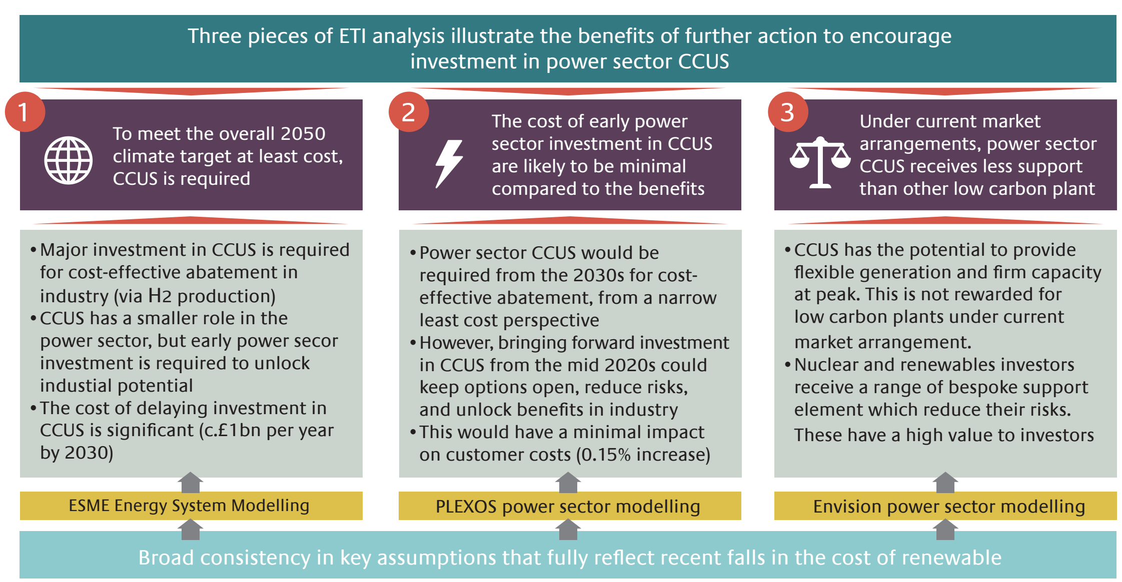
- Analysis of the impact of deploying CCUS in electricity generation specifically on electricity system costs and generation choices, again taking account of cost reductions in offshore wind and solar power. This is based on detailed electricity system modelling carried out by Baringa.

- Evidence on how current electricity market arrangements affect the case for investing in CCUS, both from a societal 'value for money perspective' and in terms of returns for private investors. This draws on a framework for assessing the value for money of electricity technologies, developed for ETI by Frontier Economics.

- Discussion of the implications for UK strategy to develop and deploy CCUS, focusing on pragmatic, deliverable next steps.

The insight concludes that there is a strong societal investment case for early deployment of CCUS in the electricity sector from the mid-2020s. Figure 1 below provides an overview of the analysis.

Figure 1
Overview of analysis



The ETI's Knowledge Base on CCUS in the UK

The ETI has built an unrivalled knowledge base on the underlying engineering challenges of delivering low carbon energy in the UK.

Since 2007 ETI has developed strong credentials in national energy system analysis, informed by the latest industrial and engineering expertise. Our analysis has been widely cited by academics, government and by the CCC in its advice to government.

The ETI has carried out an extensive programme of knowledge building projects on the challenges of deploying CCUS in the UK and has published a suite of insight reports and project documents. Full details are accessible on the ETI website but include:

- Strategic UK CCS Storage Appraisal: to identify the next phase of sites under the North Sea most suitable for storing CO_2 emissions
- Thermal Power with CCS: A project to develop an outline scheme and 'template' gas power plant design, identify potential sites and build a credible cost base, taken forward by OGCI Climate Investments
- Measurement, Monitoring and Verification of CO_2 Storage: A project to develop a marine monitoring system for underwater CCS sites
- CCS Systems Modelling Tool-Kit: A project to support the future design, operation and roll-out of cost effective CCS systems in the UK.

CCUS AND THE CLEAN GROWTH STRATEGY

Current Government CCUS strategy

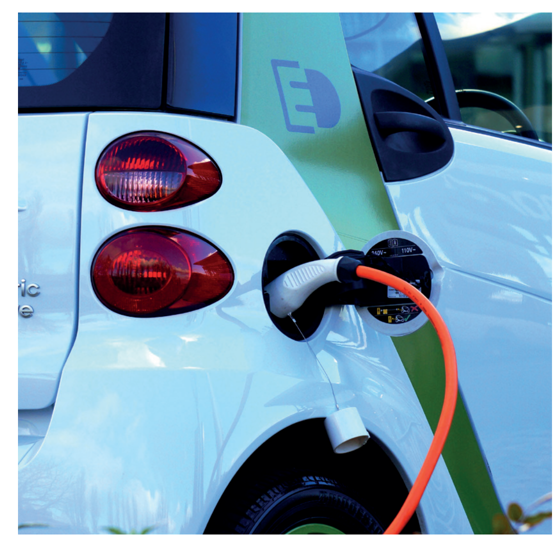
The Government indicated the broad shape of a new strategy on CCUS in its Clean Growth Strategy, published in October 2017. The following quote encapsulates the Government's current thinking on the potential role of CCUS:

> There is a broad international consensus that carbon capture, usage and storage (CCUS) has a vital future role in reducing emissions. This could be across a wide range of activities such as producing lower-emission power, decarbonising industry where fossil fuels are used and/or industrial processes as well as providing a decarbonised production method for hydrogen which can be used in heating and transport. This makes CCUS a potentially large global economic opportunity for the UK.
>
> While we have explored ways to deploy CCUS at scale in the UK since 2007, the lack of a technological breakthrough to reduce the cost of CCUS and the cost structures and risk sharing that potential large-scale projects have demanded has been too high a price for consumers and taxpayers.

The Clean Growth Strategy goes on to state that the government's new approach is 'designed to enable the UK to become a global technology leader for CCUS and ensure that government has the option of deploying CCUS at scale during the 2030s, **subject to costs coming down sufficiently.**'

In terms of specific actions, the government has committed to:

- set out a 'deployment pathway for CCUS by the end of 2018', taking account of the CCUS Cost Challenge Taskforce report delivered in July 2018
- reviewing delivery and investment models for CCUS in the UK (covering industry, power and transport and storage infrastructure) to understand how barriers to cost effective deployment can be reduced, and how the private and public sectors can work together
- funding a range of innovation activity in CCUS.



ASSESSING THE WHOLE ENERGY SYSTEM ROLE OF CCUS

Committee on Climate Change (CCC) advice on the role of CCUS

The CCC has maintained a strong position on the importance of CCUS in its advice to government, since the cancellation of the government's previous CCS Commercialisation Programme in autumn 2015.

In July 2016 the CCC published 'A Strategic Approach to Developing CCS in the UK', along with a letter from Lord Deben (CCC Chair) to Amber Rudd, then Secretary of State for Energy and Climate Change. Lord Deben recommended that:

> A strategy should be developed immediately, beginning with a clear signal of renewed commitment to a CCS industry in the UK. A review of ownership options and business models should be undertaken (by DECC or the National Infrastructure Commission), with the preferred approach and a new funding model for industry chosen as soon as possible. Funding should be allocated and the strategic locations chosen in the next 1-2 years, with the first capture contracts awarded during this Parliament.

The letter also indicated that 'an overall scale of, for example, 4-7GW of power CCS and 3-5Mt captured CO_2 from industrial plants by 2035 would be sufficient to put the UK on track to meeting its commitments cost-effectively.'

More than two years have now passed since that report and letter. In its 2018 Independent Assessment of the Clean Growth Strategy the CCC remains clear in stating that CCUS **'is part of the cost-effective pathway for an emissions reduction of 80% by 2050, and its absence could double the cost of achieving that reduction.'** This statement is supported by references to ETI evidence.

The CCC also makes clear its view that CCUS **'is essential to reach net-zero emissions, committed to under the Paris Agreement.'**

In its 2018 Progress Report on Reducing UK Emissions the CCC points out very firmly:

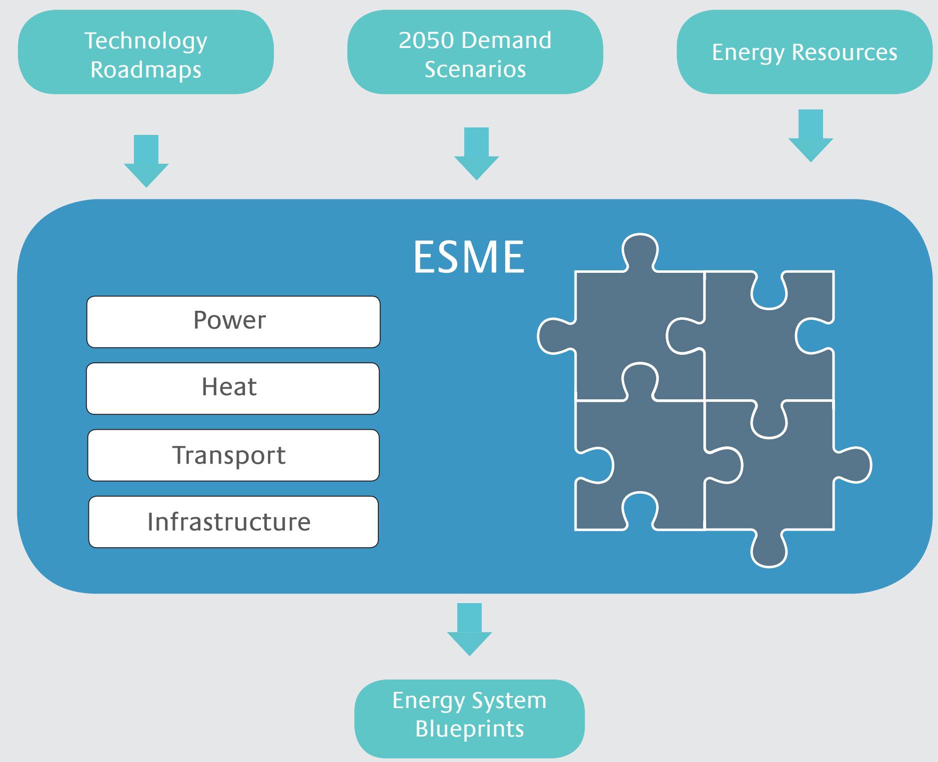
> **There is currently no strategy for the development of Carbon Capture and Storage (CCS)**, which is crucial to meeting the 2050 target at least cost. **Deployment of CCS in the power sector can be an enabler of wider roll-out.** The publication by the Government of a Deployment Pathway should be a key step in the development of such a strategy.

The 2018 progress report is unambiguous in calling for:

> **A clear, funded approach to industrial carbon capture and storage.** Industrial CCS is key for meeting future carbon targets. The Government's 2018 CCUS Deployment Pathway should provide a clear path for industrial CCS deployment as part of an overall programme of CCS deployment that stores 10MtCO_2 per annum in 2030. The Deployment Pathway should propose the delivery model to support CO_2 transport and storage infrastructure, a separate mechanism to support initial industrial CCS project(s), and the allocation of risks between Government and developers, especially relating to long-term storage liabilities. Support for initial CCS deployment should be implemented by the end of 2021, consistent with having the first CCS cluster operational by 2026. The Government should also publish its review of CCS delivery and investment models alongside the pathway.

The ETI updated its analysis of the role of CCUS in the UK low carbon transition in mid-2018. This used its whole energy system analysis capability, ESME, with updated technology cost assumptions taking specific account of recent cost reductions for renewables.

Overview of the Energy System Modelling Environment: a whole energy system model developed by the ETI



Modelling approach

- Least cost optimisation, policy neutral whole energy system model
- Represents all energy use in power, heat, transport, industry and infrastructure
- Deployment & utilisation of >250 technologies
- Pathway and supply chain constraints to 2050
- Spatial and temporal resolution sufficient for system engineering
- Probabilistic treatment of key uncertainties

Using energy system modelling to assess the potential value of CCUS

The ETI's whole system analysis has consistently shown that CCUS is a key component of strategies to minimise the costs for consumers and businesses of a transition to low carbon energy. This conclusion has remained robust under a wide range of scenarios, and is reflected in the ETI's updated UK energy system scenarios 'Clockwork & Patchwork' (published in October 2018).

The intuitive reason why CCUS is so valuable is illustrated in Figure 2. In summary CCUS is highly versatile and valuable as an enabler of a wide range of options to meet carbon targets at low cost.

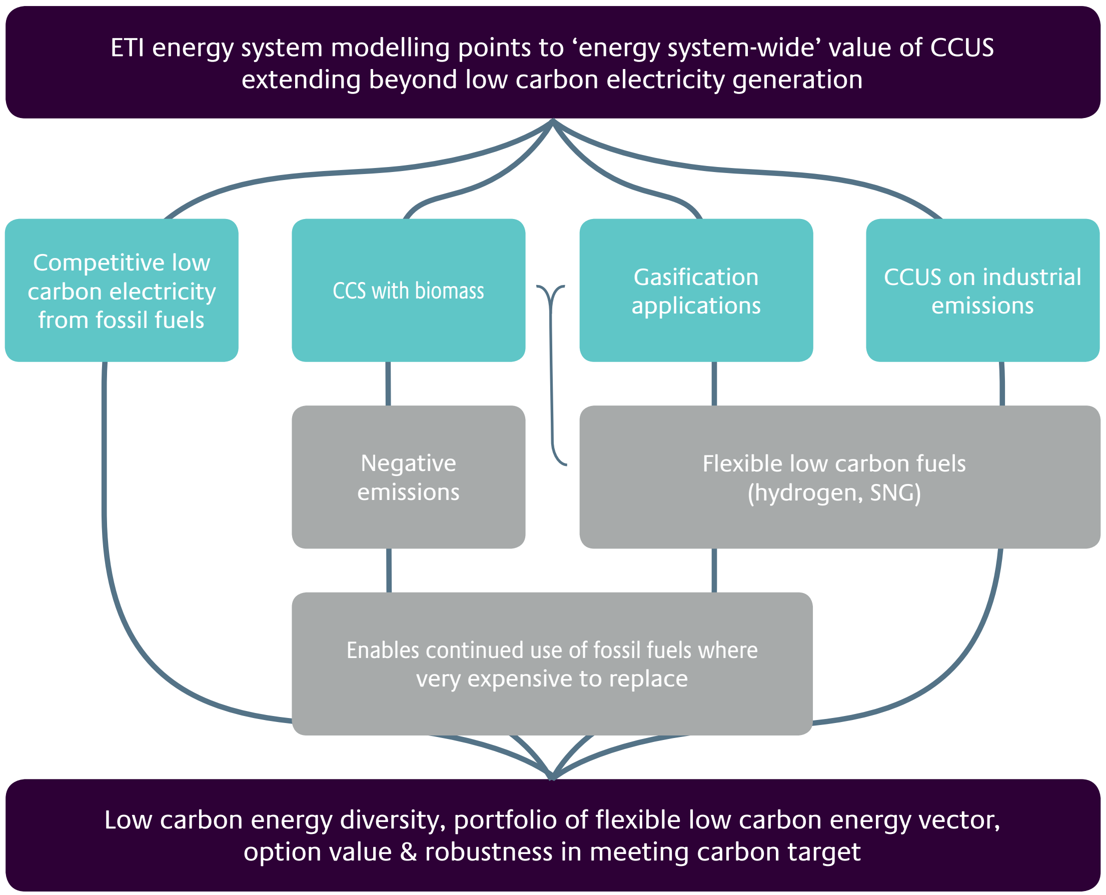


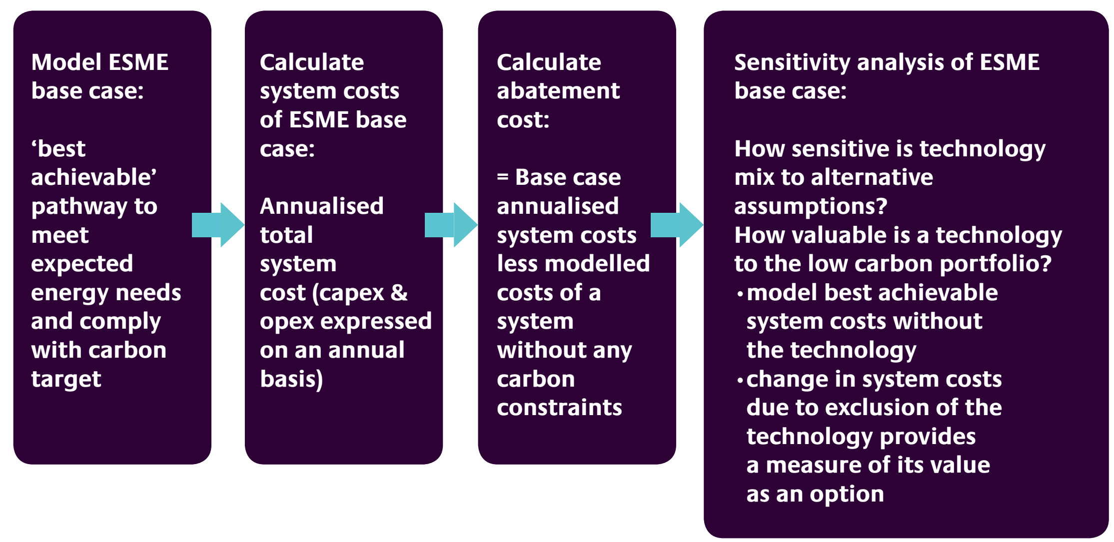
Figure 2
The whole energy system role of CCUS

ESME can be used to explore how valuable specific technologies are in contributing to the low carbon transition. The first step is to model a 'best achievable' base case of the transition path. This involves aligning model input assumptions with best current evidence on costs and performance of technology options, the best estimates of how quickly costs may be reduced in future, and information about investments that have already been 'committed' (e.g. projects currently under commissioning).

This forms the 'ESME base case' and the model calculates the associated total system costs borne by society. Sensitivity analysis of this ESME base case can be used to estimate the value of specific technologies and the impacts of delays or other constraints. The cost difference between the ESME base case and a constrained case provides a measure of the value of developing a technology option or the cost of delaying its deployment.

In constructing the ESME base case for this analysis, we used updated technology cost assumptions, taking account of the startling reductions in the costs of renewable generation technologies revealed in recent UK and European market evidence. This approach is illustrated in Figure 3.

Figure 3
Approach to sensitivity analysis using ESME



Impact of lower cost renewables on the role of CCUS

We updated ESME analysis to help us explore the impact of lower cost renewable technologies on the potential role of CCUS, particularly since the 2017 Contract for Difference (CfD) allocation round. We aimed to assess if CCUS remains a valuable option for decarbonising electricity or whether other options will now be cheaper?

The revised modelling suggests that progress in reducing the costs of renewables has not removed the need to progress the deployment of CCUS. Even with much lower cost renewables now available, the results point to:

- a continuing very significant role for CCUS in a least cost approach to UK whole energy system decarbonisation
- the desirability of significant deployment of CCUS during the 2020s as part of a least cost low carbon technology portfolio
- an important potential role for CCUS in supporting hydrogen production, and enabling negative emissions in the medium term.

The most notable features of the results are summarised in Table 1.

Table 1
Impacts of delay to CCUS deployment

Figures quoted below are 'raw form' modelled results, and therefore useful as an indicative guide to the least cost combination of technologies based on current evidence, rather than a 'realistic' forecast or a strategic analysis. For example, no account is taken of how the relatively limited trade exposure of electricity generation may offer strategic advantage for managing the demand risk of early CCUS projects.

Some individual assumptions or features of the results could arguably be refined to increase the 'realism' of outputs. Notably the modelled results include:

- Some legacy coal generation beyond 2025
- Inter-connector capacity peaking at 10GW (arguably lower than now appears likely)
- 7GW of nuclear new build by 2030
- Reliance on biomass boilers for shorter term emissions reductions in space heat
- Reliance on biomass imports (to support low carbon heat & hydrogen production)
- Rapid build-up of hydrogen production capacity during the 2020s and 30s
- Domestic use of H_2 not permitted in model run.

Adjusting any of these would increase the need to deploy other important low carbon options: renewables, new nuclear (large and small modular), interconnectors, flexibility/storage technologies and electrification of transport and heat demand.

System feature	Summary of role of CCUS in revised ESME base case
Power sector	• The 'least cost' modelled pathway in the ESME base case includes a relatively limited role for power CCUS: 4GW of gas (Combined Cycle Gas Turbines [CCGT]) with CCUS by 2040, rising to 6GW by 2050 – with declining load factors. • Major role for wind generation (27GW 2030 rising to >70GW by 2050) • Major new nuclear build (7GW by 2030 – 21GW by 2050)
Hydrogen (H_2) production	• CCUS supports H_2 production with rapid growth from 2020s • 24TWh pa of CCUS supported H_2 production by 2030 (nb Leeds demand = approx. 6TWh) rising to 70TWh by 2040 (broadly flat thereafter). • Dominated by biomass gasification (but steam methane reforming could also feature with CCUS)
Hydrogen use	• Industry: majority user of H_2 • Some use of H_2 turbines for flexible electricity from 2030s and growing HGV usage of H_2 in 2040s.
Negative emissions	• Circa 50M tonnes pa of negative emissions enable continued use of liquid fuels in transport & natural gas in heating into 2040s, and thus a more cost-effective eventual transition.
CO_2 volumes	• 15M tonnes pa by 2030, rising to circa 80M tonnes pa by 2045 • Volume dominated by CO_2 captured from biomass gasification (providing negative emissions)

Impact of delaying CCUS deployment

The potential consequences of further delay to the deployment of CCUS were tested by running three sensitivities of the ESME base case:

- 5 year delay (i.e. earliest commercial scale deployment from 2030)
- 10 year delay (i.e. earliest commercial scale deployment from 2035)
- No deployment of CCUS permitted before 2050

Impact of delay on system-wide carbon abatement costs.

Figure 4 shows the impact of delay on system-wide carbon abatement costs (i.e. the extra cost to abate carbon compared with a scenario with no constraint on carbon emissions). The broad picture is that the cost increase resulting from a five or 10 year delay in deploying CCUS could be only modest in relation to total abatement costs. The cost increase resulting from short delays to CCUS deployment is also temporary, and could largely disappear by 2050 if supply chains can respond quickly following a delay.

By contrast abatement costs roughly double if there is no deployment of CCUS before 2050.

Figure 4
Impact of CCUS delay on system carbon abatement costs

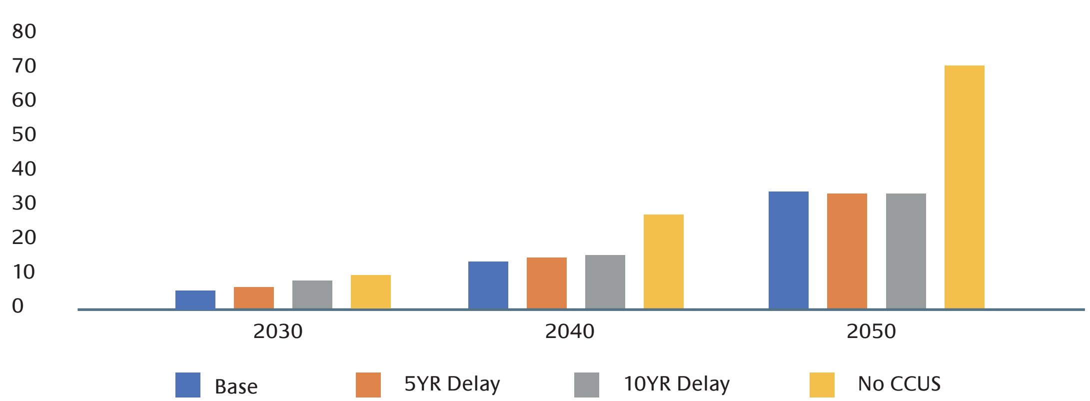
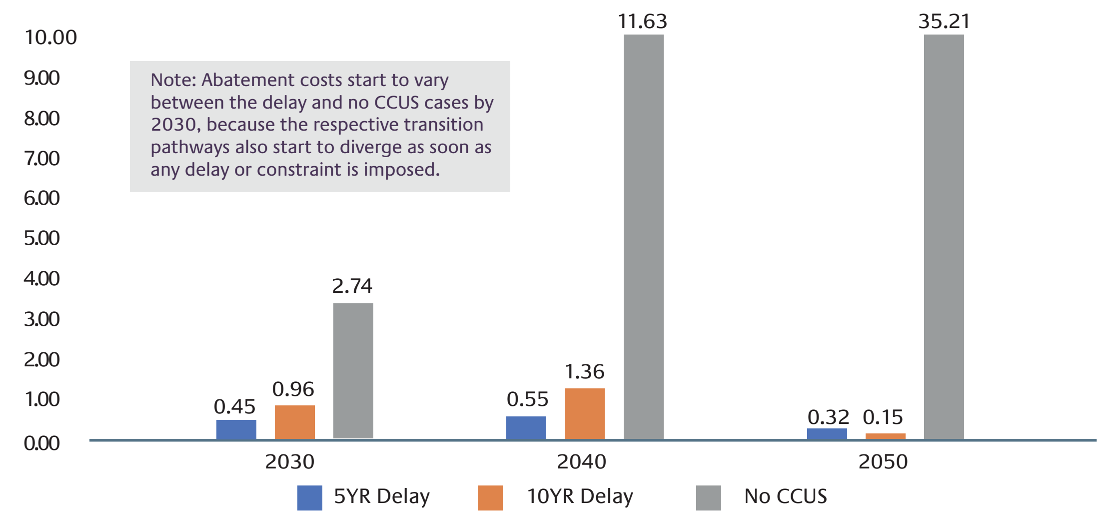


Figure 5 shows the increase in annualised energy system abatement cost compared with the ESME base case for the delay cases. (note chart 'y axis' scale limited to £10bn/yr)



The cost of a 10-year delay is nonetheless material at circa £1bn per annum by 2030, an increase of 22% over base case abatement costs. Modelled abatement costs for a 10-year delay are still 9% higher in 2040, with the difference declining to less than 0.5% only by 2050.

Impact of CCUS deployment delay on technology mix choices: electricity generation & hydrogen production/use
The modelled scenarios also illustrate how the optimal technology mix and use of other low carbon options is affected, when CCUS is delayed or not deployed. Table 2 summarises some key features of the impacts in the delay case sensitivities.

Table 2
Impacts of delay to CCUS deployment

	10-year delay	No CCUS
Power	Delay to gas power with CCUS (with only 4GW of gas CCUS deployed in 2040s) Increased reliance on wind and nuclear from late 20s to 40s.	Much greater reliance than base case on nuclear, including small modular, particularly in 2040s. Absence of CCUS makes renewables less attractive from a system perspective.
Hydrogen production	Later deployment of CCUS delays growth in H_2 production during 2020s, which relies instead on steam methane reforming. Once CCUS is available after 2035, H_2 production increases rapidly and switches to biomass gasification.	Early growth of H_2 production through steam methane reformers (14TWh in 2035). H_2 production rises to 70TWh in 2050, based mainly on electrolysis from late 2030s.
Hydrogen use	Hydrogen based industrial decarbonisation is delayed into 2030s. Industrial use grows steadily (17TWh in 2035 rising to 54TWh in 2050). Use of H_2 for electricity peaking does not emerge until 2040s.	Overwhelmingly dominated by industrial usage.

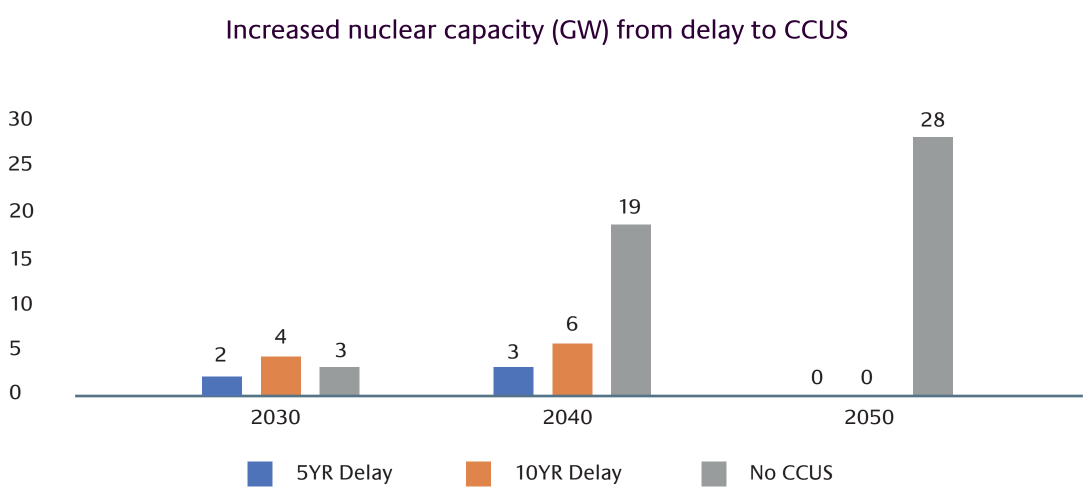
Impact of delay on deployment requirements for low carbon alternatives

Another useful way of interpreting the modelling results is to consider what they tell us about the required deployment of other low carbon technologies. If CCUS is delayed, then how much more will we need of other low carbon technologies and how much faster will we need to deploy them?

The modelling evidence strongly suggests that further delays to CCUS will mean increased deployment risks and potentially cost and supply chain pressures for other low carbon technologies.

This is most notable in relation to nuclear power. Figure 6 shows the extra deployment of other low carbon technologies in delay cases.
Whole system modelling also illustrates how any delay in CCUS development also adds uncertainty to key infrastructure investment decisions elsewhere in the energy system (e.g. in relation to future gas or hydrogen infrastructure, the extent of electricity grid enhancement).

Figure 6
Impact of CCUS delays on other low carbon capacity



The energy system role of CCUS in a low-cost renewables world

Several key points emerge from the updated ESME analysis about the role of CCUS in the world of low-cost renewables that is now emerging.

- CCUS retains a key role as part of a least cost portfolio of low carbon technologies for the UK
- Lower cost renewables mean that the role of CCUS in the electricity sector may be relatively modest in terms of capacity, with current evidence suggesting a greater reliance on wind and nuclear power
- But crucially, reduced costs for renewables do not remove the need for large scale deployment of CCUS before 2030 to unlock its potential wider value for decarbonisation. In fact, there are important complementarities between variable renewables and CCUS
- CCUS can play a key role in supporting hydrogen production, starting from the 2020s. ESME suggests that the most efficient way to produce hydrogen would be biomass gasification (therefore producing negative emissions), providing that this technology can be proven at scale. This suggests a strong case for increased innovation and early deployment funding for clean gasification technologies
- Low carbon hydrogen production reliant on CCUS is a major contributor to industrial decarbonisation. CCUS may also be important to enable capture of industry process emissions
- There are major risks in delaying deployment of CCUS. If we fail to make CCUS available at scale by 2030, the actions required to meet carbon targets will be more risky and costly
- If CCUS is delayed, the analysis suggests that cost increases could only be contained by a rapid (and therefore risky) 'catch up' deployment of CCUS capacity after 2035
- Cost pressures increase markedly if CCUS is further delayed or if a rapid rate of deployment cannot be achieved, following a delayed or slow start to deployment
- If CCUS is not developed at all before 2050, then the 'national bill' for low carbon energy in the year 2050 itself would be circa £35bn higher – equivalent to circa 1% of expected GDP (with a cumulative discounted cost over the period to 2050 of around £100bn).

CCUS FOR LOW CARBON ELECTRICITY

Analysing least cost electricity system decarbonisation

Cost efficiency in decarbonising electricity has been a key focus for policy makers in recent years. Policy makers have been concerned to contain costs for electricity consumers through levies on bills. Attention has therefore often focused specifically on the electricity system, with less emphasis on how electricity choices affect wider whole energy system costs.

The 2016 Smart Power report published by the National Infrastructure Commission has been one of the most widely quoted analyses. This referenced modelling by Imperial College which showed electricity system cost savings of £8bn per annum by 2030, provided the UK developed 'smart power' based on demand side response, storage and inter-connectors. Similar analysis has informed the government and Ofgem's smart systems and flexibility plan (July 2017).

The ETI decided to explore cost optimal pathways for decarbonising electricity out to 2050 but with a primary focus on the nearer term (i.e. pre-2030) choices. ETI commissioned Baringa to do this analysis using an electricity system modelling tool. This allowed for a more detailed exploration of electricity choices, based on more detailed hourly operational analysis across characteristic weeks[1]. This was an opportunity to explore the apparent disconnect between ESME whole energy system modelling, which points to the importance of CCUS, with recently published electricity system-focused analyses (e.g. those cited above) which have tended not to suggest any role for CCUS in UK electricity.

The modelling approach aimed to use credible assumptions about current real-world trends and technology deployment constraints. Further detail on the modelling assumptions is set out in the following section.

Insights on the potential role of CCUS in electricity generation

The modelling produced three key results about the potential for CCUS in UK electricity generation.

- A modest amount of gas power CCUS capacity features from the mid-2030s in a modelled least cost low carbon UK electricity system (up to circa 5GW), along with heavy reliance on renewables, gas and storage. Load factors for gas power CCUS remain well above 50% well into the 2040s.

- If the model is forced to deploy an early tranche of gas power CCUS (from the mid/late 2020s) system costs increase by less than 0.15%. This suggests that early deployment of commercial scale gas power CCUS would have negligible impact on overall costs for consumers, even when allowance is made for a 'first of a kind' cost premium for early gas power CCUS projects and lower cost renewables. Early deployment could drive learning and cost reduction. The modelling evidence thus challenges the emphasis on cost reduction as an apparent pre-condition of support for commercial deployment of CCUS.

- Sensitivity analysis suggests that the most significant potential drivers of system costs are changes in fuel prices or the overall level of electricity demand. Non-extreme shifts in generation mix choices generally drive only relatively slight changes to overall system costs.

Further explanation of the modelling approach and sensitivity analyses is set out in following sections. The main conclusions we draw from the modelling results are:

- The downside (cost) risks to consumers of contracting a tranche of new gas power CCUS capacity in the mid/late 2020's appear modest to negligible, compared with plausible alternatives.

- The upside potential of deploying well-scoped and sited gas power CCUS projects before 2030 is significant. It would increase the portfolio of low carbon options for electricity and wider decarbonisation with modest cost risks, thus mitigating deployment risks for other low carbon technologies (nuclear and renewables). It would also provide a potentially valuable source of firm low carbon capacity to complement renewables.

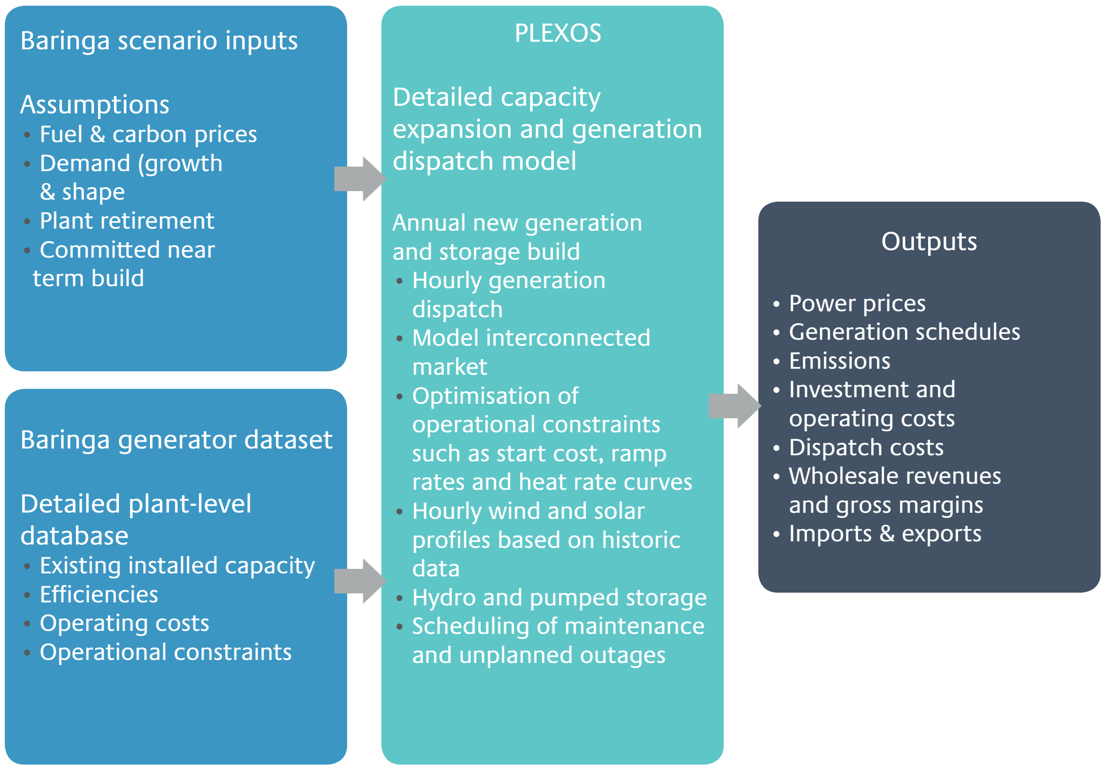
- Deployment of CCUS in electricity would provide a less trade exposed and lower risk first tranche of CO_2 storage demand, against which to establish and prove CCUS cluster infrastructure and storage capacity.

1. The electricity system modelling was set up to be broadly consistent with the ESME analysis, using consistent data input assumptions and boundary conditions.

The modelling approach

Baringa used a Plexos-based model of the UK electricity system to carry out the analysis to undertake combined capacity expansion and operational analysis. Plexos is a widely-used electricity system modelling tool with more accurate representation of the despatch characteristics of technologies/systems than possible in a whole energy system tool (e.g. ESME)[2]. Figure 7 provides a schematic of the approach.

Figure 7
Schematic of Plexos modelling



We asked Baringa to model a cost optimised pathway to decarbonise the UK power sector up to 2050, focusing particularly on the period to 2030. We asked Baringa to take account of current trends and investments, while minimising **electricity system** costs and delivering emissions reductions in line with the fifth carbon budget (i.e. circa 90g/kWh). We called this the 'Plexos current trends' case. We did not consider impacts on costs in other parts of the energy system, which were not the focus of this analysis.

2. Further technical detail on the modelling methodology and assumptions is contained in the final project documentation available on the ETI knowledge zone via www.eti.co.uk

Key elements of the approach included:

- **Central view of future demand & interconnector capacity:** A 'reasonable central view' of aggregate electricity demand; the development of demand flexibility over the period to 2030 (and beyond), and the potential for increased use of inter-connectors. This was informed by CCC analysis
- **Full account taken of existing investment commitments & trends:** The model was specified to include already committed and highly likely near-term investments in new generation capacity, with modelling optimisation of new capacity only from 2022 onwards, reflecting real-world lead-time requirements for investment decisions
- **Cost assumptions updated to reflect latest evidence:** Technology cost assumptions based on ETI's ESME dataset, with updates to reflect outturn evidence from 2017 CfD auctions, as well as the most recent ETI research on the realistic costs of developing a FOAK gas power CCUS plant in a suitable site[3]
- **Use of a balanced base case and sensitivities to explore options:** Alternative modelling constraints devised to reflect potential real-world constraints and delays in the development of nuclear and power CCUS (as opposed to idealised 'modelling assumptions' on build rates etc.); use of a sensitivity case to explore the system cost impact of investing in a tranche of gas power CCUS capacity in the generation portfolio under a range of sensitivities.

The 'Plexos current trends' case

The Plexos current trends case was deliberately built up to reflect current real-world conditions and trends. We made build rate assumptions that limited the pace of deployment of both large-scale nuclear and CCUS capacity, in line with the current slow pace of deployment.

Conservative build rate & cost assumptions for nuclear and CCUS power in Plexos current trends case

Nuclear: Build rate: first allowed in 2030 reflecting Hinkley C construction but we assume that industry is unable or unwilling to build more than one Hinkley-sized (3.2GW) development in parallel, leading to a maximum of 3 large plants by 2050.

Costs in 2030 reflect latest Hinkley C estimate ~£6,125/kW, with a longer construction period of 7.5 years (based on the IAEA average globally).

CCUS: First allowed in 2035, with a maximum development of 2 x 400MW demonstration units. We assume that industry does not start construction of further units until these have been deployed successfully. This implies no further plant until 2040 (given constructions times) and an assumed maximum of 1 unit (400MW) per year from 2040-2044 and 2 units per year thereafter to 2050.

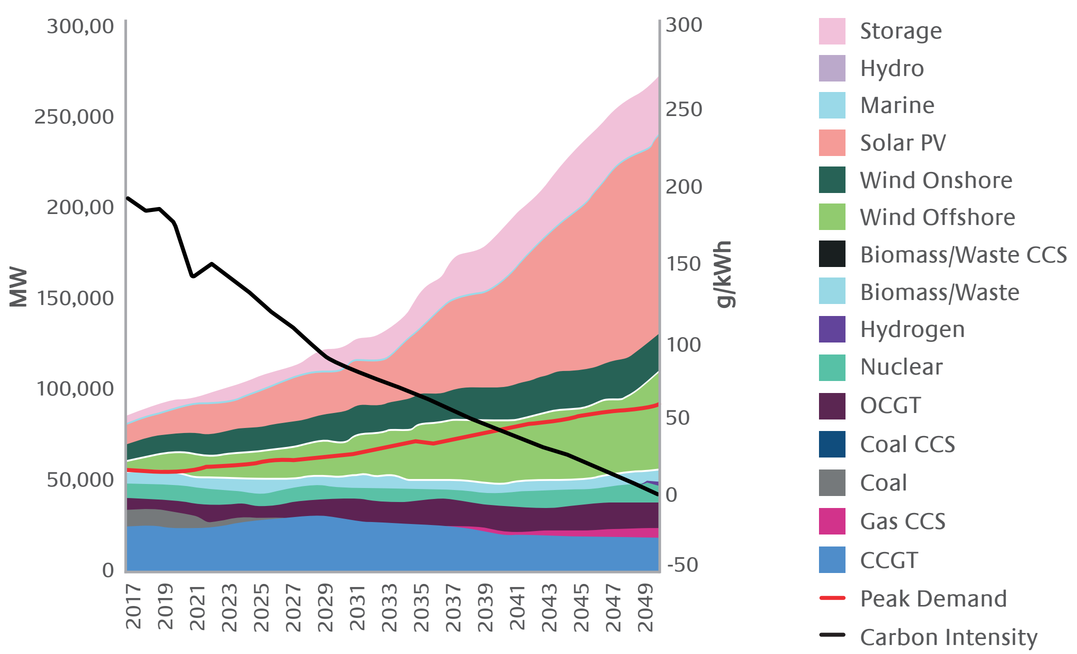
Costs in 2035 reflect ETI's FOAK assumptions with a 50% longer construction period than standard ETI assumptions.

3. CCUS cost assumptions drew upon ETI's Thermal Power with CCS project and take account of uncertainties and risk factors associated with a first of a kind (FOAK) project, with an additional contingency allowance.

Further detail on the input assumptions is contained in the Baringa report 'Cost optimal pathways to decarbonising the GB electricity sector' (2018) available in the ETI knowledge zone.

The modelling includes a very large expansion of solar capacity in the 2040s. This is not to suggest that this is a likely outcome. It is best interpreted as showing that a major new technological breakthrough (e.g. in electricity storage or demand flexibility) will be needed, if nuclear and CCUS constraints are not overcome by the 2040s.

Figure 8
Overview of the Plexos current trends case electricity generation scenario.



Key issues from sensitivity analysis

Ten sensitivity analyses were constructed to explore the importance of a range of factors to UK low carbon electricity choices. The sensitivities carried out took account of a range of factors including different assumptions about:

- costs and build rates for key technologies
- commodity prices (hydrogen, coal and gas)
- demand flexibility
- inter-connector capacity.

The key points which emerged from this analysis, additional to those mentioned earlier, are set out below.

- Developing a balanced portfolio of low carbon electricity generation options can mitigate the risk of relying too heavily on a narrow base of options, which may encounter deployment challenges or unforeseen cost pressures. The modelling suggests that non-extreme variations in the generation mix drive only modest differences in system costs.

- Tight constraints on carbon emissions in the 2040s will drive system costs up steeply unless unforeseen technological breakthroughs can be achieved. This supports the priority placed on developing all forms of system flexibility. It also suggests that negative emissions technologies within or beyond the electricity sector will be highly valuable.

- All the sensitivity cases still require low carbon base load capacity to complement renewable generation. The scale of the requirement will depend on progress in developing storage and demand side flexibility. Nuclear is the preferred base load option in the Plexos current trends case, but the economics could still shift in favour of CCUS, depending on relative cost movements and world market gas price trends. Technology neutral market incentives can drive this balance.

- Unabated gas capacity is still likely to play a key role for the foreseeable future. In the nearer term it can provide general system flexibility, but as carbon constraints tighten this role is likely to shrink to shorter-term back up at peak.

- There will be high value in unlocking flexibility in the timing of consumers' demand for electricity for space and water heating, and for vehicle charging. They may prove cheaper than other low carbon flexibility options such as large-scale batteries. The Plexos current trends demand forecast included some assumed flexibility in vehicle charging demand. Tight carbon constraints will improve the competitive position of demand flexibility compared with gas peakers. This also points to the importance of developing technology neutral market signals that accurately internalise carbon and system impacts.

Implications for power CCUS

Electricity system modelling provides a way of assessing and interrogating our current knowledge of the cost and performance of technology options, and wider implementation risks. It can provide guidance to decision makers, but is not a deterministic way to derive the 'right' technology mix. Modelling evidence must be interpreted and assessed alongside factors which cannot be modelled.

From this perspective, the modelling evidence supports the case for bringing forward early investment in commercial scale gas power CCUS. Early gas power CCUS projects will almost certainly require higher strike prices in £/MWh terms than recent offshore wind projects. But a well-sited and designed gas power CCUS project would be a valuable investment for electricity consumers. Comparison of strike prices is a poor guide to making the right portfolio of low carbon electricity generation investments.

Pre-2030 investment in power CCUS deployment unlocks longer term energy system cost savings, even when we take a relatively constrained and conservative view about potential build rates and future cost reductions. CCUS in the power sector can underpin CCUS infrastructure for industrial decarbonisation or for hydrogen production in the 2030s. Early investment can support earlier progress in risk reduction (lower investment costs), innovation and broader cost reduction.

The cost burden that would be placed on electricity consumers by a decision to deploy up to 3GW of gas power CCUS **before 2030** would be marginal at most for well-sited and scoped CCUS projects, with appropriate risk sharing.

This result holds when we take full account of:

- the entirety of electricity system costs (but without placing a value on other potential non-electricity benefits associated with CCUS deployment)
- the latest evidence on costs for proven technology choices (i.e. not risky unproven capture processes), plus a realistic FOAK cost premium for the first tranches of gas power CCUS
- the latest cost reductions for other low carbon electricity (i.e. offshore wind at £57.50/MWh and lower in future).

In summary, there is a strong cost/benefit case for deploying gas power CCUS by 2030, even with a FOAK cost premium for early projects, and the availability of low cost renewables. Deploying power CCUS can reduce risks from excessive reliance on a narrow range of low carbon electricity generation options, while also opening up industrial opportunities for CCUS applications and hydrogen production.

IMPACT OF CURRENT ELECTRICITY MARKET ARRANGEMENTS ON CCUS

Introduction to the work

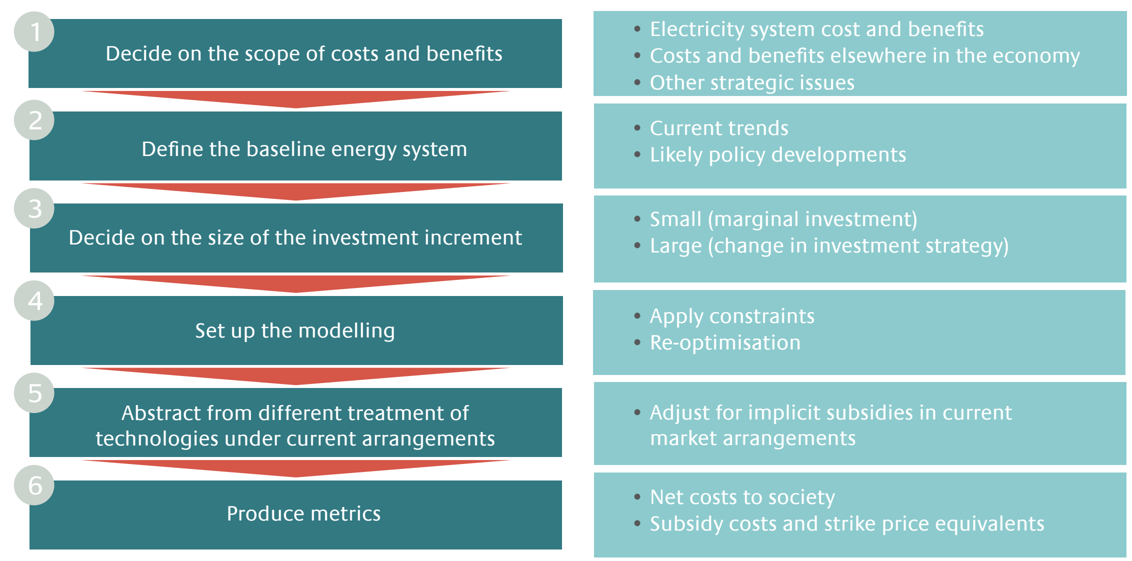
The ETI began considering value for money analysis of alternative electricity technologies, due to the apparent reliance on simplified metrics (e.g. levelised cost of electricity, or strike prices) in policy or investment decisions. These metrics do not fully reflect the externalities or impacts of technologies on whole electricity system costs (let alone whole energy system costs).

ETI commissioned a team led by Frontier Economics to develop a holistic framework for comparing the costs and benefits of electricity generation, storage and interconnection investments in Great Britain (GB). The framework is designed to take full account of whole electricity system impacts, while using transparent decision support tools that can be used and understood by decision makers.

In broad terms the value for money framework assesses potential decisions to invest in alternative electricity technologies at a given point in time (2025 was selected), by comparison with a baseline scenario. The baseline scenario is constructed to be consistent with meeting carbon budgets (and to represent existing and planned policies) so that the analysis is relevant to decisions about delivering decarbonised electricity. Several design choices were made in setting up the framework which are well-summarised in the project documentation[4]. The approach uses outputs from an underlying electricity system model (in this case the EnVision model which underlies the Dynamic Dispatch Model [DDM] used by BEIS[5]) to produce metrics and interrogable analysis.

The main steps underlying the framework are summarised in Figure 9.

Figure 9
Overview of value for money assessment framework



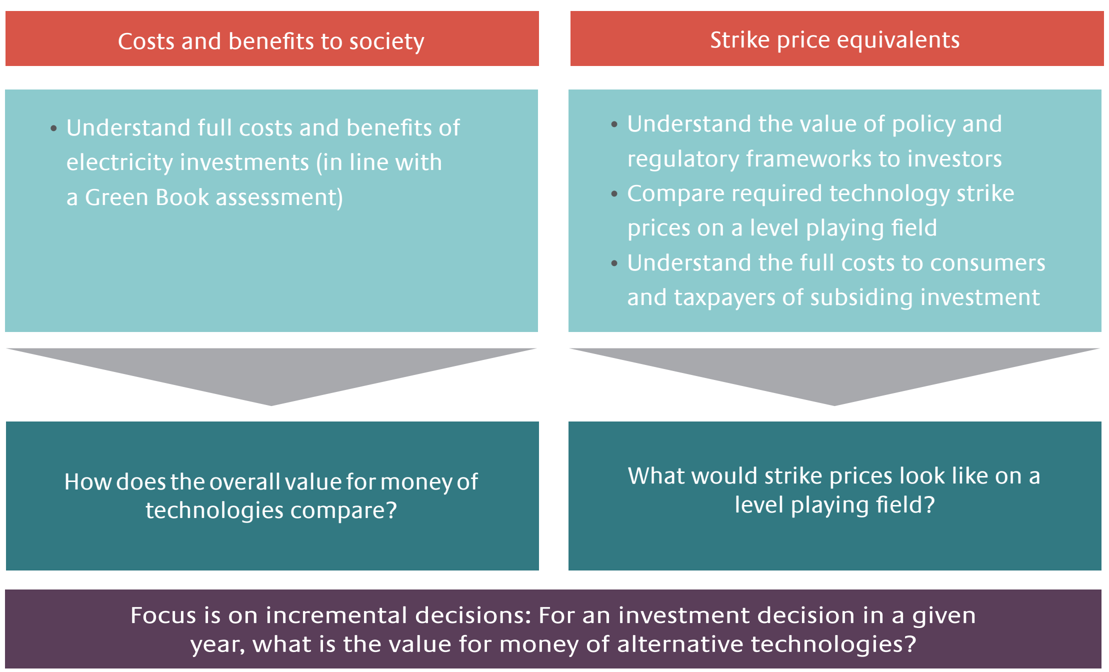
4. A Framework for Assessing the Value for Money of Electricity Technologies, Frontier Economics & Lane, Clark & Peacock, 2018
5. The Dynamic Dispatch Model (DDM) is a comprehensive fully integrated power market model covering the GB power market.

The framework considers value for money to society and consumers/taxpayers in two main ways:

- **Net costs to society:** the impact of an incremental investment both on the electricity system and on abatement costs in other sectors, using an approach consistent with the Government's Green Book.

- **Support costs and strike price equivalents:** the costs to consumers and taxpayers of supporting incremental investments, both through monetary payments and risk transfers through alternative policy arrangements and contract terms. This analysis can also produce 'strike price equivalents' which are estimates of the strike prices technologies would require, if the risk transfers and implicit support granted under current market and policy arrangements were removed.

Figure 10
Alternative views of value for money



Key takeaways relevant to CCUS electricity projects

The Frontier Economics-led team produced illustrative analysis using the framework against a baseline scenario informed by many of the assumptions constructed by Baringa (previously described). In our judgement this provides a plausible illustrative case, but specific results depend on input and baseline scenario assumptions. The baseline is important because the whole electricity system impact of a technology is as much driven by the rest of the system as by the technology itself.

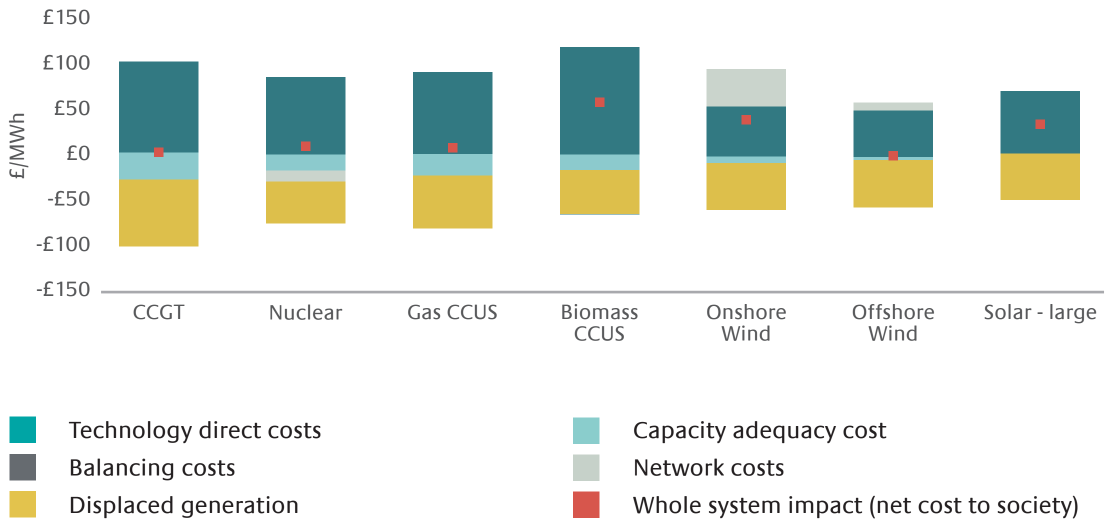
For example, the impact on costs of adding a unit of CCUS generation to a system will depend on factors including the baseline quantity of inflexible baseload plant (such as nuclear, intermittent renewables) the amount of flexible plant or infrastructure (such as CCGT, Open Cycle Gas Turbines [OCGT], storage and interconnection) and the flexibility of electricity demand.

Nonetheless, from this illustrative analysis we could draw out several generic points relevant to the case for investing in power sector CCUS projects.

- **In terms of net cost to society:** taking account of whole system impacts substantially improves the relative performance of CCUS as a low carbon electricity investment, compared to considering technology cost alone. Figure 11 is based on the illustrative analysis carried out by the Frontier Economics team. The improved value for money ranking reflects the social value of the firmness of power CCUS generation and the full valuation of carbon savings[6].

6. In this illustrative example, network costs for onshore wind are high, reflecting the assumed location of this capacity in Scotland (based on current policy) and network costing assumptions in EnVision. If we assumed a less constrained choice of location across GB, these costs would be lower.

Figure 11
Net cost to society of electricity technologies (illustrative modelling[7])



> Analysis of support costs and strike price equivalents, shows that **the competitive position of power CCUS is negatively affected by cumulative impact of current market arrangements.** This will mean that private sector investors in power CCUS will require higher hurdle rates, pushing up the headline unit costs of these projects.

> If we adjust and make comparisons on a 'level playing basis', the analysis suggests that a **well-sited and scoped gas power CCUS project could be cost competitive,** or very close to it by comparison with low carbon alternatives. Figure 12 illustrates.

7. For clarity of presentation OCGT, interconnection and storage are omitted from this chart. These are available in the full report: A Framework for Assessing the Value for Money of Electricity Technologies, Frontier Economics & Lane, Clarke & Peacock, 2018

The strike price equivalent represents the revenue investors would require if they faced the full costs and benefits associated with their technologies

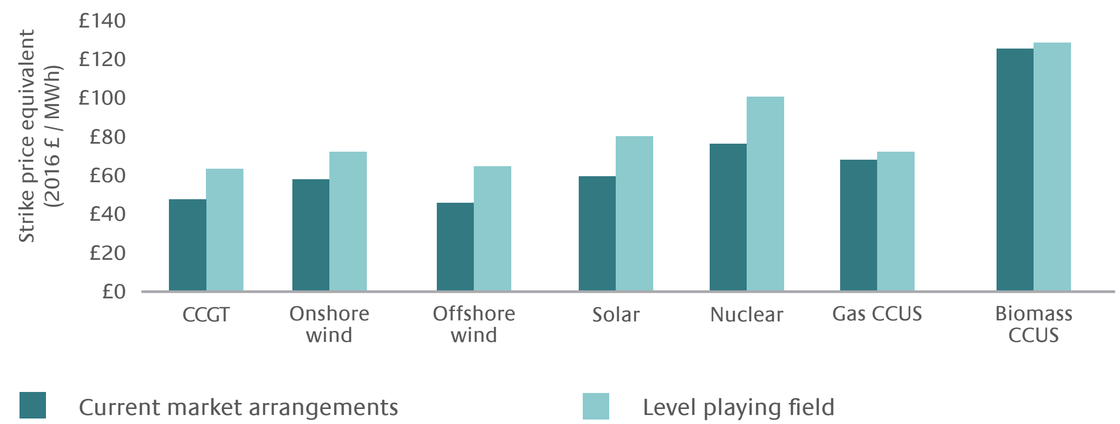


Figure 12
Strike price equivalent –
current market arrangements and level playing field

To aid interpretation of Figure 12, the assumptions built into the strike price equivalent calculations under current market arrangements (dark bars) and level playing field (light bars) are set out below.

The dark green bars reflect strike price equivalent calculations under current market arrangements as follows:

> Investors must purchase EUETS allowances and pay carbon price support top up for any CO_2 emissions

> Investors in low carbon technologies do not receive capacity market payments, in line with current arrangements

> Investors in low carbon plant benefit from reduced exposure to market price risk from CfDs

> Intermittent renewables benefit from the calculation of CfDs against an hourly reference price (rather than a baseload reference price)

> Power CCUS investors benefit from longer duration CfDs (assumed to be 25 years)

> Nuclear investors benefit from longer CfD duration and bespoke CfD terms/risk transfers

> Offshore wind investors benefit from strike prices being fixed for subsequent phases of projects

> Investors are not liable for all network cost externalities

The lighter bars reflect level playing field assumptions as follows:

- Carbon price: investors pay the BEIS appraisal value[8] of CO_2 emissions
- Investors in all technologies receive capacity market-style payments in line with generation adequacy impacts (this is estimated based on assumed reliability at peak)
- Investors hurdle rates are adjusted to reflect exposure to market price risk (i.e. the risk reduction arising from CfDs is removed). This means the benefits of both generic and bespoke CfD terms are removed
- Investors in all technologies are liable for associated modelled network cost impacts.

This work is based on a different modelling tool (EnVision), but is broadly consistent with analysis in both ESME and Plexos, in suggesting that gas power CCUS is close to competitiveness when proper account is taken of system effects and externalities.

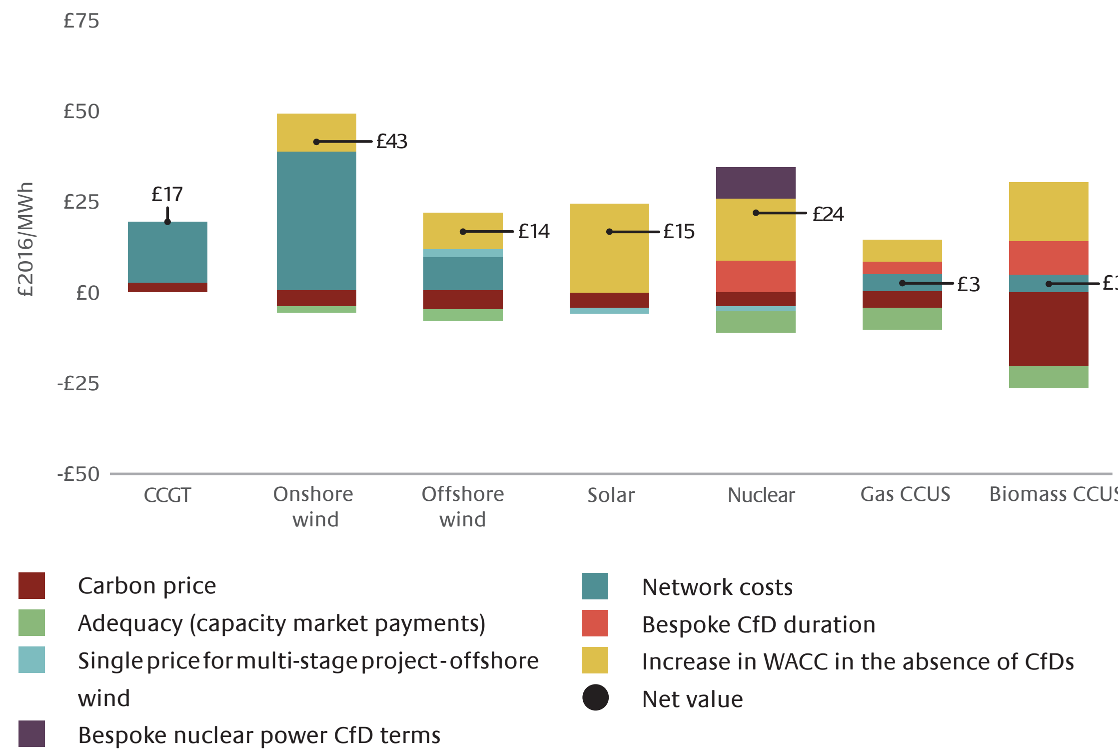
Underlying drivers of the results

This section considers why the level playing field strike price equivalent for gas power CCUS is low compared to most other technologies. The key factors include:

- The value of support provided to gas power CCUS under current market arrangements is much lower than for many of the other technologies considered (see Figure 13). This reflects a combination of factors including, in the case of gas power CCUS, lower support through risk transfer to consumers from CfD terms, and lower implicit support through unpriced externalities (full social cost of carbon based on BEIS appraisal values, generation adequacy & modelled network cost impacts)
- Gas power CCUS has a high derating factor reflecting high likely reliability at peak which is taken into account in the level playing field comparison
- The underlying FOAK technology cost assumptions are based on ETI analysis of cost evidence and achievable costs for an efficiently sited and scoped gas CCUS project[9]. These costs include a FOAK premium but are significantly lower than the £170/MWh figure quoted at time of CCUS competition cancellation in late 2015
- Overall the analysis suggests that gas power CCUS is close to cost-competitiveness, taking all relevant factors into account. Other strategic factors, such as the potential to de-risk industrial CCUS cluster development, could offer additional advantage.

Figure 13 shows the make-up of the difference between the strike price equivalents under current market arrangements and under level playing field assumptions, for several key electricity technologies.

Figure 13
Difference between strike price equivalents under current market arrangements and under level playing field assumptions



8. The BEIS appraisal value of carbon represents the marginal cost of abatement associated with meeting the UK's 2050 target. It is substantially higher than the assumed EU ETS market price.

9. Thermal Power with CCS – generic business case

IMPLICATION FOR ACTION TO PROGRESS CCUS

Updated evidence and the case for CCUS

A variety of evidence, including analysis by the CCC and the ETI, continues to suggest that CCUS is indispensable to a cost effective low carbon transition for the UK.

Delaying deployment of CCUS will certainly increase the risks and probably increase the costs of energy sector transition. This has been verified by the updated whole energy system analysis set out in section 3.

There is robust evidence that gas power CCUS is part of a low cost and low risk portfolio of options to decarbonise electricity. This holds even though renewables are now available at low cost and early power CCUS projects are likely to carry a first of kind cost premium. The startling cost reductions in renewables and storage have not removed the case for developing CCUS in electricity generation. Power CCUS can be deployed early (i.e. before 2030) with negligible impact on electricity system costs. This has been verified by updated electricity system modelling set out in section 4.

A balanced analysis also shows how current market arrangements (and commonly used cost metrics such as strike prices) do not fully reflect the relative value of power CCUS as a firm low carbon option.

Other factors supporting the case for CCS in electricity

Several other factors support the case for investing in early power CCUS projects:

- CCUS is required for cost-effective decarbonisation of industry. Electricity is a low risk sector in which to develop early CCUS deployment (and anchor loads for clusters), given its relative lack of trade exposure and existing support mechanisms
- CCUS can be deployed cost-efficiently before 2030 within an electricity generation mix that meets the fifth carbon budget
- Early power CCUS development offers potential wider strategic benefits (e.g. development of cluster infrastructure for industrial decarbonisation)
- Gas power CCUS in a favourable location for a CCUS industrial cluster represents the most straightforward, deliverable and best value approach to early deployment. The government should not risk failing to realise the future benefits and cost savings associated with CCUS, by over-emphasising cost reduction (viewed primarily from a unit or levelized cost perspective) in narrow cost metrics ahead of deployment
- Existing mechanisms (e.g. CfDs) could be used to support an early tranche of investment in power CCUS.

ABOUT THE AUTHOR

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