energy technologies institute

# THE EVIDENCE FOR DEPLOYING BIOENERGY WITH CCS (BECCS) IN THE UK

An insights report from the Energy Technologies Institute

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Bioenergy with CCS (BECCS) can deliver negative emissions (the net removal of $CO_2$ from the atmosphere) whilst also producing energy in the form of

electricity | heat | liquid fuels | gaseous fuels

By 2050 BECCS could deliver **c55m** tonnes of net negative emissions per annum

roughly half the UK emissions target in 2050

# THE EVIDENCE FOR DEPLOYING BIOENERGY WITH CCS (BECCS) IN THE UK

## A SYSTEMS OVERVIEW

Significant knowledge gaps addressed by the ETI and others over the last 10 years have...

- identified pathways to sustainable feedstock supply in the UK
- proved the ability to deliver genuine carbon savings
- demonstrated no significant technical barriers to deployment
- identified key $CO_2$ stores and progressed technology to verify store integrity

**The UK is well-placed to exploit the benefits of BECCS**

it has vast storage opportunities offshore, and strong academic & industrial experience in both bioenergy & CCS

**The next steps are to demonstrate the components of BECCS**

proving the technology, feedstock supply & logistics, and overall commercial viability

**UK government support for BECCS is vital**

BECCS should be an integral part of UK CCS and decarbonisation strategies

# EXECUTIVE SUMMARY

- Bioenergy with CCS (BECCS) is a credible, scalable and efficient technology, and is critical to deploy in order for the UK to meet its 2050 GHG emission reduction targets cost-effectively.
- Major advances in the fundamental science and technology development have been made by the ETI and others over the last ten years – significantly de-risking this value chain, and evidencing that there are no 'show-stopping' technical barriers to BECCS.
- Specifically, advances have been made in understanding:
  - The costs, efficiencies and challenges of biomass-fed combustion systems with carbon capture.
  - The evidence that numerous bioenergy value chains can deliver significant carbon savings, and sizeable negative emissions when including BECCS, based on certain feedstocks.
  - The potential availability and sustainability of feedstocks relevant to the UK.
  - The identification and assessment of high capacity, low cost, low-risk stores for $CO_2$ around the UK and the infrastructure required to connect to them.
- Analysis shows that the UK is exceptionally well-placed to exploit the benefits of BECCS, given the vast storage opportunities offshore around the UK; our experience in bioenergy deployments; and our academic and industrial research and development strength across bioenergy and CCS.
- A consistent biomass feedstock planting rate of 30,000 hectares per annum, combined with moderate imports, is sufficient to keep the UK on the required trajectory for meeting the 2050s bioenergy and negative emissions targets.
- Given these advances in understanding and de-risking – BECCS should now be an integral part of the UK's future CCS strategy.
- BECCS deployment is achievable by 2030, since all major components of a BECCS system have now been demonstrated or 'proven' individually – significantly de-risking the full-system deployment.
- In addition to the ETI work, great progress is being made in the UK and internationally, on the operational and handling aspects of biomass combustion, co-firing and CCS, through 'learning by doing' in pilot research trials and full-scale plant demonstrations, e.g. Drax's coal unit conversions to biomass in the UK, and the Boundary Dam commercial-scale coal power CCS project in Canada.
- Significant support is needed over the next 5-10 years to demonstrate a commercial deployment of BECCS technology and the wider biomass and $CO_2$ storage supply chain in the UK.

# BACKGROUND – WHY BECCS?

**To tackle the causes of climate change, the UK has committed to an 80% reduction in its greenhouse gas (GHG) emissions by 2050, compared to 1990 levels. Meeting these targets will require a massive transformation in the way energy is generated and used in the UK.**

Bioenergy technologies when combined with Carbon Capture and Storage (BECCS) can deliver negative emissions (net removal of $CO_2$ from the atmosphere) whilst producing energy in the form of electricity, heat, gaseous and liquid fuels. Negative emissions provide important emissions 'headroom' as the UK transitions towards a low-carbon energy system, since the additional 'breathing space' afforded by negative emissions reduces the need for rapid emissions reductions in sectors such as heavy duty transport and aviation which are more difficult and expensive to decarbonise. Evidence from ESME, the ETI's peer-reviewed energy system modelling environment, suggests that by the 2050s, BECCS could deliver c.-55 million tonnes of net negative emissions per annum (approximately half our emissions target in 2050), whilst meeting c.10% of the UK's future energy demand. This would reduce the cost of meeting the UK's 2050 GHG emissions target by up to 1% of GDP.

In addition to ETI analysis, several other high profile organisations have highlighted the importance of BECCS in helping to tackle global climate change, including:

- The Intergovernmental Panel on Climate Change (IPCC). In their Fifth Assessment Report[1] on mitigating future climate change, over 100 of the 116 scenarios associated with $CO_2$ concentrations between 430-480ppm in 2100 (the level that is likely to limit average temperature rises to 2˚C) depend on BECCS to deliver global net negative emissions. The IPCC found that many climate models could not limit global warming to below 2°C if the use of bioenergy, CCS and their combination (BECCS) had limited deployment.
- The Low Carbon Innovation Coordination Group (LCICG). The 2012 Bio-TINA (Technology Innovation Needs Assessment)[2] stated that, deployed properly, bioenergy and BECCS, has the potential to help secure energy supplies mitigate climate change, and create significant green growth opportunities.
- The Committee on Climate Change (CCC). In their report on setting the 5th Carbon Budget[3, 4], the CCC recommended that bioenergy should be used with CCS, and where alternative low-carbon options were not feasible or cost-effective.
- Lord Oxburgh's report on the critical role of CCS[5]. This report re-emphasises that BECCS plays a very significant role in both 2˚C and 1.5˚C modelling scenarios for global warming which are consistent with the Paris Agreement (agreed at COP21). It also echoes the ETI's views that: i) CCS technology is ready for deployment without any more fundamental research and that it can be competitive already against other forms of clean technology; and ii) that the capacity to deliver negative emissions has the potential to reduce the overall cost of decarbonisation by compensating for emissions from some hard-to-mitigate sectors, and adds flexibility into any decarbonisation plan. The report also notes that while there are a number of other potential negative emissions technologies (NETs), including NET fuel cells and direct air capture, none can be deployed cost-effectively at scale today in the same way BECCS could be. Some may develop in the future, but they would require an established CCS infrastructure to already be in place, and therefore BECCS is a natural technology to progress first.
- Committee on Climate Change (CCC) 'UK Climate action following the Paris Agreement' report[6]. This report (and it's two sister reports[7]), make it very clear that sustainable bioenergy and BECCS both play a critical role in enabling the UK to meet its 2050 GHG emission reduction commitments, and an even more central role in realising the net zero emission ambitions arising from the Paris Agreement. Specifically, it echoes ETI's views that: i) BECCS could be cost competitive by the 2030s, but requires urgent UK Government support; ii) the BECCS supply chain would need to draw on both domestically-produced and imported feedstocks; iii) CCC suggest a similar domestic planting rate of 30,000 ha/yr to the ETI[8]; and iv) they highlight the future importance of hydrogen and CCS – initially for heat via injection in to the gas grid (ETI has also explored the potential of utilising the UK's significant salt caverns for hydrogen storage[9], ultimately providing base- and peak-load electricity generation via hydrogen turbines).

The International Energy Agency Clean Coal Centre (IEACCC), whilst not focusing on BECCS specifically, list in their 5th 'Co-firing Biomass with Coal' conference papers[10], several demonstrations and trials by major producers, e.g. E.ON, Dong, Drax, GDF Suez, and scientific institutions working on the practical issues some biomass and waste fuels pose, including aspects of fouling, corrosion and downstream catalyst deactivation. This demonstrates the current commercial interest in developing biomass conversion technologies, which is a vital part of BECCS.

1 IPCC (2014): Climate Change 2014: Mitigation of Climate Change. Available from: http://ipcc.ch/report/ar5/wg3/

2 LCICG (2012): Technology Innovation Needs Assessment (TINA). Bioenergy Summary Report. Available from: http://www.lowcarboninnovation.co.uk/working_together/technology_focus_areas/bioenergy/

3 CCC (2015): The Fifth Carbon Budget: The next step towards a low carbon economy. Available from: https://www.theccc.org.uk/publication/the-fifth-carbon-budget-the-next-step-towards-a-low-carbon-economy/

4 The Government accepted the CCC's recommendations and set the fifth carbon budget at 1,725 Mt $CO_2e$ for the period 2028-2032 in the Carbon Budget Order 2016. Available from: http://www.legislation.gov.uk/uksi/2016/785/made

5 Oxburgh (2016): lowest cost decarbonisation for the uk: the critical role of CCS. Report to the Secretary of State for Business, Energy and Industrial Strategy from the Parliamentary Advisory Group on Carbon Capture and Storage (CCS). Available from: http://www.ccsassociation.org/news-and-events/reports-and-publications/parliamentary-advisory-group-on-ccs-report/

6 CCC (October 2016) Reports: https://www.theccc.org.uk/wp-content/uploads/2016/10/UK-climate-action-following-the-Paris-Agreement-Committee-on-Climate-Change-October-2016.pdf

7 'Next steps for UK heat policy' and 'Meeting Carbon Budgets – Implications of Brexit for UK climate policy' reports: https://www.theccc.org.uk/2016/10/13/concrete-action-needed-to-meet-uk-climate-commitments-following-paris-agreement-and-brexit-vote/

8 ETI (2016) Delivering GHG emission savings through UK bioenergy value chains. Available at: http://www.eti.co.uk/insights/delivering-greenhouse-gas-emission-savings-through-uk-bioenergy-value-chains

9 ETI (2015) The role of hydrogen storage in a clean responsive power system. Available at: http://www.eti.co.uk/insights/carbon-capture-and-storage-the-role-of-hydrogen-storage-in-a-clean-responsive-power-system

10 IEA Clean Coal Centre, 5th Co-firing Biomass with Coal conference (16-17th September 2015), conference papers available from: http://cofiring5.coalconferences.org/ibis/cofiring5/home

## CRITICAL KNOWLEDGE GAPS

The ETI was established in 2007, and at that time, there were considerable uncertainties and knowledge gaps around BECCS, as well as many individual elements of bioenergy and CCS development themselves. The ETI established CCS and Bioenergy programmes (with spends of £32m and £20m respectively) to address these knowledge gaps, in order to better assess and understand the potential for, and suitability of, BECCS deployment in the UK.

Specifically, ETI identified a series of questions that encapsulated uncertainties surrounding the use and commercial deployment of bioenergy and CCS in the UK. By seeking to answer them, ETI has identified and progressed the priority activities needed to quantify and reduce these uncertainties.

Collective project insights gained through our Bioenergy and CCS programmes, and informed by the work of others, has enabled us to address four key questions in relation to BECCS deployment in the UK:

1. **Can a sufficient level of BECCS be deployed in the UK to support cost-effective decarbonisation pathways for the UK out to 2050?**
2. **What are the right combinations of feedstock, pre-processing, conversion and carbon capture technologies to deploy for bioenergy production in the UK?**
3. **How can we deliver the greatest emissions savings from bioenergy and BECCS in the UK?**
4. **How much $CO_2$ could be stored from UK sources and how do we monitor these stores efficiently and safely?**

### The intention of this paper is to:

1) Highlight the progress that has been made in understanding the key uncertainties associated with BECCS through ETI's projects, which have been delivered in partnership with our industrial, academic and research partners over the last ten years, and outline the insights gained

2) Demonstrate the potential for UK deployment and the system value in supporting BECCS now in order to meet our GHG targets cost-effectively.

A more detailed description of project activities and insights can be found in the individual project insight publications referenced throughout this document.

# CONTEXT

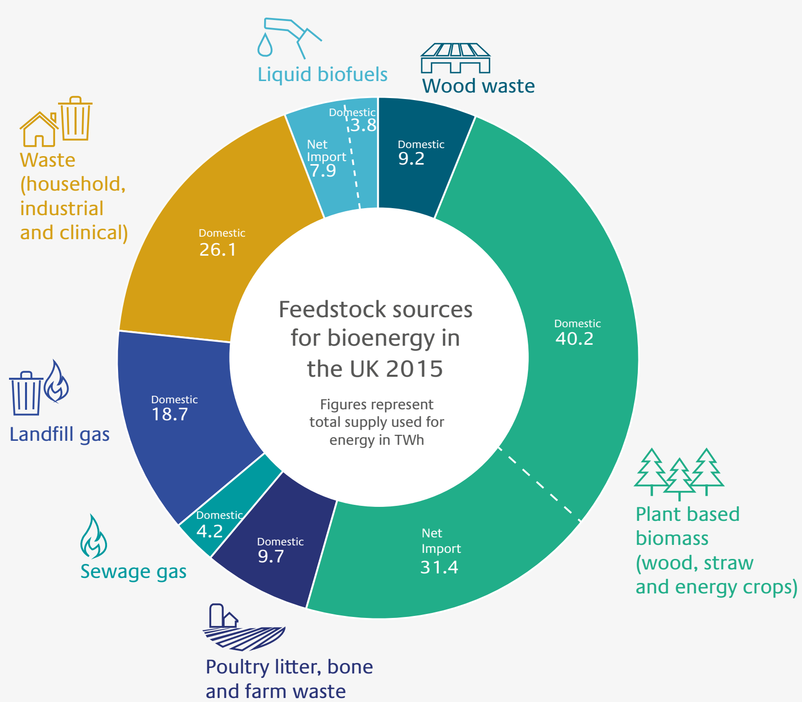
## Bioenergy

Bioenergy is the largest source of renewable energy in the UK. In 2015, Bioenergy contributed 73% of all renewable energy inputs (151 TWh/yr) and 59% of final renewable energy consumption. This met 5% of all UK final energy demand today, of which 38% was electricity, 14% transport fuels, and 48% was heat[11].

The majority of biomass and waste feedstocks are sourced in the UK, but imports of biomass and biofuels have increased in recent years to meet demand, see Figure 1 below.

Most UK bioenergy plants to date either provide power or heat. By the end of July 2016, there was 5.2 GW of bio-power capacity in the UK, and 3.1 GW of heat; plus 226 MW of biogas capacity supported under the RHI[12].

**Figure 1**
**2015 biomass and waste feedstock sources[13]**




Source: DUKES (2016), Table 6.1 Renewables and Waste Commodity Balances 2015 / Summarised by Energy Technologies Institute LLP

11 BEIS (2016): Digest of UK Energy Statistics (DUKES). Available from: https://www.gov.uk/government/collections/digest-of-uk-energy-statistics-dukes
12 BEIS (2016), July 2016 RHI Deployment Data Available from: https://www.gov.uk/government/statistics/rhi-deployment-data-july-2016
13 BEIS (2016): Digest of UK Energy Statistics (DUKES). Available from: https://www.gov.uk/government/collections/digest-of-uk-energy-statistics-dukes

## Bioenergy with CCS

Both biomass combustion and biomass gasification lend themselves to CCS through proven $CO_2$ capture technologies (on coal and oil residues). The scale of biomass in the UK today, and in particular its use in a large unit like Drax, produces $CO_2$ in sufficient quantities to deliver economies of scale in the capture of $CO_2$. On a smaller, but still important scale, the UK has the opportunity to fit CCS to existing bioethanol plants, as has been demonstrated in the USA. Although the UK has no large CCS projects, large scale underground storage in North Sea aquifers has been practised in Norway since 1996, and by 2017, 22 plants globally will be running CCS technology applications, spanning post-combustion and pre-combustion coal, natural gas steam reforming, bioenergy (corn to ethanol), and applications from power, gas production, refining, chemicals and steel. Indeed TOKYO-Toshiba Corporation has recently been selected by Japan's Ministry of the Environment to construct a carbon capture facility to capture over 500 tonnes of $CO_2$ a day from the Mikawa Power Plant (49MW)[14]. The plant aims to be operational by 2020, and it will become the world's first power plant capable of capturing carbon from a biomass power plant, and therefore the first to deliver 'negative emissions'.

14 Toshiba (2016): Toshiba and Mizuho Information & Research Institute to Lead Japan's Largest CCS Project. Press release available from: https://www.toshiba.co.jp/about/press/2016_07/pr2601.htm

# ANSWERING THE FOUR CRITICAL QUESTIONS – INSIGHTS GAINED THROUGH THE ETI'S BIOENERGY AND CCS PROGRAMMES

## 1. Can a sufficient level of BECCS be deployed in the UK to support cost-effective decarbonisation pathways for the UK out to 2050?

The ETI's ESME modelling consistently selects decarbonisation pathways for the UK that generate approximately 130TWh/yr of bioenergy (~10% final energy demand) in 2050, and deliver more than 50 million tonnes of 'negative emissions' a year through the combined deployment of bioenergy and CCS. Using our more detailed 'Bioenergy Value Chain Model' (BVCM) to understand future bioenergy sector development scenarios, we know that this 130TWh/yr final energy output requires approximately 190TWh/yr of biomass feedstock (a combination of imported and domestically grown feedstocks), and ~45TWh/yr of waste feedstocks[15]. The table below sets out our estimates for how much additional feedstock is required to meet these 2050 pathways.

| | A. Amount of feedstock currently being used for bioenergy | B. 2050s requirement | C. Additional needs from 2015 level of use to be met over next 35 years (C = B - A) | D. ETI estimates of additional feedstock potentially available in 2050 | ETI assessment of whether the 2050s requirement can be met (is B < A + D?) |
|---|---|---|---|---|---|
| UK residual waste arisings | 22 TWh/yr[16] | 45 TWh/yr | 23 TWh/yr | 29 TWh/yr (~8mT p.a.) | YES |
| Domestically-grown biomass | 40 TWh/yr[17] (plus ~4 TWh/yr being used to produce liquid biofuels) | 75-115 TWh/yr | 35-75 TWh/yr | 70-105 TWh/yr (based on conversion of 1.4mHa) | YES |
| Imported biomass feedstocks | 31 TWh/yr | 75-115 TWh/yr | 44-84 TWh/yr | 69-319 TWh/yr[18] | YES |

Our analysis indicates that the additional domestic biomass feedstock production needs could be met by converting 1.4million hectares of UK agricultural land to bioenergy crops and forestry by the 2050s. ETI has taken a conservative approach to assessing the amount of land that could potentially be available to produce domestic biomass feedstocks – limiting the amount, type and location of land to be converted based on a series of assumptions set out in earlier insight reports[19].

15 These figures exclude imported biofuels, since they are 'ready-to-use' and not actually converted to a final vector within the UK. The UK currently imports ~678 ktoe (7.88 Twh/yr). Source: BEIS (2016): Digest of UK Energy Statistics (DUKES). Available from: https://www.gov.uk/government/collections/digest-of-uk-energy-statistics-dukes

16 This excludes landfill gas and sewage gas, which has a current input value of 23 TWh/yr, producing energy largely via engines or anaerobic digestion

17 Source: BEIS (2016): Digest of UK Energy Statistics (DUKES). Available from: https://www.gov.uk/government/collections/digest-of-uk-energy-statistics-dukes

18 HMG (2012) UK Bioenergy Strategy. Available from: https://www.gov.uk/government/publications/uk-bioenergy-strategy

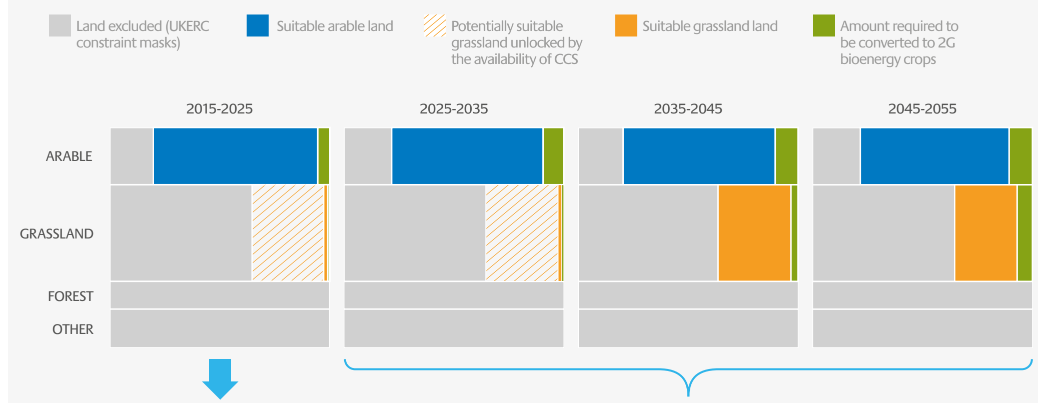
19 ETI (2015), Insights into the future UK Bioenergy Sector, gained using the ETI's Bioenergy Value Chain Model (BVCM). Available from: http://www.eti.co.uk/bioenergy-insights-into-the-future-uk-bioenergy-sector-gained-using-the-etis-bioenergy-value-chain-model-bvcm/

Work completed for us by ADAS suggests that with small changes to farming practices and food waste, there could be sufficient spare land in the UK agricultural system to meet this requirement of 1.4 million hectares of land without impacting existing levels of UK food security (see Figure 2 below). This could be targeted for conversion to biomass production. A consistent biomass feedstock planting rate of 30,000 hectares per annum, combined with moderate imports, is sufficient to keep the UK on the required trajectory for meeting the 2050s bioenergy and negative emissions targets outlined at the start of this section.

Developing an appropriate policy and regulatory framework for targeting this spare land presents an opportunity to optimise the efficiency, economic and environmental performance of the UK agricultural sector as a whole – something which is likely to be even more important in the context of the UK's development of a framework to leave the EU and the expected loss of the Common Agricultural Policy support mechanism. Targeting marginal arable land and appropriate grassland would minimise food production impacts and associated indirect Land Use Change (iLUC) emissions, and has been shown to be profitable at the farm level (Refining Estimates of Land for Biomass (RELB) project)[20].

**Figure 2**

Representation of the proposed strategic approach to targeting land use change for biomass feedstock production in the UK over the next 35 years, and suggested sources of available 'spare' land to target for biomass production.




**Short-term opportunities**
- 120kHa existing land under 1G bioenergy crops
- 90kHa economically marginal land
- 100kHa 20% of cereal & oilseed rape overproduction area
- 35kHa permanent fallow uncropped arable land
- Total **345kHa**

**Longer-term opportunities**
- 35kHa from 50% reduction in on-farm fruit & vegetable waste
- 100kHa from 50% reduction in fruit, vegetable and meat consumer waste
- 100kHa from further 20% cereal & oilseed rape overproduction area
- 500-700kHa from improved utilisation grassland
- 10kHa white land (public land being sold off e.g. FC land harvested for energy)
- Total **745-945kHa**
- **Cumulative total 1090-1290kHa before impacting existing levels of UK food security**

20 ETI (2016) Bioenergy crops in the UK: Case studies of successful whole farm integration. Available from: http://www.eti.co.uk/library/bioenergy-crops-in-the-uk-case-studies-on-successful-whole-farm-integration-evidence-pack. The RELB Land Availability report will be published in 2017.

## Answering the four critical questions – Insights gained through the ETI's Bioenergy and CCS Programmes

Continued ›

At the start of ETI's Bioenergy programme in 2008, much uncertainty and concern existed around the availability and sustainability of bioenergy at the scales required. Considerable work has been completed by ETI and others in this space over the last few years. The ETI's 4-year Ecosystem Land Use Modelling (ELUM) field trials project has significantly advanced the evidence and understanding of the sustainability of biomass feedstock production in the UK, especially around soil carbon sequestration (see summary findings) and the ability to deliver genuine carbon savings across bioenergy value chains (see Figure 5). Most importantly, it showed that given the right choice of land-use change, crop type and location – substantial emission savings can be delivered through bioenergy, and many opportunities exist to optimise the wider ecosystem service benefits from biomass feedstock production in the UK.

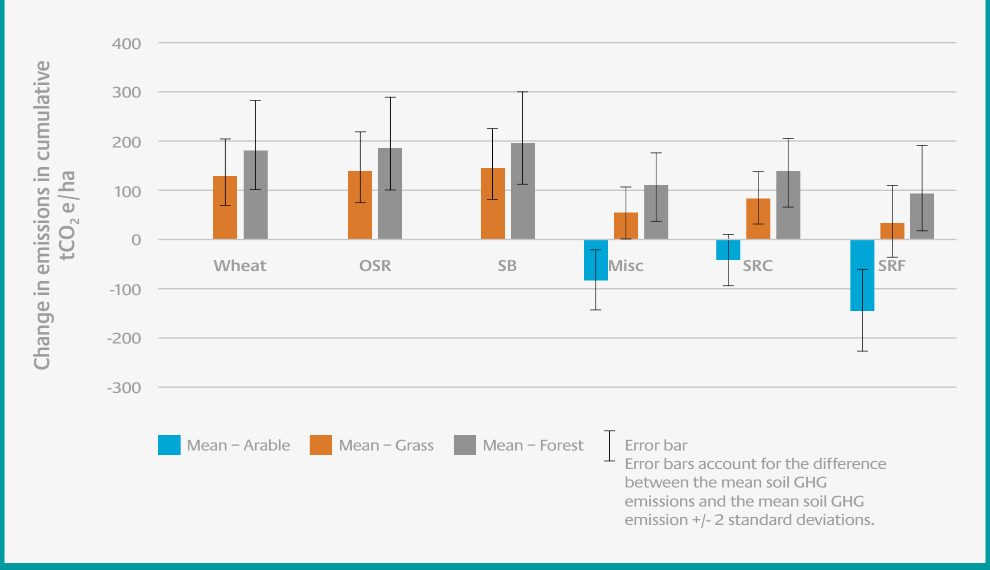
Financial sustainability can also be achieved through more strategic approaches to agricultural land use in the UK, and specifically optimising local productivity by taking account of economic, environmental and wider accessibility factors. As part of our evidence collection and assessment of land available for biomass, we have also assessed the drivers for land use change to bioenergy (Enabling UK Biomass project[21]) and the economic counterfactuals, and collated example case studies where farmers/landowners have successfully diversified part of their land to include biomass production[22].

It is important to note that the ELUM project findings are only part of the 'value chain' (i.e. soil carbon changes from biomass production), and therefore need to be read in conjunction with Figure 5, which contextualises the importance of soil carbon changes and wider direct land use change emissions, relative to the GHG emissions across the whole system-level value chain (e.g. taking in to account transport and conversion emissions too). Only this value chain assessment enables us to test whether genuine carbon savings could be delivered relative to fossil fuel baselines.

### Summary findings from ELUM[23]

- Second generation (2G) biomass, such as Miscanthus, Short Rotation Coppice (SRC) Willow and Short Rotation Forestry (SRF) grown on arable land, or grassland sites where appropriate, offer the greatest potential yield and GHG emission savings, but also could deliver wider biodiversity and ecosystem service benefits, including hazard regulation (e.g. flood prevention), disease and pest control, improving water and soil quality, and acting as wildlife/game cover
- The GHG benefits of increased planting of 2G bioenergy crops (including forestry) is apparent since crops that are well-matched to sites can start acting as net carbon sinks as soon as they start growing (see Figure 3 for national average)
- Short Rotation Forestry is likely to offer the greatest GHG savings in bioenergy value chains, particularly when grown on arable or grassland, due to its ability to deliver greatest soil carbon sequestration

**Figure 3**
Estimates derived from the ELUM model on mean soil GHG emissions over 40 years (relative to counterfactual land use), expressed as net GHG emissions per hectare across the UK. The model was validated using empirical data collected during the ELUM project.




Our analysis demonstrated that where land use change resulted in an increase in soil emissions (i.e. soil carbon losses), these were more than offset by the $CO_2$ captured and stored when that biomass feedstock was used in a BECCS value chain. Further details can be found in our previous insight report[24].

21 ETI (2015) Enabling UK Biomass. Available from: http://www.eti.co.uk/bioenergy-enabling-uk-biomass/

22 ETI (2016) Bioenergy Crops in the UK: Case Studies of successful whole farm integration. Available from: http://www.eti.co.uk/library/bioenergy-crops-in-the-uk-case-studies-on-successful-whole-farm-integration-evidence-pack.

23/24 ETI (2016), Delivering greenhouse gas emission savings through UK bioenergy value chains. Available from: http://www.eti.co.uk/delivering-greenhouse-gas-emission-savings-through-uk-bioenergy-value-chains/

# Answering the four critical questions – Insights gained through the ETI's Bioenergy and CCS Programmes
Continued ›

## 2. What are the right combinations of feedstock, pre-processing, conversion and carbon capture technologies to deploy for bioenergy production in the UK?

### a) Optimising feedstock properties for future bioenergy conversion technologies

In parallel with understanding whether bioenergy value chains deliver genuine carbon savings, and understanding the availability of different feedstocks, it is critically important to understand the characteristics of biomass and waste feedstocks, and their variability, in order to understand how energy conversion technologies may perform when utilising these feedstocks. Biomass and waste feedstocks can raise new issues with conversion that haven't been encountered with fossil fuels, such as moisture, ash (content and fusion temperature), minor constituents such as silica, calcium, potassium and chlorine, and especially for waste – issues with tars.

Building the evidence base around physical and chemical composition of different feedstocks enables process designers to assess the relative opportunities for optimising bioenergy value chains – whether it be through selection of feedstocks with particular traits; pre-treating the feedstocks in some way; blending the feedstocks to dilute any issues; adapting the conversion technology itself to better deal with any fouling, slagging or performance issues; and/or bolstering clean-up technologies to negate any changes in emissions resulting from the use of particular feedstocks. ETI has commissioned a series of projects to build this evidence base, including the Characterisation of Feedstocks; Energy from Waste; and Techno-economic assessment of biomass pre-processing (TEABP) projects[25, 26, 27]. Insights from their combined outputs will be published as an ETI insights report in 2017, and have informed the scope of the Biomass Feedstock Improvement Process (BioFIP) Demonstrator project currently being commissioned by the ETI.

Two ETI projects have looked at the future relevance of different bioenergy conversion technologies, and both have indicated that advanced gasification appears to have the greatest potential for delivering flexible low-cost energy. The Energy from Waste project compared combustion, anaerobic digestion, advanced gasification and pyrolysis, and concluded that advanced gasification (with syngas clean-up) offered the greatest potential benefits for converting waste to energy at the town scale (an optimal scale in terms of balancing economies of scale with logistical costs and associated emissions). The BVCM project assessed the current maturity, cost and performance levels of all bioenergy technologies, and consistently highlights advanced gasification as one of the key low-cost means of delivering the required carbon savings at the UK energy system level out to the 2050s.

Advanced gasification technology, although not the only option, is a key enabler of flexible energy system solutions, since the syngas produced can be converted to electricity (either directly or via hydrogen production), CHP, bio-methane and transport fuels, making it one of the most flexible, scalable, and cost-effective bioenergy technologies available. ETI has progressed this important technology by supporting the development and demonstration of 'advanced gasification', i.e. where the syngas quality is sufficiently increased and cleaner, such that it could be used consistently in an engine or turbine.

We have assessed the potential of three different types of advanced gasification and gas clean-up systems through our Waste Gasification project: plasma, low-temperature- and high-temperature-gasification and gas clean-up systems. We assessed plant designs capable of net electrical efficiencies of more than 25% (from initial 'raw waste' feedstock to power generation), and availability greater than 80%, at the 'town' scale, i.e. 5-20MWe. Three project teams (Advanced Plasma Power, Broadcrown and Royal Dahlman) evidenced their designs through significant analysis of UK waste feedstocks from different suppliers, modelling, and laboratory and pilot-scale testing of different components within their system, i.e. gasifier, gas clean-up and power generation.

ETI is progressing one of these designs to construction and demonstration, with a target operational date of Q2, 2018. Successfully delivering this Advanced Gasification Demonstrator project will be a major step in the acceleration and de-risking of this important bioenergy technology.

25 ETI's Techno-economic assessment of Biomass Pre-Processing Technologies (TEABP) project is assessing the cost-effectiveness of pre-processing, taking into account different feedstocks, storage, logistics, pre-processing and conversion technologies. Insights informed the commissioning of the Biomass Feedstock Improvement Process (BioFIP) demonstrator project. More information available from: http://www.eti.co.uk/project/techno-economic-assessment-of-biomass-pre-processing/

26 ETI's Energy from Waste project assessed the energy-bearing content and composition of different waste feedstocks in the UK, and modelled availability out to 2050. More information available from: http://www.eti.co.uk/project/energy-from-waste/

27 ETI's Characterisation of Feedstocks (CoF) project is assessing the physical and chemical properties of a selection of different UK-derived biomass feedstocks. More information available from: http://www.eti.co.uk/project/characterisation-of-feedstocks/

# Answering the four critical questions – Insights gained through the ETI's Bioenergy and CCS Programmes

Continued

## b) BECCS value chains – what carbon capture technologies do we need to develop?

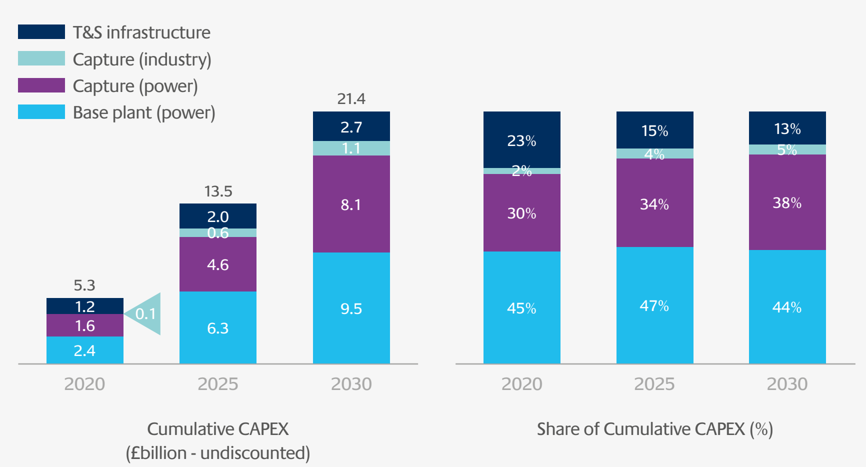
BECCS technologies represent one of the very few practical, scalable and economic means of removing large quantities of $CO_2$ from the atmosphere relevant for the UK, and the only approach which generates a useful 'by-product' – power, heat or hydrogen.

ETI work on CCS has examined key aspects of its deployment for both fossil (coal and gas) and biomass (co-firing and dedicated) feedstocks, including costs, risk and technology maturity. The Bioenergy programme has focused on the costs and challenges of BECCS technologies[28], and the CCS programme has examined risk and cost reduction in $CO_2$ transportation and storage, and the cost of $CO_2$ capture.

- The cost of $CO_2$ capture is the largest single cost element in CCS (see Figure 4), and can be comparable to the cost of the original power station. Additionally, the process of capturing $CO_2$ itself can use up to 20% of the power station output.
- Plant scale remains the principal driver of CAPEX, rather than choice of technology, with larger plants having lower specific capital costs. The weighted feedstock energy content and cost is one of the key drivers of LCOE, with biomass pellets currently being more expensive than fossil fuel feedstocks e.g. coal.

**Figure 4**

Capital costs of building a 50 Mt/yr $CO_2$ (~10 GWe) CCS network (£bn 2014 undiscounted)[29]




- A number of capture technologies warrant further development. Whilst some technologies are more likely to be operational first (post-combustion amine), it is not yet possible to identify next generation technologies which could end up being the dominant CCS/BECCS technology by 2050. It is likely that as technologies develop, such as gasification to generate more flexible fuels.
- Dedicated (100% biomass) BECCS technologies offer significant opportunity to deliver substantially more negative emissions than co-firing technologies, and would be more attractive in the longer term if and when financial incentives are applied to negative emissions and avoided carbon. In the absence of such incentives, co-firing could be a more cost-effective way of minimising penalties for positive emissions, and is likely to play an important 'transition role'.
- The TESBiC[28] project findings indicate that the most significant barriers to the deployment of BECCS technologies will be the scale of investment required, the limited price of carbon and hence the limited value of negative emissions, rather than being technical barriers.
- Most cost savings in the next two decades will be delivered through reducing costs by deployment, rather than fundamental technology breakthroughs. Combined with the low growth rate of CCS and the absence today of a commercially-ready game-changer, this means amines and pre-combustion technologies will continue to be the technology of choice in power production for several years.
- It is important that technologies offering breakthrough performance are funded through to demonstration level so that they can enter the market when other aspects of risk have been reduced.
- By the mid-2030s CCS plants may have to respond to daily demand changes, and therefore operate at lower load – technologies that offer reduced capital costs or system flexibility will be more attractive. ETI system modelling indicates new investments for this market should favour both natural gas plants due to cost, and biomass gasification due to the system value of negative emissions and flexibility in terms of the end product.

28 Techno-Economic Study of Biomass to power with CCS (TESBiC) project commissioned and funded by the ETI. Further information available at: http://www.eti.co.uk/programmes/bioenergy/biomass-to-power-with-carbon-capture-and-storage

29 ETI (2016) Reducing the cost of CCS – Developments in capture plant technology. Available from: http://www.eti.co.uk/reducing-the-cost-of-ccs-developments-in-capture-plant-technology-2/

## Answering the four critical questions – Insights gained through the ETI's Bioenergy and CCS Programmes

Continued ›

### 3. How can we deliver the greatest emissions savings from bioenergy and BECCS in the UK?

Collective insights from our ELUM and BVCM projects show that[30]:

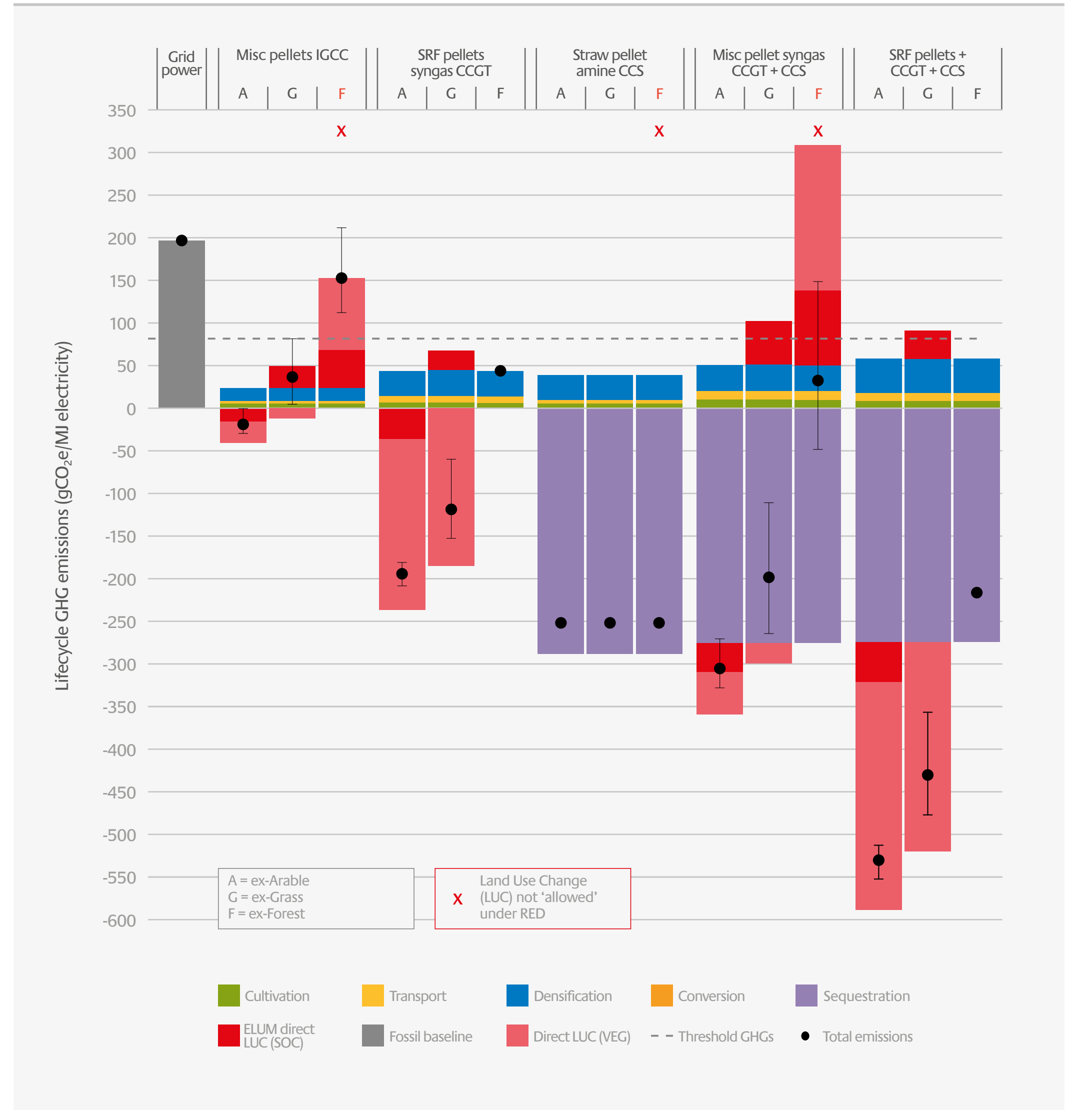
- CCS is a game-changer. Bioenergy value chains with CCS, as shown in Figure 5, render direct Land Use Change (dLUC) emissions of second-order importance. Most 2G biomass feedstocks grown in the UK and used in BECCS would deliver substantial negative emissions to the UK, and flexibility, across all key vectors of power, heat, liquid and gaseous fuels.
- If bioenergy is deployed without CCS, dLUC emissions can be material, either contributing GHG emission savings via soil carbon sequestration, or by producing additional emissions at the value chain level, depending on the choice of crop type, location and ultimate use in the energy system. Our work has reinforced the need to assess emissions across the whole value chain in order to judge the scale of carbon savings achieved, and not just view feedstock carbon debt, land-use change emissions or conversion technologies in isolation.
- The greatest emissions savings are when bioenergy is used with CCS. This combination means that biomass and waste feedstocks are 'best' deployed in conversion technologies which result in power or hydrogen – since neither have any carbon content in the resultant energy vector, and CCS can be used to capture the maximum amount of $CO_2$ from the conversion process.

The graphs shows how emissions for different bioenergy value chains vary depending on the land use prior to growing the biomass feedstock. Along the x-axis, "A", "G" and "F" denote transitions from arable, grassland and forest respectively. The emissions have been calculated over a 20 year accounting period using the rules set out in the EU Renewable Energy Directive (RED). Total net GHG emissions for each bioenergy value chain are shown by the black dots.

The change in soil carbon stock emissions are the mean values from the ELUM project. The error bars account for the difference between the mean soil carbon stock change and the mean emissions +/- 2 Standard Deviations (error bars are capped at the min or max value (in ELUM) if they fall within 2SD of the mean).

The Grid Power baseline (grey bar) is taken from the current EU default. The dotted grey line indicates a 60% saving vs the fossil baseline – the savings a bioenergy value chain should meet under sustainability rules. Please note – under sustainability rules, Forest to SRF transitions would not be deemed a land use change, and therefore no dLUC emissions are reported; whilst all other transitions from Forest would not be permitted (but the data is shown to illustrate why).

**Figure 5**
Quantifying the impact of dLUC emissions and CCS on UK bio-electricity value chains (lifecycle GHG emissions: $gCO_2e/MJ$)




30 ETI (2016), Delivering greenhouse gas emission savings through UK bioenergy value chains. Available from: http://www.eti.co.uk/delivering-greenhouse-gas-emission-savings-through-uk-bioenergy-value-chains/

# Answering the four critical questions – Insights gained through the ETI's Bioenergy and CCS Programmes

Continued ›

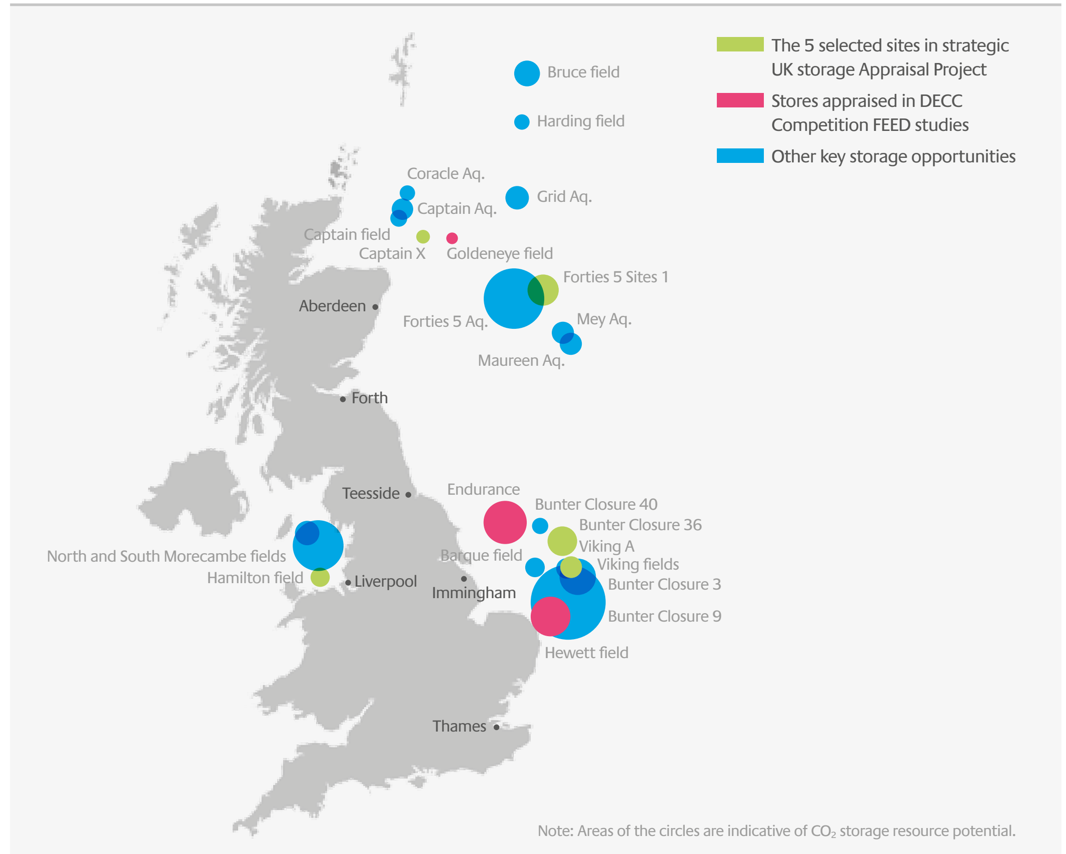
## 4. How much $CO_2$ could be stored from UK sources and how do we monitor these stores efficiently and safely?

### Storage potential

ETI has commissioned a number of projects to assess different aspects of storage of $CO_2$ around the UK. It started with the development of an atlas of UK offshore stores – a high level appraisal of about 600 potential stores (UKSAP Project), and this database is now managed by The Crown Estate and the British Geological Survey under the name of "$CO_2$Stored". In 2015, DECC funded the ETI to specify, commission and manage appraisal work (Strategic UK Storage Appraisal Project) on five geological storage sites in more detail (both depleted oil and gas fields and saline aquifers), in order to identify the amount of storage that was confidently exploitable in the short and medium term.

- The UK is endowed with a rich and diverse national offshore $CO_2$ storage resource, key components of which can be brought into service readiness without extensive appraisal programmes thanks to decades of petroleum exploration and development activity.
- The portfolio of 5 sites selected in the Strategic UK Storage Appraisal Project (see Figure 6) is geographically and technically diverse, and presents options for clean energy and industrial development around the UK.
- The ETI work, together with the three sites (Hewett, Goldeneye and Endurance) which completed FEED studies through the DECC CCS Programme, has enabled a mature and well-qualified UK storage proposition to be developed, such that more than 1.5Gte worth of stores could be fully operational by 2030. This is enough to service around 10GW of power generation and other industrial sources fitted with CCS, as highlighted in the ETI's CCS scenarios work[31].
- It is important to site new power stations with CCS close to storage sites and emission sources (e.g. on populous estuaries close to potential offshore stores, such as Thames, Mersey, Tees and Humber).
- The discounted lifecycle costs (10% discount, 2015) for this offshore pipeline and storage would add only c.£5-£9/MWh to the UK electricity price.

**Figure 6**
Selected Potential $CO_2$ Storage Sites in the UK




Source: ETI Strategic UK Storage Appraisal Project

The insights from this work were incorporated into BVCM, and enabled us to identify the optimal locations for, and nature and scale of, clusters of BECCS technologies in the UK, taking into account the likely sources of UK-grown biomass or waste feedstocks, and the port locations for imported biomass. Modelling optimised on minimal cost and GHG emissions revealed strong preferences for clusters of large, highly-efficient BECCS plants utilising gasification or combustion technology to produce hydrogen or electricity at two main shoreline hub locations (onshore points at which captured $CO_2$ is compressed and piped to the injection point of the store): Thames and Teesside. These locations are also closest to key port facilities capable of handling and distributing imported feedstock. Peterhead, Barrow and Easington were also sites of considerable $CO_2$ sequestration.

31 ETI (2015) Building the UK carbon capture and storage sector by 2030 – Scenarios and actions. Available at: https://d2umxnkyjne36n.cloudfront.net/insightReports/CCS-Building-the-UK-carbon-capture-and-storage-sector-by-2013.pdf?mtime=20160909104732.

## Answering the four critical questions – Insights gained through the ETI's Bioenergy and CCS Programmes

Continued ›

### Managing the risks of storage

Risks in storage are assessed through the process of storage appraisal. For those stores which are depleted gas fields, the activities of Oil and Gas Operators have often collected enough data to fully evaluate the store. For the bulk of the UK's storage resource however, which sit in saline aquifers, many have not been explored fully, and will require new appraisal wells to check the properties of the storage and sealing cap-rocks. In 2013, the ETI co-funded an appraisal well (the UK's first – the "Aquifer Appraisal Project") for the huge Endurance store off Yorkshire. The results were excellent and National Grid progressed design of the store, and much of the findings are published in Key Knowledge Deliverables (KKDs) on the Government website[32].

Current research and evidence shows that leakage from stores is highly unlikely. Behaviour of the $CO_2$ deep below the seabed (e.g. 2km) is expected to be observed by a suite of monitoring tools. However if $CO_2$ did escape, it would be difficult to predict with certainty exactly where and how it would reach the seabed. To enable low cost, reliable marine monitoring, the ETI initiated a project to develop a long-range mobile autonomous vehicle for measurement, monitoring and verification of storage integrity (the MMV Project) which will patrol the sea floor over large areas. The prototype (see Figure 7 below) will be trialled in the North Sea in 2017.

**Figure 7**
Autonomous marine vehicle prototype being developed through the ETI MMV project (The Autosub Long Range AUV, National Oceanography Centre, UK)

32 https://www.gov.uk/government/collections/carbon-capture-and-storage-knowledge-sharing

## CONCLUSIONS – COMPLETING THE BECCS PICTURE

**It is often helpful to view the whole system demonstration and commercial deployment of BECCS as a jigsaw puzzle, with each core element of the value chain being a separate jigsaw piece:**


Critical evidence and understanding has now been created for most of the individual jigsaw pieces through our projects, and informed by the work of others, which has enabled us to draw out key insights around BECCS.

## NEXT STEPS

The aim of this paper was to highlight the progress that has been made by ETI, our partners and others working on BECCS over the last eight years. The collective insights and progress delivered has shown that all the core component parts of a BECCS system have been significantly de-risked and advanced, with very few technical or sustainability barriers identified. The next steps needed are to put the components together in a full chain and in parallel develop the domestic bioenergy feedstock supply.

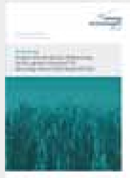
Overall, the UK is well-placed to utilise BECCS as a means of helping to meet our 2050 GHG emissions reduction targets. However, to realise the benefits of negative emissions, support is needed over the next 5-10 years to deploy a BECCS technology and $CO_2$ storage at a commercial scale.

UK government support of BECCS technology is key to the UK fulfilling its GHG carbon reduction commitments by 2050, since the final decision is a political and financial one, not fundamentally technical[33].

This progress in the technical, environmental and financial evidence and understanding, and the commercial demonstration steps being taken by others globally, should give the UK government confidence to commit to the deployment of this vital technology in the UK. The Oxburgh report suggests that full-chain CCS costs at c.£85/MWh are feasible under the right circumstances, a figure which ETI's analysis can corroborate. The report concludes that, under the right conditions, even the first CCS projects can compete on price with other forms of clean electricity. Given the evidence and progress highlighted in this report, we would urge the government to give consideration to ensuring that the UK's CCS Strategy encompasses demonstration of BECCS technology and delivering negative emissions within the next decade.

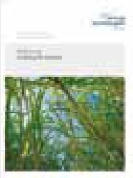
All BECCS jigsaw pieces are now clear and on the table. Others have started to put them in place internationally, and the UK should do the same.

## FURTHER READING FROM THE ETI



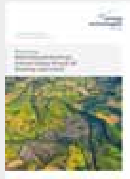
**Insights into the future UK Bioenergy sector, gained using the ETI's Bioenergy Value Chain Model (BVCM)**

www.eti.co.uk/insights/bioenergy-insights-into-the-future-uk-bioenergy-sector-gained-using-the-etis-bioenergy-value-chain-model-bvcm



**Enabling UK Biomass**

www.eti.co.uk/insights/bioenergy-enabling-uk-biomass



**Delivering greenhouse gas emission savings through UK bioenergy value chains**

www.eti.co.uk/insights/delivering-greenhouse-gas-emission-savings-through-uk-bioenergy-value-chains

**Building the UK carbon capture and storage sector by 2030**

www.eti.co.uk/insights/carbon-capture-and-storage-building-the-uk-carbon-capture-and-storage-sector-by-2030

**The role of hydrogen storage in a clean responsive power system**

www.eti.co.uk/insights/carbon-capture-and-storage-the-role-of-hydrogen-storage-in-a-clean-responsive-power-system

**Reducing the cost of CCS - Developments in Capture Plant technology**

www.eti.co.uk/insights/reducing-the-cost-of-ccs-developments-in-capture-plant-technology

33 As also stated in Lord Oxburgh's review (2016): lowest cost decarbonisation for the uk: the critical role of CCS. Report to the Secretary of State for Business, Energy and Industrial Strategy from the Parliamentary Advisory Group on Carbon Capture and Storage (CCS). Available from: http://www.ccsassociation.org/news-and-events/reports-and-publications/parliamentary-advisory-group-on-ccs-report/

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