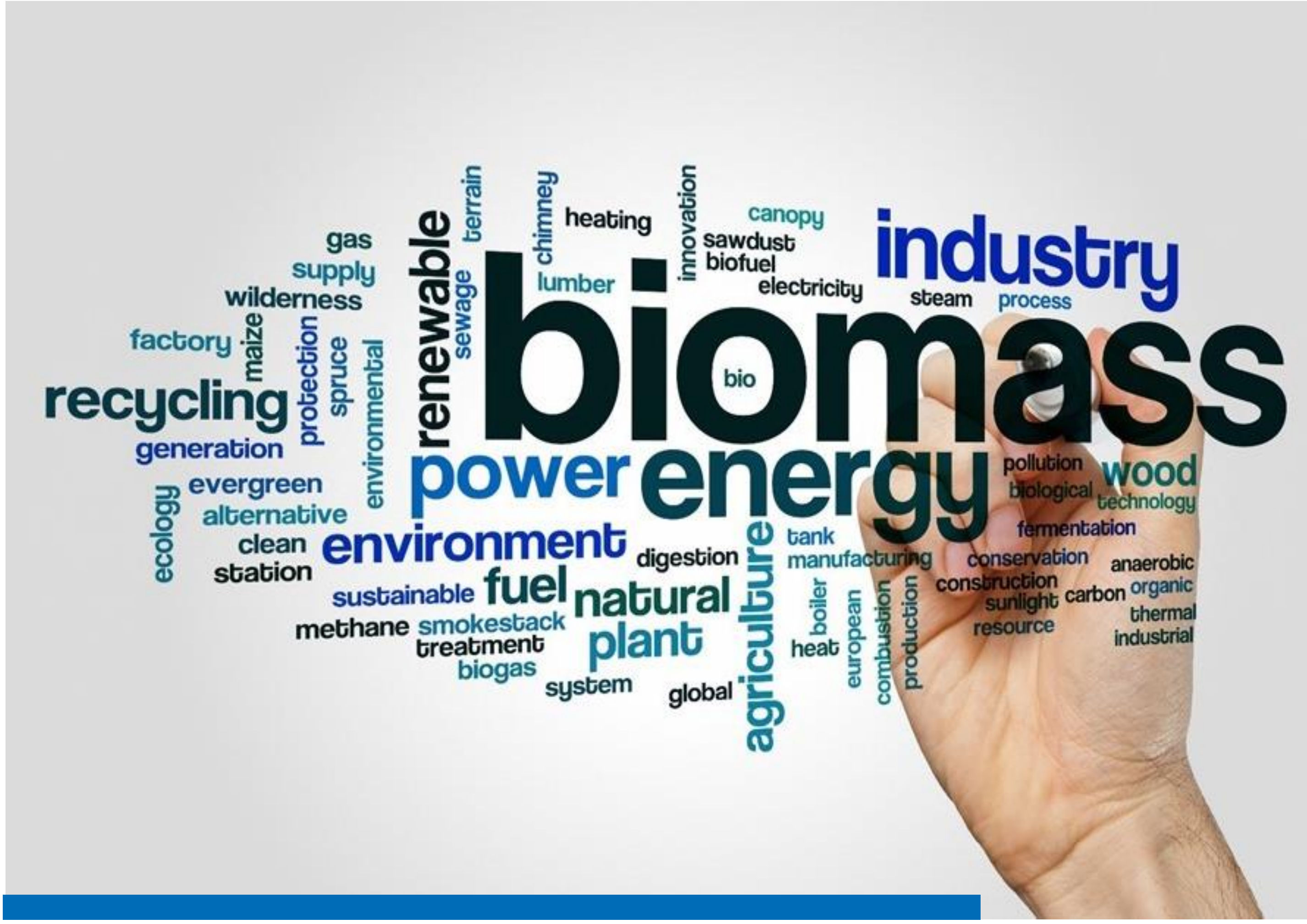

Analysing the potential of bioenergy with carbon capture in the UK to 2050

Summary for policymakers

Report for BEIS

TRN 1700/11/2018

ED 60592 | Final | Date 01/08/2020

Customer:

Department for Business, Energy and Industrial Strategy

Customer reference:

TRN 1700/11/2018

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01 August 2020

Ricardo Energy & Environment reference:

Ref: ED60592- Final

Executive Summary

The UK Government's net zero emissions ('net-zero') target for 2050 requires significant reduction of emissions across a wide range of sectors including power generation and industry. It is now well-recognised that carbon capture, utilisation and storage (CCUS or CCS) will play a key and necessary role in achieving this target. Not only does CCS represent a huge opportunity for the UK to become a global technology leader but it also has a key role to play in tackling climate change and significantly reducing CO_2 emissions. The ambitions set out in the Paris Agreement and the associated IPCC's 1.5ºC Special Report make it clear that CCS is necessary worldwide if temperature rise is to be kept below 1.5ºC. Also, the Committee on Climate Change (CCC) report 'Net Zero: the UK's contribution to stopping global warming'[1] in 2019 highlighted the crucial role of CCS in achieving zero carbon and stated that 'CCS is a necessity not an option'.

The Government stated their approach to CCUS in the Clean Growth Strategy[2]. This is designed to enable the UK to become a global technology leader for CCUS and ensure that government has the option of deploying it at scale during the 2030s. The CCUS Cost Challenge Taskforce[3] set out in 2018 the industry's view on how best to progress CCUS in the UK and to allow it to be deployed at scale in the next decade. Based on this work, the Government published a CCUS Action Plan setting out next steps to be undertaken by Government and industry in order to achieve deployment in the 2030s, subject to costs coming down significantly.

In 2019, BEIS announced £26M funding, through the CCUS Innovation and CCU Demonstration Programmes, to support innovation in CCUS technologies and to help undertake FEED studies of proposed CCU demonstrations across the UK. In March, the Government announced in the Budget 2020 that it will commit £800M to fund CCS infrastructure. The announcement made prior to the 2020 Covid-19 lockdown involves a pledge to support the development of two CCUS clusters and the demonstration of CCS on a CCGT power plant in the 2020s. This announcement sends a strong signal to industry and the world ahead of COP26 that the UK is committed to achieving its net zero target and aspires to become a global leader in the development of CCS.

The deployment of CCUS in the next three decades in the UK has the potential to further decarbonise the power sector while ensuring the continued use of flexible gas generation as the UK transitions to the increasing use of renewables. CCUS could also play a major role in decarbonising UK industry and protecting jobs as well as creating new jobs. In addition, CCUS is now seen as a key element in creating a hydrogen infrastructure across the UK through the demonstration and production of blue hydrogen which is seen as an essential step in transitioning to green hydrogen. Furthermore, CCUS combined with biomass is considered a carbon dioxide removal (CDR) technology which offers a great opportunity to achieve negative emissions.

Bioenergy Carbon Capture and Storage (BECCS)

CO_2 removal technologies, also called negative emission technologies (NETs) or Greenhouse Gas Removal technologies (GGRs), have been highlighted by both the IPCC and the CCC as a necessity if emission reduction targets are to be achieved. Such technologies will help alleviate pressure on sectors which are difficult to decarbonise by 2050, such as aviation. The UK is leading worldwide efforts on demonstrating CCUS on biomass power generation with Drax pioneering the demonstration of bioenergy CCS (BECCS) in the UK.

[1] https://www.theccc.org.uk/wp-content/uploads/2019/05/Net-Zero-The-UKs-contribution-to-stopping-global-warming.pdf
[2] https://www.gov.uk/government/publications/clean-growth-strategy
[3] https://www.gov.uk/government/groups/ccus-cost-challenge-taskforce

BECCS is one of a suite of negative emission methods including direct air carbon capture and storage (DACCS) and biochar in addition to nature-based methods which rely on soils and biomass to sequester CO_2. The development of BECCS requires wide-scale deployment of CCS. Despite major BECCS technologies being mature, to date, there are only few BECCS plants worldwide, mainly in industrial applications (dominated by the bioethanol sector) and not power plants. The Global CCS Institute quotes a wide range of costs for BECCS ranging from $15 to $400/tonne CO_2 avoided with BECCS on bioethanol plants being cheapest (due to high CO_2 concentrations released from bioethanol plants in comparison to that in flue gas from biomass power plants).

Drax are currently demonstrating the use of innovative solvents and technology (developed by C-Capture[4]) to capture CO_2 from a side stream from one of the power station's biomass boilers. A recent announcement of collaboration between Drax and Mitsubishi Heavy Industries (MHI) will lead to a new 12-month CO_2 capture pilot to capture 300 tonnes of CO_2 /day. This pilot will help understand the challenges involved and will move Drax a step closer to becoming carbon negative by 2030 and thus helping the UK become a leader in BECCS technology applied to power generation.

Wide scale deployment of BECCS in the UK will have great benefits in terms of negative emissions and will have economic benefits in terms of employment and GVA. However, this is associated with challenges, barriers and costs which need to be understood in order to target policies effectively.

The purpose of this study is to evaluate the costs and benefits of BECCS and analyse what the UK needs to consider in the coming decade to speed the deployment of BECCS. The study relies on review of the recent literature, key stakeholder consultation and modelling of the techno-economics and life cycle emissions of BECCS technologies. While BECCS also has significant potential for negative emissions through deployment on energy-from-waste (EfW) plants across the UK, the focus of the current study is on wood feedstocks (mainly wood pellets, agricultural wastes and waste wood) and energy crops.

Supported by evidence from previous studies, this study emphasises that the main obstacle for BECCS worldwide is the availability of land, water and fertiliser to supply biomass. The UK access to some of the global biomass sources would decrease to 2050 as countries establish their own biomass plants or inter-regional competition as increased Climate Change targets begin to take effect. In order to understand the full potential of BECCS in the UK, the availability of biomass worldwide needs to be considered. Another consideration is to locate BECCS in such a way as to minimise fuel transport (i.e. reducing life cycle emissions from biomass transport) while at the same time being close to CO_2 storage sites. Sites where biomass can be sourced locally are attractive but impacts on the ecosystem, land requirements, flooding and other environmental factors need to be considered.

Another consideration for BECCS is to start with low-hanging fruit in terms of CO_2 capture technology. Currently chemical absorption via amines and other innovative solvents is the most established and well-understood from an operational point of view. Although the energy penalty for CO2 capture with amines is significant (3.2-4 MJ/kg CO_2 captured), innovative solvents which halve this energy requirements are being developed. Still, efforts and support should continue to demonstrate emerging technologies on biomass plants such as the supercritical CO_2 cycle technology by NetPower, chemical looping and Molten Carbonate Fuel Cells (MCFCs).

Despite the key role NETs can play, currently there is no mechanism to support their deployment and no regulatory framework in place mandating or incentivising them. For examples BECCS and DACCS are not mandated or sufficiently incentivised in the EU ETS and efforts are currently underway to

[4] https://www.c-capture.co.uk/

address this issue. Government has indicated that a call for evidence on negative emission technologies, including methods to incentivise them, will be issued later this year. Developing support mechanisms and framework is considered essential to help the deployment of BECCS as soon as the technology becomes available. This support should consider large power stations where large and complex CO_2 transport and storage infrastructure is needed as well as small scale localised units where the carbon dioxide can be captured and stored locally for further distributions via major suppliers thus taking advantage of an existing supply chain.

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1 Introduction

Bioenergy with carbon capture and storage (BECCS) is one of several technologies including direct air carbon capture and storage (DACCS) and biochar, all termed as carbon dioxide removal (CDR) technologies. These technologies remove CO_2 from the atmosphere thus offering the great potential of achieving negative emissions, thought to be essential to fulfil net zero targets by 2050.

BECCS has been applied in industry worldwide with several existing examples, mainly in bioethanol plants. However, no examples of BECCS in power generation exist yet on a large scale. The Drax power station in Yorkshire is pioneering worldwide efforts to demonstrate BECCS in the power generation sector and have recently taken several steps to move closer to piloting the technology.

BECCS offers a great potential for achieving UK targets but its deployment on a wide scale is associated with challenges and barriers which need to be considered at this early stage. **This report** aims to provide preliminary analysis of what the UK needs to consider in terms of feedstock and technologies when deciding whether and how to deploy BECCS. The information presented here is based on a comprehensive review of the literature; stakeholder consultation and engagement; and modelling of biomass availability, levelised cost of electricity (LCOE), life cycle emissions (LCEs) and economic impact assessment of BECCS.

The study reviews a wide range of potential biomass conversion and CO_2 capture technologies for BECCS and identifies the promising combinations of technologies. Current status and maturity of the different technologies based on their application in other sectors as well as challenges and barriers to deployment is discussed. Deployment scenarios for BECCS are suggested and a cost-benefit analysis is undertaken to compare these technologies. In addition, the environmental benefits are evaluated based on a life cycle approach considering the full life cycle of the feedstock. Finally, the economic impacts (job creation, GVA) and damage related to air emissions from BECCS deployment to 2050 are evaluated.

The analysis is based on data on BECCS in the UK and globally, with an emphasis on application in the power sector for electricity generation. The biomass sources considered in this report are those that are currently and could potentially be available to the UK: forestry and forestry residuals, agricultural residues, energy crops and wastes. Despite the potential which Energy-from-Waste (EfW) have in achieving negative emission targets (due to biogenic content in waste), the focus of the study is on power generation utilising wood feedstocks (wood pellets and waste wood) and energy crops and not on EfW plants.

Energy crops include woody crops such as short rotation coppice and grassy energy crops such as miscanthus. The work also includes the UK's access to traded biomass fuels, such as forest residues from Europe and North America and potential future energy crops from the same regions plus South America.

Section 1.1 below provides a summary of the potential for BECCS in the UK. In order to undertake the economic impact assessment described in Section 4, deployment scenarios for BECCS in the UK were suggested and are presented in Section 1.2.

Section 2 presents the key considerations for biomass availability and sustainability, while Section 3 presents a comparison in terms of costs and life cycle emissions of the potential BECCS technologies.

Finally, Section 4 discusses the benefits and challenges facing BECCS deployment in the UK and presents results from the economic impacts assessment in terms of GVA and employment associated with BECCS deployment.

1.1 The potential for BECCS in the UK

The UK Government's 'net-zero' target for 2050 requires significant reduction of emissions across a wide range of sectors including power generation and industry. In order to meet these targets a step change is needed in the way energy is generated and used in the UK. Options include reduction of energy consumption and the use of alternative renewable energy technologies that generate less emissions. However, these may not on their own achieve the targets, so options for removing carbon dioxide (CO_2) from the atmosphere are also being examined. These include afforestation and the capture and storage of CO_2 underground ('CCS', or if also with CO_2 utilisation 'CCUS'). Currently CCUS for power generation is being demonstrated with fossil fuels in the US and Canada, but there is also potential to use it with bioenergy (BECCS)[5]. When combined with biomass as the fuel, CCS or CCUS can be referred to as 'negative emission' technologies (NETs).

The term 'negative emissions' refers to the permanent removal of CO_2 from the atmosphere, resulting in lower levels of CO_2 compared to when the process started. In BECCS, carbon dioxide is captured as the biomass grows and is stored in its living structures. When biomass is converted to energy there is a release of CO_2. However, if the biomass conversion process could be combined with CCUS, a large proportion of the CO_2 released during the conversion stage could be captured and permanently stored underground. Provided that supply chain emissions are sufficiently low; this then results in a net reduction in the amount of CO_2 in the atmosphere over the life cycle of the biomass plant. In this way, BECCS offers an accelerated route to reducing atmospheric CO_2.

The need for negative emissions

In the UK (and internationally) the impetus for BECCS comes from a recognition that it will be difficult and costly to achieve the Paris Agreement global climate change ambitions without using this technology. The Intergovernmental Panel on Climate Change (IPCC) included BECCS as one of the technologies in their Fifth Assessment Report (2014) with 100 of 116 scenarios considering BECCS as one of the routes to decarbonisation. Furthermore, in the 2018 IPCC report, BECCS is used in 3 out of 4 model pathways used to limit global warming to 1.5°C. The IPCC state that 'negative emission' technologies are considered as options in the modelling, as these allow an 'overspend' of carbon budget to compensate for sectors that are difficult to decarbonise. According to the IPCC, BECCS deployment of up to 1 $GtCO_2$/year by 2030 and up to 16 $GtCO_2$/year by 2050 is needed to achieve the required emission reduction targets.

The Energy Technologies Institute, ETI (2015) identified several priority technologies with BECCS and emphasized its value in achieving targets as it provides a means for achieving zero or even 'negative emissions' in both the power and industrial sectors. The report by the ETI emphasised that 'failure to deploy bioenergy and CCS will have a high impact on the cost of achieving the climate change targets.'

In their latest review on BECCS, the Committee on Climate Change (CCC), the independent UK body that advises the Government on emissions, considers that maximising the feasible opportunities to decarbonise across the energy, heating, transport, industry, and agriculture sectors with currently known or anticipated technologies could reduce annual UK emissions slightly further than 80% by 2050, but not to lower than 130 $MtCO_2$ / year. Achieving these additional levels of reduction will require the deployment of technologies with negative CO_2 emissions. The CCC also states that carbon capture and storage as a whole needs to be deployed at a scale to achieve 10 $MtCO_2$ removal per annum by 2030. This, however, is a challenging deployment target and will require significant support for CCS in general including BECCS.

[5] Although several BECCS plants exist in industry, including a bioethanol CCS project in Illinois, no demonstrations currently exist for BECCS in the power sector.

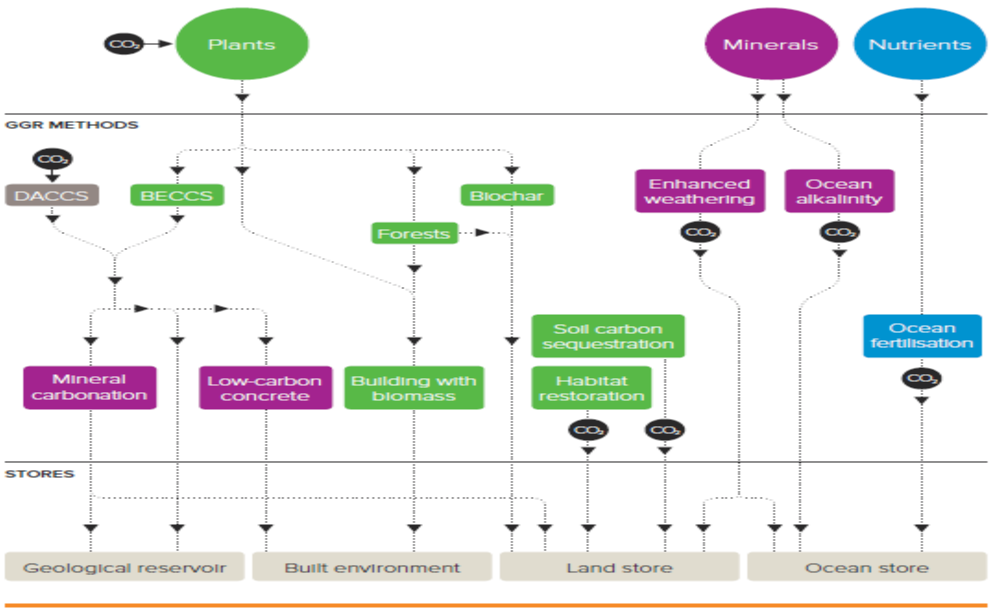
Furthermore, in a recent review[6], the Royal Society and Royal Academy of Engineering (RAEng) emphasised that up to 50 $MtCO_2$/year in 2050 might be required from BECCS. However, BECCS, like CCS as a whole, is a pre-commercial technology. The UK is fortunate in being well-placed in bioenergy development and also having suitable CO_2 storage capacity. This means that there is currently an opportunity for the UK to become a global technology leader for carbon capture, utilisation and storage and to work with industry and internationally to drive down the cost of the technology's deployment[7].

Figure 1.1, drawn from analysis by the Royal Society and Royal Academy of Engineering in 2018, shows the options for greenhouse gas (GHG) removal and how BECCS fits into these options.

There is a considerable opportunity to develop BECCS as part of a suite of options to decrease carbon emissions. The value of BECCS is that it offers an option that could result in negative emissions to offset more difficult to decarbonise sectors. Globally there are significant opportunities for deployment, which means that early development in the UK would place UK developers with an advantage in the global market too. The challenges and impacts involved in this scale up of BECCS include significant biomass demand (both in the UK and globally), the impact of which (on land and water use) need to be considered within any BECCS deployment strategy.

The studies listed above concluded that BECCS provides a real opportunity for the UK, with the potential to remove 20 - 70 $MtCO_2$/year by 2050. This corresponds to electricity generation capacity of 2 – 6 GWe by 2050, generating 17-60TWh/year (5-15% of the current UK's electricity generation) and biomass fuel demand of 10-60 Mt/year in 2050. It should be noted that current electricity generation from biomass in the UK is 35.6TWh /year (See section 2.1.1). The land and water requirements as well as life cycle emissions should be considered for this large demand of biomass when the UK decides on whether and how to deploy BECCS.

Figure 1.1 Nature-based and technological options for CO_2 removal



Source: Royal Society and Royal Academy of Engineering, (2018)

Notes: (1) DACCS: Direct air capture and carbon storage
(2) Afforestation, reforestation and forest management is considered in the Royal Society and Royal academy of Engineering analysis.

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[6] The Royal Society and the Royal Academy of Engineering (2018) Greenhouse gas removal www.royalsociety.org/greenhouse-gas-removal and www.raeng.org.uk/greenhousegasremoval

[7] This summarises the findings of the CCUS Cost Challenge Task Force in 2018.

Box 1.1 Technological options for CO_2 removal

Options for negative emission technologies include a wide range of technologies with BECCS, DACCS and biochar being the most common ones.

BECCS refers to the application of CCS to biomass conversion (i.e. combustion, gasification, pyrolysis). Only few plants exist worldwide, mainly in bioethanol production with BECSS applications in power generation. The Global CCS Institute quotes a cost of BECCS of $15-$400 depending on application with bioethanol being the cheapest. Technologies such as post-combustion capture via amine or potassium carbonate absorption are well-established and ca be applied for biomass combustion and gasification. However, the challenges of flue gas from biomass plants in comparison to industrial applications still need to be demonstrated on a large scale as being currently undertaken by Drax.

It should be noted that **one of the key sectors for BECCS is its application to EfW plants**. Such plants are ideally located in industrial sectors and with proximity to CO_2 storage sites. Due to the biogenic content in waste, adding CCUS to EfW reduces net carbon in the system and makes this a more effective option than alternative disposal options (e.g. landfilling). Recent studies (Energy Systems Catapult, 2020) evaluated the potential for CCUS on EfW plants in the UK and concluded that costs are comparable to those of other industrial abatement techniques. The focus of the current study by BEIS is on power generation from wood feedstocks (including wood pellets, agricultural waste and waste wood) and energy crops. Power generation in EfW plants is outside the scope of the current study and needs to be investigated further.

Direct Air Carbon Capture and Storage (DACCS) refers to the chemical scrubbing of CO_2 directly from the ambient air before storing it. This is similar to carbon capture and storage technology used to capture emissions from power plants and industrial facilities except that the source CO_2 is ambient air rather than flue gas. The challenge is that CO_2 concentrations in ambient air are very small and the energy requirements are significant. A 2018 study[8] quoted costs of $94-$232/t of CO_2. DACCS is still a new technology and, while it shows enormous potential for scaling up, examples worldwide are first of their kind and so this technology still requires public support to advance in the UK.

Biochar results from pyrolysis of biomass. It requires treating biomass in a way that enables it to store bio-carbon in a stable form thus providing resistance to decomposition when mixed with soil. Methods are still not yet mature. In pyrolysis systems used for power and heat generation, both biochar and BECCS can be complementary rather than competitive. A promising technology for capturing 50-60% of CO_2 resulting from syngas combustion in small scale pyrolysis-based CHP systems. Effectively, for a 50 kWe pyrolysis system, 1,300 tonnes of CO_2 / annum can be captured in the resulting biochar.

Like BECCS, both DACCS and biochar are still in the early stages of demonstration. Support for negative emission or CO_2 removal technologies should consider all these three technologies as all three have significant potential for achieving net zero targets. Also, any regulatory frameworks and finance mechanisms should aim to encourage all technologies rather than focus on a specific one.

1.2 Deployment scenarios for BECCS in the UK

The deployment scenarios described here are based on the latest evidence and on feedback from the stakeholder consultation. It should be noted that these are rough estimates of potential deployment in 2030, 2040 and 2050 for the purpose of undertaking the analysis described in Section 4.

[8] https://www.cell.com/joule/fulltext/S2542-4351(18)30225-3

Currently, BECCS is being applied in the form of a pilot scale demonstration at the Drax power station utilising a chemical absorption technology (post-combustion) developed by the UK company C-Capture. This is the first plant worldwide to capture CO_2 in the power sector from the combustion of 100% biomass. The pilot plant utilises a side stream of the flue gas from one of the Drax biomass boilers and has an equivalent electrical generation capacity of around 35-50 kWe. The pilot capture plant is designed to capture around 350 tCO_2 per year (corresponding to a fuel input of around 200 tonnes of wood pellets / year and 300 MWh/year of electricity generation.)

The objective of the Drax pilot demonstration is to gather the information and evidence necessary to facilitate the full conversion of one of the biomass-fired units (660 MWe) to BECCS. The information gathered will be used to design and build a capture plant on one of the boilers (which would have a capacity around 10,000 times greater than the current demonstration plant).

Based on the evidence above, our analysis for this study thus assumes a deployment level of 500 MWe of BECCS in 2030, based on chemical absorption technology as this is the technology currently being trialled for BECCS in the UK. This deployment level will require biomass feedstocks of 15 TWh/year, which is achievable for the UK in 2030. This BECCS capacity is likely to form a part of the wider CCS deployment campaign and assuming that a single 500 MWe biomass plant in 2030 becomes technically feasible. The costs and investment associated with each of the deployment scenarios are further detailed in Sections 3 and 4.

In estimating deployment levels for 2040 and 2050, we have assumed exponential growth for BECCS as part of the wider CCS deployment. For our scenario analysis in Section 4, we assume 3 to 5 additional BECCS units come on line by 2040 (i.e. 3-5 × 500 MWe units, equating to additional capacity of 1.5-2.5 GWe between 2030 and 2040). This is equivalent to an exponential growth rate constant of 0.1-0.15 per year.

Based on current technology maturity levels (highest TRL, as outlined in Section 3, and also being currently demonstrated at Drax), post-combustion capture is the most promising for BECCS in power-generation in the next 10 years. For our analysis in Section 4, we assume that post-combustion capture will continue to play a key role in 2040 with 2 to 4 additional units installed. In addition, oxyfuel is also expected to emerge as a competitor in 2040 with one 500 MWe oxyfuel unit (based on the conventional Rankine steam cycle) assumed in 2040.

We anticipate that other post-combustion technologies such as molten carbonate fuel cell (MCFC) may also become commercially feasible by mid 2030s and deployable by 2040. This is based on the fact that this technology is currently being demonstrated in the US and plans are in place to demonstrate it in the UK.

Oxyfuel combustion based on supercritical CO_2 (the Allam cycle) is being currently demonstrated by NetPower on gas power plants in the US. NetPower are hoping to commercialise the technology by 2020 but further efforts are still needed to improve efficiency and reduce the electricity consumption of the air separation unit (ASU). This, however, will be applied to natural gas-based power plants in the first instance. In principle, the Allam cycle can be applied as a BECCS technology in combination with biomass gasification plants but a wide range of challenges will need to be overcome before this becomes a reality at large scale (~500 MWe). As a result, no BECCS plants based on the supercritical CO_2 cycle are assumed before 2050.

In 2050, a similar exponential rate of growth of 0.1-0.15 $year^{-1}$ is assumed leading to BECCS deployment levels in the range 6-9 GWe (12-18 × 500 MWe units), including 2-3 GWe of post-combustion capture, 3-4 GWe of oxyfuel and 1-2 GWe of pre-combustion capture (based on physical absorption).

Based on the reasoning above, the deployment levels expected for BECCS in 2030, 2040 and 2050 in the power generation sector are shown in Table 1.1. The total deployment level in 2050 is 8-12 GWe. Based on our modelling of biomass availability, the total biomass available to the UK from both domestic and global sources is 249 TWh/year corresponding to a total generation capacity of 12 GWe.

It should be emphasised that these assumptions are for BECCS in the power generation sector only and exclude BECCS deployment in the hydrogen and biofuel sectors[9] which are likely to add to the deployment levels in Table 1.1. However, this is likely to require additional biomass resources in 2050. It should be noted that BECCS in the power sector will be competing for biomass with other sectors and so the deployment levels shown below may be reduced.

Table 1.1 BECCS deployment scenarios for power generation 2030-2050

BECCS incremental deployment, GWe	To 2030	2030-2040		2040-2050		Cumulative to 2050	
		Low	High	Low	High	Low	High
Total	**0.5**	**1.5**	**2.5**	**6**	**9**	**8**	**12**
Post-combustion capture	*0.5*	*1*	*2*	*2*	*3*	*3.5*	*5.5*
Oxyfuel	*0*	*0.5*	*0.5*	*3*	*4*	*3.5*	*4.5*
Pre-combustion capture	*0*	*0*	*0*	*1*	*2*	*1*	*2*

[9] https://www.imperial.ac.uk/media/imperial-college/grantham-institute/public/publications/briefing-papers/BECCS-deployment---a-reality-check.pdf

2 Biomass feedstock issues

2.1 Biomass in the UK

Biomass is defined as degradable matter that can be used as feedstock for energy production. The Renewable Energy Directive (RED II)[10] defines biomass as "the biodegradable fraction of products, waste and residues from biological origin from agriculture (including vegetal and animal substances), forestry and related industries including fisheries and aquaculture, as well as the biodegradable fraction of industrial and municipal waste".

When considering whether and how to deploy BECCS in the UK, it is important to first understand issues regarding biomass availability and sustainability. In the UK the most common biomass feedstocks used for electricity generation are wood, waste wood, straw, chicken litter, mixed wastes (usually waste residues after recycling and landfill gas) and wet wastes or residues such as sewage and manures[11]. As stated in Box 1.1 above, the current study focuses on power generation from wood feedstocks including wood pellets and waste wood and from energy crops but excludes EfW plants.

The availability of biomass supply for electricity generation should be central to any BECCS deployment strategy. Currently the UK uses some 16 Mt of biomass from forestry and agricultural sources and 12 Mt of waste biomass for large scale electricity generation (this does not include wet wastes)[12].

2.1.1 Current use of biomass in the UK

In 2018, 35.6 TWh of electricity were generated from biomass[13] in the UK, compared to 3.9 TWh/year in 2000; a significant growth in capacity. Around 68% of this (24.3 TWh) came from plant biomass and 32% from wastes[14]. The estimates of the biomass requirements for BECCS in the previous section indicate that this level of biomass use is satisfactory to achieve the expected 2030 BECCS deployment levels but would need to at least double in order to achieve the expected BECCS deployment in 2040.

2.1.2 How much biomass is available to the UK?

The UK has shown that it can develop electricity generation from biomass and the necessary supply chains rapidly. The challenge for BECCS is that it requires large (>20 MWe) biomass power stations for economies of scale. The UK has only achieved large scale supply to date by importing large quantities of biomass, predominantly from North America, East Europe and Russia.

The BEIS UK and Global model of biomass feedstocks and prices[15] shows that, depending on price and constraints on supply that need to be addressed, the UK can produce an accessible resource of 290 to 530 PJ/year by 2030. This corresponds to 80.5 to 147 TWh/year total available for all possible consumption including BECCS in the power sector and industry and other applications. The lower

[10] Directive 2009/28/EC on the promotion of the use of energy from renewable sources https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009L0028&from=EN

[11] These wet wastes or residues are used in anaerobic digestion to produce biogas or biomethane. As these are not considered for BECCS at present we have not considered them further in this report.

[12] These tonnages are 'as received', which means that they do not take the moisture content or the calorific value of the fuel into account.

[13] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/791293/Energy_Trends_March_2019.pdf

[14] Data from UK energy statistics, DUKES, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/736148/DUKES_2018.pdf

[15] See: https://www.gov.uk/government/publications/uk-and-global-bioenergy-resource-model This model makes a number of assumptions about the price of biomass and factors that may constrain biomass availability under different scenarios. Sustainability constraints are in addition to the figures shown here.

estimate is realistic for current conditions and is enough to achieve the BECCS deployment levels in 2030 (requirement for BECCS alone is about 15 TWh/year) and 45-75 TWh/year in 2040. The total available biomass from domestic and global sources in 2040 and 2050 is estimated to be 154 and 249 TWh/year, respectively. In order to achieve the higher levels, there needs to be significant investment to address barriers to biomass supply chains. Prices for a substantial part of this resource are likely to be higher than current prices.

It should be noted that the upper limit of 249 TWh/year in 2050 corresponds to a BECCS deployment capacity of 12 GWe in 2050 which allows for the deployment levels given in Table 1.1.

For the UK to develop its full potential for biomass supply, a significant part of this supply (8-15% of the UK potential resource) will need to come from the development of energy crops on up to 350,000 ha land (in 2030)[16]. This estimate excludes land used for food production, so that the planting of energy crops does not impact on current food production levels. However, it does have implications for land and water use in the UK. Any increase to 2050 could also come from investment in forestry (afforestation and short rotation forestry) as well as further development of energy crops.

In addition to this, the UK can access overseas biomass feedstock. Ricardo (2017) analysis estimated that between 26.9 and 74.8 PJ could additionally be accessed by the UK from international sources. This estimate of future supply from international sources allows for both the development of biomass supply internationally and the increasing demand which might be seen for biomass in other countries.

Currently (2019) the UK is the dominant player in international biomass trade, but it is expected that as other countries develop renewable energy targets they will compete for international biomass and the UK will then be part of a stronger but more competitive market. Currently international biomass chains are dominated by wood pellet production in North America, specifically south east USA and Canada (British Columbia). Additional traded biomass pellet production arises in Russia and the Baltic region of Europe. In the Far East, Viet Nam and Australia are potentially important players. Future markets could also include South America, notably Brazil, Chile and Uruguay; and Africa (although some commentators think that Africa will be a net importer of biomass[17]).

Future biomass supply chains were considered by Ricardo (2018)[18], which reviewed current supply chains and potential future forestry and energy crop resources. This work examined issues that constrain supply chain development, including availability of finance, market development, logistics, institutional, capacity building and technical barriers that impact the development of supply chains. A summary of the key risks/barriers that need to be addressed that were identified in this work is provided in Box 2.1.

Box 2.1 Barriers to the development of large-scale international biomass supply chains

A number of factors act together to constrain the development of biomass supply chains in many regions that could supply biomass. The key ones are:

- Availability of finance in some countries, both access to finance and perceived risks for investment in some countries.
- Market barriers, including factors such as the absence of a clear market for the supply chain, currency volatility and inter-regional market competition.
- Physical barriers, including transport and logistics costs, inadequate or no infrastructure, planting and harvesting equipment.
- Technical barriers, including an ability to meet fuel standards; lack of familiarity with energy crops (and also, for energy crops, selection of the right crop/cultivar for local conditions, establishment costs and the need to increase yields to decrease price); degradation of

[16] According to the Royal Academy of Engineering report (2018), Lovett *et al*. estimate there is 1.5 Mha of available, poorer quality or non-agricultural land that could be used for greenhouse gas removal technologies in general.

[17] See, for example, http://www.criterionafrica.com/wp-content/uploads/2017/06/Africa-will-Import-not-Export-Wood.pdf

[18] Ricardo (2018) Global Biomass Markets (in publication)

material in storage/transit; lack of experience in pelletisation in some potential supply countries; and the need for handling and storage facilities.
- Institutional barriers such as governance and lack of experience or proven track record in biomass supply. In addition to this the UK has sustainability standards, which countries will need to comply with.
- Capacity building - the need and capacity to develop skills, technical know-how etc.

Analysis by Ricardo in 2017 also estimated that the UK access to some of the global biomass sources would decrease to 2050 as countries establish their own biomass plants or inter-regional competition as increased Climate Change targets begin to take effect. CCC (2018)[19] discusses the considerable uncertainty over the level of sustainable biomass resource that could be available to the UK in 2050:

- Future UK production of bioenergy resources from forestry and agriculture depends on decisions taken over the coming decade on tree planting, forestry management and the use of land for growing energy crops.
- Demand from competing uses will depend on factors such as levels of timber construction, paper and card usage for packaging, and new products such as bio-based plastics and bio-based chemicals.
- The availability of UK biogenic wastes (such as food waste, wood waste and some agricultural wastes) depends on broader trends in resource usage (e.g. the circular economy) and policy decisions on waste reduction, reuse and recycling.
- Whether substantial international biomass resources can be produced sustainably and made available for international trade depends on global developments, including population growth, dietary habits and land availability as well as governance frameworks. (Note: It will also depend on how demand for international biomass increases and whether greater demand will result in a scale up of biomass supply due to more stable markets or just competition for the same resources. This will in turn be will be dependent on targets set in other global regions; and it is not currently clear whether there will be BECCS hubs developed elsewhere in the world that are also net importers of biomass).
- Innovation in technology, agricultural strategies and crop genetics may mean that biomass production can increasingly be decoupled from productive land, potentially facilitating a scale up of supply that requires fewer trade-offs with other land-uses. Essentially this refers to advances in production of both food and energy crops and improved agricultural strategies, which allow higher yields and more efficient production, addressing issues such as competition for land and the potential of vulnerable or important habitats.

2.2 CO_2 emissions from biomass production and transport

Representative greenhouse gas (GHG) emissions from the cultivation, processing and transport of a variety of biomass feedstocks are shown in Table 2.1. They are based on data from the B2C2 solid and gaseous biomass carbon calculator[20], with shipping distances based on an example port for the region.

Table 2.1 clearly show the impact of pelletisation, typically carried out for woody feedstocks imported to the UK in order to improve their energy density, allow easier transport and meet phytosanitary requirements, in increasing emissions.

Similarly, the impact of transport on emissions is clearly seen, with shipping and additional road transport for movement to and from ports adding up to 11 g CO_2-eq/MJ of fuel compared to UK based fuels.

[19] Committee on Climate Change (2018) Biomass in a low-carbon economy.
[20] UK Solid and Gaseous Biomass Carbon Calculator v2.0 (build 36). Available at: http://www.e4tech.com/b2c2temp/

Table 2.1: GHG emissions from the production and transport of feedstocks (g of CO_2 equivalent per MJ of feedstock)

Feedstock	Region of origin	Cultivation g CO_2 /MJ	Pelleting g CO_2/MJ	Road transport g CO_2/MJ	Shipping g CO_2/MJ	Total g CO_2/MJ
Non-pelletised feedstocks (chips, bales etc.)						
Forestry: small round wood	UK	0.5		1.4		2.0
Forestry residues	UK	0.5		1.4		2.0
Sawmill residues	UK	0.0		1.3		1.3
Perennial energy crops	UK (SRC willow chips)	1.7		0.8		2.5
	UK (Miscanthus bales)	2.4		2.6		5.0
Agricultural residues	UK			1.2		1.2
	Europe			3.7	0.6	4.4
	Africa/Asia			3.7	5.2	8.9
Waste wood	UK	0.3		0.8		1.1
Straw (bales)	UK	3.2		2.4		5.6
Poultry litter	UK			2.0		2.0
Pelletised feedstocks						
Forestry: small round wood	UK	0.6	5.9	1.9		8.4
	Europe	0.6	5.4	5.3	0.6	12.0
	USA	0.6	5.4	5.3	4.5	15.8
	Canada	0.6	5.4	5.3	5.2	16.5
	South America	0.6	5.4	5.3	7.8	19.1
Forestry residues	UK	0.6	5.9	1.9		8.4
	Europe	0.6	5.4	5.3	0.6	12.0
	USA	0.6	5.4	5.3	4.5	15.8
	Canada	0.6	5.4	5.3	5.2	16.5
	South America	0.6	5.4	5.3	7.8	19.1
Sawmill residues	UK	0.0	5.9	1.2		7.2
	Europe	0.0	5.4	4.4	0.6	10.4
	USA	0.0	5.4	4.4	4.5	14.3
	Canada	0.0	5.4	4.4	5.2	14.9
	South America	0.0	5.4	4.4	7.8	17.5
Perennial energy crops	UK (SRC willow)	1.9	5.9	1.7		9.5
	UK (Miscanthus)	2.5	5.2	2.3		10.0
	Europe	0.6	5.4	5.1	0.6	11.7
	USA	0.6	5.4	5.1	4.5	15.6
	Canada	0.6	5.4	5.1	5.2	16.2
	South America	0.6	5.4	5.1	7.8	18.8
Agricultural residues	UK	0.0	5.2	1.7	0.0	6.9
	Europe	0.0	5.4	3.7	0.6	9.8
	Africa/Asia	0.0	5.4	3.7	5.2	14.3

2.3 Use of biomass for BECCS

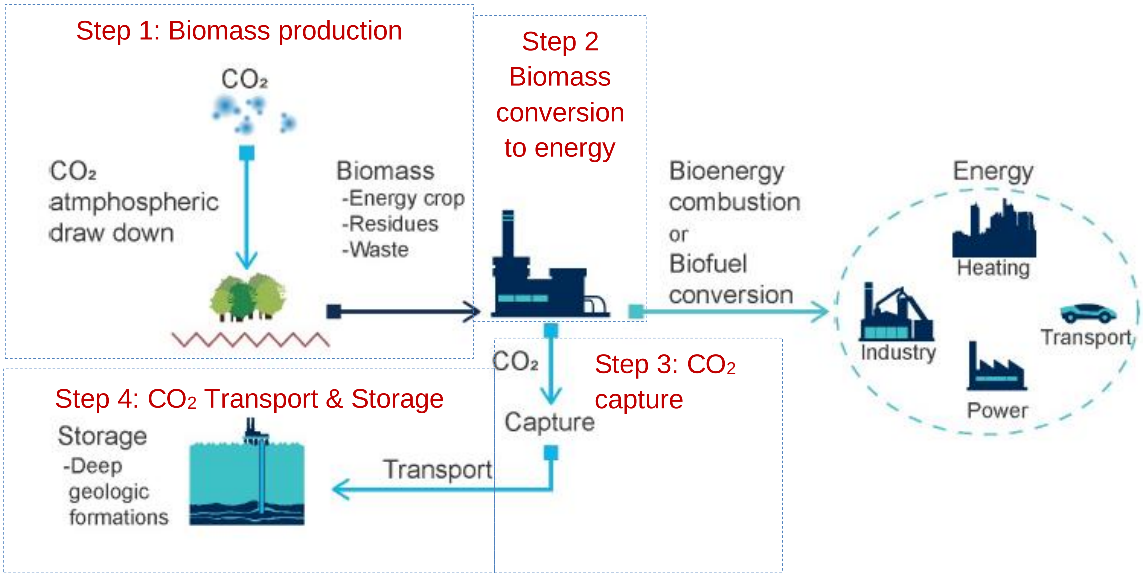
The major use of biomass in electricity generation is currently wood, predominantly in the form of wood pellets derived from forest residues (bark and tree thinnings that are leftover from the forestry sector). The other common use of biomass materials for energy includes residues from agriculture and wastes, though there are currently no >100MWe scale power plant operating on these feedstocks because they are dispersed and bulky to transport. It is likely that in the short to mid-term BECCS plants would utilise wood as a feedstock, but that in the longer term a much wider range of feedstocks might be used, particularly if technologies for densifying feedstocks to allow more cost-effective transport are developed.

The other potential biomass feedstocks that could be produced at scale are energy crops. These will be required if the UK is to expand bioenergy without using food crops. Most analysis indicates that biomass energy will be limited unless energy crops are developed. This will not happen without a long-term stable policy to encourage the development of sustainable energy crops. In this study energy crops were modelled to understand how viable their development is for BECCS in the future.

3 Technologies for bioenergy CCS

BECCS is a four-stage process, involving production of biomass (as discussed in Section 2), conversion of biomass to energy, capture of CO_2 from this process, and transport and storage of that CO_2. This is shown in Figure 3.1, taken from the Global CCS Institute annual report. In this section we examine steps 2 and 3, biomass conversion to energy and carbon capture technologies. This section of the report concentrates on electricity generation: transport and industrial use options are not considered.

Figure 3.1 Flow chart of BECCS



Source: Modified from Global CCS Institute (2019)

3.1 Biomass conversion

The first stage in BECCS is the conversion of biomass feedstock to energy. There are a number of technologies that can be used to convert solid biomass feedstocks to electricity. These are:

Combustion technologies

- Under 20 MWe combustion systems will be used to heat shell or tube boilers to produce steam. Electricity is then generated using the steam.
- Above 20 MWe, up to the largest scale combustion furnaces the heat from the biomass is more likely to be used in water tube boilers. Steam from this process is then used to generate electricity.

Both systems can also be used in combined heat and power generation, where some of the generated heat can be utilised for useful purposes, displacing fuel that otherwise would be used to generate that heat.

Advanced conversion technologies

Biomass can also be converted to gas via anaerobic digestion or thermochemical processes such as gasification or pyrolysis. Anaerobic digestion systems tend to be small in size in terms of power generation, but gasification plants have been proposed that are in the range of 10 to over a 100 MWe. There are two gasification options for biomass:

- Thermal degradation of a solid fuel in the absence of air or oxygen: this results in a char (pyrolysis in which the input feedstock does not come into contact with any oxidant).

- The partial combustion of a solid fuel to yield a “product” or “synthesis” gas (referred to as syngas): in this case, the biomass feedstock comes into direct contact, and reacts with, the oxidant. This is the more usual type of gasification deployed in the UK.

Compared to combustion, gasification provides additional functionality. As well as being able to use the gaseous energy carrier to provide power (for example, via a gas turbine) and/or heat, it can also be used to provide hydrogen, other fuels and/or chemicals. However, to realise these benefits, the syngas must firstly be cleaned and conditioned to meet the requirements of the syngas conversion process, i.e. the engine, a gas turbine or a chemical synthesis process. Most usually gasification involves the partial combustion of a solid fuel to yield a product gas. This technology is available commercially at small scale, but large-scale gasification of a size required for BECCS is yet to be demonstrated widely.

Table 3.1 Summary of biomass conversion technologies

Conversion technology	Technology Readiness Level (TRL)	Used with biomass in the UK?	Scale
Combustion technologies	Fully commercial (TRL 9)	Yes, in many power stations for several years	<1MW to 300MWe.
Advanced conversion: gasification	Pilot scale to first of a kind commercial (generally TRL 7-9)	Yes, but generally at small scale. Large scale yet to be proven at commercially. Some larger scale demonstrations.	Small, <300kWe, mainly cogeneration schemes with some registered under the RHI. Heat only demonstrations at 1 to 20 MWe, with proposals for larger scale (Ricardo database).

Biomass combustion technologies are at a more advanced stage in comparison to biomass gasification, both in the UK and globally. However, gasification systems offer the advantage of the possibility of integration with a hydrogen economy.

While further research and demonstration is needed on biomass gasification systems and associated pre-combustion capture, focus for early deployment of BECCS can be on biomass combustion, more specifically on chemical absorption systems which are more established than other post-combustion alternatives based on membranes or emerging next generation technologies such as molten carbonate fuel cells.

3.2 CO_2 capture technologies

There are three main components in the CCUS chain[21]These are: electricity generation from power plants with CO_2 capture, transportation of captured CO_2 to storage sites and finally its utilisation and/or long-term storage. In this section we summarise the options for CO_2 capture.

Three main approaches to CO_2 capture are being developed. These can be deployed in different ways covering all options for bioenergy:

1. **Post-combustion capture** refers to the removal of carbon dioxide from a power station flue gas. The captured CO_2 is then compressed and transported to storage in suitable geological formations.

[21] Not including the harvesting, processing and transportation of biomass for BECCS, which is covered elsewhere in this document.

2. **Oxyfuel systems** involve firing a combustion system with oxygen diluted with flue gases to yield a flue gas more concentrated in CO_2 for easier purification.
3. **Pre-combustion capture systems** are suitable for gasification systems where CO_2 is captured from the syngas exiting the process before this syngas is then combusted in a gas turbine for power generation. Pre-combustion capture of CO_2 using physical solvents such as Selexol or Rectisol is usually proposed with integrated gasification combined cycle (IGCC) systems[22].

These systems are described in more detail below to provide an indication of their application, commercial status, advantages and any disadvantages. This draws on discussions by TESBiC (2014), Wood (2018) and IEAGHG (2014).

3.2.1 Post combustion capture

Several options to separate CO_2 from post combustion flue gases are available. These use chemical, membrane and physical methods and include most commonly: amine scrubbing; low temperature solid sorbents; post combustion ionic liquids; enzyme technologies; membrane separation; and high temperature sorbents (often referred to as 'calcium looping'). Recently, molten carbonate fuel cell systems have also been proposed and are currently being tested at pilot scale in the US.

Options for post-combustion capture were reviewed in detail and consulted upon with stakeholders. One important attribute is whether the technology can be retrofitted on an existing power station or if it needs to be built into the design. This determines whether the technology could be trialled/ demonstrated now, or if demonstration would require a completely new bioenergy CCS plant.

By far, chemical absorption, specifically using amines (monoethanolamine, MEA, being the most common) and potassium carbonate are the systems most commonly available for CO_2 removal from gas streams (e.g. in hydrogen and ammonia production from steam reforming). For flue gas streams, the removal of CO_2 poses challenges not only due to the large scale and large amounts of CO_2 involved but also the low concentrations of CO_2 in flue gas. Furthermore, for biomass combustion, technical challenges also arise from the additional impurities present in the flue gas. A major challenge for the deployment of amine systems on fossil fuel power plants (and biomass power plants) is the energy penalty (i.e. steam diverted from the power generation process for use in solvent regeneration) associated with the capture process.

Chemical absorption, whether based on amines or other innovative solvents, such as currently being demonstrated at Drax, is the most likely technology to be commercially available for BECCS in the next decade. Other post-combustion capture approaches include pressure or temperature swing adsorption and membranes. However, these are currently more applicable and cost-effective for applications much smaller than needed in power stations.

3.2.2 Oxy-combustion capture

Oxy-combustion involves the combustion of a fuel in a mixture of oxygen and recycled flue gas, rather than air, to produce a flue gas that comprises mainly carbon dioxide and water, rather than nitrogen and carbon dioxide. The carbon dioxide concentration in the flue gas from an oxy-combustion firing system is, therefore, significantly higher than in the flue gas from an air firing system, and hence the carbon dioxide can be cleaned, compressed and stored with significantly less downstream processing than would be necessary with air firing. The major disadvantage is the additional auxiliary power requirement of operating the Air Separation Unit (ASU) to produce the oxygen, and the CO_2 Purification Unit (CPU).

Oxy-combustion technology options include:

[22] IGCC – Integrated gasification combined cycle – this option uses gasification technology for conversion of biomass to syngas and its subsequent clean up.

- Oxy-fuel boiler with cryogenic oxygen separation from air and based on the Rankine cycle of steam for power generation where in this case the CO_2 is compressed and transported offsite for storage while water vapour is recycled for further power generation.
- Ion-exchange membrane separation of oxygen from air
- Chemical-looping-combustion using solid oxygen carriers
- Supercritical CO_2 cycle (Allam Cycle) for power generation in which air is removed from the CO_2 stream by condensation and the amount of CO_2 equivalent to that resulting from combustion is transported offsite for storage. A proportion of the CO_2 is recycled for power generation.

A major issue for oxy-combustion is the energy demand of the ASU. While oxyfuel combustion with power generation via the steam-based Rankine cycle has been demonstrated at pilot scale, this technology is still not commercially-available (TRL of 7). The supercritical CO_2 / Allam cycle-based oxyfuel combustion is currently being demonstrated using natural gas as the fuel (at a pilot scale of 50 MW_{th}) in the US. Demonstration on biomass will require gasification of the biomass which in itself still faces technical challenges for application at a large scale. The Allam cycle when applied to gas power plants offers advantages in terms of high efficiency (around 55% for natural gas systems) but efficiencies are theoretically lower for biomass-based plants (around 35-40%).

Other advantages of supercritical CO_2-based BECCS would be the fact that the CO_2 exits the system at high pressures ready for transport so saving on compression energy. Also, the systems, when fully developed and commercialised, are likely to be smaller and more compact (so lower material requirements for equipment manufacturing) than steam cycle-based systems and so are likely to have lower capital costs in the long-term. Nevertheless, the technology still needs to be demonstrated on a large scale for natural gas before it can even be demonstrated for BECCS and deployed on a large scale for biomass.

3.2.3 Pre-combustion capture

Pre-combustion capture in power plants is applicable for gasification systems where the CO_2 is extracted from the syngas (following the gas shift reactor, i.e. reactor where carbon monoxide in the syngas is converted to CO_2 resulting in a stream with a relatively high CO_2 concentration, 35-40%) before combustion. Options include IGCC with solvent absorption, membrane separation of hydrogen from syngas and sorbent enhanced reforming using carbonate looping.

Physical solvent-based CO_2 removal has been applied for many years in the chemical industry and is a well-established method. Its advantage over chemical absorption via amines or potassium carbonate is due to the lower energy requirement for solvent regeneration. Physical absorption is more suitable at high gas pressures as is the case with the syngas resulting from IGCC power plants. It should be noted that physical absorption of CO_2 has been shown to work on syngas from lignite gasification for over two decades (e.g. Great Plains Synfuels plant[23]). The demonstration of this in combination with power generation (i.e. IGCC) is, however, still challenging. While IGCC has been demonstrated (e.g. the Nuon Power Buggenum IGCC plant in the Netherlands[24]) at a scale of several hundreds of megawatts, many planned IGCC plants with CCS have been cancelled in the US and worldwide over the past decade[25]. In addition, several large-scale biomass gasification projects have been cancelled in the UK in recent years. Biomass gasification on a large scale still faces technical challenges with syngas clean-up, mainly of tar, being the key one. The syngas needs to have a specific gas composition with an acceptable range of impurities. Several gas cleaning methods including physical filtration, thermal cracking and catalytic reforming for tar removal are already

[23] https://www.netl.doe.gov/research/Coal/energy-systems/gasification/gasifipedia/great-plains

[24] https://www.netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/nuon

[25] http://www.sccs.org.uk/expertise/global-ccs-map

developed but there is still a need for more efficient methods for application at a large commercial scale[26].

Based on the fact that the several IGCC with CCS plants have been cancelled in recent years (e.g. the Kemper CCS project in the US) and that tar removal challenges have still to be overcome, it is believed that pre-combustion capture will not be available in the short term.

3.3 Current and near-future technology options

Table 1.1 outlines the estimated BECCS deployment levels for post-combustion, pre-combustion and oxyfuel-based CO_2 capture. Within each of these three categories, our literature and stakeholder review identified a number of bioenergy and carbon capture systems that are at a TRL >5 and a high deployment potential in the period 2030-2050. Based on information on costs, levelised cost of CO_2 capture, impacts on the efficiency of electricity generation, and potential challenges, we have identified technologies that we believe show the most promise for deployment on power plants in the UK.

The literature review has indicated that based on published evidence the most promising CCUS technologies that could be linked to biomass electricity generation are:

- Post-combustion capture based on amine absorption (co-firing and dedicated) or other solvents such as potassium carbonate;
- Pre-combustion capture based on IGCC with solvent absorption;
- Oxyfuel combustion including combustion with cryogenic O_2 separation (co-firing and dedicated), combustion based on supercritical CO_2 cycle (the Allam Cycle technology).
- Chemical looping and carbonate looping.

To understand which technologies offer the greatest potential, we have undertaken a comparative analysis of the levelised cost of electricity (LCOE) and carbon sequestration for different BECCS systems that could be deployed in the UK by 2030. We have undertaken analysis to confirm LCOEs figures reported in the literature. This then provided confidence in the data available for use in estimating life cycle emissions (LCEs) and the economic impacts of BECCS in the UK (Section 4).

Box 3.1 Data sources

The literature reviewed was examined for techno-economic data which could be used to produce estimates of the levelised cost of electricity (LCOE) produced from each type of plant. Costs were sought for both a typical ‘nth’ of a kind (NOAK), and for ‘first of a kind’ FOAK plant.

Detailed costs and operational parameters are available from a recent engineering study by Wood (2018) for BEIS for large dedicated biomass NOAK plant for post combustion capture based on amine absorption, IGCC with pre-combustion capture and oxyfuel combustion with cryogenic CO_2 separation.

Less detailed and less complete cost estimates are available for a dedicated biomass chemical looping plant and co-firing carbonate looping plant from work conducted by the Energy Technologies Institute (ETI) as reported in Gough et al (2018). Some further details on cost assumptions for these plants are also available from Bhave et al (2017). Gough et al (2018) and Bhave et al (2017) also contain cost data for the types of BECCS plants considered by Wood (2018), but the data in the latter was consider more detailed and reliable.

[26] Zhang, S., Asadullah, M., Dong, L., Tay, H.–L., Li C.-Z. (2013). An advanced biomass gasification technology with integrated catalytic hot gas cleaning. Part II: Tar reforming using char as a catalyst or as a catalyst support. *Fuel*, *112*, 646-65

No cost data was found in the published literature for molten carbonate fuel cell technology and Allam cycle technology. Some indicative costs for the capital costs of plant were supplied by stakeholders during the consultation but are not considered robust.

3.3.1 LCOE analysis

Using data from the sources indicated above, LCOE costs were estimated for each of the plants where reasonably detailed costs were available. The key parameters for each of the plant are given in Table and a more detailed breakdown of capex costs, and other project costs is provided at Appendix 1. The further breakdown of capex costs given in Appendix 1 is based on information contained in original sources, supplemented where data was not available with information from the Integrated Environmental Control Model (IECM)[27].

In the case of the chemical and carbonate looping plant, Gough et al (2018) did not include pre-construction costs or infrastructure costs (CO_2 pipeline and grid connection), so these were estimated using the same assumptions as in Wood (2018). Similarly, assumptions about plant availability and lifetime were assumed as in Wood.

The plant sizes considered in the literature and as set out in Table 3.2 are larger than dedicated biomass plant built to date and securing a biomass supply chain for these sizes of plant could be challenging. For example, the plant using post-combustion capture based on amine absorption would require about 2 million tonnes of wood pellets annually as fuel; equivalent to about 30% of UK imports of wood pellets in 2017[28].

For biomass fuel costs (UK energy crops or imported wood pellets) a central price of £25/MWh was used for the LCOE analysis here, with a range of £15/MWh to £40/MWh used for sensitivity analysis.

The cost of CO_2 transport and storage for all NOAK plant was assumed to be £19/tCO_2 as in Wood (2018). The hurdle rate used was assumed 9.1%, as assumed by BEIS in current (2019) analysis of several CCS technologies.

Table 3.2 Key assumptions for plant

Plant type	Capacity		Efficiency		Costs [a]			Carbon capture rate
	Gross	Net	Gross	Net	Capex	Fixed Opex	Variable Opex [b]	
	MWe	MWe	%	%	£/kW	£/kW	£/kW	%
Post-combustion – Amine absorption	498	396	38.5%	30.6%	2,793	146	9	90.0%
Oxyfuel combustion	598	402	46.3%	31.1%	3,209	164	8	89.9%
Pre-combustion - IGCC	493	356	44.5%	32.1%	3,664	198	11	90.8%
Carbonate looping	326	300	43.9%	40.4%	2,683	141	8	97.0%
Chemical looping	325	300	44.5%	41.0%	2,121	111	6	92.0%

a: Costs per kW are on basis of net capacity and exclude grid connection

b: Variable Opex excludes fuel costs

LCOEs estimated for the BECCS plants range from £138/MWh for chemical looping technology to £204/MWh for the IGCC plant (Figure). The two most significant contributions to LCOE are capex cost and fuel costs. The latter are particularly significant for the plant with lower efficiencies (post-

[27] https://www.cmu.edu/epp/iecm

[28] The UK imported 6.8 Mt of wood pellets in 2017; DUKES 2018 Table g.6 Imports and exports of wood pellets and other wood 2008-2017

combustion amine, oxyfuel combustion and IGCC) where fuel demand is higher. The higher efficiencies that should be possible in carbonate and chemical looping BECCS plants mean that the LCOEs estimated for these plants are lower, although it should be remembered that the cost estimates for these plants are not as detailed and may not be as robust. The influence of biomass price on the LCOEs (for NOAK) is shown in

Figure . Tabulated results are provided in Appendix 2.

Based on stakeholder consultation, indicative CapEx costs for a NOAK Allam cycle plant are around £1,500/kW, considerably lower than for other BECCS technologies. Combining this value with an estimated net efficiency of 37.8% for a plant operating on gasified biomass and estimates of operating costs based on levels typical of other BECCS plants gives an LCOE of about £130/MWh (for the central biomass price of £25/MWh). However, given the lack of firm data on CapEx and OpEx, this value should be considered indicative only.

Figure 3.2 Breakdown of LCOE costs for central biomass fuel price (NOAK)

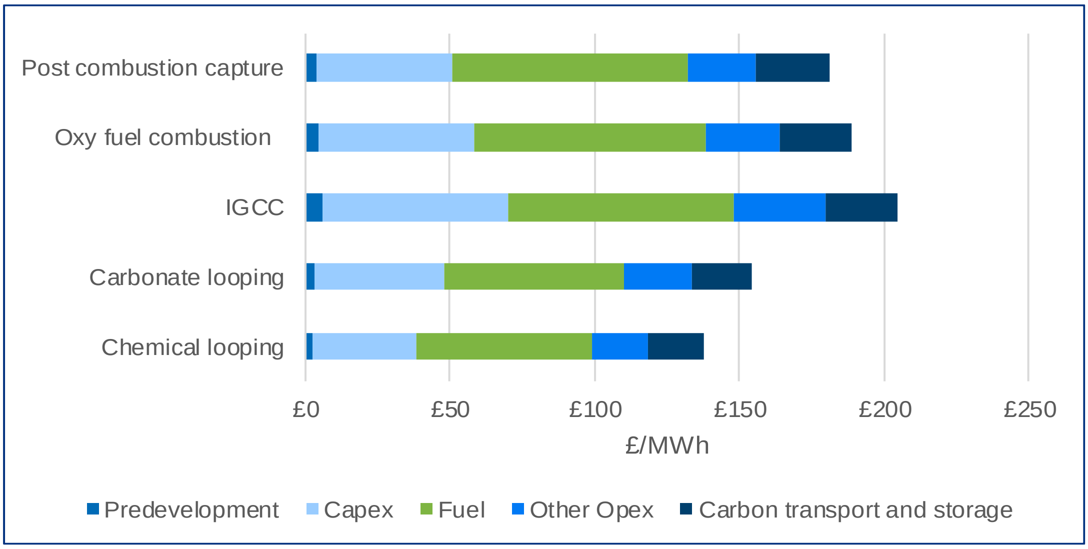
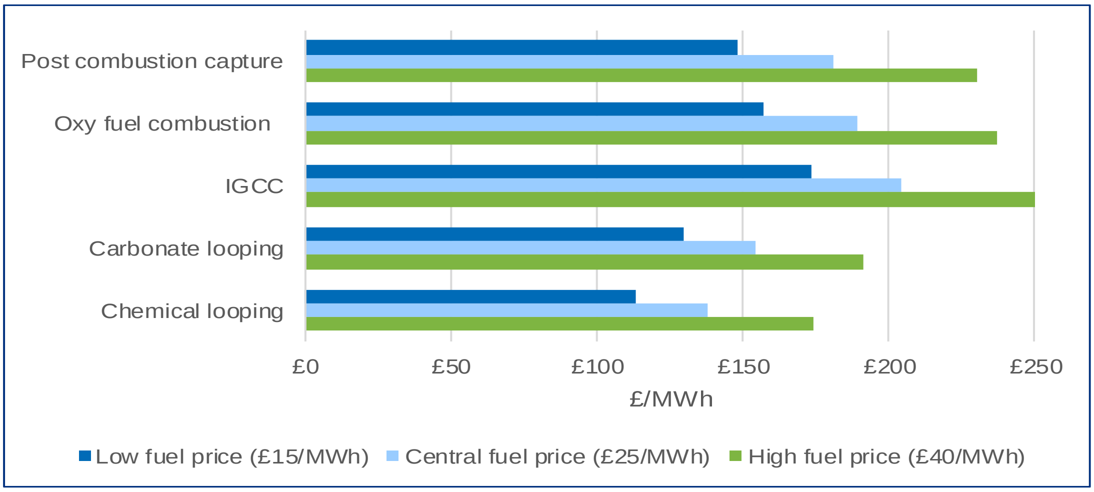


Figure 3.3 Influence of biomass price on LCOEs (NOAK)

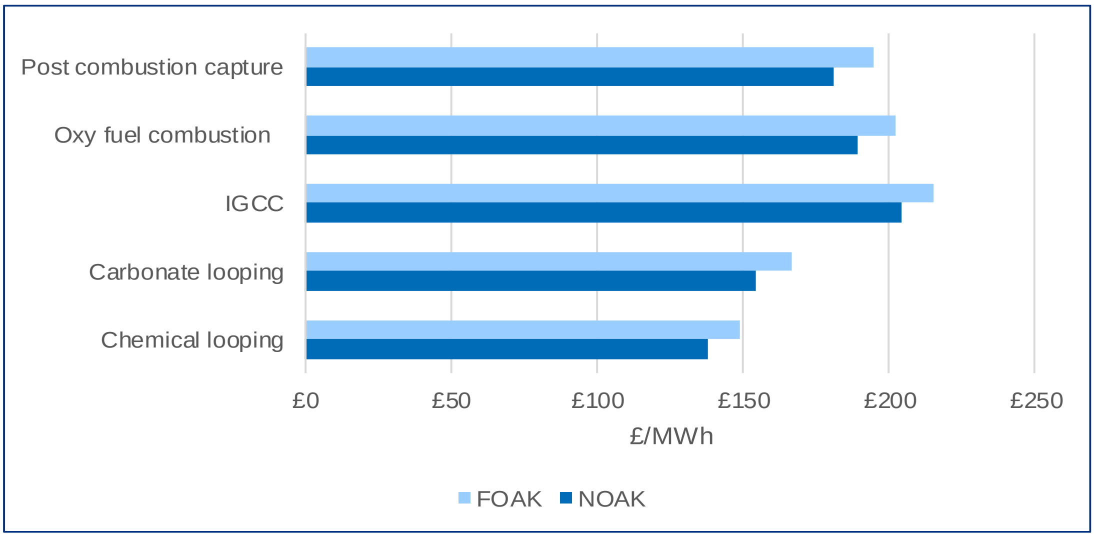


LCOEs for first-of-a-kind plant

The LCOE for FOAK plant has been estimated from the cost of NOAK plant, assuming as in Leigh Fisher (2016) that the capex cost of CCS related elements in NOAK plant will be 25% lower than in

FOAK plant for technologies using post combustion capture, and 20.5 % lower for technologies using pre-combustion capture. The cost of carbon transport and storage (again based on Leigh Fisher) is assumed to be 25% higher for FOAK plant than for NOAK plant. Overall, this means that the LCOE for FOAK plant are likely to be about 15% higher than those for NOAK plant (Figure). An indicative cost for a FOAK carbonate looping BECCS plant of around £370/MWh was estimated based on an approximate Capex cost of just under £1600/MW.

Figure 3.4 Comparison of LCOEs for FOAK and NOAK plant for central biomass price



3.3.2 Carbon costs

3.3.2.1 Cost of carbon stored

The cost of carbon stored is calculated as the LCOE (in £/MWh) multiplied by the annual average electricity generated and divided by the quantity of carbon stored.

The quantities of carbon stored annually by each of the BECCS plants and the cost per tonne of carbon stored are given in Table . Plant with higher net efficiencies (carbonate looping and chemical looping) utilise less fuel, so less carbon passes through the plant in the fuel and therefore less carbon is captured. Quantities stored are therefore lower than for the post combustion amine and oxyfuel combustion plant. In the case of the IGCC plant, the smaller size and lower load factor for the plant mean that less carbon is stored annually than for the post-combustion and oxy-fuel plant.

Table 3.3 Quantities and cost of carbon sequestered

	Net capacity	Carbon stored		£/t C stored		
	MWe	Mt/year	t CO_2/MWh$_e$	Low fuel price	Central fuel price	High fuel price
Post combustion amine	396.2	4.2	1.33	£112	£136	£173
Oxy fuel combustion	402.1	4.1	1.31	£120	£145	£182
IGCC	356.1	3.4	1.28	£136	£160	£196
Carbonate looping	300	2.4	1.09	£119	£142	£176
Chemical looping	300	2.3	1.01	£112	£136	£172

3.3.2.2 Cost of carbon avoided

The cost of carbon avoided is calculated based on the difference in LCOEs for the BECCS plant and a reference plant, divided by the difference in CO_2 emissions per MWh for the BECCS plant and the reference plant. The reference plant in this study has been taken as a natural gas fired CCGT plant, with a net efficiency of 62.3% and an LCOE of £45.5/MWh as defined in Wood (2018).

The difference in CO_2 emissions is typically done, as in Wood (2018), on the basis of the carbon emissions at the point of combustion; i.e. based on CO_2 emissions from combustion that are not sequestered and are released in the flue gases. In addition, we have also examined the cost of carbon avoided on a life cycle basis by including the upstream emissions from fuel production. Lifecycle emissions from a range of biomass feedstocks that could be used in BECCS plants in the UK were examined in the study, as were the quantities of feedstocks that might potentially be available in the future. Combining this information, it was considered that three representative feedstock types should be considered: UK energy crops (SRC or miscanthus) in chipped form; UK energy crops in pelleted form; and imported wood chips. Typical emissions associated with production and transport of these feedstocks to a BECCS plant are shown in Table 3.4, together with an indication of the range in values that might be seen due to variations in cultivation practices, and, in particular for imported wood pellets, transport distances. For the reference plant upstream emissions from natural gas production were taken as 28.4 g CO_2/kWh of gas[29].

Table 3.4 Lifecycle emissions from production of biomass fuels

Feedstock	Lifecycle emissions from production of biomass g CO_2/kWh of fuel		
	Low	Central	High
UK energy crops (chipped)	8.8	18.0	21.6
UK energy crops (pelleted)	34.2	35.9	43.0
Imported wood pellets	37.5	57.0	68.7

The contribution of these upstream emissions to the overall lifecycle emissions (covering direct combustion emissions and upstream emissions from feedstock production and delivery to sites) per unit of electricity from each of the BECCS plants is shown in Table 3.5.

Table 3.5 Lifecycle carbon emissions and carbon stored per MWh of electricity generated at BECCS plants

Technology	Upstream emissions kg CO_2/MWh			Combustion emissions kg CO_2/MWh	Total emissions kg CO_2/MWh			Carbon stored kg CO_2/MWh
	UK energy crops		Imported		UK energy crops		Imported	
	Chipped	Pelleted	Wood chips	All fuels	Chipped	Pelleted	Wood chips	All fuels
Post combustion amine	59	117	186	148	206	265	334	1,330
Oxy fuel combustion	58	115	183	147	205	262	330	1,307
IGCC	56	112	178	107	163	219	285	1,056
Carbonate looping	44	89	141	34	78	122	175	1,085
Chemical looping	44	87	139	88	132	176	227	1,014

[29] Value for upstream gas emissions from UK Government GHG Conversion Factors for Company Reporting 2018.

The table shows for the different technology options and the three types of feedstock a comparison of life cycle emissions, covering direct combustion emissions and upstream emissions from feedstock production and delivery to site. Combustion emission are dependent on the efficiency of the technology and so chemical and carbonate looping, and pre-combustion capture show lower direct emissions. Note that upstream emissions depend on the amount of fuel required which also is a function of efficiency, albeit to a lower extent. Based on the analysis shown in Table 3.5, post-combustion capture and oxyfuel combustion have higher life cycle emissions and because of the greater fuel throughput needed due to their lower generating efficiency store more carbon per MWh generated. Also note that the combustion emissions shown in Table 3.5 are biogenic CO_2 emissions whereas those related to upstream activities are fossil based CO_2, e.g. from diesel used for cultivation and transport.

The cost of carbon avoided on both a combustion only and a lifecycle basis is shown in Figure 3.5 for a central biomass price. In estimating the cost of carbon avoided, the biogenic emissions associated with combustion of the biomass are not included as these are considered, when the biomass has been sustainably sourced, to be short cycle carbon. The influence of life cycle emissions associated with the production of the feedstock is significant for both pelleted fuels, with impacts much stronger, as would be expected for those technologies as they have a lower net generating efficiency. When using chipped UK energy crops, the cost of carbon avoided is estimated as £429 to £498/t CO_2 on a lifecycle basis, apart from looping technologies where the cost is substantially lower (£279 to £329/t CO_2). However, if imported wood pellets are used then the estimated cost of carbon avoided on a lifecycle basis rises to over £720/t carbon avoided for post combustion amine technology and oxyfuel technology and pre-combustion capture. If the biogenic CO_2 emissions which are not captured are included in the calculation of cost of carbon avoided, then the cost of carbon avoided rises – on a life cycle basis - by about £340 to £390/t CO_2 for the post-combustion, oxy-fuel and pre-combustion technologies and by £40 to £100/ t CO_2 for the looping technologies (assuming a central fuel price and chipped UK energy crops).

Figures 3.6 and Figure 3.7 respectively show the influence on the cost of carbon avoided of biomass price and of assessing emissions on a combustion only basis or a life cycle basis (for pelleted UK energy crops).

Figure 3.5 Cost of carbon avoided on combustion only and lifecycle basis

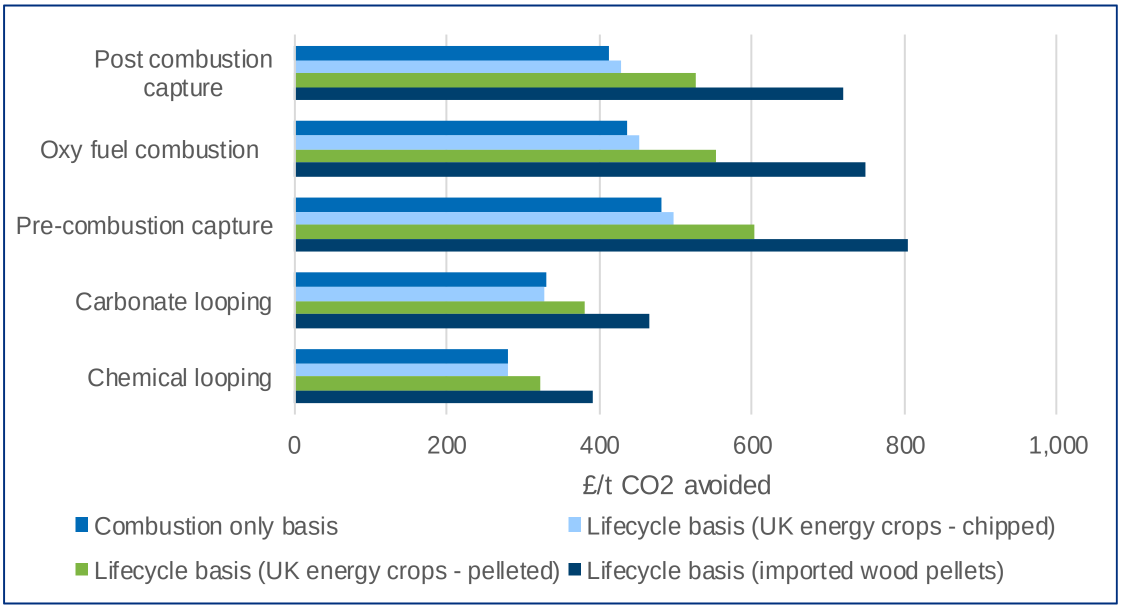


Figure 3.6 Influence of biomass price on cost of carbon avoided on combustion only basis

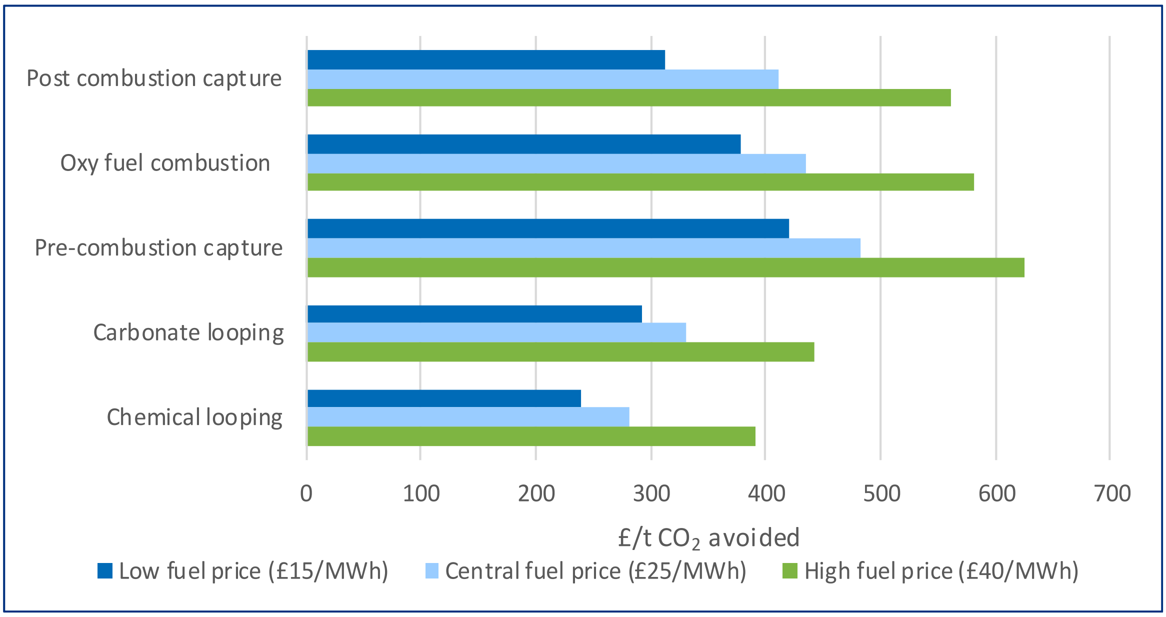
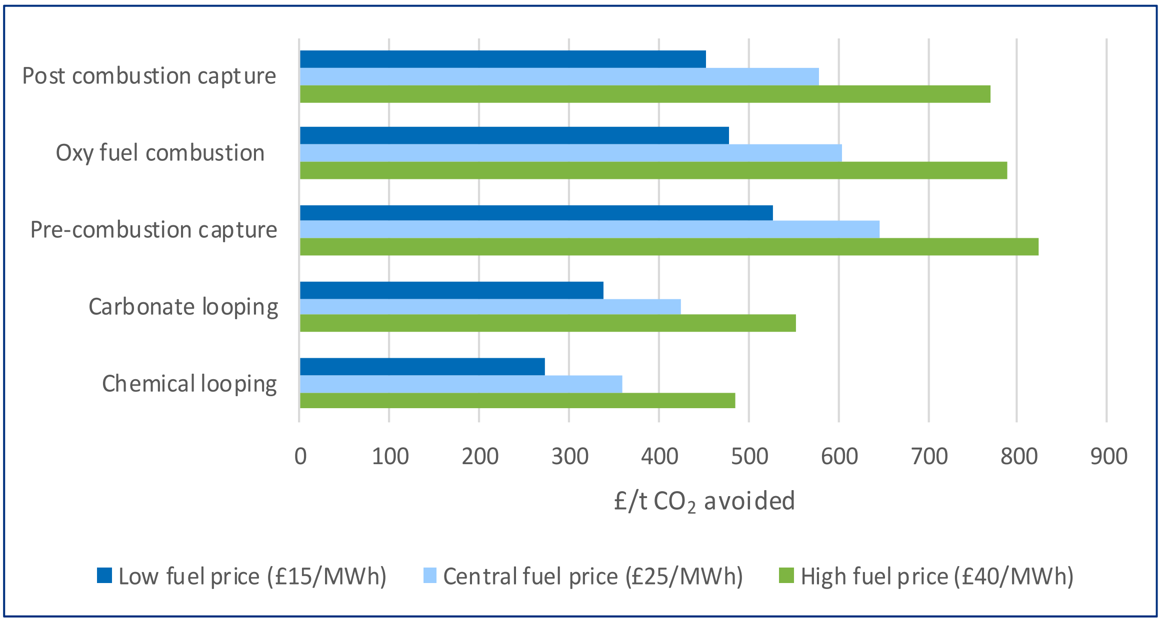


Figure 3.7 Influence of biomass price on cost of carbon avoided on lifecycle basis (pelleted UK energy crops)



4 Challenges and impacts of BECCS

This section introduces the challenges and impacts associated with BECCS deployment. In addition, the economic and environmental impacts are also evaluated and described in Section 4.2. A simple model has been developed to estimate value to the UK from the deployment of BECCS in 2030, 2040 and 2050. The cost associated with air emissions resulting from the deployment of BECCS in the period 2030-2050 has also been evaluated.

4.1 Challenges and barriers for the deployment of BECCS

The barriers to deployment of BECCS are those related to the deployment of CCUS in general (including carbon dioxide transport and storage infrastructure) as well as barriers to biomass power generation. Barriers include technical, financial and economic, regulatory and policy, social, environmental and supply chain issues. These are discussed in detail below.

One of the potential barriers is the absence of **regulatory** mechanisms to encourage implementation and address the uncertainty regarding financing mechanisms, specifically related to CO_2 transport and storage. Although outside the scope of this study, the development of the CO_2 transport and storage infrastructure is key to developing CCS industry as a whole in the UK. The UK has significant amounts of performance and cost data on biomass combustion for a variety of options (pulverised fuel, circulating fluidised-bed, grate furnace, etc.) and on the implications of applying carbon capture technologies to the flues of such technologies. In addition, there is ample evidence on life cycle emissions from biomass fuels from different geographical locations. The availability of such data should allow, as needed, the development of incentivisation schemes and support mechanisms for carbon capture and storage as a whole (including transport and storage), which could then facilitate the deployment of BECCS in the UK.

There is currently a lack of data on full scale performance and costs of BECCS. There is a need to gather data that allows risks in scale-up to be addressed, e.g. risks in the biomass supply chain, including large-scale development of energy crops.

There are still social acceptance and public perception issues surrounding the deployment of CCS that will also apply to BECCS. These may include some misconceptions and, perhaps, a lack of awareness of CCS. Addressing these will be particularly important in gaining acceptance of projects at local level. Recent studies found that pairing CCS with other technologies such as renewables led to higher support for it. For example, while shale gas, underground coal gasification and heavy industry with CCS are less supported by the public, bioenergy with CCS is more supported[30].

Technical challenges related to technology-specific performance (e.g. biomass gasification at large scale, biomass impurities, energy penalty associated with absorbent regeneration for post-combustion capture or with the ASU for oxyfuel, etc.) are also a challenge. Engineering challenges include improving energy efficiency relative to conventional power generation and CCS. The risks of the full CCS chain are also highlighted. Although individual parts of the CCS chain are demonstrated and well-understood, a challenge is to ensure that failure of one component does not result in failure of the whole project. The Royal Society (2018) lists risks associated with flue gas composition from biomass combustion, transport of CO_2 at high pressure and integrity of CO_2 storage. Other risks include land use change and competition with food.

One of the key challenges is improving capture efficiencies and driving down the **costs of CO_2 capture**. Demonstration of the technology and its mitigation potential at commercial scale is vital to decrease costs and attract finance. Scale up for both biomass production and CCUS infrastructure need to be addressed. In addition, lack of data to support BECCS analysis, including costs, energy use in operation, efficiencies, proven mitigation potential and payback periods is another challenge.

[30] https://www.nature.com/articles/s41599-019-0217-x

The Royal Society (2018) lists costs in the range $140 to $270/t CO_2 captured, but these are highly sensitive to assumptions on biomass cost, electricity sale price, plant lifetime and efficiency.

One of the key challenges for the deployment of BECCS in the UK is the creation of **value chains** across sectors and countries, including development of skills for production of biomass in some countries and infrastructure to scale up production.

Lack of fiscal incentives and the length of the payback time is another challenge. BECCS is associated with high technical and financial risk and financiers need to have long term confidence in biomass supply chains, particularly energy crops. Poor access to finance for new biomass supply chains, particularly in under-developed and developing economies, means that the deployment of BECCS will be difficult unless mechanisms are developed.

Considering the wider CCS chain (i.e. CO_2 transport and storage), monitoring and verification of data on the impacts of long-term storage of CO_2, including the development of monitoring tools is required. Also, CO_2 storage liability and limitations in the current insurance market is an issue.

Regarding biomass feedstocks, there is a need to develop good practice in biomass supply for large scale supply. Currently the cost of logistics for some biomass sources, e.g. lack of infrastructure to enable economies of scale (e.g. for processing and storage of biomass, particularly storage at ports) is a barrier. In addition, there is lack of access to skills in development of biomass supply to meet fuel specification and sustainability requirements. Furthermore, the supply for some biomass is widely-dispersed and alternatives that could offer improved costs over current fuel processing are not currently available. There is reluctance to grow biomass energy crops on the part of farmers and land owners due to the upfront costs of establishing the crops, the time for a return on this investment, the lack of an established market and the need for consistent policy to enable these supply chains to develop over time. Biomass availability and sustainability, development of energy crops and competition for biomass resources and land are also issues that also need to be considered. For energy crops development in some countries understanding/identifying land ownership can be a challenge.

Finally, there is a need to understand the skill requirements for wide scale deployment of BECCS. Planning in terms of types of engineers (process, mechanical), geologists, legal experts, researchers and other skills needs to be undertaken carefully to ensure there is no shortage of the skills needed for the deployment of BECCS over the next 30 years.

4.2 Benefits and impacts of BECCS

BECCS can have a significant impact on the UK economy (GVA, job creation) as well as having environmental impacts. Impacts from the production of biomass and the long-term performance of CCUS are complex to monitor and not well understood. Impacts of biomass production may include:

- land use impacts (direct and indirect, including displacement of food production);
- increased water and fertiliser use;
- ecosystem and biological diversity impacts in the landscape where bioenergy production is proposed;
- social impacts related to land allocation in some regions;
- impacts on the supply and price of other commodities through competition for biomass resources or land.

These impacts may be mitigated, but independent evidence of mitigation may be difficult to provide. Governance systems that demonstrate holistic benefits or mitigation of potential impacts are currently not available.

While BECCS leads to reductions in CO_2 emissions, it may lead to increases in localised and regional air emissions. However, air emissions from biomass can easily be mitigated and reduced below acceptable levels. An understanding of the nature of these air emissions should be undertaken as part of project development in order to allow mitigation strategies to be implemented.

Although CO_2 transport and storage are outside the scope of this report, when the wider CCS chain is considered, the risk of CO_2 leakage may become an important issue. This is a high impact factor according to the CCUS Cost Challenge Task Force (2018)[31] but is low probability as there is significant weight of evidence on monitoring of CO_2 storage sites.

If poorly implemented, BECCS options could lead to trade-offs with other local/global needs (such as land rights, food production, intensification of agriculture and forestry practices, biodiversity and other sustainable development factors).

4.2.1 Economic impacts of BECCS

The economic impacts of BECCS in terms of Gross Value Added (GVA) to the UK economy and employment associated with construction and with the operation of the plant have been estimated for the deployment scenarios presented in Section 1.2. The results are presented below.

4.2.1.1 Assessment of GVA

To estimate GVA, capital expenditure for the power plant and infrastructure were broken down into key elements (e.g. feedstock handling, boiler, CO_2 capture) based mainly on data from Wood (2018) but supplemented with data from the Integrated Environmental Control Modelling (IECM) tool for the post-combustion plant. For each cost element, a further assessment was made of the breakdown of that cost by types of activity (e.g. engineering and design, manufacturing), and for each of those activities the UK share of the market. Combining these data with the overall costs for the plant gives an estimate of the spend in the UK for each of the three typical plant considered. Spend in the UK is estimated to be about 30% of the total cost of the plant (including pre-construction costs, owner's costs and infrastructure costs). The estimate of spend in the UK per plant was combined with the number of plants of each type assumed to be deployed in the scenarios to give the spend in the UK in each of the ten-year periods considered.

The GVA generated directly within each relevant sector from this spend is estimated using vales for GVA effect taken from input/output tables for the UK[32]. The appropriate values for the sector in which the expenditure occurs were selected (Table 4.1). Estimates of indirect GVA (i.e. GVA generated in other sectors of the economy) are made using Type 1 GVA multipliers from the same input/output tables. Induced effects are estimated using Type II multipliers. As these are not available for the UK, but are available for Scotland, UK values have been estimated from Type I multipliers by reference to the ratio of Type I to Type II multipliers for Scotland.

Table 4.1 Values used for GVA effect and GVA multipliers

Activity	Representative sector		GVA effect	GVA multipliers	
	SIC	Name		Type I	Type II
Power plant construction	41-43	Construction	0.8	2.0	2.5
CO_2 capture	41-43	Construction	0.8	2.0	2.5
Grid connection	35.1	Electricity, transmission and distribution	0.7	3.0	3.3
CO_2 transport	35.2-3	Gas distribution sector	0.7	2.4	2.7
CO_2 storage	06 & 07	Extraction Of Crude Petroleum And Natural Gas & Mining Of Metal Ores	0.9	1.5	1.8

31 https://www.cslforum.org/cslf/sites/default/files/documents/Publications/BECCS_Task_Force_Report_2018-04-04.pdf

32 2015 Input-Output Analytical Tables (for UK), available from https://www.ons.gov.uk/economy/nationalaccounts/supplyandusetables/datasets/ukinputoutputanalyticaltablesdetailed

Estimates of GVA generated in the sectors concerned up to 2050 are £5 billion in the low deployment scenario and £7 billion in the high deployment scenario (Table 4.2 and Table 4.3), and rise to £12 billion and £17 billion respectively if indirect and induced effects are taken into account.

Table 4.2 Estimates of GVA for low deployment scenario (undiscounted)

	2021 to 2030 £M	2031 to 2040 £M	2041 to 2050 £M	Total 2020 to 2050 (undiscounted) £M
Direct spend in UK	369	1,167	4,486	6,021
Direct GVA	305	964	3,707	4,976
Indirect GVA	275	869	3,339	4,483
Induced GVA	119	375	1,443	1,937
Total GVA	699	2,208	8,490	11,397

Table 4.3 Estimates of GVA for high deployment scenario (undiscounted)

	2021 to 2030 £M	2031 to 2040 £M	2041 to 2050 £M	Total 2020 to 2050 (undiscounted) £M
Direct spend in UK	369	1,536	6,519	8,423
Direct GVA	305	1,269	5,388	6,962
Indirect GVA	275	1,144	4,853	6,272
Induced GVA	119	494	2,097	2,709
Total GVA	699	2,907	12,338	15,943

4.2.1.2 Additional employment

Man-years associated with the construction of the plant are estimated by dividing spend in the UK by the output associated with a construction job (£49,453)[33]. Full time equivalent construction jobs are then estimated by applying a standard 10 man-years to 1 permanent job ratio. Estimates of jobs associated with operation of a plant are taken from Wood (2018). As for GVA these estimates are then combined with the number of plants deployed to give total direct jobs associated with the deployment scenarios.

Table 4.4 Estimates of jobs associated with construction of BECCS plants

	2021 to 2030	2031 to 2040	2041 to 2050	Total 2020 to 2050
Low deployment scenario	746	2,359	9,070	12,175
High deployment scenario	746	3,105	13,181	17,033

Table 4.5 Estimates of jobs associated with operation of BECCS plants

	2030	2040	2050
Low deployment scenario	83	339	1,361
High deployment scenario	83	422	1,940

[33] From Table 8 of the Labour productivity Tables q4 2018, produced by ONS and available at https://www.ons.gov.uk/employmentandlabourmarket/peopleinwork/labourproductivity/datasets/labourproductivitytables110andr1

4.2.2 Environmental impacts of BECCS

4.2.2.1 Carbon savings

The carbon stored associated with each deployment scenario is estimated based on carbon capture rates for the individual plants as reported in Section 3. An estimate is also made on the basis of carbon avoided, by assuming electricity generated at the BECCS plants would otherwise have come from a modern gas fired CCGT, (329.4 kg CO_2/ MWh). The CO_2 from the BECCS plant which is emitted (i.e. not captured) is assumed to have a 'zero' GWP as it is of biogenic origin and is not netted off the CO_2 avoided.

The value of the CO_2 stored and CO_2 avoided is estimated using the latest estimates of the value of carbon in 2030, 2040 and 2050. Carbon savings and their monetary values are shown in the Tables below.

Table 4.6 Carbon savings and their value in the low deployment scenario

	2030 (kt CO_2/year)	2040 (kt CO_2/year)	2050 (kt CO_2/year)	2030 £m/year	2040 £m/year	2050 £m/year
CO_2 stored	4,153	16,602	60,708	336	2,588	14,019
CO_2 avoided	1,029	4,131	15,215	83	644	3,514

Table 4.7 Carbon savings and their value in the high deployment scenario

	2030 (kt CO_2/year)	2040 (kt CO_2/year)	2050 (kt CO_2/year)	2030 £m/year	2040 £m/year	2050 £m/year
CO_2 stored	4,153	20,755	84,092	336	3,235	19,419
CO_2 avoided	1,029	5,160	21,093	83	804	4,871

4.2.2.2 Air quality impacts

The emissions of air pollutants (in particular NOx and PM) associated with BECCS plants is unknown at present. Emissions from both the power plant element and the carbon capture and storage element would be regulated (as are all large power plant) under the Industrial Emissions Directive[34]. As such they are subject to Best Available Techniques (BAT) controls which are "*designed to prevent or, where that is not practicable, to reduce emissions into air, water and land and to prevent the generation of waste, in order to achieve a high level of protection of the environment taken as a whole*". In practical terms this means that an installation needs to apply for a permit and is subject to conditions, including emission limit values, based on BAT Conclusions (or BREF Guidance notes where BAT Conclusions are not yet in place).

The BAT Conclusions for large combustion plant were published in July 2017 and apply to new large combustion installations and cover boilers, gas turbines and IGCC. BAT-Associated Emission Levels (BAT-AELs) which would be the legal basis of emission limit values in permits for new plant are provided as exhaust gas concentrations for conventional fuels and technologies. The BAT conclusions do not explicitly cover use of hydrogen fuel (which would be the case in the pre-combustion plant considered here) or enhanced oxygen combustion (as in the pre-combustion capture plant). This is relevant because the use of hydrogen and enhanced-oxygen combustion air will produce lower (dry) exhaust gas volumes per unit of energy (because of the absence/lower

[34] Chapter 2 of Directive 2010/75/EU on Industrial Emissions (IED) and the UK implementing regulations (e.g. Env Permitting regs for England & Wales). CCS is also a regulated activity under Chapter 2 of IED

concentrations of CO_2 and nitrogen compared to conventional combustion) and hence the BAT-AEL concentrations may need to be adjusted to suit these new technologies.

In the absence of data on air pollutant emissions from the proposed plant, emissions on a per GJ of fuel combusted basis derived from the BAT-AELS for conventional new biomass plant have been adopted as a basis to estimate air pollutant emissions and assess air quality impacts. This assumption is made on the basis that it is likely that BECCS plant would be required to have emissions (on a per GJ of fuel combusted basis) that are no higher than conventional large scale biomass plant[35].

Emissions factors used are shown in Table 4.8 and were combined with estimates of the monetary value of damage caused by emissions of these pollutants from Defra's Air quality damage cost guidance[36].

Table 4.8 Emissions factors used to assess air quality impacts

	NO_x g/GJ	PM2.5 g/GJ	SO_2 g/GJ
Post combustion and oxyfuel	48.5	1.5	12.1
Pre-combustion plant (IGCC)	25.7	0.2	0.3

Table 4.9 Estimates of damage caused by air pollutant emission

	2030 £M/year	2040 £M/year	2050 £M/year
Low deployment scenario	6	24	80
High deployment scenario	6	30	106

[35] It is possible that complying with emissions limits set under the IED could add capital and operating costs to BECCS plant considered in this report. It was not possible to assess within this study what those additional costs might be. This is partly due to the uncertainty regarding what the emissions limits might be in terms of flue gas emissions, and therefore the level of pollution abatement techniques and technology that might be required to meet them, and partly because the level of pollution abatement assumed in the reference data sets is unclear.

[36] Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/770576/air-quality-damage-cost-guidance.pdf. Values used are for Part A processes and assume a stack height of greater than 100 m and a population density of between 250 and 1000 persons per km^2.

5 Conclusions

Modelling by the IPPC and other agencies worldwide has shown that 2050 emission reduction targets are not achievable without CO_2 removal technologies, also known as negative emission technologies (NETs) or Greenhouse Gas Removal technologies (GGRs). These include nature-based methods where the CO_2 is sequestered in soil and biomass as well as technological approaches including direct air carbon capture and storage (DACCS), biochar and bioenergy CCS (BECCS). BECCS refers to a suite of technologies where carbon dioxide is removed and captured from biomass power generation (combustion or gasification plants) and from biomass- and waste-based industrial processes.

BECCS is a promising negative emissions technology. Most of the technology components including biomass power generation, CO_2 capture, transport and storage is technically proven so, in theory, some BECCS technologies could be developed relatively quickly. It is considered part of many analysis pathways aimed at limiting global warming. This provides opportunities for the UK to develop expertise in an important climate change technology that can be deployed globally.

A real benefit from the quick deployment of BECCS in the UK is to provide an opportunity for the UK to develop skills as well as performance, cost and environmental data. In addition, development of energy crops for biomass use can, if undertaken sustainably (e.g. replacing high intensity crops or using poorer quality marginal land), improve biodiversity and soil carbon, although care must be taken to ensure these benefits are achieved. BECCS can also contribute significantly to the creation of direct and indirect jobs and skills at local and regional level in the UK.

This report undertook preliminary analysis to estimate the economic and environmental impacts that BECCS can have in the UK in 2030, 2040 and 2050. Analysis was undertaken for two deployment scenarios, a low BECCS deployment and a high BECCS deployment. It should be noted that BECCS has significant potential as negative emission technology when also applied to industrial sectors, but these were not covered in this analysis. In addition, recent studies have also shown that the application of CCUS to EfW plants in the UK can reduce emissions by around 18Mt CO_2/year and at a cost similar to other industrial abatement options. The deployment of BECCS on EfW plants has not been considered as part of the current analysis which focusses on power generation from wood feedstocks and energy crops.

Analysis shows that the damage caused by air emissions under the high BECCS deployment scenario in the UK in 2030, 2040 and 2050 could amount to £6M/year, £30M/year and £106M/year respectively. However, the value of carbon stored from BECCS could be in the range of £14-19Bn/year in 2050. Furthermore, the construction of BECCS power plants can lead to the support of thousands of construction jobs in the next two decades. In addition, it is estimated that operation of BECCS plant in 2030, 2040 and 2050 could support 80, 330-400 and 1250-1750 permanent jobs respectively. The total value added to the UK economy (GVA) between 2025 and 2050 is estimated at around £16Bn resulting from direct, indirect and induced GVA.

BECCS offers great opportunities for the UK. However, challenges and barriers need to be overcome in order to make deployment of BECCS a reality as summarised below.

Biomass feedstocks

In order to understand the potential for BECCS in the UK, it is important to first understand issues surrounding biomass availability and sustainability. Currently, the most common biomass feedstocks for power generation in the UK are wood, waste wood, straw, and mixed wastes (usually waste residues after recycling and landfill gas). Wood pellets is the major use of biomass in electricity generation followed by residues from agriculture and wastes, which are bulky to transport.

The other potential biomass feedstocks that could be produced at scale are energy crops. These will be required if the UK is to expand bioenergy without using food crops. Most analysis indicates that biomass energy will be limited unless energy crops are developed. A long-term stable policy to encourage the development of sustainable energy crops is needed for this to happen.

Currently the UK uses around 16 Mt of biomass from forestry and agricultural sources and 12 Mt of waste biomass for large scale electricity generation. In order for BECCS to become economically feasible, large power stations need to be demonstrated in the UK in the next decade. We estimate that the UK can produce around 80.5 TWh/year to 147 TWh/year of biomass. In order for the UK to develop its full potential for biomass supply, a significant part of this supply (8-15% of the UK potential resource) will need to come from the development of energy crops on up to 350,000 ha land (Global CCS Institutes quotes 300-700 million ha of land needed to meet CO2 emission reduction targets through BECCS). An additional 7-20 TWh/year can be accessed through international markets. We estimate that the UK access to some of the global biomass sources would decrease to 2050 as countries establish their own biomass plants or inter-regional competition as increased Climate Change targets begin to take effect.

Whether substantial international biomass resources can be produced sustainably and made available for international trade depends on global developments, including population growth, dietary habits and land availability as well as governance frameworks. This will in turn be dependent on targets set in other global regions; and it is not currently clear whether there will be BECCS hubs developed elsewhere in the world that are also net importers of biomass. This will affect BECCS deployment in the UK. In order to have better understanding of BECCS potential in the UK, a wider international study and evaluation of biomass feedstocks is required.

A key consideration is to investigate optimum locations for BECCS power plants. This needs to consider sites adjacent to CO_2 storage sites while at the same time evaluating the potential for sourcing biomass locally in order to reduce life cycle emissions from international biomass transport. However, impacts on the ecosystem, air emissions, land requirements and other environmental impacts need to be evaluated. A framework for assessing these impacts and guidance to effectively select the most appropriate sites for BECCS are needed.

Although not being part of the current analysis, many EfW plants are located in major industrial clusters with proximity to CO_2 storage sites. Deployment of CCUS on EfW could provide a benefit on that regard but this needs to be evaluated on a case by cases basis due to the technical challenges which can be encountered with certain feedstocks.

Technology options

BECCS is one of a series of several negative emission technologies available to the UK. Currently, no regulatory framework exists in the UK or in the EU to incentivise NETs. Current evidence shows that the post-combustion capture of CO_2 from flue gas streams is the most advanced option for CCS in general. The two CCS demonstrations in the US (Petra Nova) and Canada (Boundary Dam) are both post-combustion capture plants on coal power stations. In addition, the Drax BECCS demonstration in the UK also utilises the post-combustion capture concept utilising chemical absorption.

It is thus believed that, based on current evidence, post combustion based on well-established solvents such as amines or emerging innovative solvents such as the one developed by C-Capture is likely to be the technology to support initial deployment given its maturity compared to other capture technologies. In agreement with recent studies, our analysis shows that post-combustion capture has lower LCOEs and offers greater opportunities in terms of technology readiness and life cycle emission savings. Additional support needs to be provided in the next two decades to demonstrate and commercialise emerging technologies that could offer benefits in terms of efficiency, costs and LCOEs (e.g. chemical looping, carbonate looping, molten carbonate fuel cell and biomass-based supercritical CO_2 cycle).

It should also be noted that BECCS can also be applied to small scale biomass CHP engines where the CO_2 can be captured and stored locally for further distribution to industry. A wide range of CO_2 application exist in the UK including food & drink industry, poultry and pig farming, sodium carbonate manufacture, urea and fertiliser production, concrete curing and as refrigerant gas with CO_2 prices ranging from £70 to £180 / tonne of CO_2. The existence of this CO_2 market encourages the deployment of BECCS on small scale technologies eliminating the need for expensive and complex CO_2 transport and storage infrastructure in the short term until such infrastructure is fully developed. The high costs of CO_2 capture from these small units is balanced by existing high commercial CO_2 prices in an established supply chain. In addition, technologies such as pyrolysis CHP also offer an additional revenue stream in terms of the biochar produced from the process which offers additional carbon capture benefits. It is thus believed that incentives and support for demonstrating BECCS should also include small scale technologies and decentralised systems.

Appendices

Appendix 1: Technical and cost data

Table A1.1 Technical data

	Capacity (gross) MWe	Capacity (net export) MWe	Gross generating efficiency %	Net generating efficiency %	Lifetime years	Carbon capture rate %	Availability (normal operation) %
Post combustion amine	498	396.2	38.5%	30.6%	25	90%	90%
Oxy fuel combustion	598	402.1	46.3%	31.1%	25	90%	90%
IGCC	493.3	356.1	44.5%	32.1%	25	91%	85%
Carbonate looping	326	300	43.9%	40.4%	30	97%	85%
Chemical looping	325	300	44.5%	41.0%	30	92%	85%

Table A1.2 Cost data (NOAK plant)

	Pre-licensing £M	Regulatory and public inquiry £M	Construction £M	Infrastructure £M	Owner's costs £M	Fixed Opex £M/year	Variable O&M £M/year	Annual electricity output TWh/year	Feedstock requirement TWh/year	Feedstock cost £M/year
Post combustion amine	11.1	23.3	1,106.7	29	77.5	58.3	11.4	3.12	10.2	255.2
Oxy fuel combustion	12.9	27.0	1,290.3	29	90.3	66.3	11.0	3.17	10.2	254.8
IGCC	13.0	27.3	1,304.7	29	91.3	70.8	10.4	2.65	8.3	206.5
Carbonate looping	8.1	17.3	805.0	29	40.3	42.7	7.9	2.23	5.5	138.2
Chemical looping	6.4	13.9	636.3	29	31.8	34.0	7.4	2.23	5.4	136.2

Table A1.3 Breakdown of construction costs

	Feedstock handling £M	Boiler £M	Gasifier £M	Power block / turbine island £M	Air Separation unit £M	CO_2 capture £M	CO_2 compression £M	Balance of plant £M	Total construction cost £M
Post combustion amine	33.4	407.9		193.2	0.0	257.6	64.4	150.2	1,106.7
Oxy fuel combustion	86.4	398.1		196	240.3	107.1	60.2	202.2	1,290.3
IGCC	43.8		468.6	360.7	125.1	54.4	45.5	206.6	1,304.7
Chemical looping	45.0	326.7			71.3	82.4	34.5	76.4	636.3

Appendix 2: Tabulated results

Table A2.1 Components of LCOE for NOAK plant (including transport and storage costs)

	Pre-development £/MWh	Capex £/MWh	Fixed Opex £/MWh	Variable Opex £/MWh	Use of system charges £/MWh	Fuel (central fuel price) £/MWh	CO_2 transport and storage £/MWh	LCOE (low fuel price) £/MWh	LCOE (central fuel price) £/MWh	LCOE (high fuel price) £/MWh	Price of CO_2 emissions £/MWh
Post combustion amine	£4	£47	£19	£1	£3	£82	£25	£149	£181	£230	£23
Oxy fuel combustion	£5	£53	£22	£1	£3	£80	£25	£157	£189	£237	£23
IGCC	£6	£64	£28	£2	£3	£78	£24	£173	£204	£251	£20
Carbonate looping	£3	£45	£19	£1	£3	£62	£21	£130	£154	£191	£5
Chemical looping	£2	£36	£15	£1	£3	£61	£19	£114	£138	£175	£14

Note: Price of CO_2 emissions assumes that the biogenic carbon emitted is valued using the price of carbon and assumes FOAK plant begins operation in 2029 and NOAK plant in 2031

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