UKERC Technology and Policy Assessment

Bioenergy with carbon capture and storage, and direct air carbon capture and storage:

Examining the evidence on deployment potential and costs in the UK

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The Technology and Policy Assessment (TPA) Theme of UKERC

The TPA was set up to inform decision-making processes and address key controversies in the energy field. It aims to provide authoritative and accessible reports that set very high standards for rigour and transparency. Subjects are chosen after extensive consultation with energy sector stakeholders and upon the recommendation of the UKERC Research Committee and Advisory Board, comprised of independent experts from government, academia and the private sector.

The primary objective of the TPA is to provide a thorough review of the current state of knowledge using systematic review protocols. New research, such as modelling or primary data gathering may be carried out when essential. It also aims to explain its findings in a way that is accessible to non-technical readers and is useful to policymakers.

Executive Summary

As a signatory to the 2015 UNFCCC Paris Agreement, the UK has committed to pursuing efforts to limit global temperature rises to 1.5°C. This UKERC TPA working paper has been prepared to support the Committee on Climate Change's advice to the UK government on the implications of the Paris Agreement on its long-term emissions reduction targets. In their recent reports, the Intergovernmental Panel on Climate Change have highlighted that large-scale carbon dioxide removal (CDR), defined as any anthropogenic activity that results in the *net* removal of CO_2 from the atmosphere, is critical to meeting the Paris Agreement target. This review addresses two technological CDR solutions that have been demonstrated: bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS). The overarching questions which this review addresses, for both BECCS and DACCS, are:

1. *What is the potential contribution that these technologies could make to CO_2 removal and potentially CO_2 emissions reductions to achieve net zero emissions in the UK?*
2. *What are the current and projected costs, globally and in the UK, of these technologies and how plausible are projected cost reductions (including evidence for the benefits to be derived from economies of scale/technology learning)?*

A systematic review resulted in an evidence base of 170 documents. Of these, only 20 documents assess DACCS technology explicitly. This highlighted the scarcity of literature on DACCS. BECCS has received more attention, in large part due to its inclusion in Integrated Assessment Models (IAMs). Independent, bottom-up techno-economic assessments of DACCS technologies are particularly lacking. Only four of such assessments were found in the literature dating back to 1996; and several studies have taken these and sought to optimise the DACCS processes defined within them, so as to refine the energy and economic cost estimates. With the exception of one analysis, these assessments were published before 2012 so the cost estimates may be considered to be dated. Five companies have been identified as commercial developers of DACCS. Two of these, *Carbon Engineering* and *Climeworks*, have provided cost estimates for their technologies. Recent studies seeking to evaluate the climate change mitigation potential of DACCS have assumed these values in their analyses. Owing to the proprietary nature of the underlying technologies used for DACCS, and their presentation of projected future costs (as opposed to current costs), it is difficult to independently verify capture costs and subsequent mitigation potential using DACCS. Further work is needed to develop independent, bottom-up techno-economic assessments of DACCS, and demonstration to prove its commercial viability at scale. The potential implications of DACCS on the environment (as some archetypes of the technology consume water) also need further investigation.

DACCS is a significant consumer of energy, the bulk of which is the heat needed to regenerate the capture material. This review found that there are significant uncertainties in the energy and economic costs of DACCS, depending on the underlying technology it is based on. Capturing a million tonnes of CO_2 annually could require 0.1–1.2 TWh_e/yr and 0.6–2.5 TWh_{th}/yr. Therefore, if deployed at scale, DACCS will present a non-negligible additional demand to both the electricity and heat systems, which would require careful consideration in planning the evolution of those systems. Costs of CO_2 removal (accounting for associated emissions from energy supply) via DACCS range from £100–540/tCO_2. Despite the large energy requirements, the bulk of DACCS cost is capital expenditure. Several DACCS developers are pursuing modular technology designs that could benefit from economies of scale through mass production.

The carbon price floor in the UK, and carbon prices in the EU-ETS and voluntary carbon offset markets are significantly lower than DACCS cost estimates. Additionally, there is no separate incentive for CDR in the UK, which means that DACCS is currently not commercially viable. The scalable/modular nature of some DACCS archetypes, however, presents opportunities for DACCS demonstration and a route to commercialisation. DACCS' non-reliance on a bio-geophysical resource such as biomass makes it geographically-flexible. Plants could therefore be sited near stranded energy resources to provide low-cost energy. Alternatively, DACCS could be sited near to isolated/merchant CO_2 markets (*e.g.* greenhouses and beverage companies) which typically source CO_2 at high prices (up to £200/tCO_2). Whilst the utilisation of DACCS-derived CO_2 may aid early demonstration, it does not contribute to climate change mitigation as CO_2 emissions to the atmosphere are only delayed. Mitigation necessitates permanent sequestration of CO_2. The development CO_2 transport and storage infrastructure, and incentive(s) for permanent CO_2 storage, in the UK is therefore a pre-requisite for large-scale deployment of DACCS (and BECCS), and remains an important bottleneck to the deployment of a range of options that could capture and store CO_2.

The literature on BECCS is relatively large compared to DACCS. Out of the 170 documents reviewed, over 100 documents were specific to BECCS, with a majority of bottom-up assessments of BECCS potential and techno-economic studies. BECCS technical potential is correlated with bioenergy technical potential, and can be therefore be determined in part through bioenergy resource assessments – whether at global or country scale. BECCS potential in the UK was assessed between 3 and 60 $MtCO_2$/yr. These ranges are a function of the UK local bioenergy supply, on how this supply is distributed amongst the different bioenergy conversion routes to CDR, and on lifecycle emissions of each BECCS value chain. As the UK has considerable CO_2 storage potential (80 $GtCO_2$), it is possible that the UK could import biomass feedstock to extend BECCS deployment beyond this technical potential. When considering bioenergy imports, the maximum technical potential of BECCS increases to 100–160 $MtCO_2$/yr. However, the difficulty in certifying imports, the potential public concern around the UK importing biomass, and the implementation of a stricter sustainability criteria for biomass feedstock emissions, may limit the role that imported biomass could play in UK emission abatement targets.

In the context of the updated bioelectricity GHG threshold of the UK's CfD scheme, the biomass supply of bioelectricity plants may be limited to local waste biomass feedstock. This could impact biomass feedstock suppliers, who still heavily rely on subsidies and contract farming with the bioenergy industry, hence further limiting biomass feedstock production in the UK. The extent to which BECCS technical potential is therefore both sustainable and economic, remains uncertain at the global scale, and relatively unknown at the UK scale. Further research on the environmental impact(s) of BECCS deployment in the UK is needed to address this question.

BECCS cost estimates in the literature span a wide range, with values as low as £12/tCO_2 and as high as £314/tCO_2. The multiplicity of BECCS pathways (*e.g.* electricity, biofuel) and technologies (*e.g.* fermentation or gasification) is a first driver of variability. Additionally, differences in boundaries for both the cost and CO_2 balance result in BECCS cost being provided alternatively as a cost per ton of CO_2 avoided (*i.e.* as compared to a counterfactual), captured, or removed (*i.e.* CO_2 captured minus life cycle GHG emissions). Based on UK specific CAPEX and feedstock cost data from the literature, BECCS removal cost in the UK was assessed as between £70 and £130/tCO_2 when using local biomass, and between and £150 and £200/tCO_2 when using imported biomass. Two conflicting driving forces of BECCS cost were identified: 1) the potential decrease in capital cost from a "first of a kind" plant to an "nth of a kind plant" 2) the potential increase in feedstock cost, as sustainability criteria toughened and demand for biomass feedstock increases. A sensitivity analysis showed that overall, BECCS cost was more sensitive to feedstock cost. Whilst the "real cost" of BECCS can be determined by demonstration/real size BECCS projects, the uncertainty of the evolution of feedstock costs over time may therefore be one the main economic bottlenecks to BECCS deployment.

The financial viability of BECCS plant is still likely to rely on a revenue stream associated with the service of carbon dioxide removal, especially in the case of large scale bioelectricity plants. A review of the literature indicates that CO_2 prices between £25 and £190/tCO_2 are required for BECCS plants to be competitive with their unabated alternative. In the context of the UK, this assessment showed that a negative emission credit between £75 and £210/tCO_2 (depending on the feedstock cost) was required for a BECCS plant to breakeven (net present value is equal to zero). This is still much higher than the current value of the CO_2 price set by the EU ETS scheme, which suggests the need for the creation of a separate incentive scheme specific to CDR.

Table ES.1: Summary of barriers and opportunities for BECCS and DACCS deployment in the UK

	BECCS	**Both technologies**	**DACCS**
Barriers	• Feedstock availability: technical and social (*e.g.* farmers) • (Cross-border) biomass sustainability certification • Conflicting driving forces of BECCS cost: CAPEX cost reduction by scale up (economies of scale, tech learning) vs. biomass cost increase by scale-up	• Need for CO_2 transport and injection infrastructure • Policy framework (CO_2 negative emission credit, CO_2 pricing)	• Availability of cheap low-carbon energy (waste heat, curtailed renewable energy, *etc.*) • High cost
Opportunities	• Existing bioenergy industry (*e.g.* Drax)	• Well-characterised CO_2 storage in the UK • Industrial clusters of CO_2 emitters (for CO_2 transport and storage) • Niche markets: CO_2 utilisation (though not carbon negative), offsets	• Modularity and scalability • Geographically-flexible so can exploit stranded energy resources or merchant CO_2 markets • Can utilise waste heat from industry

Contents

1. Introduction

1.1. The need for negative emissions globally, and in the UK

This UK Energy Research Centre (UKERC) Technology and Policy Assessment (TPA) working paper has been prepared to support the Committee on Climate Change (CCC) in their advice to the UK government on the implications of the Paris Agreement on the UK's long-term emissions reduction targets.

In their recent reports, the Intergovernmental Panel on Climate Change have highlighted that large-scale carbon dioxide removal (CDR), defined as any anthropogenic activity that results in the net removal of CO_2 from the atmosphere, is critical to meeting the 2015 Paris Agreement aspirations. Depending on the scale and pace of mitigation action, between 2 and 16 billion tonnes ($GtCO_2$) of CDR could be globally required by mid-century (Joeri Rogelj et al. 2018; Huppmann, Rogelj, et al. 2018). Whilst 2-3 $GtCO_2$ could be achieved through afforestation/better soil carbon management, so-called "CDR technologies" such as bioenergy with carbon capture and storage (BECCS) or direct air carbon capture and storage (DACCS) would need to be deployed to achieve higher CDR levels (Kemper 2015; Gough & Upham 2010; IEA Greenhouse Gas R&D Programme (IEA GHG) & Ecofys 2011) (Ranjan & Herzog 2011; R. Socolow et al. 2011).

In the UK, the CCC has estimated that 50 MtCO2/yr could be sustainably removed from the atmosphere by 2050 to offset residual emissions, and contribute to the UK meeting its emissions reductions targets legislated by the 2008 Climate Change Act (Committee on Climate, 2016). This was based on a proposed global objective to keep global temperature rise close to 2°C (with 50% probability). With the ratification of the Paris Agreement, political efforts have refocused on further limiting global temperature rise to 1.5°C. The role that the UK might play in global CDR deployment, with which technology or mix of technologies, and at what cost, remains unclear. Exploring the deployment potential and costs of both BECCS and DACCS in the UK, and how these might compare with other regions, is the purpose of this working paper.

Research questions

The overarching questions which this project addresses, for both bioenergy with carbon capture and storage (BECCS) and direct air capture (DAC) of atmospheric CO_2), are:

1. *What is the potential contribution that these technologies could make to CO_2 removal and potentially CO_2 emissions reductions to achieve net zero emissions in the UK?*
2. *What are the current and projected costs, globally and in the UK, of these technologies and how plausible are projected cost reductions (including evidence for the benefits to be derived from economies of scale/technology learning)?*

1.2. Overview of CDR technologies

Several solutions have been identified as viable options to deliver net negative flows of CO_2 emissions at scale. These include bio-energy with carbon capture and storage (BECCS), direct air capture and carbon capture and storage (DACCS), afforestation/reforestation (AR), augmented ocean disposal ("ocean liming"), enhanced weathering of minerals, the lime-soda process and biochar. The technologies have been the subject of many quantitative and qualitative studies to determine their technical and economic feasibility, estimate their potential performance and costs, and identify the barriers to their development and adoption (Minx et al. 2017; Fuss et al. 2018; Gregory F. Nemet et al. 2018; EASAC 2018; Smith & Friedmann 2017).

Box 1.1 Reason for focus on BECCS and DACCS in this working paper

Afforestation/reforestation (AR) has been demonstrated as feasible at scale. However, integrated assessment models (IAMs) have shown that in addition to AR, further sources of CDR will be required to meet the Paris Agreement target. Of the technological solutions that have been proposed as potential sources of CDR in the literature, only BECCS and DACCS have been demonstrated as technically feasible at scale without significant side effects. Additionally, they both offer CDR *via* geological sequestration of CO_2, and the UK boasts significant CO_2 storage capacity offshore in the North Sea which gives it a geographic advantage for the deployment of BECCS and DACCS. Lastly, decarbonisation efforts have led to an evolving energy system which is increasingly reliant on renewable energy sources. BECCS and DACCS also directly interact with the energy system since BECCS is an energy producer while DACCS is a consumer, and deployment strategies for either technology must therefore be considered holistically within the energy system transition.

1.3. Methodology

The research was undertaken using a systematic review protocol (see Box 1.2), which typically provides a rationale for the choice of sources and lists the main databases, bibliographies, catalogues, personal contacts and other sources that are to be searched. The protocol also specifies the years to be covered and the search criteria used. In addition to those documents found during the search process, the project team also reviewed any other documents which had been suggested by expert group members (see Annex). All costs shown are in 2018 GBP. The HMRC foreign exchange yearly averages[1] and GDP deflator rates[2] have been used to convert historic costs.

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[1] https://www.gov.uk/government/publications/exchange-rates-for-customs-and-vat-yearly

Search Terms

The search terms and evidence categorisation are described below:

‘negative+emissions+potential’
‘negative+emissions+cost’
‘carbon+dioxide+removal+potential’
‘air+capture+cost+reduction’
‘greenhouse+gas+removal+potential’
‘air+capture+potential+UK’

Although the focus of this paper is on BECCS and DACCS, the terms ‘negative emissions’, ‘carbon dioxide removal’ and ‘greenhouse gas removal’ (which are often used interchangeably with CDR) were included in the search terms to ensure more generally relevant material was found during the search process. The search terms were applied to the databases below. The search terms used and the total number of hits returned from each string were recorded. Where a particular search string returned a large number of hits, only the first 100 results were examined for initial relevance, based on the document title and abstract. The number of hits deemed relevant on this initial examination were recorded, along with details of each document that passed this first stage assessment.

Databases / sources

Scopus

Relevance ratings

A rating (1 or 2) was assigned to each piece of evidence that appeared to be relevant based on the initial examination. This allowed the project team to subsequently focus their attention only on documents which were most directly useful in addressing the research question i.e. documents assigned a relevance rating of 1.

These relevance ratings are:

1. Article shows clear data and/or discussion directly focussed on the research question.
2. Article shows clear data and/or discussion that is related to but not directly focussed on the research question.

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[2] https://www.gov.uk/government/collections/gdp-deflators-at-market-prices-and-money-gdp

1.4. Structure of this working paper

The remainder of this working paper is structured as follows: Chapter 2 provides an overview of the evidence base on BECCS and DACCS costs and potentials, and the sources of data (both quantitative and qualitative) used by the project team. Chapter 3 and 4 detail the main findings for DACCS and BECCS, respectively, and Chapter 5 concludes the working paper.

Box 1.2 The UKERC Technology and Policy Assessment Theme

Guiding principles

The UKERC technology and policy assessment (TPA) team was set up to address key controversies in the energy field and to provide authoritative inputs to decision-making processes through accessible and credible reports that set high standards for rigour and transparency. The principles by which the TPA ensures these standards are:

- Appropriate stakeholder participation and engagement including consultation on prospective assessment questions, and consultation on emerging findings.
- Clarity and transparency of analysis, including clear, published criteria for choosing and refining questions, and protocols that can be readily criticised and replicated.
- Expert scrutiny and the consideration of a range of perspectives, including selection of an expert team to work on each assessment, appointment of advisors to bring a range of perspectives to each assessment, and the solicitation of commentary and input during the assessment process.

The TPA approach

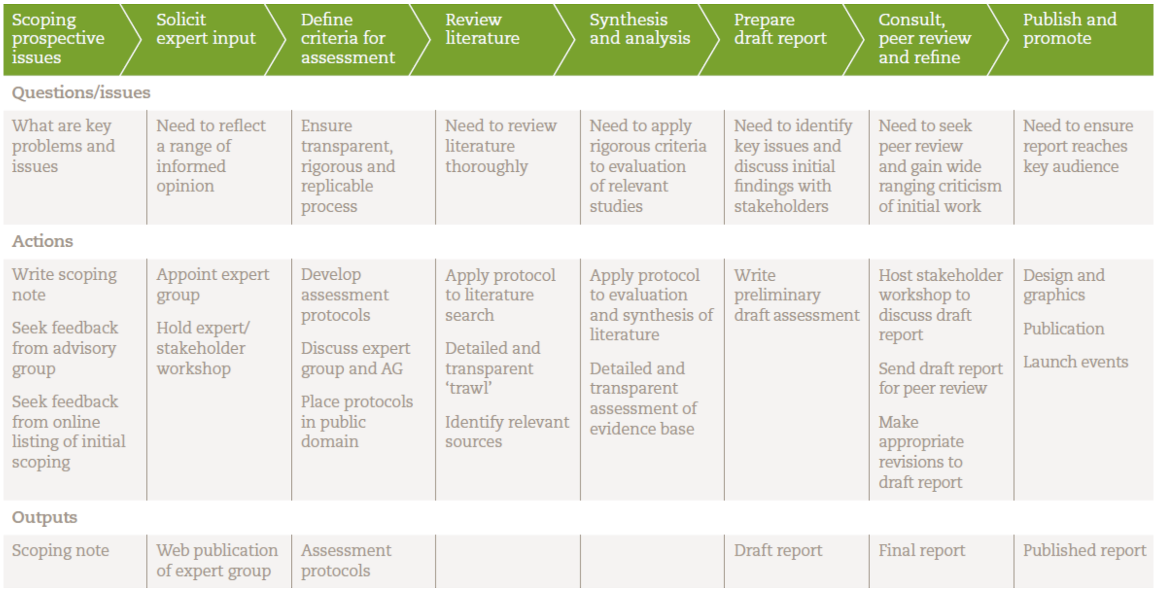
The TPA approach learns from the practice of systematic review, which aspires to provide convincing evidence for policymakers and practitioners, avoid duplication of research, encourage higher research standards and identify research gaps. This *evidence based* approach is common in areas such as education, criminal justice and healthcare.

The goal is to achieve high standards of rigour and transparency. However, energy policy gives rise to a number of difficulties for prospective systematic review practitioners and the approach is not common in energy. We have therefore set up a process that is inspired by the evidence based approach, but that is not bound to any narrowly defined method or techniques.

This assessment protocol describes this process in detail. It provides a specification of the means by which we will consult stakeholders and solicit expert input, specifications for searching the literature, and criteria against which relevant findings will be assessed.

Assessment sequence

The TPA has identified a series of steps that need to be undertaken in each of its assessments. These steps, derived from the practise of *systematic review* in non-energy policy analysis, are outlined in Figure 1.1.



	Scoping prospective issues	Solicit expert input	Define criteria for assessment	Review literature	Synthesis and analysis	Prepare draft report	Consult, peer review and refine	Publish and promote
Questions/issues								
	What are key problems and issues	Need to reflect a range of informed opinion	Ensure transparent, rigorous and replicable process	Need to review literature thoroughly	Need to apply rigorous criteria to evaluation of relevant studies	Need to identify key issues and discuss initial findings with stakeholders	Need to seek peer review and gain wide ranging criticism of initial work	Need to ensure report reaches key audience
Actions								
	Write scoping note Seek feedback from advisory group Seek feedback from online listing of initial scoping	Appoint expert group Hold expert/ stakeholder workshop	Develop assessment protocols Discuss expert group and AG Place protocols in public domain	Apply protocol to literature search Detailed and transparent ‘trawl’ Identify relevant sources	Apply protocol to evaluation and synthesis of literature Detailed and transparent assessment of evidence base	Write preliminary draft assessment	Host stakeholder workshop to discuss draft report Send draft report for peer review Make appropriate revisions to draft report	Design and graphics Publication Launch events
Outputs								
	Scoping note	Web publication of expert group	Assessment protocols			Draft report	Final report	Published report

Figure 1.1 – Typical process for TPA studies

2. Critical assessment of the literature

The systematic literature review undertaken for this project revealed 170 documents that are either directly relevant (relevance criteria 1: 110 documents) or potentially relevant (relevance criteria 2: 60 documents). Whilst the earliest articles reviewed were published in the 1990s, over 70% of the literature was published in the last three years, which shows a clear acceleration of the research activity on carbon dioxide removal. In terms of technologies covered, over half of the research material was specific to BECCS, and only 10% was specific to DACCS, which highlights that BECCS dominates the discussion on carbon dioxide removal. 20% of the research material however covered both BECCS and DACCS or CDR in general. In terms of scale and geographic distribution, over 40% of the studies were performed at the global scale, which shows that a lot of the research effort is still focused on the global potential and impacts of CDR deployment. Among studies performed at a regional scale, or at least written in a specific regional context, the UK is one of the most prolific regions totalling 20% of the research material.

2.1. Quality of the DACCS literature

Of the 170 documents reviewed during this work, only 20 were found to focus on DACCS exclusively. An additional 17 documents assess DACCS alongside BECCS or other CDR technologies. The evidence base has been divided into 3 categories:

- Original technical assessments: These use thermodynamic or comparative analyses to determine the energy cost of DACCS processes (Lackner 2009; Stolaroff et al. 2008; Baciocchi et al. 2006; Zeman 2007; Darton & Yang 2018; Pritchard et al. 2015). Comparative analyses determine the energy and/or economic costs of DACCS by comparing DACCS with existing gas separation techniques. Due to the wide range of efficiencies achievable by different techniques, such estimates have large uncertainties.

- Original techno-economic assessments: The studies evaluate both the energy and economic cost of DACCS processes (Keith et al. 2018; R. H. Socolow et al. 2011; Zeman 2014; Mazzotti et al. 2013; Krekel et al. 2018; Simon et al. 2011). In the bulk of these studies, only part of the cost – often the cost contactor equipment or energy – are quantified (Keith et al. 2006; Holmes & Keith 2012; Nikulshina et al. 2006; Stolaroff et al. 2008).

- Other: These include: reviews of proposed processes for DACCS (Martin et al. 2017; Azapagic et al. 2018; Sanz-Pérez et al. 2016); integration of DACCS in energy systems or integrated assessment models (Wohland et al. 2018); or assessments of political economy issues. For the latter, this is not done exclusively for DACCS but for CDR in general.

Nature of the evidence base

As explained in Chapter 3, there are significant disparities in the cost of DACCS found in the literature. This is because of the scarcity of complete and independent bottom-up techno-economic assessments of the processes proposed. Owing to this, studies that seek to evaluate the climate change mitigation potential of DACCS using integrated assessment models use cost projections provided by the developers of the technology (Wohland et al. 2018). Often, the costs provided are of what is considered achievable as opposed to the current case (Climeworks 2019; Global Thermostat 2019; Keith et al. 2018). Additionally, the proprietary nature of the underlying technologies employed by the developers make it difficult to independently verify cost estimates of current or future deployment.

Gaps in the literature

There is a scarcity of independent bottom-up techno-economic assessments of DACCS technology. Where first-of-a-kind costs are established, assumptions of cost reduction or technology learning achievable are not substantiated.

The DACCS technologies proposed in the literature utilise significant amounts of material (for large equipment needed to contact air), chemicals (for sorbents and sorbent regeneration) and energy (as processes are energy intensive). Furthermore, some DACCS technologies are consumers of water, while others produce it. Despite this being widely-acknowledged, life-cycle assessments to evaluate the material/waste/environmental implications of DACCS deployment are absent from the evidence base.

The DACCS land footprint is often cited as negligible or minimal but no original evidence is available that has quantified the amount of land needed for a commercial-scale facility. Additionally, where size of technology is discussed, the additional spatial requirements of CO_2 compression and transport infrastructure are not considered.

2.2. Quality of the BECCS literature

Five categories of studies emerge within the identified BECCS literature:

- Review-type studies (15%), looking solely at BECCS or a portfolio of CDR technology, provide quantifications of CO_2 removal technical potential, indicative costs, and flag broader environmental and economic impacts of the large scale deployment of BECCS.

- Bottom-up assessments of BECCS potential (20%) at the regional or global scale, with a focus on environmental and economic impacts on BECCS such as land use, water use, biodiversity loss, *etc.*

- Techno-economic studies (30%) combined, in some cases, with life cycle assessments (LCA) of specific BECCS technological pathways in a given region.

- Top-down and integrated assessment studies addressing the role of BECCS in decarbonising the energy system and the economy (12%). Whilst such studies provide insights into the value and required scale of BECCS, limited information as to actual potential and costs of BECCS is usually provided. For these reasons, this category was considered of relevance 2 within the context of this work.

- The last emerging category are inter-disciplinary studies investigating the political environment, market opportunities, value creation and social considerations of deploying BECCS (11%). The UK share of studies within this category is higher than the average (1/3), which perhaps signals a willingness to address these questions to make BECCS a commercial reality in the UK.

Most review-type studies were found to be performed in a global context. Whilst very insightful in providing cost and potential ranges for BECCS, some of the ranges tend to be repeated from one review to another. A second shortcoming of these reviews is that the various assumptions behind each data point or range is not necessarily specified (with the exception of Fuss *et al.* 2018), which makes the critical assessment of these results challenging.

In studies performed at regional-scale, it is difficult to determine the extent to which the data provided can actually be considered specific to a given region. For example, in assessing BECCS potential in the UK, the authors use data from a BECCS bottom-up assessment performed at the global level (Smith, Davis, et al. 2016) and apply them to a regional assessment of land availability (Smith, Haszeldine, et al. 2016; Alcalde et al. 2018). More generally, the extent to which BECCS environmental impacts, explored at the global scale, remain valid in the context of the UK, is a gap in the literature.

There is a great deal of heterogeneity among techno-economic assessments of BECCS when it comes to the following assumptions: 1) terminology/definition of the cost results presented, for example per ton of CO_2 avoided as opposed to captured; 2) counterfactual scenario chosen; 3) choice of boundaries to perform the cost balance, in particular which stages of the value chain are included in the economic analysis; 4) choice of boundaries to perform the carbon balance, in particular which supply chain emissions are considered to calculate the net negative emissions potential as opposed to the gross negative emissions potential of the process; and 5) critical cost assumptions including feedstock costs and plant capital cost (CAPEX). These result in a great variation in BECCS cost, and renders the comparison process from one study to another difficult. Section 4.3 highlights these differences and presents a calculation of BECCS cost as a function of the plant CAPEX and feedstock cost, in an attempt to compare BECCS performance in different regions.

Finally, whilst some CAPEX reduction trajectories over time are proposed in some of the studies, the majority of the cost data presented tends to represent the cost of an “Nth of a kind Plant” (NOAK), operating within an existing CCS infrastructure, which charges the plant for the service of CO_2 transport and storage. Cost data within this assessment should therefore not be interpreted as the actual cost of a first BECCS project – in the UK or elsewhere.

3. Direct air carbon capture and storage (DACCS)

3.1. Overview

The DACCS is the direct extraction of carbon dioxide (CO_2) from the atmosphere using a sorbent. The diluteness of CO_2 in ambient air (it currently comprises 411 parts per million) makes extraction very energy-intensive. Additionally, large volumes of air must be processed to obtain a significant amount of pure CO_2. Both these factors may lead to high costs. However interest in DACCS is growing as a result of concerns about other options, such as the availability of sustainable biomass or impacts of large scale bioenergy production on ecosystem services. DACCS may also offer advantages in terms of wide geographical deployment options and the modular designs may lead to economies of scale in manufacture. A small number of developers are currently taking forward DACCS demonstration and testing. The DACCS technologies currently being developed can broadly be classified as either absorption-based or adsorption-based, as described below:

Absorption-based

These processes use chemical sorbent that react with CO_2 in air. Due to their strong CO_2-binding affinities, hydroxide-based solvents are typically employed. DACCS technology using sodium hydroxide (NaOH) (Baciocchi et al. 2006; Zeman 2007), potassium hydroxide (KOH) (Keith et al. 2018) and calcium hydroxide ($Ca(OH)_2$) (Lackner et al. 1999) have been proposed in the literature.

Fig. 3.1 illustrates a typical absorption-based DACCS process using sodium hydroxide (NaOH) (R. H. Socolow et al. 2011). NaOH reacts with the CO_2 in air to form sodium carbonate (Na_2CO_3) while the treated air is returned to the atmosphere. To regenerate the capture solvent, the carbonate is reacted with calcium hydroxide ($Ca(OH)_2$). $Ca(OH)_2$ is obtained by thermally-decomposing lime ($CaCO_3$) in a calciner and then hydrating it. Regeneration requires the binding energy between CO_2 and hydroxide to be overcome, therefore a large energy input, usually high-grade heat at a temperature of 900-1000°C, is required (R. H. Socolow et al. 2011; Sanz-Pérez et al. 2016). In the illustrated example, heat is provided to the calciner by burning natural gas in pure oxygen which is obtained from an air separation unit, which incurs additional capital and energy costs. The resulting CO_2 from combustion is sequestered in the process. Burning natural gas in air would necessitate an additional separation step to remove nitrogen (78% of air), and would therefore add complexity and incur additional costs. To avoid the additional CO_2 emissions from natural gas use, however, it has been suggested that renewable electricity can provide heat for DACCS (Wohland et al. 2018). Electricity is also required for fans (to move air through the absorber or contactor), liquid pumps and CO_2 compression.

Decarbonisation efforts have led to the increasing penetration of variable renewable energy (VRE) sources in the power system. Due to the variability of VRE supply, instances may arise where power generation from VRE surpasses demand. Consequently, VRE generation may need to be curtailed. It has been suggested that surplus renewable energy can be used to operate a DACCS facility, with the CDR achieved furthering climate change mitigation aims. Excess VRE generation often leads to periods of lower electricity prices; so operating DACCS during curtailment events can therefore lead to lower operational costs. However, the lower utilisation of the DACCS asset will lead to a higher capital expenditure (CAPEX) contribution to the CO_2 removal cost, because the same CAPEX is invested for a lower amount of captured CO_2. This added cost of variability may more than offset the energy cost reduction achieved from utilising cheaper curtailed energy. Additionally, with the regeneration of the sorbent occurring at ~900°C in the calciner, repeated cooling and heating of this equipment due to intermittent energy supply poses threats to process stability and will be a source of efficiency loss (Daggash et al. 2018). Absorption-based DACCS technologies are therefore ill-suited to flexible operation. This may limit prospects for absorption-based DACCS in an energy system increasingly dependent on VRE.

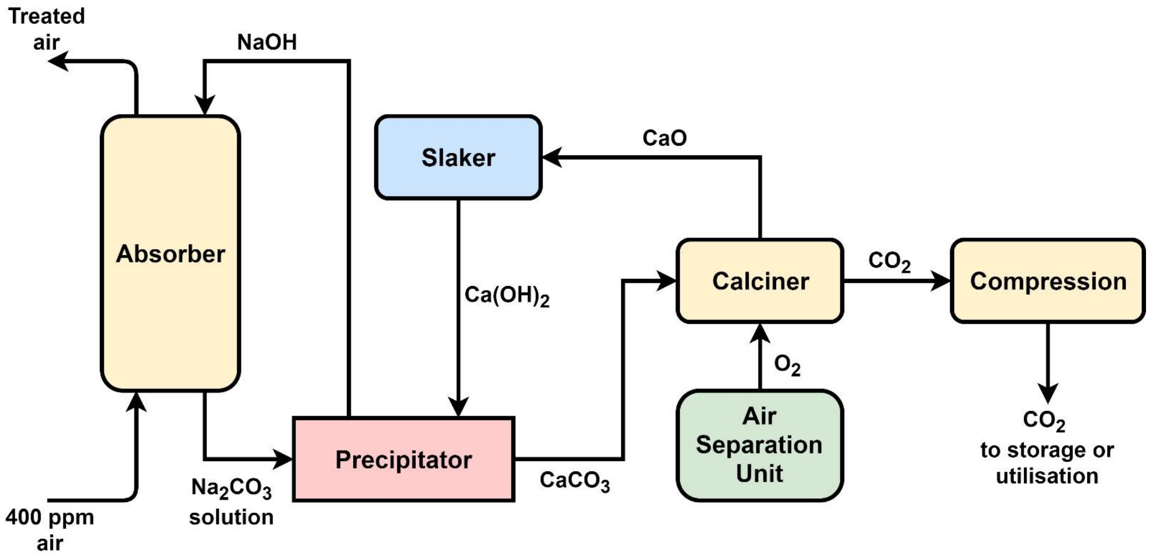


Figure 3.1: A chemical absorption process for DACCS

The absorption archetype of DACCS is however advantageous due to its similarity to the Kraft process that has been used in the pulp and paper industries since 1884 (Sanz-Pérez et al. 2016). Consequently, the unit operations of the process use mature technologies (absorbers, calciners, air separation units, *etc.*) that are readily available commercially. This enables DACCS developers to present deployment scale cost projections with greater confidence.

Adsorption-based

Aqueous amine solutions have historically been used to remove CO_2 from CO_2-rich streams, *e.g.* natural gas streams, and are now used for air purification in submarine and space shuttles (Sanz-Pérez et al. 2016). The bulk of the literature investigating sorbents for DACCS focuses on the use of solid-supported amine material. These amine-functionalised sorbents adsorb CO_2 onto the surface of the solid support or into its pores; typically, no chemical reaction is involved. Regeneration of the sorbent is achieved through changes in temperature, pressure or moisture/humidity, because the CO_2-binding capabilities of amine-functionalised sorbents vary with these environmental conditions (Kulkarni & Sholl 2012; Sanz-Pérez et al. 2016).

The bulk of energy input required for adsorption-based DACCS is for the regeneration of the sorbent. However, unlike in absorption-based DACCS, the regeneration typically requires low-grade heat (at temperatures of less than 120°C) which can be provided by waste heat or low-grade steam. The lower operational temperatures allow for smaller, modular designs of the CO_2 collector units, and increased flexibility of operation (since repeated heating and cooling of sorbent and equipment to high temperatures is not necessary). Adsorption-based DACCS is therefore potentially better-suited for integration into an energy system dominated by variable renewable energy sources, though variability of operation—and hence lower utilisation rates—may lead to additional costs (as discussed above).

It is important to note that whilst DACCS technologies can technically be operated anywhere, capture performance will differ based on environmental conditions. Moisture/humidity swing adsorption-based systems, for example, require low-humidity conditions for CO_2 capture from the atmosphere. Therefore, CO_2 removal at scale would be most effective when the technology is situated in an arid environment (Wang et al. 2013; Lackner 2015). For archetypes of DACCS technology that consume water, such performance issues may geographically-constrain their deployment (R. H. Socolow et al. 2011; Martin et al. 2017). It should be noted that some DACCS archetypes are *net* producers of water.

3.2. Global deployment status of DACCS

There are currently five developers of DACCS technology globally. Table 3.1 details the state of their operations. Whilst the technical feasibility of DACCS has been demonstrated by Climeworks (in Switzerland) and Carbon Engineering (in Canada), scalability is yet to be proven.

Table 3.1: Status of DACCS technology developers (Infinitree LLC 2017; Skytree 2018; Lackner 2015; Keith et al. 2018; Global Thermostat 2019; Climeworks 2019)

Developer	Technology	Status	Capture cost
Carbon Engineering	Absorption using sodium hydroxide.	1 tCO_2/day demonstration plant in Squamish, CA. CO_2 used for fuel synthesis, not permanent sequestration.	£84-170/tCO_2
Climeworks	Adsorption using amine-functionalised sorbent. Modular collector design.	Commercial operation at three facilities capturing a total of 990 t_{CO2}/year. Only one facility (in Iceland) geologically stores the CO_2, others use CO_2 for horticulture or fuel synthesis.	First-of-a-kind cost of £450/tCO_2. Target cost of ~£75/tCO_2.
Global Thermostat	Adsorption using amine-functionalised sorbent	Pilot and commercial demonstration. Plan to sell CO_2 to the beverage industry.	Target cost of ~£40/tCO_2
Infinitree	Proprietary technology. Collectors are modular plug-and-go systems that need a 120V outlet.	Research and concept	Not provided.
Skytree	Adsorption using proprietary sorbent. 'Plug & play' modular collector design that delivers CO_2 when connected to a power source.	Pilot demonstration for outdoor use	Not provided.

Whilst CDR is potentially valuable to deep decarbonisation efforts, there are currently few financial incentives that reward the provision of the service. Mainstream carbon pricing and emissions trading mechanisms penalise CO_2 emissions but do not credit CO_2 removal. Incentives such as the 45Q tax credit in the US and offset credit scheme in Alberta, Canada, credit CO_2 sequestration, not *net* CO_2 removal explicitly. Carbon prices and traded volumes are too low in voluntary carbon offset markets to encourage investment in DACCS. Because of this, developers have focused on niche markets to deliver commercial viability. Carbon Engineering and Skytree are looking to use the captured CO_2 for synthetic fuel production, whereas Climeworks and Infinitree currently use their technologies for atmosphere enrichment in greenhouses.

3.3. DACCS potential

DACCS is purported to have several advantages compared to conventional capture technologies (CCS from large point sources):

- **Resource independence**: Unlike BECCS, DACCS mitigation potential is not reliant on the supply of a bio-geophysical resource such as biomass. Therefore, scaling up DACCS does not pose threats to the ability of the environment to deliver ecosystem services. Additionally, although some land is required to site a DACCS plant, its total terrestrial footprint is considered minimal (Climeworks 2019; Fuss et al. 2018), provided the land used to generate energy to power the process is excluded (Smith, Haszeldine, et al. 2016). For modular DACCS technologies, many units are required for large-scale capture (a typical collector captures only 0.1 tCO_2/day). Improper spatial arrangement of collectors could therefore lead to inefficiencies and sub-optimal performance, when stripped air with lower CO_2 content from one collector enters another. Details of spatial requirements in the literature, however, are yet to reveal the factors that may constrain deployment.
- **Location flexibility**: The required inputs to DACCS (chemicals, energy and air) are not geographically constrained, therefore the siting of a DACCS facility is flexible. Additionally, in the absence of extensive CO_2 transport infrastructure, DACCS could be located at the site of CO_2 storage or utilisation (Sanz-Pérez et al. 2016).
- **Modularity**: The modular nature of the DACCS archetypes being developed presents opportunities for significant cost reductions from mass production. This is unlikely to be the case for large-scale CCS which employs more mature technologies.

Given these characteristics, DACCS mitigation potential is theoretically only limited by energy availability for CO_2 capture, technology costs and CO_2 storage capacity. The relevant literature was reviewed to determine the energy and economic costs of DACCS technologies. The availability and geographic distribution of CO_2 storage capacity is discussed in Chapter 4.

Fig. 3.2 illustrates the energy cost of CO_2 capture via the DACCS processes described in the literature. They have been classified according to the method of capture, i.e. absorption- or adsorption-based. Absorption-based DACCS processes identified from the literature use sodium hydroxide for separation and a calcium-based cycle to regenerate the sorbent (as described in section 3.1). The bulk of the energy input is heat: 1500–2500 kWh_{th} is needed to capture a tonne of CO_2. Additionally, 220–500 kWh_e/tCO_2 of electricity is required. Where no electricity requirements are explicitly specified, such as in (Keith et al. 2018) configuration A, it is assumed that natural gas is used to generate power to drive fans, liquid pumps and CO_2 compression.

There is greater variability in the energy requirement estimates for adsorption-based DACCS. This is because, often, the adsorbent material used is not specified and energy requirements are based on thermodynamic analyses, not a commercial-scale process or technology. Only (Kulkarni & Sholl 2012; Krekel et al. 2018) have specified the amine-functionalised resin used for capture and provided costing for a commercial-scale process. The developer Climeworks has provided energy and economic cost estimates from their pilot facilities, but not the technical details on the process. Electrical and thermal requirements for these processes are 200–1000 kWh_e/tCO_2 and 640–1700 kWh_{th}/tCO_2, respectively.

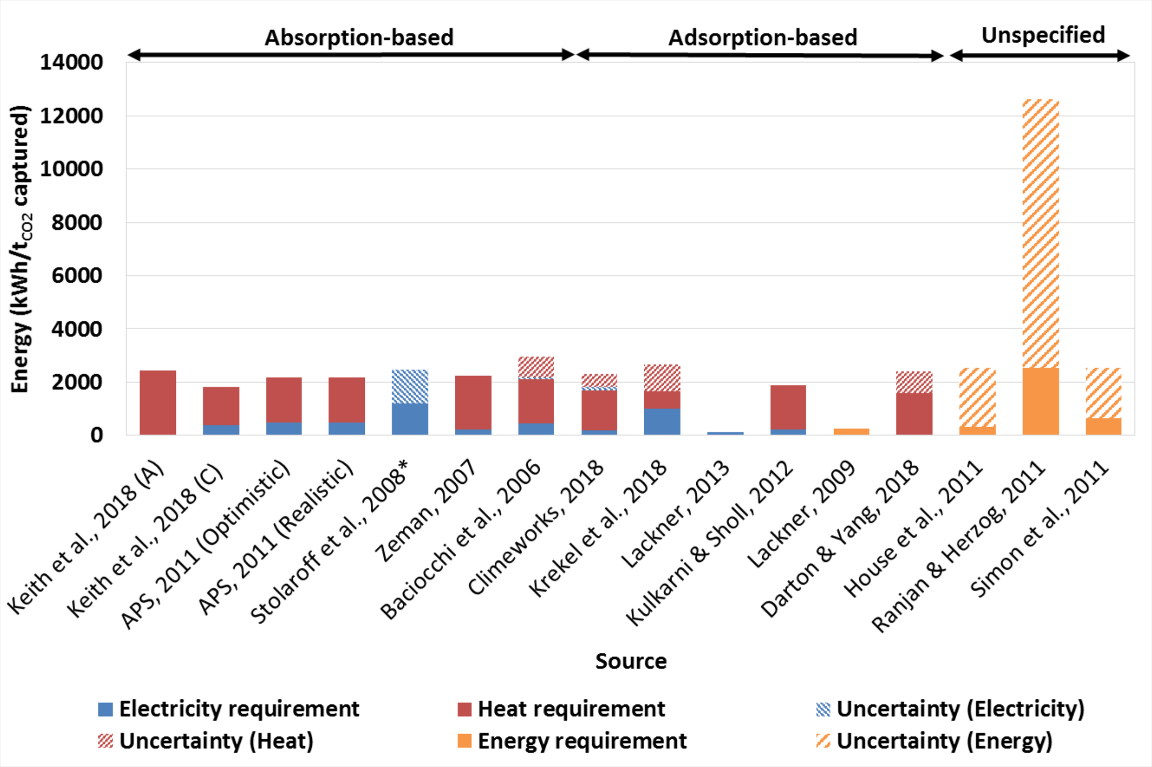


Figure 3.2: Energy requirements of DACCS processes proposed in the literature. *Stolaroff et al. (2008) only estimate the energy cost of capture/contactor. Uncertainty in energy requirements is due to assumptions on process 2nd law efficiency or optimisation. Sources: (Gutknecht et al. 2018; Lackner 2013; House et al. 2011; Ranjan & Herzog 2011; Keith et al. 2018; R. H. Socolow et al. 2011; Stolaroff et al. 2008; Zeman 2007; Baciocchi et al. 2006; Climeworks 2019; Krekel et al. 2018; Darton & Yang 2018; Simon et al. 2011)

Where the process is 'Unspecified', DACCS energy requirements have been deduced from thermodynamic analyses of the minimum work of separation, and assumptions on achievable second law efficiencies based on other gas separation techniques. The second law efficiency is the ratio of the actual work needed to separate a tonne of CO_2 from ambient air, relative to the minimum work of separation. In the literature, second law efficiencies of 1–50% have been assumed to be achievable, thus the wide range of energy inputs illustrated in Fig. 3.2.

3.4. DACCS costs

In section 2.3, it was highlighted that there is a dearth of bottom-up of cost estimates of DACCS in the literature. As illustrated in Fig. 3.3, many studies only evaluate the cost of part of the DACCS process (*e.g.* capture, energy costs, *etc.*). Rigorous costs estimates of commercial-scale absorption-based DACCS cite capture costs of £170-380 per tonne of CO_2 captured (R. H. Socolow et al. 2011; Holmes & Keith 2012). The only developer of this technology cite achievable costs of £84-170/tCO_2; this is not the CO_2 capture cost of the pilot plant but what is expected for a commercial-scale unit capturing 1 million tonnes of CO_2 annually (Keith et al. 2018).

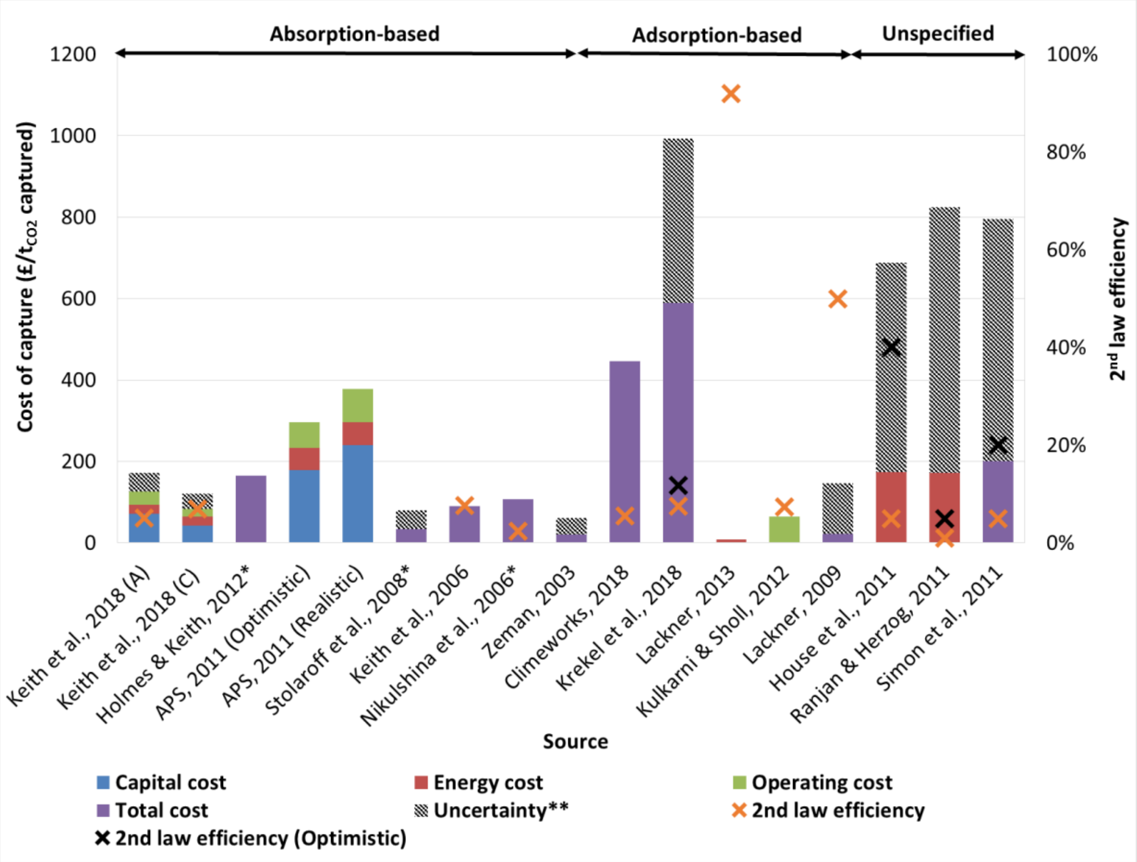


Figure 3.3: Cost of capture via DACCS processes proposed in the literature. *Only capture/contactor costs included. **Uncertainty due to the range of fuel prices, 2nd law efficiencies, optimisation and/or technology learning considered. Sources: (Rogelj et al. 2016; Keith et al. 2018; Holmes & Keith 2012; R. H. Socolow et al. 2011; Stolaroff et al. 2008; Keith et al. 2006; Nikulshina et al. 2006; Krekel et al. 2018; Wang et al. 2013; Lackner 2013; Kulkarni & Sholl 2012; House et al. 2011; Ranjan & Herzog 2011; Simon et al. 2011)**.**

Adsorption-based technologies often require hardware to be designed for the specific process, *i.e.* not commercially-available equipment (Gebald et al. 2013; Keith et al. 2018; Wang et al. 2013). This results in significant uncertainties in the cost estimates found in literature. (Krekel et al. 2018) evaluated the CO_2 production cost of a commercial-scale DACCS plant using a supported polyethyleneimine sorbent to be

£590–990/tCO_2 captured, depending on the energy source used[3]. Other estimates are much lower, however they are derived from incomplete economic analyses (Kulkarni & Sholl 2012), and optimistic assumptions of achievable second law efficiencies (Lackner 2013; Lackner 2009) and/or technology cost reduction (Lackner 2009)[4]. Real-world gas separation techniques typically have second law efficiencies of 5-40% (House et al. 2011); assumptions beyond that are therefore considered optimistic. Owing to the wide range of process efficiencies that are purportedly achievable, thermodynamic analyses result in large disparities in energy and economic cost estimates (see 'Unspecified' in Fig. 3.1 and 3.2).

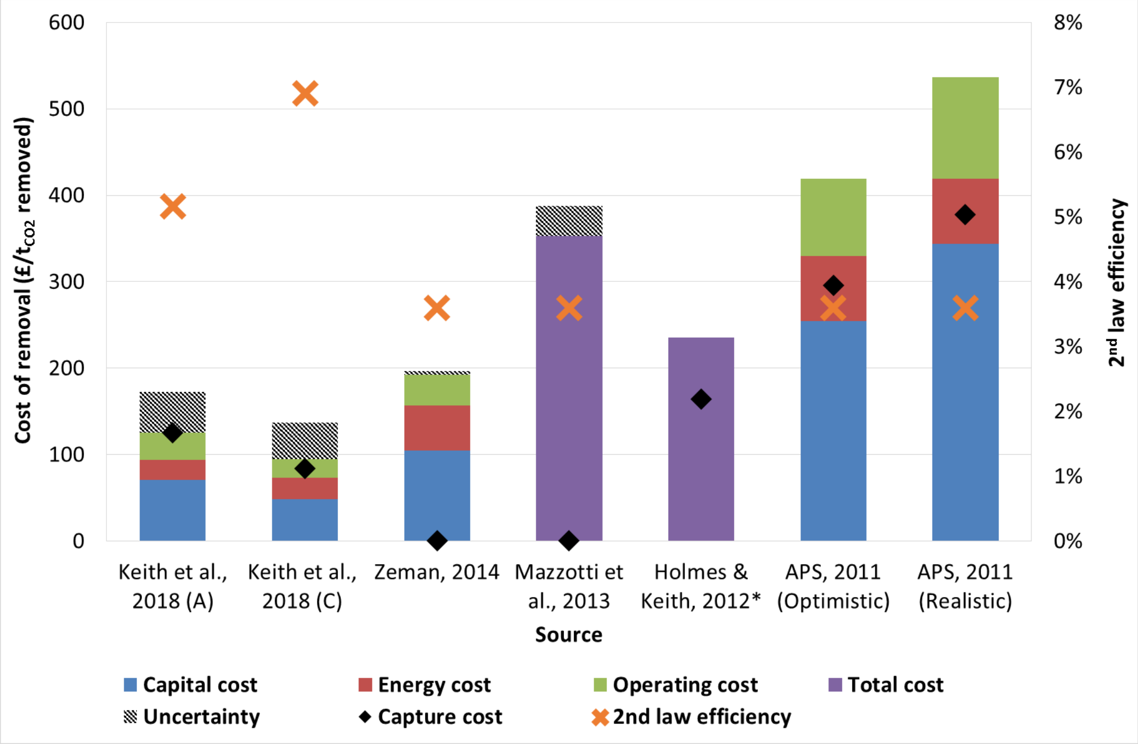


Figure 3.4: Cost of CO_2 removal from the atmosphere. *Only capture/contactor costs provided. **Uncertainty due to the range of fuel prices, 2nd law efficiencies, optimisation and/or technology learning considered. Sources: (Keith et al. 2018; Zeman 2014; Mazzotti et al. 2013; Holmes & Keith 2012; R. H. Socolow et al. 2011)**.**

The *net* removal for CO_2 from the atmosphere is dependent on the type of the energy used to power DACCS. If fossil fuel-derived energy is used, the associated CO_2

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[3] Cost of capture is heavily influenced by energy costs. Energy costs assumed: natural gas: £45/MWh$_e$, wind: £74/MWh$_e$, solar heat: £223/MWh$_e$.

[4] First prototype costs of £110/tCO_2 are expected. Nth-of-a-kind costs of £17/tCO_2 are then assumed as achievable with learning-by-doing and "further advances in the technology".

emissions from energy production must be considered in the overall CO_2 balance of the DACCS facility. The sources of heat and electricity are not always specified in the literature, but where they have been, the CO_2 removal costs have been calculated and illustrated in Fig. 3.4. All the costs shown are for absorption-based processes. Independent cost estimates (excluding those provided by technology developers) suggest DACCS removal costs of £190-540 per tonne of CO_2 removed from the atmosphere. Despite the large energy requirements of DACCS, capital costs comprise the majority of the CO_2 removal cost.

3.5. Barriers and opportunities for DACCS deployment in the UK

It has been argued that DACCS deployment could ease the cost of decarbonisation of the UK energy system (Daggash et al. 2019). Discussed below are the factors that potentially give the UK a competitive advantage in the commercialisation of DACCS technologies (noting that the importance of CCS infrastructure and clusters is common to BECCS and DACCS).

Availability of low-carbon energy

DACCS costs and mitigation potential have been shown to be dependent on the nature and cost of energy used to drive the process. The use of zero-carbon energy maximises the CO_2 removal from the atmosphere. Thus, the availability of low-cost renewable energy presents an opportunity for DACCS deployment. In recent years, decarbonisation efforts have led to an increase in variable renewable energy (VRE) generation capacity in the UK, and this trend is expected to continue. The variability of supply posed by wind and solar power means instances may arise where generation surpasses demand or where VRE output has to be limited because of transmission constraints. The costs profile of VRE increases the likelihood of this surplus power being available cheaply. Instead of curtailing this power, DACCS could utilise this energy for CO_2 removal. Thus, DACCS derives value from its ability to access 'stranded' renewables that are geographically-sited where they cannot otherwise access a market, rather than its ability to manage variability of energy supply. This strategy is being exploited by Carbon Engineering, a DACCS developer (see Box 3.1). Reliance on curtailed power for DACCS is however insufficient to realise the scale of mitigation needed from CDR, but co-locating DACCS with stranded VRE assets in the UK may be a route to demonstration and commercialisation.

Box 3.1 Carbon Engineering

Carbon Engineering is a Canadian-based company developing DACCS technology for the production of carbon-neutral fuels. Their absorption-based technology uses sodium hydroxide and a unique contactor design to extract CO_2 from ambient air.

The pilot plant in Squamish, Canada, captures 1 tonne of CO_2 per day. This is then combined with hydrogen obtained *via* water electrolysis to synthesize liquid fuels such as gasoline and diesel. The company's "Air to Fuels" strategy plans to take advantage of low-cost variable renewable electricity (by co-locating DACCS with VRE plants) to drive fuel synthesis at scale. In the pilot plant, however, the electricity is being used for hydrogen production (a feedstock for fuel synthesis), whilst the DACCS process is natural gas-powered. "Air to Fuels" produces low-carbon fuel for transportation, which can serve as an to alternative to biofuels and electric vehicles.

Carbon Engineering has raised funding for the commercialisation of its technology from private investors, including BHP Billiton Petroleum, Chevron Technology Ventures and Occidental Petroleum, and public grants from the governments of British Columbia and Alberta. In March 2019, the company completed an equity financing round of USD $68 million, marking the largest private investment in DACCS technology to date.

Source: (Carbon Engineering 2018; Keith et al. 2018)

Scalability and modularity

The modular collector design being pursued by some DACCS developers (Climeworks 2019; Infinitree LLC 2017; Skytree 2018) is more likely to experience significant cost reductions from mass production. The small-scale size of the individual units also present opportunities for proof of concept (POC) by co-location with industrial facilities or power producers that can supply waste heat to drive the capture process (see Box 3.2). Siting DACCS facilities within industrial clusters (see section 3.6) creates opportunities for the utilisation of waste heat from industrial operations.

Niche markets

Due to its modularity and location-flexibility, DACCS has a competitive advantage in satisfying small, distributed or remote demands (Lackner 2015). This makes DACCS suitable to serve CO_2 markets which are typically small and distributed in nature, as described below:

- Merchant CO_2: CO_2 used in a wide range of applications, including carbonation of beverages, food processing, and chemical synthesis, is referred to as merchant CO_2. The majority of merchant CO_2 is sourced from ammonia plants (which in turn rely on natural gas), with selling prices typically around £150/tCO_2 but could be higher as was the case during the 2018 supply shortage. Merchant markets tend to be small and distributed, therefore DACCS can exploit its location-flexibility to supply them with CO_2 and facilitate a transition from their reliance on fossil fuels.

- Commercial agriculture: CO_2-enriched atmospheres in greenhouses have been shown to improve crop yields. Currently CO_2 is sourced from the exhaust gases of power plants or boilers, or natural gas combustion; these are then trucked or pipelined to the greenhouse, and are therefore dependent on the availability of transport infrastructure. DACCS can produce CO_2 on-site and eliminate this infrastructural necessity. CO_2 can also be used for the cultivation of algae, a potential source of food, biofuel or energy (biomass-derived heat or electricity).

- Synthetic renewable fuels: Surplus energy availability due to the proliferation of variable renewable energy sources can be used for DACCS. Where storage infrastructure is yet to be developed, the captured CO_2 can be utilised for the production of synthetic liquid fuels (see Boxes 3.1 and 3.2). Due to the large infrastructure and energy costs of producing CO_2 feedstock via DACCS, and the fuel itself, synthetic fuels are likely to be expensive (Daggash et al. 2018).

- Carbon offsetting: Carbon offsets are measurable and verifiable emissions reductions activities that can be traded in voluntary markets or compliance markets (where government regulation mandates emissions reductions or the purchase of offsets) (Hamrick & Gallant 2018). Increasingly, private actors are purchasing offsets voluntarily, including from DACCS plants (see Boxes 3.1 and 3.2), to minimise the carbon footprint of their operations. Although not strictly speaking a niche market, this may support the demonstration and scale-up of DACCS. Although the carbon prices in voluntary offset markets are currently low, with increasingly stringent emissions reduction targets and/or carbon pricing, commercial-scale DACCS could offer carbon offsets to companies or industries with more expensive mitigation options.

Box 3.2 Climeworks

Climeworks AG is a Swiss-based company developing adsorption-based DACCS technology for a wide range of applications. They have nine facilities in six countries, targeting different market segments: the food and beverage industry, commercial agriculture, the energy sector, and the automotive industry.

Their first commercially-operated facility in Hinwil, Switzerland, is sited atop an incineration plant which provides it with waste heat. The CO_2 product is sold to greenhouse owners for atmosphere enrichment to boost tomato and cucumber yields.

Climeworks have also partnered with Reykjavik Energy for the *CarbFix2* project. This pilot-scale plant (DAC-1) is sited at a geothermal plant in Hellisheidi, Iceland, which provides it with low-grade heat. It is expected to capture 50 tonnes of CO_2 annually. *CarbFix2* will store the air-captured CO_2 permanently in basalt rock, thereby leading to permanent sequestration, *i.e.* CDR. CarbFix2 has received funding from the European Union's Horizon 2020 research and innovation programme.

In October 2018, Climeworks' DAC-3 plant was launched in Troia, Italy. DAC-3 is to provide 150 tonnes of CO_2 per year to the Horizon 2020 research project STORE&GO, which aims to demonstrate how power-to-gas technologies can be used for energy storage. Air-captured CO_2 and hydrogen obtained *via* solar-powered electrolysis of water are used to produce methane. The methane is then liquefied and used to power 'green lorries'.

Thus far, Climeworks AG has raised $51 million in funding from both private investors and public grants, including from the Swiss government.

Source: (Climeworks 2019)

CCS infrastructure

The availability of a CO_2 transport and storage (T&S) infrastructure is a pre-requisite for large scale utilisation of both BECCS and DACCS. Whilst niche/merchant uses for CO_2 may provide avenues for technology demonstration, the need for the permanent sequestration of CO_2 to guarantee CDR means large volumes of CO_2 will need to be transported to geological (or other) storage, since transforming CO_2 into other products only delays their emissions into the atmosphere. Although the UK has been shown to have significant CO_2 storage capacity, it lacks any CO_2 transport infrastructure that provides access to these geological reservoirs. Given the scale at which CDR, and more broadly, CCS, needs to be deployed, the development of extensive CO_2 transport infrastructure (which is most likely to be pipeline based) in the UK is critical. Lessons from the current and past CCS projects are helpful. In particular, issues associated with CCS cross chain integration and long-term storage monitoring increase the perceived risks of investors to take on a CCS project, hence increasing the cost of investment. The absence of any incentives for permanent CO_2 storage, coupled with the UK's low carbon prices, do not support investment in CCS. It has been suggested that lowering these risks by public-private projects and government involvement is crucial to enable the take up of the CCS industry, both globally and in the UK (Bui et al. 2018).

Clusters

The approach to the delivery of CCS in the UK has assumed a solely private sector-led delivery of the technology at scale, and management of all the technical and commercial integration risks (Bui et al. 2018). Among this is the development of T&S infrastructure by first movers which is likely be initially underutilised due to insufficient CO_2 supply, and therefore unable to generate sufficient revenues. Co-locating CDR and CCS facilities (within power or industrial sectors) will aggregate the supply of CO_2 to the T&S network. This allows for a critical mass and greater economies of scale to be achieved sooner, hence lower project costs. Clusters will also reduce the distance that CO_2 would need to be transported to storage sites (mostly offshore in the UK); aside from keeping costs down, this will avoid costly pipeline easement negotiations with landowners (Bui et al. 2018).

Social acceptability

The public acceptance of new technologies is crucial to their widespread adoption (G. F. Nemet et al. 2018). As described in Chapter 1, CDR needs to be achieved at scale, not just in remote locations or applications, to meet climate change mitigation ambitions, and therefore acceptability will need to be addressed. BECCS, by virtue of its implications for land availability and local ecosystems, may face significant barriers to large-scale deployment. DACCS however has a small land footprint, comparable to a medium-sized industrial facility. Consequently, it does not pose the threat of exacerbating land availability issues that may affect food prices or ecosystem services. Additionally, as DACCS is not reliant on a geographically-dependent resource, facilities could be sited in remote regions to avoid public resistance. For commercial-scale DACCS, which will involve CO_2 transport and storage, however, there needs to be further investigation to understand the trade-offs between capture (especially if done in remote regions) and storage costs. Nonetheless, DACCS will have to overcome potential opposition to CCS, as well as perceptions that the deployment of CDR creates a moral hazard by delaying climate change mitigation efforts (Honegger & Reiner 2018; Minx et al. 2018; G. F. Nemet et al. 2018).

3.6. Key points

- Lack of complete, independent bottom-up techno-economic assessments of DACCS technology in the literature.
- Large uncertainties in the estimates of the energy and economic costs of DACCS.

- Developers cite first-of-a-kind capture costs of £450/tCO_2, and nth-of-a-kind costs of £80-170/tCO_2.
- Insufficient carbon prices and the absence of a credit for CDR means DACCS is not commercially viable in the UK.
- Modular design of some DACCS archetypes may offer economies of scale in mass manufacture and allow it to exploit stranded renewable energy, and/or serve small and distributed CO_2 markets.

4. Bioenergy with carbon capture and storage (BECCS)

4.1. Overview of BECCS technologies

BECCS covers any technological route combining the conversion of a biomass feedstock to energy, with the capture and geological storage of the CO_2 released upon this conversion. Considering the variety of biomass feedstocks types (*e.g.* sugar and starch crops, lignocellulosic biomass, organic wastes), biomass conversion routes (*e.g.* gasification, combustion, fermentation), and capture options (*e.g.* pre-, post- or oxy-combustion capture), there is not one single BECCS technology. However, BECCS technologies can be categorised in three pathways:

- BECCS to power (bioelectricity) via combustion in pulverised combustion (PC) plants, fluidised bed combustion (FBC) plants, chemical looping combustion plants (CLC) and combined heat and power (CHP) plants to produce heat in addition to power, or via gasification in an integrated combined cycle (IGCC).

- BECCS to gaseous or liquid biofuels via fermentation (bioethanol), or gasification (bio syngas or bio-sng) followed by Fisher-Tropsch conversion (biodiesel).

- BECCS to bio-hydrogen via fermentation, gasification or pyrolysis.

CO_2 capture, transport and geological storage can be applied to all conversion pathways, but the CO_2 capture technology applied depends on the conversion pathway. In pathways involving biomass combustion, the CO_2 can be captured via a post-combustion system when combustion happens in air, an oxy-combustion system for combustion in oxygen, and a chemical loop integrated to the combustion technology in the CLC technology. In the case of biomass gasification, the CO_2 is captured with a pre-combustion system from the syngas. In biomass fermentation, pure CO_2 ($> 99\%$ purity) is released during fermentation, and can be directly captured. Figure 4.1 summarises these pathways.

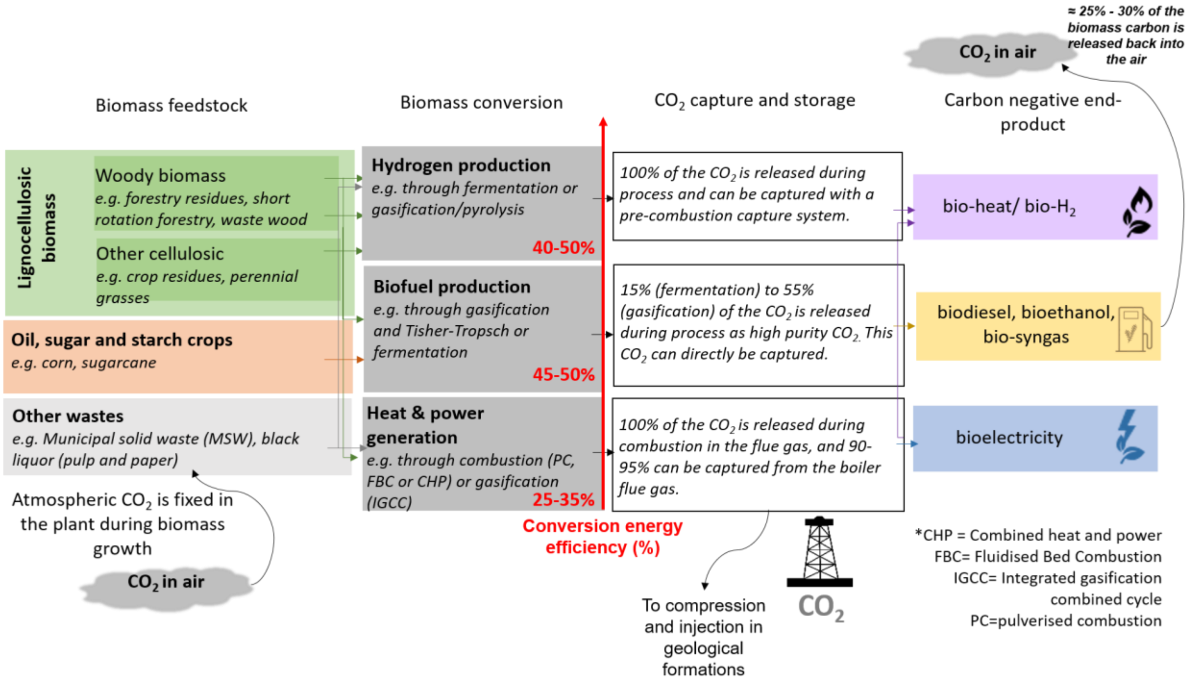

Figure 4.1: Illustration of different BECCS pathways (adapted from Fajardy et al. 2019). Pathways provide different value to the energy system: whilst BECCS via biofuels provide less negative emissions than BECCS via bioelectricity, it potentially provides more useful energy to a hard-to-decarbonise sector.

Each technological option differs in their performance and energy product output. Key metrics to measure the performance of a BECCS technology include cost, conversion energy efficiency (useful energy generated from the raw biomass energy), and CO_2 capture efficiency (how much of the biomass feedstock CO_2 is captured during the conversion).

Conversion energy efficiencies are typically higher for the BECCS via biofuels pathway, at around 45–50% (Johnson et al. 2014; Laude et al. 2011), as opposed to BECCS via power, which efficiency can be found anywhere between $20\%_{HHV}$ (Hetland et al. 2016) and $38\%_{HHV}$ (Bui et al. 2017), including the CO_2 capture system efficiency penalty. This results in varying operating costs for each technology, and different quantity of energy products generated, hence in the BECCS technology having a different value within the energy system it is operating in. Given the same amount of biomass feedstock, the BECCS to biofuel pathway can for example generate more useful energy in the form of biofuel than the BECCS to power pathway yields bioelectricity. Depending on what this energy product displaces in the energy system, this could lead to more CO_2 avoided in the BECCS to biofuel scenario. From a cost perspective, the CO_2 released from pathways involving biomass fermentation is more concentrated and therefore cheaper to capture, than in pathways involving biomass gasification for which the CO_2 is captured from the syngas, or to a greater extent biomass combustion for which the CO_2 is captured from the boiler exhaust gas.

From a CO_2 capture efficiency perspective however, only 15% (for fermentation to bioethanol (Laude et al. 2011)) to 55% (for gasification to biodiesel (Johnson et al. 2014)) of the biomass feedstock carbon is released into CO_2 during the process, whilst 25 to 30% remains in the biofuel and will be re-emitted back into the atmosphere upon end-use of the biofuel. In a BECCS via power pathways however, close to 100% of the biomass carbon can be released upon combustion, of which 90 to 95% can be captured from the flue gas and stored. BECCS via power typically leads to more negative emissions per unit of biomass feedstock than BECCS via biofuels.

Finally, the energy product generated by each pathway can have different value to the energy system. Whilst low carbon alternatives to decarbonise the power sector already exist, such as wind and solar, some sectors such as heat and transport have currently fewer alternatives. The production of aviation biofuels for example, displacing fossil kerosene, may have more value in decarbonising the energy system, than producing bioelectricity displacing a low carbon alternative, or even biofuels displacing electric vehicles (Committee on Climate Change 2018a).

The importance of biomass sustainability

Regardless of the pathway chosen, biomass feedstock needs to be produced or collected, upgraded to a usable fuel (dried, pelleted, and/or ground) and transported to the location of the conversion plant. This is referred to as the biomass supply chain, and has been identified as being the key driver of the sustainability of a bioenergy or BECCS process (Stoy et al. 2018; Fajardy & Mac Dowell 2017; Dale et al. 2014; Smith & Torn 2013; Smith, Davis, et al. 2016). The potentially high resource and carbon intensity of BECCS value chain has sparked controversy around the actual ability of BECCS to deliver negative emissions and energy, without having detrimental consequences on the wider economy and ecosystem (Vaughan & Gough 2016; Gough et al. 2018; Dooley & Kartha 2018; Anderson & Peters 2016). Within this context, several metrics and impacts are important to consider when assessing BECCS performance:

CO_2 negativity and net CO_2 efficiency

The underpinning assumption behind BECCS delivering negative emissions is that bioenergy is carbon neutral. This assumption can be challenged when considering the greenhouse gases emissions occurring along the biomass supply chain from energy use, direct and indirect land use change – the conversion of a land to bioenergy production causing further land conversion elsewhere (Harper et al. 2018; Fargione et al. 2008; Searchinger et al. 2008), and field nitrous oxide emissions (Smith, Davis, et al. 2016) from fertiliser application. For a BECCS system to be carbon negative i.e. delivering negative emissions, biomass supply chain emissions need to be kept to a minimum and not outweigh the CO_2 captured at the conversion plant. Figure 4.2 illustrates the potential CO_2 leakages along the value chain of a BECCS to power system. Out of the 1 ton of CO_2 initially captured in the biomass feedstock, only 0.5 ton of CO_2 are actually removed from the atmosphere. In other words, the CO_2 efficiency of the system – the fraction of biomass CO_2 which is actually removed from the atmosphere, is only 50%.

Energy return on investment

Another key assumption when deploying BECCS technologies in climate scenarios is that BECCS produces energy in addition to removing CO_2 from the atmosphere. However, multiple energy uses along the biomass supply chain, and the energy efficiency penalty imposed by the CO_2 capture system, constitute a significant energy usage. From an energy return on investment perspective (which measures the energy output over the energy input of a system) this potential large energy usage could result in BECCS having a very low energy return, or even an energy return below one (where more energy is required to fuel the system than the system produces) (Fajardy & Mac Dowell 2018). This metric, partly correlated with BECCS carbon negativity, also needs to be carefully measured when deploying BECCS value chains.

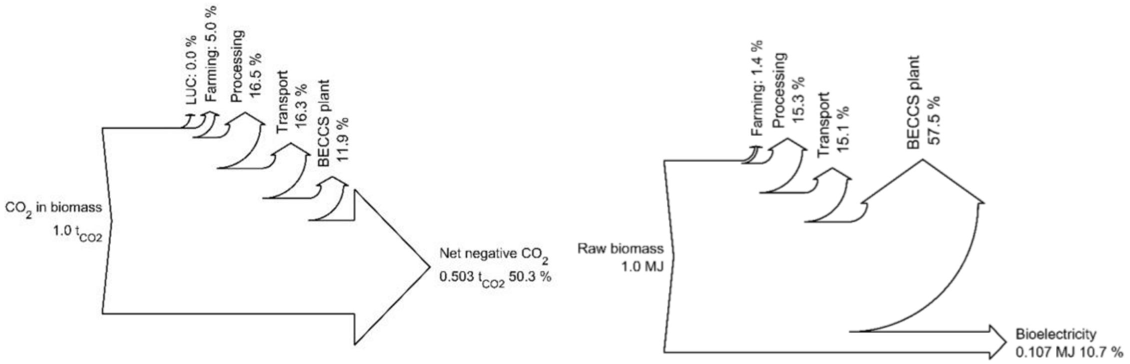

Figure 4.2: CO_2 (left) and energy (right) leakages along a BECCS value chain, due to CO_2 emissions, energy use and biomass feedstock loss along the value chain[5]. From the energy and CO_2 initially in the biomass, only 50% effectively becomes negative emissions, and 11%, net energy (Adapted from Fajardy & Mac Dowell 2018)**.**

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[5] *Values obtained for BECCS plant in the UK using miscanthus pellets produced in southern US. A total biomass feedstock loss of 16% over the whole feedstock supply chain (production, processing, transport) is also considered and accounted for in the CO_2 and energy balances.*

BECCS land use and land use change

When relying on bioenergy feedstock from agriculture or forestry, BECCS land intensity has been identified as one of the central challenges of BECCS deployment. Levels of BECCS requirements in climate models could require between 100 and 800 Mha of land (Huppmann, Kriegler, et al. 2018; J. Rogelj et al. 2018). To put these numbers in context, the total surface used for agriculture today is 1,600 Mha (FAO 2016). Such deployment could cause direct land use change (the clearing of a land for bioenergy production) as well as indirect land use change (the reallocation of the previous land use elsewhere, causing further land use change (Searchinger et al. 2008)). In addition to CO_2 emissions impacting BECCS carbon balance, such land conversions could bring about economic-environmental impacts including food price increases (Hasegawa et al. 2018; Wiltshire 2016) and biodiversity losses (V. Heck *et al*. 2018). Using waste biomass from forestry and agriculture can be considered as alternatives, providing the biomass collection rate is sustainable, and does not cause, for example, soil nutrient depletion (Monforti et al. 2015). Other niche opportunities to decrease BECCS pressure on land use have been investigated, including using municipal solid wastes (Pour et al. 2018), agricultural residues remediating abandoned land with high yielding grasses (Lossau et al. 2015; Smith et al. 2013; Milbrandt et al. 2014), or using marine biomass (Beal et al. 2018).

Other environmental impacts

Other impacts of the supply chain including water use, biodiversity loss, and biochemical flows (related to fertiliser use), and soil depletion, have been identified as potential negative impacts of BECCS supply chains, at the global (Boysen et al. 2017; Heck et al. 2018; Dooley & Kartha 2018; Smith, Davis, et al. 2016) and regional (Stoy et al. 2018; Smith, Haszeldine, et al. 2016) levels, and need to be included when assessing the sustainability of BECCS value chain.

Careful accounting of emissions, resource use (energy, land, water) and impacts on the ecosystem (land use change, biodiversity loss, biochemical flows) is therefore required for BECCS systems to deliver sustainable negative emissions.

4.2. Global requirement vs. global deployment status of BECCS

The scale of BECCS deployment in climate models depends on the portfolio of carbon dioxide removal technologies available, and assumptions as to how much and how fast current greenhouse gas emissions are mitigated. In the latest IPCC report on limiting global warming to 1.5°C, BECCS reaches a deployment level as high as 22 $GtCO_2$/yr by the end of the century in a fossil fuel intensive scenario (P4), and as low as zero in a low energy demand scenario (P1), where all the need for carbon dioxide removal can be fulfilled by better land management and afforestation/reforestation (AFOLU). In a median scenario, BECCS capacity reaches 12 $GtCO_2$/yr (Huppmann, Kriegler, et al. 2018; J. Rogelj et al. 2018).

At the time of writing, the installed BECCS CO_2 removal capacity is just above 1 $MtCO_2$ per year. The first BECCS plant, operating since 2017, is the Decatur corn-based bioethanol plant in Illinois, which captures around 1 Mt of CO_2 per year, storing the CO_2 in a sandstone reservoir underneath the plant (Gollakota & McDonald 2014). In early 2019, the Drax thermal power plant in the UK, which has converted four of its six 660 MW boilers to dedicated biomass combustion, started a BECCS pilot project with the company C-capture to capture 1 tCO_2 a day. Due to the small quantities of CO_2 captured, no CO_2 storage or utilisation has however been considered in this project. Other BECCS projects in planning include the North Dakota BIGCC plant with CCS and a bioethanol plant with CCS in Kansas.

CCS projects including capture from both fossil and biogenic sources capture about 30 Mt of CO_2 per year. Even when considering all CCS projects, these values are still orders of magnitude below the gigatonne-scale requirement of carbon dioxide removal selected by climate models.

4.3. BECCS technical and sustainable potential

Global assessment

The global potential of BECCS has long been quantified in the 10-15 $GtCO_2$/yr range (Psarras et al. 2017; McLaren 2012; EASAC 2018; Kemper 2015; Smith, Davis, et al. 2016). In response to the controversy around the potential detrimental effects of such a large scale deployment, recent attempts to re-evaluate physical and sustainability constraints to this deployment have been performed.

The cumulative CO_2 storage potential of Europe, North America, Brazil, China, Australia, Japan and South Africa, where quantitative geological surveys have been performed, amounts to 7,000 $GtCO_2$ (Global CCS Institute 2017). It would appear therefore that CO_2 storage from a global point of view is not likely to be the limiting factor of BECCS global deployment.

Identified as a key bottleneck is the global technical and/or sustainable bioenergy potential. Such assessments are dependent on assumptions as to what is in fact considered sustainable, and are therefore found within a wide range in the literature (Creutzig et al. 2015; Slade et al. 2014; Bauen et al. 2009; Beringer et al. 2011; Strapasson et al. 2017; Fuss et al. 2018). Whilst pessimistic assessments find the global potential to be around 60 EJ/yr, and optimistic assessments over 350 EJ/yr (Fuss et al. 2018), there tends to be a broader agreement of the literature around 100 EJ/yr

(Creutzig et al. 2015). Figure 4.3 illustrates the potential gap between what is required in climate models (left) and ranges of global potential per feedstock type across the literature right).

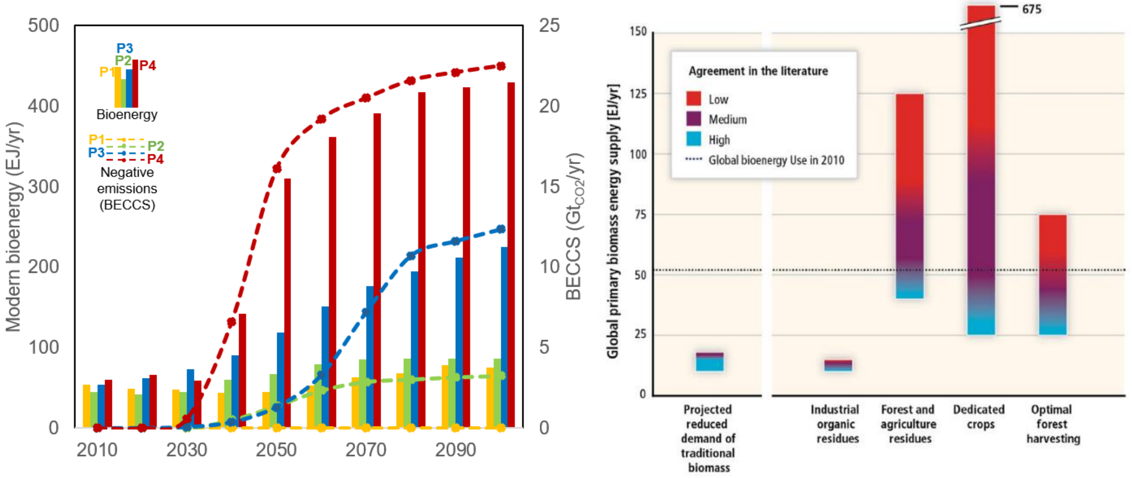

Figure 4.3: Global bioenergy requirement in climate models (adapted from Huppmann, Kriegler, *et al.* 2018; Rogelj, Popp, *et al.* 2018) **(left) and technical bioenergy potential (right). Whilst up to 400 EJ of bioenergy are required annually by the end of the century, agreement around global technical bioenergy potential within the literature tends to lie around 100 EJ/yr.**

How this technical bioenergy supply translates into carbon removal potential via BECCS depends on assumptions regarding BECCS pathway, characteristics of the biomass feedstock and performance of the BECCS value chain. Assuming a biomass value chain CO$_2$ efficiency between 50% and 80%[6], a typical biomass heating value of 18 GJ/ton and carbon content of 50%, using 100 EJ in BECCS systems would enable the removal of 5.3 to 8.4 GtCO$_2$ from the atmosphere per year. If converted to biofuels, assuming a net CO$_2$ efficiency between 8 and 50%[7], 0.9 to 5.1 GtCO$_2$/yr could be removed from the atmosphere.

A handful of bottom up assessments also investigated how the consideration of planetary boundaries (Steffen et al. 2015) could further limit the deployment of BECCS (Séférian et al. 2018; Boysen et al. 2017; Heck et al. 2018), resulting in a *sustainable*

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[6] Supply chain CO$_2$ efficiency assumed between 60 and 90% combined with a 90% capture efficiency of a BECCS power plant (see Figure 4.2).

[7] Supply chain CO$_2$ efficiency assumed between 60 and 90% combined with a 15% capture efficiency for bioethanol-CCS plant (Laude et al. 2011) to a 55% capture efficiency of a biodiesel-CCS plant (Johnson et al. 2014).

potential of BECCS, much lower than the *technical* potential of BECCS. In Heck *et al.* 2018 limiting BECCS deployment within a “safe” zone of a subset of planetary boundaries, including biochemical flows, biodiversity loss, land use change and water use, limited global carbon dioxide removal to 0.2 $GtCO_2$/yr, which is two orders of magnitude lower than what is required by the end of the century in most scenarios (Heck et al. 2018).

UK assessment

To assess BECCS technical potential, two potential bottlenecks need to be considered: bioenergy availability and CO_2 storage availability.

The UK boasts a diverse and well-characterised CO_2 offshore storage capacity in the North Sea. Results from the ETI UK CO_2 storage appraisal project indicate that the UK has a technical offshore CO_2 storage capacity of 80 $GtCO_2$ (Energy Technologies Institute 2013). Considering that the order of magnitude for UK CO_2 removal target is around 50 $MtCO_2$/yr, the UK CO_2 storage capacity is not likely to be a bottleneck to BECCS deployment.

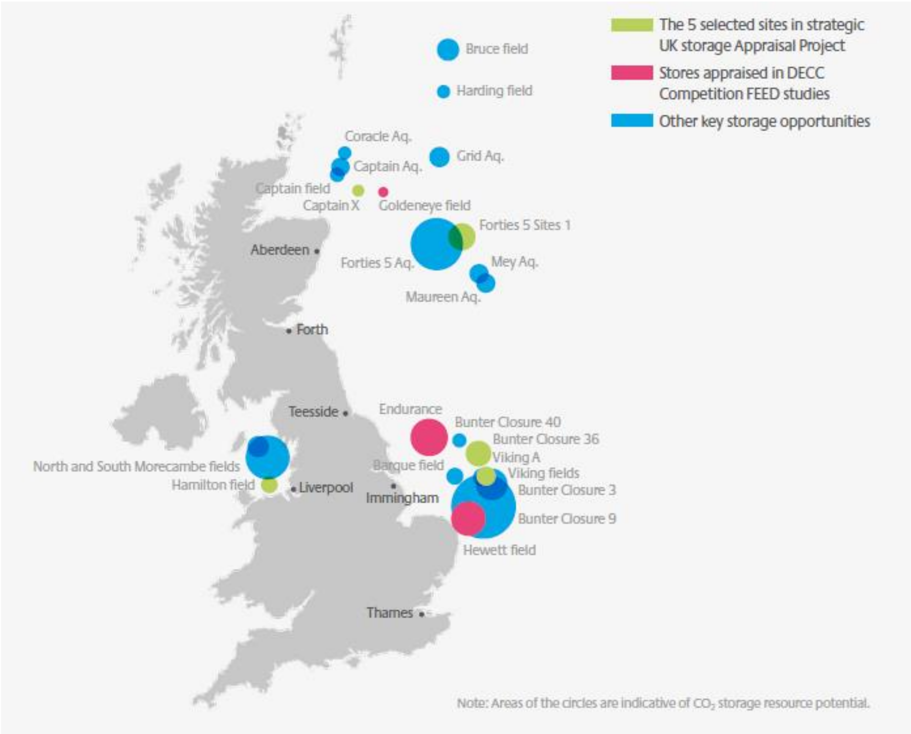

Figure 4.4: Potential offshore CO_2 storage sites around the UK (ETI 2018)**. Total CO_2 storage capacity has been estimated to 80 $GtCO_2$/yr.**

In terms of technical bioenergy supply, the Committee on Climate Change recently published two reports on land use (Committee on Climate Change 2018b) and on the bioenergy industry in the UK (Committee on Climate Change 2018a). Depending on supply and policy scenarios, 0.36 to 0.72 EJ/yr of bioenergy could be produced in the UK. Using the same methodology as above, this could translate to a UK removal potential between 20–60 Mt CO_2/yr with BECCS power plant, and between 3–40 Mt/yr with BECCS biofuel plants. Considering the UK large CO_2 storage capacity, the CCC also explored scenarios of biomass imports to the UK. This increases the UK total bioenergy potential to 0.50 to 1.98 EJ/yr, which translates into a CO_2 removal potential between 30 and 160 $MtCO_2$/yr with BECCS power plants, and between 4 and 100 $MtCO_2$/yr with biofuels plants.

These results for the indigenous biomass supply are consistent with other UK specific studies which have quantified BECCS deployment at the UK scale (Alcalde et al. 2018; Smith, Haszeldine, et al. 2016). In Smith *et al.*, a carbon removal potential between 17 and 66 $MtCO_2$/yr was obtained by combining BECCS land footprint calculated in a previous global scale study (Smith, Haszeldine, et al. 2016) and an assessment of the UK available land area for bioenergy production. A similar study was performed for Scotland alone, in which 0.52 Mha of the land area identified as both available and suitable for bioenergy production could yield between 1.6 to 6.2 $MtCO_2$/yr (Alcalde et al. 2018). These assessments assume BECCS power plants using biomass feedstock from high productive crops such as miscanthus or willow, grown on available land.

To the best of our knowledge, there is no bottom-up assessment of BECCS sustainable potential in the UK which includes environmental constraints to BECCS deployment, such as water or biodiversity conservation. However, BECCS deployment in the UK may be expected to cause less environmental damages than in regions with higher land availability and biodiversity. In a study performed at the global scale, it was suggested that land use change caused by BECCS deployment in Western Europe would remain within planetary boundaries, *i.e.* would not be detrimental to the environment (see Figure 4.3 in Heck *et al.* 2018).

4.4. BECCS costs

Global assessment

BECCS cost can vary significantly as a function of the technology, region and feedstock cost. In a recent review by Fuss *et al.* 2018, BECCS costs in the literature could be found as low as £12/tCO_2 and as high as £315/tCO_2. BECCS pathways involving gasification (£20–60/tCO_2), or fermentation (£15–140/tCO_2) are typically cheaper than ones involving combustion of the biomass (70 to £230/tCO_2), which can be explained by the lower cost of pre-combustion CO_2 capture or capture from fermentation, as compared to post- or oxy- combustion capture.

There are however significant overlaps between each technological route, and uncertainty ranges can be explained by different assumptions regarding counterfactual sceanrios, feedstock cost, CAPEX, and choice of boundaries for the cost and CO_2 balance.

A significant amount of costs in the literature are presented as *avoided costs,* i.e. the the cost of the BECCS process (absolute or relative to an anabated technology) per ton of CO_2 avoided as compared to an unabated counterfactual. Abanades *at al.* calculates the cost of BECCS oxy-combustion plant with calcium looping to be between £30 and £60 per ton of CO_2 avoided as compared to a coal plant (Abanades et al. 2011). In Sanchez *et al.* the cost of CO_2 avoided of a BIGCC plant varies between £52/tCO_2 when a coal IGCC plant is considered as the counter factual, and £64/tCO_2 when a natural gas plant is considered as the counterfactual (Sanchez & Callaway 2016). Whilst these values are relevant when comparing different decarbonisation technologies, there are not useful when comparing different carbon dioxide removal technologies.

To compare different dioxide removal technolgies, calculating the absolute cost of CO_2 removal is more insightful. However, as discussed in section 4.1, the amount of CO_2 captured at the plant does not necessarily coincide with the amount of net CO_2 removal, when accounting for upstream supply chain. When accounting for the whole process life-cycle GHG emissions, the amount of CO_2 removal can be much lower than the amount of CO_2 physcally captured at the BECCS plant (see section 4.2), which results in the cost of CO_2 removal being higher than cost of CO_2 captured. In Figure 4.5, “CO_2 captured” indicates the cost of CO_2 captured at the process level, whilst “CO_2 removed” indicates the cost of net CO_2 removal including supply chain and process GHG emissions to a various degree. In Laude *et al.*, the cost of BECCS via bioethanol increases from £38-112/tCO_2 when only CO_2 from fermentation is captured (case A), to £169-187/tCO_2 when CO_2 from an auxiliary boiler using residual biomass (case B). However, a carbon balance on the whole value chain performed in this study shows that case A is actually not carbon negative when including the feedstock upstream emissions, and case B is only slighly carbon negative (Laude et al. 2011). The cost of CO_2 removal would therefore actually be infinite in case A, and higher than £169-187/tCO_2 in case B, which would be consistent with other CO_2 removal costs assessments for the same technology including life cycle emissions, which found between £190 and £310/tCO_2 (IEA Greenhouse Gas R&D Programme (IEA GHG) & Ecofys 2011). Similarly in Johnson *et al.* 2014, the cost of BECCS increases from £15-30 per ton of CO_2 captured, to about £200/tCO_2 per negative emissions generated (Johnson *et al.* 2014). In Ranjan *et al.* 2011, a sensitivity analysis on BECCS avoided cost to upstream emissions is performed, and BECCS cost increases from £120/tCO_2 with no upstream emissions, to £320/tCO_2 when upstream emisisons account for 60% of the CO_2 captured at the power plant (Ranjan & Herzog 2011). Figure 4.5 summarises BECCS costs in the literature by definition of ton of CO_2 – captured, avoided and removed – and techologies.

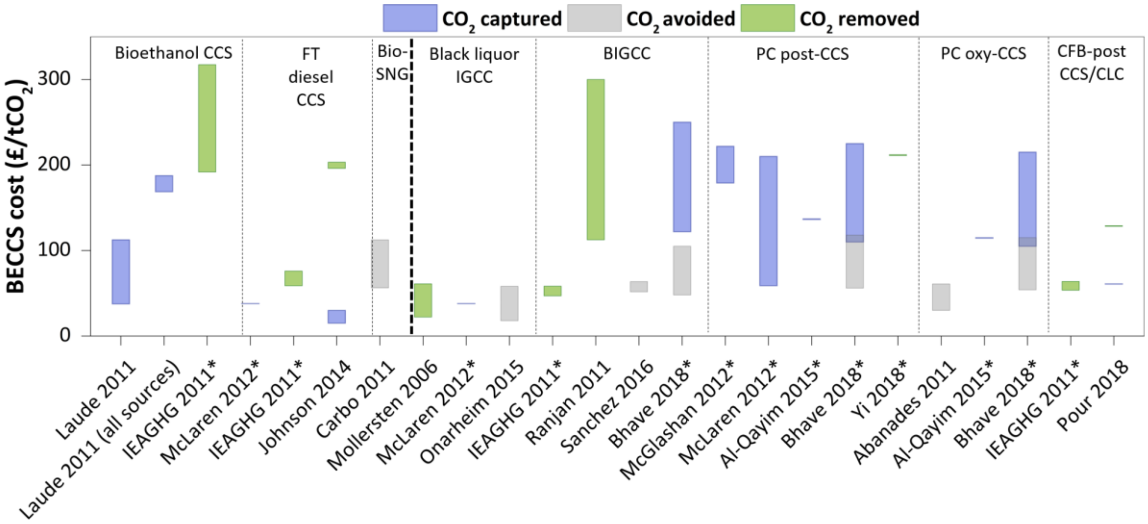

Figure 4.5: Ranges of BECCS cost in the literature for different BECCS pathways. Factors such as system boundaries (for both cost and CO$_2$ balance), CAPEX and feedstock cost, or the evaluation against a counterfactual scenario (avoided cost) explain the variation from one study to another, and the uncertainty within each study. Overall, CO$_2$ removal costs tend to be higher than avoided or captured costs, hence the importance for studies to provide the absolute BECCS cost, accounting for the full life cycle emissions and no counterfactual scenario. Sources: (Carbo et al. 2011; Möllersten et al. 2006; Onarheim et al. 2015; Bhave et al. 2017; McGlashan et al. 2012; Al-qayim et al. 2015; Yi et al. 2018; Laude et al. 2011; Abanades et al. 2011; IEA Greenhouse Gas R&D Programme (IEA GHG) & Ecofys 2011; McLaren 2012; Johnson et al. 2014; Ranjan & Herzog 2011; Sanchez & Callaway 2016; Pour et al. 2018)

UK assessment

Whilst some of the studies included in the systematic literature review were performed in the context of the UK or Europe in general (signalled with a * in Figure 4.5), it is difficult to determine the extent to which any cost data available in the literature is actually specific to a given region, especially considering the very limited numbers of actual BECCS pilot projects in the world. Regional factors likely to directly impact BECCS cost are the capital cost of the BECCS plant, and the biomass feedstock cost. Figures 4.6 and 4.7 present different CAPEX and feedstock costs assumptions in various studies.

Among studies performed in a European or UK context, some CAPEX assumptions/calculations for BECCS power plants can be found as low as £1,200–2,000/kW (Yi et al. 2018; Al-qayim et al. 2015). In Yi *et al.*, it is assumed that adding CO$_2$ capture to a biomass plant only results in a £40/kW CAPEX increment, as compared to the £1,050/kW CAPEX increment between an unabated coal plant and a coal plant with CO$_2$ capture (Yi et al. 2018). At the other end of the cost range, more conversative CAPEX values for BECCS power plants can be found around £4,400–5,600/kW, with cost reductions assumptions by learning and economies of scale resulting in costs around

£3,000–4,300/kW (Bhave *et al.* 2017; IEA 2016[8]). In the IEA 2016 World Energy Outlook cost assumptions, CAPEX values for Europe and the US are significantly higher (£3,700–4,800/kW) than CAPEX values in China or India (£2,500 – 3,900/kW) (IEA 2016). This can be explained by differences in cost of capital, material and labour between regions.

Another factor with a significant impact on BECCS cost is the biomass feedstock cost. Factors such as electricity and fuel costs, material and fertiliser cost, and biomass yield in the case of dedicated energy crop, result in a potential wide range of feedstock cost. Whilst prices for baled corn stover in China can be found as low as £6–/MWh of biomass primary energy (Ren et al. 2015), miscanthus pellets production costs in the UK can be found between £12 and £19/MWh (Hastings 2017). Biomass feedstock cost also significantly increases with transport, with the cost of imported wood pellets in the UK between £27 and £37/MWh (UK Department for Business Energy & Industrial Strategy 2016; Bhave et al. 2017). Biomass feedstock cost is also likely to increase as the bioenergy demand increases (IEA Greenhouse Gas R&D Programme (IEA GHG) & Ecofys 2011). In a BECCS cost IEAGHG report, biomass feedstock cost is projected to increase from £17/MWh when global bieonergy demand is only 4 EJ, to £190/MWh if global bioenergy demand increases to 74 EJ.

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[8] The CAPEX of a BECCS power plant was calculated using the differential CAPEX between a coal + CCS plant (£2,500–4,200 /kW) and coal power plant (£500–1,600 /kW), and adding it to the CAPEX of a biomass power plant (£1,200–1,900/kW) (IEA 2016).

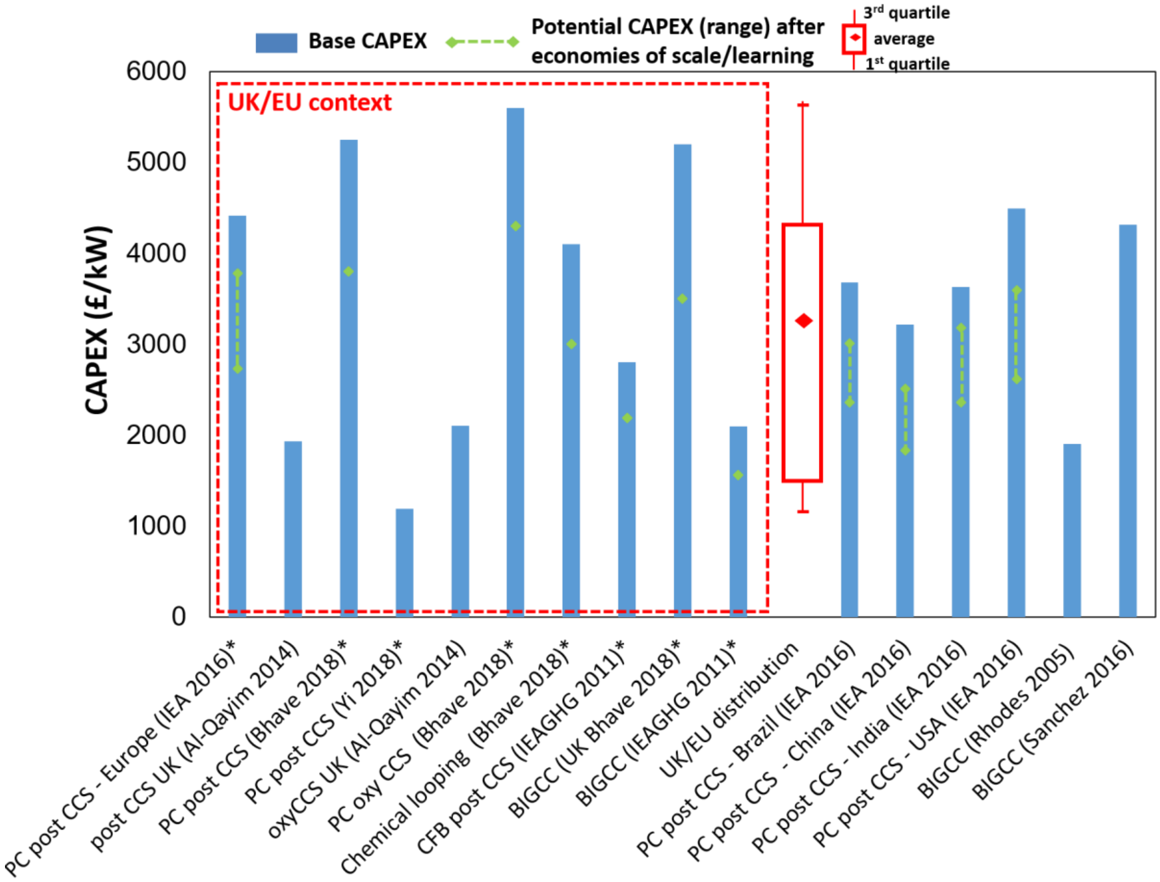

Figure 4.6: Ranges of BECCS CAPEX in the literature for different technologies and different regions. BECCS CAPEX in a UK/EU context is found between £1,500 and £4,300/kW. (Sources: adapted from IEA 2016; Al-qayim *et al.* 2015; Bhave *et al.* 2017; Yi *et al.* 2018; IEAGHG 2011; Rhodes & Keith 2005; Sanchez & Callaway 2016)

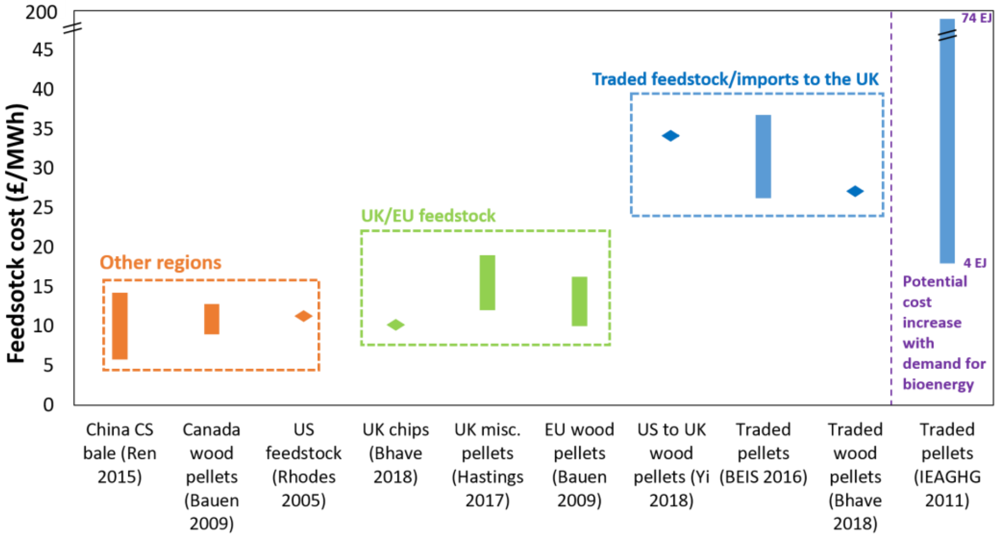

Figure 4.7: Ranges of biomass feedstock cost in the literature for different biomass types and different region. Indicative biomass feedstock costs in the UK are found within a £10-20/MWh range,

while imported feedstock could cost between £17 to £40/MWh (excluding feedstock cost increase with demand in IEAGHG 2011)**. Sources:** (Ren et al. 2015; Bauen et al. 2009; Hastings 2017; Yi et al. 2018; Rhodes & Keith 2005; UK Department for Business Energy & Industrial Strategy 2016; IEA Greenhouse Gas R&D Programme (IEA GHG) & Ecofys 2011)

Projecting the trajectory of BECCS cost over time is therefore not straightforward. Whilst technology learning and economies of scale could bring down the CAPEX and OPEX of BECCS over time, the upward trajectory of biomass feedstock cost could cancel out/outweigh this trend. To further explore these effects, the cost of BECCS power plant was computed for different CAPEX and feedstock costs. In this thought experiment, the cost of a 500 MW plant operating at a 80% load factor with a 26% power generation efficiency was calculated. A £20/tCO_2 disposal cost is included in the cost, and biomass feedstock supply chains emissions of 30 kgCO_2/MWh of raw bioenergy were considered. The results are presented in Figure 4.8.

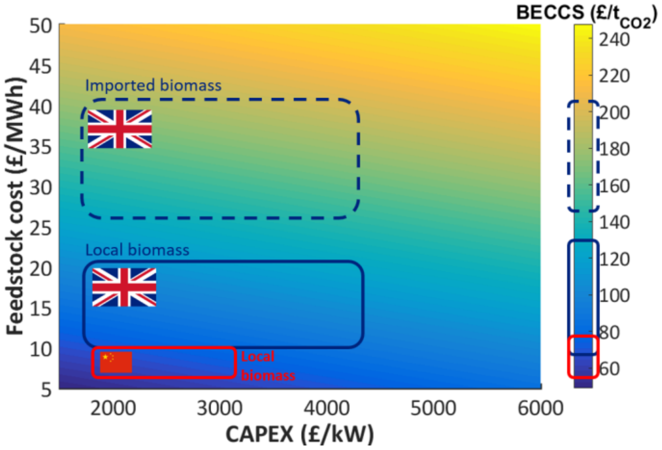

Figure 4.8: Cost of a large scale BECCS power plant (key assumptions include: 26%$_{HHV}$ efficiency, 30kgCO_2/MWh biomass supply chain emissions, 85% capacity factor, £20/tCO_2 storage cost) as a function of feedstock cost and plant CAPEX. BECCS cost is more sensitive to the cost of the biomass feedstock to the CAPEX of the plant. CO_2 removal cost via BECCS in the UK could be between £70 and £130/tCO_2 with local biomass, and over £200/tCO_2 with imported biomass.

A first insight from this thought experiment is that BECCS cost is more sensitive to feedstock cost than CAPEX. If biomass feedstock cost increased to £190/MWh over time, costs could approach £700/tCO_2, even at low CAPEX values. This suggests that maintening a low biomass feedstock cost over time is a higher priority than lowering BECCS CAPEX.

Based on the CAPEX and feedstock costs obtained from the literature, these results also indicate the potential costs of BECCS under different scenarios. Assuming the CAPEX of a UK BECCS power plant is between £1,500 and £4,300/kW, the cost of a BECCS plant operating with local biomass (10–20/MWh feedstock) could be between £70 and

£130/tCO_2 removed. Operating with imported feedstock however, the cost of a BECCS plant in the UK could increase to £200/tCO_2. This is more than twice the potential cost of doing BECCS in China, assuming a BECCS CAPEX between £1,800 and £3,200/MWh, and a feedstock cost between £6 and £9/tCO_2. In a hypothetical globalised carbon dioxide removal market, this could potentially impact the UK's ability to compete with other regions of the world. Another outcome could be that the UK may choose to pay other regions to provide the service of carbon dioxide removal, instead of doing its own. The implications of these cost differences are further explored in section 4.5.

4.5. Barriers and opportunities for BECCS deployment in the UK

Financial incentives

Because of inherently higher capital and operating costs than unabated plants, BECCS plants are unlikely to be competitive without a revenue stream associated with the additional service of carbon dioxide removal (Kemper 2015; IEA Greenhouse Gas R&D Programme (IEA GHG) & Ecofys 2011). Furthermore, whilst BECCS, as opposed to DACCS, boasts a revenue from generating energy, the value of a revenue stream associated with CO_2 abatement or CO_2 removal is thought to be more important to the plant economic viability than the revenue stream associated with energy generation (Mac Dowell & Fajardy 2017; Platt et al. 2018).

The EU Emissions Trading Systems is one of the current mechanisms to incentivise the deployment of low carbon technologies by allowing GHG emitters to trade GHG permits at a market-adjusted CO_2 price. However, in the context of rewarding facilities providing the service of carbon dioxide removal, no negative emissions credit or permit is currently included in these trading frameworks, which means there is no additional revenue for actively removing CO_2 from the atmosphere, as opposed to not emitting any. If a support mechanism in the form of a negative emission credit (NEC) were to be implemented, it is not clear if it would be different or ultimately equal to the current CO_2 price (Platt et al. 2018). In the context of carbon negative electricity generation, many studies have quantified the breakeven CO_2 price required to make a BECCS power plant competitive with unabated fossil plants. These values naturally depend on several assumptions regarding the technology (for *e.g.* CAPEX and feedstock cost), but also regarding the energy system the BECCS system operates in, including the levelised cost of electricity (LCOE) of other power generation technologies, the wholesale electricity price and other forms of incentives received by the power plant operator (such as the Renewable Obligation Certificate or Contract for Difference schemes).

Table 4.1: Range of CO_2 prices required for BECCS systems to be competitive.

Source	CO_2 price (£/tCO_2)	Region	Notes
PC post/oxy CCS (Akgul et al. 2014)	130–190	UK context	no revenue from electricity considered – CO_2 price for LCOE of the BECCS plant to equate that of reference coal plant
PC post CCS (Al-qayim et al. 2015)	70	UK context	no revenue from electricity considered – CO_2 price for LCOE to equate that of reference coal plant
BIGCC-CCS (Rhodes & Keith 2005)	120–130	USA context	no revenue from electricity considered – CO_2 price for LCOE to equate that of reference coal plant
IEAGHG 2011(IEA Greenhouse Gas R&D Programme (IEA GHG) & Ecofys 2011)	50	EU context	Exogenous CO_2 price – 3.5 $GtCO_2$ of negative emissions are found economically feasible with this price on CO_2.
Pulp & paper mill CCS (Onarheim et al. 2017)	50–70	Finland	Negative emission credit required to retrofit CCS on pulp and paper mill

Overall, CO_2 prices between £25 and £190/tCO_2 have been considered as required for BECCS systems to be financially viable. To put these numbers in context, over the period 2016-2018, the EU CO_2 price has been oscillating between 5 and 25 euros/tCO_2.

Without the option of generating a tradeable CO_2 permit, and/or a high enough CO_2 price, the *economic* potential of BECCS as opposed to its *technical* or *sustainable* potential, could be significantly reduced. In a study on BECCS potential by the IEAGHG in 2011, a CO_2 price of £50/tCO_2 could enable the deployment of 3.5 $GtCO_2$/yr, which is still much less than the technical potential evaluated at 10 $GtCO_2$/yr (IEA Greenhouse Gas R&D Programme (IEA GHG) & Ecofys 2011).

The breakeven carbon price heavily depends on the assumptions made for the BECCS system, including the plant CAPEX, feedstock costs, and wholesale energy prices (when revenues associated with energy generation are considered). The same thought experiment used in section 4.4 was used to calculate the breakeven negative emission credit (NEC) required for a large-scale BECCS power plant to have a zero net present value (with an 8% return), assuming a whole sale electricity price of £60/MWh, as a function of CAPEX and feedstock cost. Results are presented in Figure 4.9. Considering typical BECCS CAPEX and indigenous/imported feedstock cost in the UK, a negative emissions credit between £75 and £130 could be required for a UK BECCS plant to be economically viable if operating with UK biomass. If using traded pellets, this could increase to £90 to £210/tCO₂.

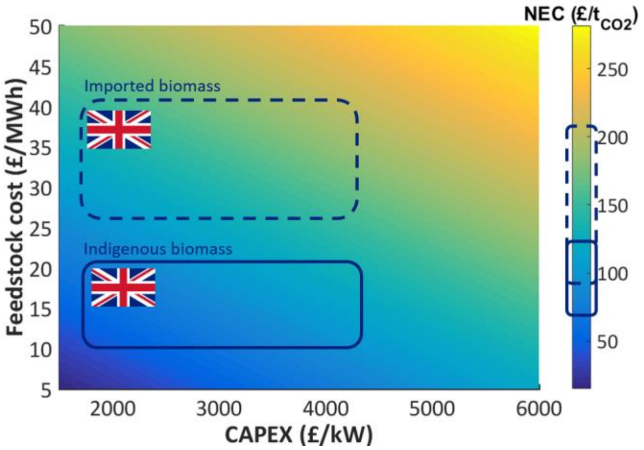

Figure 4.9: BECCS negative emission credit required for a BECCS power plant to get a zero net present value (8% return) (key assumptions include: 26%$_{HHV}$ efficiency, 30 kgCO$_2$/MWh biomass supply chain emissions, 85% capacity factor, £20/tCO$_2$ storage cost, £60/MWh wholesale electricity price) as a function of feedstock cost and plant CAPEX.

Other revenues of a UK BECCS plant could involve incentives for generating low carbon and renewable energy. The UK renewable policy framework, in the form of contract for difference and feed-in tariffs, has enabled the development of the bioenergy industry in the UK. In 2018, the bioenergy sector contributed to 9% of the electricity production, 2% of the transport consumption, and 6% of the overall fuel and heat consumption. In 2018, Drax power plant converted a fourth boiler to dedicated biomass at a much lower cost than the previous ones, making it one of the largest plant of its kind world-wide, and the total capacity of smaller scale CHP plant amounts to 326 MW (IEA Bioenergy 2018). Bioelectricity plants still rely heavily on subsidies, and the forthcoming changes to these subsidies which will affect new plants operating with an energy efficiency lower than 70% (BEIS 2019), might hinder this deployment and orientate bioenergy projects towards cheaper/smaller scale waste-based CHP projects, which will be more difficult to reconcile with the scale of CO$_2$ capture. These schemes are however considered insufficient to jump-start the deployment of a BECCS, or CDR, industry (Honegger & Reiner 2018), and need to be combined with a revenue stream associated with the service of carbon dioxide removal.

Involvement of other bioenergy stake holders

Ensuring the security and the sustainability of the biomass supply is a crucial enabler of BECCS. As far as agricultural biomass is concerned, involving farmers to collect and sell crop residues or grow energy crops on set-aside parcels of land, while monitoring the sustainability of the feedstock, is a challenging task. The inherent uncertainty around the economic viability of bioenergy production on set-aside land or marginal land could be a strong deterrence factor (Buck 2016). Economic analysis has shown that growing energy crops on marginal and abandoned lands increased the cost per ton in spite of the lower rent, because of the naturally or economically inferior nature of these lands (Keller et al. 2015). However, a 2017 study showed that the production of high yielding and resilient bioenergy crops such as miscanthus could be commercially viable at a contracted farm gate price of £75/t. It is worth noting however that this market price was partly achieved through the supporting policy framework of Contract for Difference for electricity production (Hastings 2017), whose reform in March 2019 might impact miscanthus producers. A stakeholder engagement study in the field of dedicated energy crops for anaerobic digestion in the UK showed that the primary driver for stakeholders was income generation, while the primary benefit was diversification, and the primary challenge was policy uncertainty (Röder 2016). This climate of uncertainty is illustrated by the failure of some of the UK government funding mechanism such as the Energy Crop Scheme (ECS) aiming to incentivise farmers to grow bioenergy crop on set-aside land. Although this policy enabled the successful development of local initiatives in the UK (ETI 2016), it was discontinued due to lack of applicants (Committee on Climate Change 2018a).

Political and social acceptability

BECCS social impact and perception has been identified as a potential driver/barrier to BECCS deployment (Fridahl 2017; Honegger & Reiner 2018; Buck 2016), though to date CDR and CCS in general remain relatively little known to the public (Karayannis et al. 2014; Bui et al. 2018). A first potential social acceptability barrier common to all CDR is the perception of CDR as a high-risk gamble on the future, delaying mitigation action today. If the gamble were to fail, the chance of meeting climate goals would be very low (Anderson & Peters 2016; Vaughan & Gough 2016). As far as public perception of CCS is concerned, social survey and stakeholder engagement studies have revealed heterogeneous views, often correlated with the interviewed population's degree of awareness on issues such as climate change or energy security (Karayannis et al. 2014). In the context of the UK for which the CO_2 storage capacity is mostly offshore, "Not In My BackYard" reactions potentially arising with onshore storage projects is less likely to be a concern (Bui et al. 2018).

An issue specific to BECCS, and potentially more controversial, is the public perception of bioenergy. Along with the intensification of bioenergy production in the year 2000's arose the controversy around the carbon intensity of bioenergy supply chain and the environmental and economic impacts of bioenergy production including deforestation, biodiversity loss, and food price increase (Honegger & Reiner 2018). In 2016, Drax power station in the UK sourcing some of its biomass feedstock from managed forests in the US sparked the debate around importing biomass from overseas. This was confirmed in a 2016 ETI survey on UK public perception on bioenergy, which showed that, whilst 80% of the respondents were supportive of an increase in bioenergy use in the UK, 60% of the respondents were not favourable to the UK importing all of its biomass supply. Public perception also depends on local communities being stakeholders or not of bioenergy projects. A survey in Germany has shown that the perception of bioenergy plants was positive among communities for which the bioenergy industry was contributing to their welfare (Kortsch et al. 2015). To date, quantitative studies exploring the micro-economic impacts of deploying bioenergy and BECCS are scarce (Patrizio *et al.* 2018 for the USA). This highlights the importance of including potential economic benefits of deploying bioenergy and BECCS (for example job creation) in the UK economy.

Sustainability certification and GHG accounting

The sustainability of the biomass supply is integral to a) BECCS actually delivering negative emissions in a way which is not detrimental to the wider ecosystem, and b) BECCS being well received in public opinion. Implementing sustainability criteria and certification frameworks to assess these criteria is therefore crucial to BECCS deployment. At least three aspects need to be covered: (1) a life cycle GHG threshold for biomass supply, (2) sustainable forest management for biomass from the forestry sector and (3) broader sustainability issues including water use, biodiversity loss and land use change.

In order to be carbon negative, biomass supply chain fossil emissions, added to potential land use change emissions, cannot outweigh the BECCS plant's CO_2 removal potential. In the UK, a bioelectricity sustainability criteria combined with an OFGEM certification framework warrants life cycle emissions of bioelectricity production to be below 295kgCO_2/MWh of bioelectricity. This was implemented in the context of the UK Contract for Difference (CfD) incentivising scheme for renewable electricity production, and is to be updated to a much lower value of 29kgCO_2/MWh of bioelectricity (BEIS 2018). Whilst required to improve BECCS carbon efficiency, this new measure narrows the range of potential biomass supplies for BECCS plants, including biomass imports. As an example, Drax power plant which reported a 114kgCO_2/MWh bioelectricity life cycle assessment in 2015 (or 31.6gCO_2/MJ in DRAX GROUP plc 2015), will have to drastically improve some of its integrated feedstock supply chain in the US, and/or rely on new local sources of biomass feedstock, to keep benefiting from the CfD scheme.

Integral to BECCS being carbon negative is the assumption that the biomass is carbon-neutral. This assumption can be challenged in the case of forestry biomass obtained in a way which depletes the forest carbon stock, for example by whole tree harvests or forestry residues collection at unsustainable rates. Sustainable forestry certifications (Romero et al. 2017) and global mapping of sustainable forestry zones (Geo-wiki Forest 2019) are key in this context. This is particularly important in the context of biomass imports in the UK, as whilst over 75% of forests in the UK are certified “sustainably managed”, these statistics decrease to 11 to 30% in the US, and less than 10% in Brazil (Geo-wiki Forest 2019).

For the broader impacts of BECCS on the ecosystem to be limited, including water resource pollution and/or depletion, biodiversity loss, increased biochemical flows, competition with other land uses (for example food production), careful monitoring of land use change and water management practices need to be integral part of the sustainability certification process. The bioenergy sustainability criteria of the updated EU Renewable initiative RED II which is now including land use change is a step in this direction. As these impacts have been found to be limited in the UK (see section 4.2), these considerations are particularly important in the context of biomass imports, which also makes the certification crediting more challenging due to the geographical dispersion of the BECCS value chain stakeholders.

4.6. Key points

- BECCS CO_2 removal potential can be evaluated based on UK bioenergy assessments. The sustainability of this technical potential remains however uncertain, and could further restrict BECCS potential in the UK.
- UK potential could be larger if imported biomass is used since the UK has substantial CO_2 storage potential. However, a range of sustainability related concerns about imported biomass resources would need to be addressed.
- There is a lack of consistency in cost data provided by the techno-economic assessments of BECCS configurations, both in definitions - CO_2 avoided, captured or removed, and the extent of life cycle cost and emissions considered in both the cost and carbon balances.
- Key drivers of BECCS cost include capital and feedstock cost. Whilst the capital cost could decrease over time with economies of scale and learning, the potential increase of feedstock cost with bioenergy demand remains a significant cause of uncertainty.

- As is the case with DACCS, the absence of a credit for CDR harms the potential for BECCS to compete with alternatives.

5. Conclusions

This review has revealed that the evidence base for the technical and commercial viability of DACCS is limited. A lack of bottom-up evaluation studies and independent primary techno-economic assessments in the literature mean that significant uncertainties exist in estimates of technical and economic performance of DACCS. DACCS is a very energy-intensive process due to the diluteness of CO_2 in air. The range of energy input estimates identified from this review suggest that to capture 1% of the UK's annual GHG emissions[9] via DACCS would require 0.5-5.5 TWh_e/yr of electricity and 2.8-11.5 TWh_{th}/yr of heat. The potential deployment of DACCS must therefore be considered in the planning of power and heat systems transitions.

Commercial developers of DACCS technologies have suggested that future DACCS costs of £75-95/tCO_2 removed are achievable. The academic literature reviewed, however, suggests higher removal costs of £190-540/tCO_2. The current absence of an incentive for CDR and the relatively low carbon price in the UK render DACCS commercially unviable. Additionally, the lack of CO_2 transport and storage (T&S) infrastructure (a pre-requisite to the large-scale deployment of DACCS and BECCS) discourages investment in the technologies.

Further work is required to evaluate the technical and economic potential of the archetypes of DACCS technologies being developed within the UK context. The broader implications of DACCS deployment on land and local resources (such as water) also require investigation.

The review also revealed that whilst the majority of the research material concerns the BECCS technology, most of it has been focused on its potential and cost at the global scale, rather than at the regional scale. BECCS potential in the UK was assessed as between 3 and 60 $MtCO_2$/yr when only considering indigenous biomass, and between 100 and160 $MtCO_2$/yr when considering imports. However, the environmental impacts of UK biomass, social opposition to bioenergy (*e.g.* biomass imports), and stricter threshold for biomass lifecycle GHG emissions in regulatory frameworks, could further limit BECCS potential deployment in the UK. Furthermore, whilst explored at the global scale, the environmental impacts of BECCS deployment remain fairly unknown at the UK scale. Further study is therefore needed to determine if the UK technical bioenergy potential is both sustainable and economic.

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[9] Latest figures from the Department for Business, Energy and Industrial Strategy show that the UK emitted 460 $MtCO_{2e}$ of GHGs in 2017.

Reviews of BECCS costs indicate values as low as £12/tCO_2 and as high as £314/tCO_2. The costs of a bioelectricity plant in the UK was assessed between £70 and £130/tCO_2 when using local biomass, and between and £150 and £200/tCO_2 when using imported biomass. Whilst the capital cost of BECCS could decrease with learning and/or economies of scale, the potential increase in feedstock cost associated with higher demand and toughening of lifecycle GHG emissions threshold are key economic challenges facing BECCS. In the context of a UK bioelectricity plant, CO_2 prices between £75 and £210/tCO_2 (depending on the feedstock cost) may be required for a plant to achieve an 8% return. Though BECCS is a net producer of energy (as opposed to DACCS which is a net consumer) a revenue associated with CO_2 removal is also likely to be required for a BECCS plant to be economically viable.

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7. Annex

Expert Group

The project team engaged with a small team of expert advisors to bring their experience and perspectives to bear on the subject. The expert advisors were asked to comment on the scope of the project and the approach, advise and assist the project team in the selection of relevant evidence sources, and review draft outputs. The expert advisors were:

David Joffe, Committee on Climate Change
Vivian Scott, University of Edinburgh

The project team are very grateful to the expert advisors for their contributions and input. Responsibility for the contents of this research report rests entirely with the authors.

Full list of documents reviewed

Lead author	Year	Short title	Relevance rating (1-2)	Country/ Region/Scale	Technology	Potential?	Cost?	Governance/policy?
Adanez, J	2018	Chemical looping combustion of solid fuels	1		BECCS		y	
Adelman, S.	2017	Geoengineering: rights, risks and ethics	1		both			y
Akgul, O.	2014	A mixed integer nonlinear programming (MINLP) supply chain optimisation framework for carbon negative electricity generation using biomass to energy with CCS (BECCS) in the UK	1	UK	BECCS	y	y	
Alcalde, J.	2018	The potential for implementation of Negative Emission Technologies in Scotland	1	UK	Both			
Arasto, A.	2014	Bio-CCS: Feasibility comparison of large scale carbon-negative solutions	1	global	BECCS	y	y	
Arasto, A.	2014	Feasibility of significant CO2 emission reductions in thermal power plants–	1		BECCS	y	y	

		comparison of biomass and CCS						
Baik, E.	2018	Geospatial analysis of near-term potential for carbon-negative bioenergy in the United States	1	USA	BECCS	y	y	
Beal, C.M	2018	Integrating Algae with Bioenergy Carbon Capture and Storage (ABECCS) Increases Sustainability	1	USA	BECCS	y	y	
Bellamy, R.	2018	‘Slippery slope’ or ‘uphill struggle’? Broadening out expert scenarios of climate engineering research and development	1	UK	Both		n	y
Bergout, N.	2019	Assessing deployment pathways for greenhouse gas emissions reductions in an industrial plant – A case study for a complex oil refinery	1	Europe	BECCS			
Bertram, C.	2018	Targeted policies can compensate most of the increased sustainability risks in 1.5 °C mitigation scenarios	1	Global	BECCS			y
Bhave A.	2018	Screening and techno-economic assessment of biomass-based power generation with CCS technologies to meet 2050 CO2targets	1	UK	BECCS		y	
Boysen, L. R.	2017	Trade-offs for food production, nature conservation and climate limit the terrestrial carbon dioxide removal potential	1	Global	BECCS	y		
Boysen, L. R.	2017	The limits to global-warming mitigation by terrestrial carbon removal	1	Global	BECCS	y		
Buck, H. J.	2016	Rapid scale-up of negative emissions technologies: social barriers and social implications	1	Global	both			y
Bui M.	2018	Carbon capture and storage (CCS): the way forward	1	Global/UK	Both	y	y	y
Caldecott, B.	2014	Stranded Carbon Assets and Negative Emissions Technologies	1	Global	both	y	y	y
Campbell-Arvai, V.	2017	The influence of learning about carbon dioxide removal (CDR) on support for mitigation policies	1	Global	both			y
Carbo, M. C.	2011	Bio energy with CCS (BECCS): Large potential for BioSNG at low CO2 avoidance cost	1		BECCS	y	y	
Caserini, S.	2019	Affordable CO2 negative emission through hydrogen from biomass, ocean liming, and CO2 storage	1	Italy	BECCS			
Coffman, D.M	2017	Carbon dioxide removal and the futures market	1	UK	both			y
Committee on Climate Change (CCC)	2018	Biomass in a low - carbon economy	1	UK	BECCS	y	n	
Creutzig, F.	2014	Economic and ecological views on climate change mitigation with bioenergy and negative emissions	1	Global	BECCS	y		

Creutzig, F.	2014	Bioenergy and climate change mitigation: an assessment	1	Global	BECCS	y		
Cummings, C. L.	2017	Public perceptions of climate geoengineering: a systematic review of the literature	1		both			y
da Silva, F.T.F	2018	CO2 capture in ethanol distilleries in Brazil: Designing the optimum carbon transportation network by integrating hubs, pipelines and trucks	1	Brazil	BECCS	y	y	
Darton, R	2018	Removing Carbon Dioxide from the Atmosphere – Assessing the Technologies	1	UK	DACCS			
Dooley, K.	2018	Land-based negative emissions: risks for climate mitigation and impacts on sustainable development	1	Australia, Global	BECCS and AR			y
EASAC	2018	Negative emission technologies: What role in meeting Paris Agreement targets?	1	Global	Both	y	y	y
Fajardy M.	2018	Investigating the BECCS resource nexus: delivering negative emissions	1	Various (incl. UK)	BECCS	y	y	
Fajardy M.	2017	Can BECCS deliver sustainable and resource efficient negative emissions?	1	Various (incl. UK)	BECCS		y	
Fridahl M.	2017	Socio-political prioritization of bioenergy with carbon capture and storage	1	Global	BECCS			y
Fuss S.	2018	Negative emissions - Part 2 : Costs , potentials and side effects	1	Global	Both	y	y	y
Fuss S.	2016	Research priorities for negative emissions	1	Global	Both	y	y	y
Geden, O.	2018	Targeting carbon dioxide removal in the European Union	1	EU	both			y
Gough C.	2018	Challenges to the use of BECCS as a keystone technology in pursuit of 1.5c	1	Global	BECCS	y	y	y
Gough C.	2010	Biomass energy with carbon capture and storage (BECCS): a review	1	Global	BECCS	y	y	y
Gutknecht, V.	2018	Creating a carbon dioxide removal solution by combining rapid mineralization of CO2 with direct air capture	1		DACCS			
Harper A.	2018	Land-use emissions play a critical role in land-based mitigation for Paris climate targets	1	Global	BECCS			
Haszeldine, S.	2018	Negative emissions technologies and carbon capture and storage to achieve the Paris Agreement commitments	1	UK	both			y
Heck V.	2018	Biomass-based negative emissions difficult to reconcile with planetary boundaries	1	Global	BECCS	y		
Hetland, J.	2016	Carbon-negative emissions: Systemic impacts of biomass conversion: A case study on CO2 capture and storage options	1	Indonesia	BECCS			
Holmes, G.	2012	An air–liquid contactor for large-scale capture of CO2 from air	1		DACCS		y	
Honneger M.	2017	The political economy of negative emissions technologies: consequences for	1	Germany, UK, EU,	Both	n	n	y

		international policy design		global?				
House, K. Z.	2011	Economic and energetic analysis of capturing CO2 from ambient air	1	USA	DACCS			
IEAGHG	2011	Potential for Biomass and Carbon Dioxide Capture and Storage	1	Global	BECCS	y	y	
Johansson, V.	2019	Biomass in the electricity system: A complement to variable renewables or a source of negative emissions?	1	Sweden	BECCS			
Johnson, N.	2014	How negative can biofuels with CCS take us and at what cost? Refining the economic potential of biofuel production with CCS using spatially-explicit modeling	1	USA	BECCS	y	y	
Karki,	2017	Achieving Negative Emissions with the Most Promising Business Case for Bio-CCS in Power and CHP Production	1	Finland	BECCS		y	
Keith, D. W.	2018	A Process for Capturing CO2 from the Atmosphere	1	Canada	DACCS			
Keith, D.W.	2006	Climate Strategy with Co2 Capture from the Air	1	US	DACCS		y	
Kemper J.	2015	Biomass and carbon dioxide capture and storage: A review	1	Global	BECCS	y	y	y
Khorshidi	2016	Techno-economic evaluation of co-firing biomass gas with natural gas in existing NGCC plants with and without CO2capture	1	Australia	BECCS		y	
Klein, D.	2014	The value of bioenergy in low stabilization scenarios: an assessment using REMIND-MAgPIE	1	global	BECCS			
Koelbl, B. S.	2015	Socio-economic impacts of future electricity generation scenarios in Europe: Potential costs and benefits of using CO2Capture and Storage (CCS)	1	Europe	BECCS	y	y	
Kouri, S	2017	The Potential for CCUS in Selected Industrial Sectors – Summary of Concept Evaluations in Finland	1	Finland	BECCS	y	y	
Krause, A.	2018	Large uncertainty in carbon uptake potential of land-based climate-change mitigation efforts	1			Y		
Krekel, D.	2018	The separation of CO2 from ambient air – A techno-economic assessment	1	Global	DACCS			
Lackner, K.	2009	Capture of carbon dioxide from ambient air	1	Global	DACCS			
Lomax, G.	2015	Reframing the policy approach to greenhouse gas removal technologies	1	Global - UK	Both	y	y	y
Luckow, P.	2010	Large-scale utilization of biomass energy and carbon dioxide capture and storage in the transport and electricity sectors under stringent CO2 concentration limit scenarios	1	USA	BECCS			
Mac Dowell, N.	2017	Inefficient power generation as an optimal route to negative emissions via BECCS?	1	UK	BECCS		y	

Mac Dowell, N.	2016	On the potential for BECCS efficiency improvement through heat recovery from both post-combustion and oxy-combustion facilities	1		BECCS	y		n
Marcucci, A.	2017	The road to achieving the long-term Paris targets: energy transition and the role of direct air capture	1	Global	DACCS	y	y	
Martin, D.	2017	Carbon Dioxide Removal Options: a Literature Review Identifying Carbon Removal Potentials and Costs	1	Global	Both			
McGlashan, M.	2012	High-level techno-economic assessment of negative emissions technologies	1	UK	both	y	y	
McLaren, D.	2012	A comparative global assessment of potential negative emissions technologies	1	Global	Both	y	y	y
Meerman, J.C.	2017	Negative-carbon drop-in transport fuels produced *via* catalytic hydropyrolysis of woody biomass with CO_2 capture and storage	1	USA	BECCS	Y	Y	
Minx J.	2018	Negative emissions - Part 1 : Research landscape, ethics and synthesis	1	Global	Both	y	y	y
Moe, E.	2018	The post-carbon society: Rethinking the international governance of negative emissions	1	Norway-EU/Global	Both			
Moreira J.	2016	BECCS potential in Brazil: Achieving negative emissions in ethanol and electricity production based on sugar cane bagasse and other residues	1	Brazil	BECCS	y	y	
Nemet G.	2018	Negative emissions - Part 3 : Innovation and upscaling	1	Global	Both	y	y	y
Onarheim, K.	2018	Performance and cost of CCS in the pulp and paper industry part 2: Economic feasibility of amine-based post-combustion CO2 capture	1	Norway	BECCS	y	y	
Onarheim, K.	2017	Performance and costs of CCS in the pulp and paper industry part 1: Performance of amine-based post-combustion CO2capture	1	Norway	BECCS	y	y	
Patrizio P.	2018	Reducing US coal emissions can boost employment	1	USA	BECCS	y	y	
Platt, D.	2019	A novel approach to assessing the commercial opportunities for greenhouse gas removal technology value chains: Developing the case for a negative emissions credit in the UK	1	UK	Both			
Pour N.	2018	Potential for using municipal solid waste as a resource for bioenergy with carbon capture and storage (BECCS)	1	Australia	BECCS	y	y	
Pour, N.	2018	Opportunities for application of BECCS in the Australian power sector	1	Australian	BECCS			
Pour, N.	2017	A Sustainability Framework for Bioenergy with Carbon Capture and Storage (BECCS) Technologies	1	Australia	BECCS		y	

Pritchard	2015	Thermodynamics, economics and systems thinking: What role for air capture of CO2?	1	UK	DACCS		y	
Psarras P.	2017	Slicing the pie: how big could carbon dioxide removal be?	1	Global	Both	y	y	
Ranjan, M.	2011	Feasibility of air capture	1	US	DACCS			
Rau, G.H.	2018	The global potential for converting renewable electricity to negative-CO2-emissions hydrogen	1	USA	BECCS	Y	Y	
Rhodes, J.	2005	Engineering economic analysis of biomass IGCC with carbon capture and storage	1	USA	BECCS		y	
Sanchez, D.	2018	Federal research, development, and demonstration priorities for carbon dioxide removal in the United States	1	USA	both			y
Sanchez, D.	2016	Optimal scale of carbon-negative energy facilities	1	USA	BECCS	y	y	
Sans-Pérez, E. S.	2016	Direct Capture of CO2 from Ambient Air	1	Global	DACCS			
Seferian, R.	2018	Constraints on biomass energy deployment in mitigation pathways: the case of water scarcity	1	Global	BECCS	Y	N	N
Selosse	2014	Achieving negative emissions with BECCS (bioenergy with carbon capture and storage) in the power sector: New insights from the TIAM-FR (TIMES Integrated Assessment Model France) model	1	France	BECCS	y	y	
Shepherd, J. G.	2012	Geoengineering the climate: an overview and update	1		both			
Smith, L. J.	2013	Ecological limits to terrestrial biological carbon dioxide removal	1	Global	BECCS	y		
Smith, P	2018	Impacts on terrestrial biodiversity of moving from a 2°C to a1.5° Ctarget	1	Global - incl. UK	BECCS	y		
Smith, P.	2016	Preliminary assessment of the potential for, and limitations to, terrestrial negative emission technologies in the UK	1	UK	BECCS	y	y	
Smith, P.	2016	Biophysical and economic limits to negative CO2 emissions	1	Global	Both	y	y	
Stolaroff, J. K.	2008	Carbon Dioxide Capture from Atmospheric Air Using Sodium Hydroxide Spray	1	Global	DACCS			
Stoy P.	2018	Opportunities and Trade-offs among BECCS and the Food, Water, Energy, Biodiversity, and Social Systems Nexus at Regional Scales	1	USA	BECCS			
Strapasson, A.	2017	On the global limits of bioenergy and land use for climate change mitigation	1	Global	BECCS	y		
Stravakas, V.	2018	Striving towards the Deployment of Bio-Energy with Carbon Capture and Storage (BECCS): A Review of Research Priorities and Assessment Needs	1	EU	BECCS	Y	Y	Y

Tagomori I.	2018	Designing an optimum carbon capture and transportation network by integrating ethanol distilleries with fossil-fuel processing plants in Brazil	1	Brazil	BECCS		y	
The Royal Society	2018	Greenhouse gas removal	1	UK	Both			
Tokimatsu	2015	Global Zero Emissions Scenarios: Assessment of Climate Change Mitigations and their Costs	1	Global	CDR in general			
Turner, P.A	2018	The global overlap of bioenergy and carbon sequestration potential	1	Global	BECCS	y		
UNEP (Smith, P)	2017	Chapter 7: Bridging the Gap – Carbon dioxide removal	1	Global	Both	y	y	y
Van vliet	2009	Fischer-Tropsch diesel production in a well-to-wheel perspective: A carbon, energy flow and cost analysis	1	Netherlands	BECCS	y	y	
Vaughan , N.	2016	Expert assessment concludes negative emissions scenarios may not deliver	1	UK, Global	BECCS			
Werner, C.	2018	Biogeochemical potential of biomass pyrolysis systems for limiting global warming to 1.5 °C	1	Germany	BECCS	Y	Y	
Wiltshire, A.	2016	Implications for food security of large scale BECCS deployment	1	UK/Global	BECCS			
Wohland, J.	2018	Negative Emission Potential of Direct Air Capture Powered by Renewable Excess Electricity in Europe	1	Europe	DACCS			
Woolf, D.	2016	Optimal bioenergy power generation for climate change mitigation with or without carbon sequestration	1		BECCS	y	y	
	2011	Direct Air Capture of CO2 with Chemicals: A Technology Assessment for the APS Panel on Public Affairs	1	USA	DACCS			
Ali, U.	2017	Comparative potential of natural gas, coal and biomass fired power plant with post -combustion CO2 capture and compression	2	UK	BECCS			
Ali, U.	2018	Part-load performance of direct-firing and co-firing of coal and biomass in a power generation system integrated with a CO2capture and compression system	2	UK	BECCS			
Alonso-Moreno, C.	2018	The Carbon Dioxide-Rumen Fermentation Processes-strategy, a proposal to sustain environmentally friendly dairy farms	2	Spain	BECCS			
Balcombe, P.	2018	The carbon credentials of hydrogen gas networks and supply chains	2	UK	BECCS			
Bosetti	2015	Sensitivity to energy technology costs: A multi-model comparison analysis	2	Global	BECCS		y	
Boucher, O.	2013	Rethinking climate engineering categorization in the context of climate change mitigation and adaptation	2	Global	CDR in general			y
Brethome, F.	2018	Direct air capture of CO2 via aqueous-phase absorption and crystalline-phase	2		DACCS	y		

		release using concentrated solar power						
Bui, M	2017	Thermodynamic Evaluation of Carbon Negative Power Generation: Bio-energy CCS (BECCS)	2	UK	BECCS			
Caldeira, K.	2016	Reflecting on 50 years of geoengineering research	2		both			y
Choi, Hong Il	2019	Performance and potential appraisal of various microalgae as direct combustion fuel	2	South Korea	BECCS			
Daggash, H. A.	2019	The role and value of negative emissions technologies in decarbonising the UK energy system	2	UK	Both			
den Elzen, M. G. J.	2014	The impact of technology availability on the timing and costs of emission reductions for achieving long-term climate targets	2	Global	BECCS	y		
Dietz, S.	2018	The Economics of 1.5°C Climate Change	2	Global	both	y		
Edmonds, j.	2013	Can radiative forcing be limited to 2.6 Wm−2 without negative emissions from bioenergy AND CO2 capture and storage?	2	Global	BECCS			
Fajardy, M.	2018	The energy return on investment of BECCS: is BECCS a threat to energy security?	2	Various regions, incl. UK	BECCS			
Favero, A.	2013	Trade of woody biomass for electricity generation under climate mitigation policy	2	Global	BECCS			
Fosbol, P.L	2017	Design and Simulation of Rate-based CO2 Capture Processes Using Carbonic Anhydrase (CA) Applied to Biogas	2	Denmark	BECCS			
Garðarsdóttir, S. O.	2018	Investment costs and CO2 reduction potential of carbon capture from industrial plants – A Swedish case study	2	Sweden	BECCS	y	y	
Hanak, D.	2018	Combined heat and power generation with lime production for direct air capture	2	UK	DACCS (alternative)	y	y	
Heck, V.	2015	Is extensive terrestrial carbon dioxide removal a 'green' form of geoengineering? A global modelling study	2		both			
Hoseinzade, L.	2019	Techno-economic and environmental analyses of a novel, sustainable process for production of liquid fuels using helium heat transfer	2	Global	BECCS	y	y	
Houghton, R.A	2018	Negative emissions from stopping deforestation and forest degradation, globally	2	Global	Other CDR	Y		
Jenkins, S.	2017	New CO2-capture approaches push against cost hurdles	2		DACCS			
Jiang, K.	2018	Emission scenario analysis for China under the global 1.5 °C target	2	China	BECCS	y		
Jones, C. D.	2016	Simulating the Earth system response to	2	Global	CDR in			

		negative emissions			general			
Keller, D.	2017	The Carbon Dioxide Removal Model Intercomparison Project (CDRMIP): rationale and experimental protocol for CMIP6	2	Global	DACCS and other CDR			
Klein, D.	2014	The value of bioenergy in low stabilization scenarios: an assessment using REMIND-MAgPIE	2	Global	BECCS	y		
Kreidenweis, U.	2016	Afforestation to mitigate climate change: impacts on food prices under consideration of albedo effects	2		Other CDR			
Kriegler, E.	2013	Is atmospheric carbon dioxide removal a game changer for climate change mitigation?	2		both	y	y	
Larkin, A.	2019	What if negative emission technologies fail at scale? Implications of the Paris Agreement for big emitting nations	2	Global	CDR in general			
Lawrence, M. G.	2018	Evaluating climate geoengineering proposals in the context of the Paris Agreement temperature goals	2	Global	both	y		y
Ledo, A.	2018	Perennial-GHG: A new generic allometric model to estimate biomass accumulation and greenhouse gas emissions in perennial food and bioenergy crops	2	Global	BECCS	y		
Lockley, A.	2018	Carbon dioxide removal and tradeable put options at scale	2	UK, EU, Global	Both			Y
Lordan, C-M.	2018	Contribution of forest wood products to negative emissions: historical comparative analysis from 1960 to 2015 in Norway, Sweden and Finland	2	Norway, Sweden, Finland	Other CDR			
Majumdar,	2018	Research Opportunities for CO2 Utilization and Negative Emissions at the Gigatonne Scale	2	US, global	both			
McComarck, C. G.	2016	Key impacts of climate engineering on biodiversity and ecosystems, with priorities for future research	2	Global	CDR in general			
Moreira J.	2016	Atmospheric CO2 capture by algae: Negative carbon dioxide emission path	2	Brazil	BECCS	y		y
Moriarty, P.	2018	Energy policy and economics under climate change	2	Global				y
Muri, H.	2018	The role of large—scale BECCS in the pursuit of the 1.5°C target: an Earth system model perspective	2	Global	BECCS			
Obersteiner, M.	2018	How to spend a dwindling greenhouse gas budget	2	Global	BECCS			
Oreggioni, G.D	2017	Environmental assessment of biomass gasification combined heat and power plants with absorptive and adsorptive carbon capture units in Norway	2	Norway	BECCS			
Oshiro, K.	2017	Transformation of Japan's energy system to attain net-zero emission by 2050	2	Japan	BECCS	y	y	

Rau, G.H.	2018	Negative-CO2-emissions ocean thermal energy conversion	2	USA	Other CDR			
Rickels, W.	2018	Integrated Assessment of Carbon Dioxide Removal	2	Global	CDR in general			
Rodriguez, B.S	2016	Decarbonizing the EU energy system by 2050: an important role for BECCS	2	EU	BECCS			
Rose, S. K.	2014	Bioenergy in energy transformation and climate management	2	Global	BECCS	y		
Royer-Adnot, J.	2017	Economic Analysis of Combined Geothermal and CO2 Storage for Small-Size Emitters	2	France	BECCS		y	
Ryden, M	2017	Negative CO2 Emissions with Chemical-Looping Combustion of Biomass – A Nordic Energy Research Flagship Project	2	Sweden	BECCS			
Sanchez, D.	2018	Near-term deployment of carbon capture and sequestration from biorefineries in the United States	2	USA	BECCS	y	y	y
Sanchez, D.	2015	Biomass enables the transition to a carbon-negative power system across western North America	2	USA	BECCS		y	
Sands, R.D.	2018	U.S. CARBON TAX SCENARIOS AND BIOENERGY	2	USA	BECCS			Y
Schwinger. J.	2018	Ocean Carbon Cycle Feedbacks Under Negative Emissions	2	Global	CDR in general			
Shue, H.	2017	Climate dreaming: negative emissions, risk transfer, and irreversibility	2		BECCS			y
Smith, P.	2016	Soil carbon sequestration and biochar as negative emission technologies	2	UK	Other CDR	y	y	
Strefler, J.	2018	Potential and costs of carbon dioxide removal by enhanced weathering of rocks	2	Germany	Other CDR	Y	Y	
Strefler, J.	2018	Between Scylla and Charybdis: Delayed mitigation narrows the passage between large-scale CDR and high costs	2	global	both	y	y	
Taillardat, P.	2018	Mangrove blue carbon strategies for climate change mitigation are most effective at the national scale	2	Singapore	Other CDR			
Tollefson, J.	2018	Sucking carbon dioxide from air is cheaper than scientists thought	2	Global	DACCS			
van Vuuren, D. P.	2018	Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies	2	Global	BECCS	y		
Yamagata, Y.	2018	Estimating water–food–ecosystem trade-offs for the global negative emission scenario (IPCC-RCP2.6)	2	Global	BECCS	y		