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Bioenergy with Carbon Capture & Storage

According to global climate and economic models, removing greenhouse gases from the atmosphere will be necessary to limit global warming to 1.5°C. Among Greenhouse Gas Removal (GGR) techniques, models assume that Bioenergy with Carbon Capture and Storage (BECCS) could play a prominent role. This POSTnote summarises why BECCS has been included in the models, outlines the challenges and trade-offs of deploying at scale, and considers policy options for supporting its development.

Overview

- Bioenergy with Carbon Capture and Storage (BECCS) is a system of technologies. It combines biomass (plant matter or organic waste) for energy generation, with the capture and permanent storage of the resulting carbon dioxide (CO_2) emissions.
- BECCS is one of the 'negative emissions' technologies projected to play a major role in global climate mitigation. It will be needed if the Paris Agreement goals are to be met.
- The scale of BECCS projected in some models has raised concerns around the sustainability of bioenergy and overall carbon footprint of BECCS required to deliver negative emissions.
- Its development requires robust and transparent policy and sustainability frameworks; with environmental, economic and social dimensions; as well as Carbon Capture and Storage (CCS) infrastructures that do not yet exist.

Background

The Paris Agreement sets a global target to limit global warming to well below 2°C above pre-industrial temperatures and pursue efforts to limit this rise to 1.5°C (POSTnote 594). Doing so will require that 'net' human-caused CO_2 emissions are reduced to zero around 2050 or soon after.[1] Net emissions refer to total emissions minus Greenhouse Gas Removal (GGR) (sometimes known as Carbon Dioxide Removal, CDR). There is a large body of evidence suggesting that some level of GGR is needed to achieve the aims of the Paris Agreement (POSTnote 549).

A BECCS process removes atmospheric CO_2 (the GHG that contributes most to climate change) using a combination of technologies. Broadly, it uses plant growth to absorb CO_2, generates energy from the biomass (such as through combustion) then stores the CO_2 emitted so that it cannot contribute to climate change. Estimates of the mitigation potential of BECCS vary considerably. A 2019 Special Report by the Intergovernmental Panel on Climate Change (IPCC) suggested it could remove 0.4 to 11.3 billion tonnes of CO_2 ($GtCO_2$) per year by 2100, with the higher figure representing around a quarter of current global CO_2 emissions.[2] There are a number of potential challenges associated with the widespread use of BECCS, primarily around scale and land availability. In addition, there are risks relying on the technology when significant uncertainties exist around its cost and its potential to achieve negative emissions.[3]

BECCS within integrated models

'Integrated assessment models' (IAMs, Box 1) are used to support policy-makers by assessing how emissions may change in the future. The models describe the global economy, energy and land use systems to produce 'pathways' that illustrate how the Paris Agreement aims could be met.[4] Most pathways that limit global warming to 1.5°C rely on large-scale deployment of BECCS and afforestation (which enhances forest cover from planting trees).[5,6]

Reducing emissions and using GGR

Annual CO_2 emissions must reach net zero to limit global warming. There is a trade-off between how quickly emissions

Box 1: Integrated Assessment Models (IAMs)
IAMs are complex models developed by scientists to estimate the most cost-effective scenarios to meet global temperature targets.[10] These models are based on various, but complementary, narratives and assumptions, with high degrees of uncertainty:
- **Shared Socio-economic Pathways (SSPs)**, a set of assumptions about future population and economic growth, education, urbanisation and technological developments.
- **Representative Concentration Pathways (RCPs)**, which describe different levels of future greenhouse gas (GHG) emissions and set mitigation targets for global warming.

By combining these, researchers developed Illustrative Model Pathways to help policy makers shape their decisions about climate change mitigation policies.[24]

are reduced and how much GGR will be needed to limit global warming to a given temperature.[7] The faster emissions are reduced from now, the less GGR will be needed.[8,9] The pathways suggest that GGR will still be required to meet the Paris Agreement goals.[10] Rapid ambitious mitigation would reduce the need for GGR, without fully eliminating it, and allow GGR technologies to offset residual emissions.[11,12]

Exceeding the 1.5˚C target
Many pathways in which global warming is limited to 1.5˚C feature a situation where this target is initially exceeded, before GHG concentrations (and hence the global temperature) are brought back down by removing excess CO_2 from the atmosphere with GGR.[13] The extent and duration of such scenarios would depend on the rate of emissions reduction and deployment of GGR at scale.[14] The implications of exceeding targets are unknown and have raised scientific and ethical concerns.[15,16] Environmental responses to such a situation are uncertain, as it is not clear if impacts on environmental systems from going beyond certain temperatures can be easily reversed.[17] This puts a burden on future generations to adjust to unknown consequences.[18,19]

Limitations of models
Integration of other GGR techniques
IAMs only feature afforestation and reforestation alongside BECCS, rather than a wider portfolio of GGR technologies. This is partly because other GGR technologies are further from commercialisation than BECCS.[9,20] These include 'Direct Air Capture', enhanced weathering, or restoration of habitats such as peatlands and wetlands (POSTnote 549). Multiple GGR technologies deployed at modest scale would carry less risk than a single technology deployed at much larger scale.[21]

Underpinning assumptions
Many models are optimised for the most cost-effective solutions and readiness of technologies. BECCS has the potential to generate energy carriers (such as electricity or fuels), making it more cost-effective within the models compared to other GGR.[22,23]

Some of the assumptions in the IPCC pathways that affect large-scale deployment of BECCS are uncertain, including:
- The amount of land freed by dietary changes and the use of marginal land (such as degraded agricultural land).
- A large increase in biomass yields.
- Any policy frameworks that will be ready to deploy BECCS at scale within the next few decades (see *Governance*).[9,25–27]

Component parts of BECCS
BECCS encompasses several technologies:
- Growing and processing biomass, which absorbs atmospheric CO_2 over its lifetime.
- Transporting the biomass and converting the energy within it into a useable form.
- Capturing the CO_2 emissions from this conversion, then compressing, transporting and storing the CO_2 somewhere so that it cannot contribute to climate change. This is known as Carbon Capture and Storage (CCS).

If the amount of CO_2 stored is greater than the CO_2 emitted during the life cycle of these processes (as assessed with life cycle analysis), then CO_2 has been removed from the atmosphere, resulting in net negative emissions.[28–30]

Bioenergy as an energy source
The uses of biomass for energy generation vary depending on the type of raw material and the conversion technology (POSTnote 410). The main materials used to produce bioenergy (feedstocks) are:
- **Energy crops.** Edible crops (maize, corn) and dedicated herbaceous or woody crops (miscanthus, willow).
- **Forestry resources.** Residues from the timber industry (forest bark, thinnings, branches, sawdust).
- **Waste.** Agricultural residues (such as straw, rice husk, sugarcane bagasse), post-consumer waste wood, food waste, sewage sludge, manures.[31–35]

These feedstocks can then be used for:
- **Power or heat generation** by combusting the biomass in a power plant to supply the electricity system or using the heat, for example in a specific industrial plant.
- **Fuel and chemicals production**. This includes bioethanol, biogas, biodiesel, jet-fuel and hydrogen.

The amount of carbon stored by BECCS is dependent, not only upon the feedstock used to generate the initial bioenergy and its supply chain, but also the processes involved, the removal system, the purity of CO_2 and its end use.[36–38] Power generation stores more of the carbon fixed in the biomass than biofuels because the tailpipe CO_2 emissions from vehicles are not captured.[39,40] However, biofuels can displace emissions from fossil fuels, and may be necessary to help decarbonise some transport modes such as aviation (POSTnote 616).

Carbon Capture and Storage (CCS)
CCS involves capturing CO_2 emissions, compressing the CO_2 then transporting and permanently storing it underground to prevent it from entering the atmosphere. Technologies for capturing CO_2 from industrial processes are established and have been applied to coal, oil and natural gas combustion; and hydrogen and bioethanol production. Government-assisted projects in the USA, Norway, Canada and Australia have been successful and reduced the associated costs and risks.[41,42]

Storage sites are geological structures, such as depleted oil and gas fields, saline aquifers or un-mineable coal seams (POSTnote 335). Deep saline formations have the largest global storage capacity, estimated to be between 1000 to 10,000 $GtCO_2$.[43] There is some evidence that the CO_2 storage capacity of depleted North Sea oil and gas fields is larger than any potential UK storage need.[44–47]

There are some concerns that stored CO_2 could leak back into the atmosphere over the lifetime of storage sites, raising questions around who would be liable for such leaks. However, there is evidence that leakage risk is very small and decreases over time if the sites are properly selected, characterised and managed.[43] Many carbon capture projects currently use the CO_2 in economically productive processes such as in enhanced oil recovery, horticulture, and building material and synthetic fuel production (POSTbrief 30).[48]

Combining bioenergy and CCS

Five bioethanol manufacturing facilities around the world currently capture 1.5 million tonnes of CO_2 ($MtCO_2$) per year.[42] This is less than 1% of the lower range of estimates of BECCS' technical potential. The US Decatur biorefinery is the only large-scale facility (it stores 1 $MtCO_2$ per year). It has only demonstrated the feasibility of the combined technologies for bioethanol production using maize. Other potential applications for BECCS have yet to be demonstrated at such a scale, particularly when using feedstocks that are more complex and heterogeneous such as waste. BECCS could also be used in different industries and energy-intensive industrial processes (such as steel, cement or paper).[49,50]

Challenges for developing BECCS

There are several challenges to overcome if BECCS is to provide negative emissions at scale.

Sustainability of bioenergy

The implications of increased bioenergy use are the main source of uncertainty when modelling the mitigation potential of BECCS in IAMs. Estimates of bioenergy by 2050 vary from 100 to 300 exajoules (EJ) per year (equivalent to 17 and 51% of the global primary energy supply in 2017, respectively).[51,52] However, high levels of bioenergy can have side effects with significant risks for:

- Food security (growing biomass for bioenergy competes with agricultural crops for land),
- Ecosystems and biodiversity (POSTnote 617),
- Water and nutrient scarcity (intensive use of soils and fertilisers can lead to land degradation).[2,53,54]

The most important factors affecting these risks are land availability and productivity.[2] The IPCC analysis suggests that bioenergy production should be sustainable, without providing a clear definition of the term. The definition of sustainability is often contested (POSTnote 408), but it is considered to have environmental, economic and social dimensions.[55]

In practice, the sustainability of bioenergy is often context-specific, depending on its location, feedstock, production method and supply chain. In particular, land-use change emissions associated with the expansion of bioenergy production will determine whether climate change benefits are realised (Box 2).

Estimates of additional land requirements for BECCS range from 100 million to 400 million hectares.[56] The biomass requirements for BECCS arising from most IAMs are much greater than the estimated amount of sustainable biomass that could be produced (around 100 EJ).[57] These models focus upon cost optimisation and do not take into account sustainability constraints, leading to potential scenarios with unsustainable large-scale use of BECCS.[58,59]

Sustainability Criteria for Bioenergy

The Global Bioenergy Partnership, an intergovernmental initiative, defines 24 indicators for sustainable bioenergy around three dimensions (environmental, social and economic). These include life cycle GHG emissions, jobs in the energy sector, the price of a national food basket and infrastructures for bioenergy distribution.[60] The International Organization for Standardization has developed bioenergy sustainability criteria (ISO 13065). These are used to compare bioenergy processes or products, but do not set any thresholds or limits.[61]

The EU Renewable Energy Directive requires that large scale heat and power bioenergy systems deliver an 80% emissions reduction compared to existing fossil fuel systems by 2026. This is based on life cycle analysis, which includes direct and indirect land use change emissions.[62] In the UK, the Renewable Obligation and Renewable Transport Fuel Obligation look at sustainability beyond carbon accounting.[63–65] Similarly, in California, the Renewable Fuel and Low Carbon Fuel Standards were created to decarbonise road transportation fuels and include CCS aspects to incentivise negative emissions.[70] However, these policies provide a flat incentive for saving

Box 2: Carbon cycle and payback time of bioenergy

Biomass at maturity, on a given area of land, is known as a carbon stock. Plants still actively storing CO_2 (including even mature forests) are referred to as carbon sinks.[66,67]

CO_2 emissions from burning biomass are counted as 'zero' in the energy sector to avoid double-counting, because carbon loss from harvesting plants is counted in the land sector. The carbon accounting in the two sectors are not linked and has led to the widespread perception that bioenergy is always 'carbon neutral'. In reality, net emissions from bioenergy can be substantial depending on their carbon cycle.[68] Dedicated energy crops have short carbon cycles (<2 years) so the CO_2 emitted upon combustion can be re-sequestered by crop regrowth. For forests, however, regrowth is much slower. The time needed to offset the carbon emitted from bioenergy combustion depends on several factors:

- The nature of the feedstock (and if it is regrown)
- The carbon stock of the land before harvesting (initial carbon debt)
- Indirect land use change emissions
- Bioenergy supply chain emissions (such as transportation).[69]

The point at which this carbon debt will be paid back is called the carbon payback period (or carbon break even time). This amount of time can vary from one or two years (marginal land, dedicated woody crops) to more than hundreds of years (wood from mature natural forests).

carbon relative to fossil fuels, and do not incentivise any further savings.[71] Moreover, current sustainability schemes do not include emissions from the conversion of biomass itself to energy (Box 2).

Trade-offs in biomass uses for BECCS
There is debate about which biomass resources could be used for BECCS to deliver negative emissions.[72–76] This is in part because of the carbon accounting frameworks as well as differences in payback time of different feedstocks (Box 2).[77] Forests provide services such as amenity values, biodiversity and soil stabilisation, as well as construction products and bioenergy.[16,69] Residues from the timber, board or paper industries are used for bioenergy because they have short carbon payback periods.[78] However, The European Academies' Science Advisory Council (EASAC) advised that whole trees should only be used for materials and construction, as atmospheric levels of CO_2 released from the combustion of stem wood can have negative impacts on the climate (increased GHG emissions) for decades to centuries.[79,80] EASAC concluded in 2019 that relying on forest biomass for renewable energy increases the risks of exceeding the Paris targets.[72,81,82]

The International Energy Agency stresses that current sustainability frameworks need to be reinforced to:

- Fully integrate the carbon impact of supply chains, especially with forestry management schemes. The carbon removed using BECCS may be negated if emissions rise from long payback times (Box 2) and supply chain emissions.[83]
- Understand the interconnections between bioenergy and food security.
- Promote transparency in land use change and forestry resources management.[31]

Technical and economic challenges
Technological and economic challenges for BECCS include:

- Engineering challenges from using biomass instead of fossil fuels in power and industrial plants (such as lower energy density, higher ash content, and the presence of corrosive elements and alkali deposits).[84,85]
- The scale of capital and operational costs, as well as the energy penalty from CO_2 capture.[26,86] In some cases, CO_2 capture units can be retrofitted to existing power and industrial plants. However, some argue that new alternative low carbon facilities would have higher energy efficiency and capture more of the CO_2.[43]
- Vicinity to existing CCS clusters. In addition to a sustainable biomass supply chain, BECCS facilities would need access to CO_2 transport and storage infrastructures, which are yet to be built.[45] The UK Government has identified five potential CCS clusters across the UK. However, the longer it takes to implement CCS, the more likely it is that BECCS would be a dominant use around which facilities should be clustered.[87,88]

Governance of BECCS
The rate of deployment of BECCS will depend on both CCS and GGR future policy frameworks.[89] There is currently no international policy mechanism in place to support the implementation of BECCS. This is particularly an issue when the supply chain is geographically dispersed or has yet to be put in place (with implications for biomass import, CCS infrastructure and offshore CO_2 storage).

Incorporating BECCS into carbon markets
'Carbon markets' are mechanisms that put a price on CO_2 emissions to incentivise firms to install CO_2 reduction measures, such as energy efficiency or CCS. Including BECCS within carbon markets, so that operators earn revenue for permanently storing CO_2, is often considered to be an economically efficient way of supporting it.[90,91] However, no existing carbon market currently includes negative emissions. The EU Emissions Trading System (EU ETS), the largest carbon market globally, does not currently differentiate between reducing industrial emissions and actively storing them.[92] The '45Q' carbon tax credit in the US has supported CCS, but mainly for enhanced oil recovery projects. It has no mechanism to consider the negative emissions potential of projects.[93] New policy measures to incentivise a positive impact on the climate through permanent CO_2 removal would be needed for BECCS and other GGR.

Public acceptability
An assumption implicitly used in IAMs is that the social acceptability of GGR technologies will be a barrier to their development.[94] There have been a number studies on the public acceptance of CCS alone, some of whose findings could be applicable to BECCS.[95] Biomass for bioenergy on its own has a relatively high acceptability of 70% in the UK.[96] However, some researchers argue a whole systems approach is needed to consider the bioenergy, CCS and negative emissions aspects at a social level, together with carbon accounting and technological considerations.[97] This would involve engaging affected communities and other stakeholders.[18,98]

UK approaches
The Committee on Climate Change (CCC) suggested in 2019 that GGR will be needed to achieve the statutory UK target of net zero GHG emissions by 2050, and that UK afforestation will provide only part of this. According to CCC modelling, the UK mitigation potential of BECCS ranges from 20 to 51 $MtCO_2$ (equivalent to 5-14% of UK CO_2 emissions at 2018 levels).[88,104] A 2019 report on GGR, commissioned by BEIS, suggested that BECCS will be one of the largest GGR options in the UK.[100] The UK Government will set out preferred options for CCS business models in early 2020 (GGR technologies will not be included).[101] A UKRI Strategic Priorities Fund of £32 million was created in 2019 to demonstrate GGR technologies, including BECCS, and address their challenges.[102] Achievement of negative emissions at scale remains uncertain and will require transparent and flexible policy mechanisms.[103] The report suggested several policy pathways and short-term measures to develop a market for GGR before 2050. These include integrating BECCS in the EU ETS, supporting pilot and demonstration schemes, and investing in CCS infrastructures.[100]

The Drax power plant in North Yorkshire is the first trial BECCS project in the UK. Two-thirds of its generators use wood pellets to produce power, and the site has a demonstrator carbon capture unit to capture around one tonne of CO_2 per day. Drax plans to scale up this technology by 2027 and investigate CCS transport and storage in the North Sea.[99]

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Endnotes

1. IPCC (2018). *Special Report: Global Warming of 1.5 ºC.*
2. IPCC (2019). *Special Report: Climate Change and Land*.
3. Royal Society, Royal Academy of Engineering (2018). *Greenhouse Gas Removal*.
4. IPCC (2014). *Fifth Assessment Report WGI: Summary for policymakers*.
5. IPCC (2019). *Climate Change and Land: Summary for Policymakers*.
6. Doelman, J. C. *et al.* (2019). Afforestation for climate change mitigation: Potentials, risks and trade-offs. *Glob. Change Biol.*,
7. Fuss, S. *et al.* (2014). Betting on negative emissions. *Nat. Clim. Change*, Vol 4, 850–853.
8. Mander, S. *et al.* (2018). The Climate-Change Mitigation Challenge. in *Biomass Energy with Carbon Capture and Storage (BECCS): Unlocking Negative Emissions*. 187–203. John Wiley & Sons, Ltd.
9. EASAC (2018). *Negative emission technologies: what role in meeting Paris Agreement targets?*
10. IPCC (2018). *Global Warming of 1.5°C: Summary for Policymakers*.
11. Smith, P. *et al.* (2016). Biophysical and economic limits to negative CO2 emissions. *Nat. Clim. Change*, Vol 6, 42–50.
12. National Farmers Union (2019). *Achieving Net Zero: Farming's 2040 Goal.*
13. Tokarska, K. B. *et al.* (2019). Path independence of carbon budgets when meeting a stringent global mean temperature target after an overshoot. *Earths Future*, Vol 7,
14. Ricke, K. L. *et al.* (2017). Constraints on global temperature target overshoot. *Sci. Rep.*, Vol 7, 1–7.
15. Tachiiri, K. *et al.* (2019). Effect on the Earth system of realizing a 1.5°C warming climate target after overshooting to the 2°C level. *Environ. Res. Lett.*,
16. Röder, M. *et al.* (2019). Understanding the timing and variation of greenhouse gas emissions of forest bioenergy systems. *Biomass Bioenergy*, Vol 121, 99–114.
17. Lenton, T. M. *et al.* (2019). Climate tipping points — too risky to bet against. *Nature*, Vol 575, 592–595.
18. Gough, C. *et al.* (2018). Social and Ethical Dimensions of BECCS. in *Biomass Energy with Carbon Capture and Storage (BECCS): Unlocking Negative Emissions*. 251–276. John Wiley & Sons, Ltd.
19. Lenzi, D. (2018). The ethics of negative emissions. *Glob. Sustain.*, Vol 1,
20. Realmonte, G. *et al.* (2019). An inter-model assessment of the role of direct air capture in deep mitigation pathways. *Nat. Commun.*, Vol 10, 1–12.
21. Minx, J. C. *et al.* (2018). Negative emissions—Part 1: Research landscape and synthesis. *Environ. Res. Lett.*, Vol 13, 063001.
22. van Vuuren, D. P. *et al.* (2018). Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. *Nat. Clim. Change*, 391–397.
23. Köberle, A. (2019). The Value of BECCS in IAMs: a Review. *Curr. Sustain. Energy Rep.*, Vol 6, 107–115.
24. Hausfather, Z. (2018). Explainer: How 'Shared Socioeconomic Pathways' explore future climate change. *Carbon Brief*.
25. Larkin, A. *et al.* (2018). What if negative emission technologies fail at scale? Implications of the Paris Agreement for big emitting nations. *Clim. Policy*, Vol 18, 690–714.
26. Fuss, S. *et al.* (2018). Negative emissions—Part 2: Costs, potentials and side effects. *Environ. Res. Lett.*, Vol 13,
27. Anderson, K. *et al.* (2019). Debating the bedrock of climate-change mitigation scenarios. *Nature*, Vol 573, 348–349.
28. Falano, T. *et al.* (2018). Life Cycle Assessment. in *Biomass Energy with Carbon Capture and Storage (BECCS): Unlocking Negative Emissions*. 117–127. John Wiley & Sons, Ltd.
29. Schakel, W. *et al.* (2014). Comparative life cycle assessment of biomass co-firing plants with carbon capture and storage. *Appl. Energy*, Vol 131, 441–467.
30. Gibon, T. *et al.* (2017). Life cycle assessment demonstrates environmental co-benefits and trade-offs of low-carbon electricity supply options. *Renew. Sustain. Energy Rev.*, Vol 76, 1283–1290.
31. IEA (2017). *Technology Roadmap: Delivering Sustainable Bioenergy*.
32. Welfle, A. *et al.* (2018). The Supply of Biomass for Bioenergy Systems. in *Biomass Energy with Carbon Capture and Storage (BECCS): Unlocking Negative Emissions*. 17–46. John Wiley & Sons, Ltd.
33. Stafford, W. *et al.* (2017). WIDER Working Paper 2017/87 - Biofuels technology: A look forward.
34. Committee on Climate Change (2018). *Biomass in a Low-Carbon Economy*.
35. Welfle, A. *et al.* (2014). Securing a bioenergy future without imports. *Energy Policy*, Vol 68, 1–14.
36. Zhang, D. *et al.* (2019). Unlocking the potential of BECCS with indigenous sources of biomass at a national scale. *Sustain. Energy Fuels RSC Publ.*,
37. Fajardy, M. *et al.* (2018). Investigating the BECCS resource nexus: delivering sustainable negative emissions. *Energy Environ. Sci.*, Vol 11, 3408–3430.
38. Thornley, P. *et al.* (2013). Biofuels: balancing risks and rewards. *Biofuels Sci. Soc.*, Vol 3,
39. Fajardy, M. *et al.* (2019). BECCS deployment: a reality checkv. *Grantham Institute Briefing paper No 28*.
40. Fajardy, M. *et al.* (2017). Can BECCS deliver sustainable and resource efficient negative emissions? *Energy Environ. Sci.*, Vol 10, 1389–1426.
41. CO2RE Database [online]. Global CCS Institute. Accessed 04/03/20.
42. Global CCS Institute (2019). *Bioenergy and Carbon Capture and Storage 2019 Perspective*.
43. IEA (2016). *20 Years of Carbon Capture and Storage*.
44. British Geological Survey (2006). Industrial CO2 emissions and CO2 Storage Potential in the UK.
45. Hammond, G. P. (2018). System Characterisation of Carbon Capture and Storage (CCS) Systems. in *Biomass Energy with Carbon Capture and Storage (BECCS): Unlocking Negative Emissions*. 129–162. John Wiley & Sons, Ltd.
46. BEIS [online]. Carbon Capture and Storage Knowledge Sharing Platform. Accessed 04/03/2.
47. ETI (2015). Building the UK Carbon Capture and Storage Sector by 2030.
48. Hepburn, C. *et al.* (2019). The technological and economic prospects for CO 2 utilization and removal. *Nature*, Vol 575, 87–97.
49. The Bellona Foundation *et al.* (2018). From Mitigation to Negative Emissions: The Case for Bio CCS in the Nordics.
50. Bhave, A. *et al.* (2017). Screening and techno-economic assessment of biomass-based power generation with CCS technologies to meet 2050 CO2 targets. *Appl. Energy*, Vol 190, 481–489.
51. IPCC (2012). *Renewable Energy Sources and Climate Change Mitigation*.
52. IEA [online]. Global Energy Statistics. Accessed 04/03/20.
53. Heck, V. *et al.* (2018). Biomass-based negative emissions difficult to reconcile with planetary boundaries. *Nat. Clim. Change*, Vol 8, 151.
54. Smith, P. (2018). Bioenergy in the IPCC Assessments. *GCB Bioenergy*, 428–431.
55. United Nations (1987). *Bundtland Report*.

56. Vaughan, N. E. *et al.* (2018). Evaluating the use of biomass energy with carbon capture and storage in low emission scenarios. *Environ. Res. Lett.*, Vol 13, 044014.
57. Harper, A. B. *et al.* (2018). Land-use emissions play a critical role in land-based mitigation for Paris climate targets. *Nat. Commun.*, Vol 9, 1–13.
58. Bauer, N. *et al.* (2018). Global energy sector emission reductions and bioenergy use: overview of the bioenergy demand phase of the EMF-33 model comparison. *Clim. Change*,
59. IPCC (2019). *Climate Change and Land Report: Summary for Policymakers*.
60. Global Bioenergy Partnership [online]. GBEP Report on Sustainability Indicators for Bioenergy. Accessed 04/03/20.
61. International Organisation for Standardization (2015). ISO 13065.
62. European Commission [online]. Renewable Energy Directive. Accessed 04/03/20.
63. Ofgem (2016). Biomass sustainability.
64. Thornley, P. *et al.* (2009). Sustainability constraints on UK bioenergy development. *Energy Policy*, Vol 37, 5623–5635.
65. Upham, P. *et al.* (2009). Substitutable biodiesel feedstocks for the UK: a review of sustainability issues with reference to the UK RTFO. *J. Clean. Prod.*, Vol 17, S37–S45.
66. IEA Bioenergy [online]. Carbon Neutrality. Accessed 04/03/20.
67. The Royal Society (2001). *The Role of Land Carbon Sinks in Mitigating Global Climate Change*.
68. Harvey (2018). Congress Says Biomass Is Carbon-Neutral, but Scientists Disagree. *Scientific American*.
69. EASAC (2017). *Multi-functionality and Sustainability in the European Union's Forests*v.
70. California Air Resources Board [online]. Low Carbon Fuel Standard Program. Accessed 04/03/20.
71. Thornley, P. *et al.* (2015). Maximizing the greenhouse gas reductions from biomass: The role of life cycle assessment. *Biomass Bioenergy*, Vol 81, 35–43.
72. EASAC (2018). *Commentary on Forest Bioenergy and Carbon Neutrality*.
73. Brack, D. (2017). *Woody Biomass for Power and Heat*. Chatham House.
74. Kulhlmann, W. (2018). Are Forests the New Coal? *Environ. Pap. Netw.*, 6.
75. EU Biomass Legal Case [online]. The Case. Accessed 04/03/20.
76. FERN (2018). *Six problems with BECCS*.
77. Tanzer, S. E. *et al.* (2019). When are negative emissions negative emissions? *Energy Environ. Sci.*, Vol 12, 1210–1218.
78. Committee on Climate Change (2018). *Sustainable Forest Management (Annex 1).*
79. Ter-Mikaelian, M. T. *et al.* (2015). The Burning Question: Does Forest Bioenergy Reduce Carbon Emissions? A Review of Common Misconceptions about Forest Carbon Accounting. *J. For.*, Vol 113, 57–68.
80. Forest Research (2018). *Carbon impacts of biomass consumed in the EU*.
81. EASAC (2019). *Forest bioenergy, carbon capture and storage, and carbon dioxide removal: an update.*
82. Norton, M. *et al.* (2019). Serious mismatches continue between science and policy in forest bioenergy. *GCB Bioenergy*, Vol 11, 1256–1263.
83. Smith, P. *et al.* (2000). Transport carbon costs do not negate the benefits of agricultural carbon mitigation options. *Ecol. Lett.*, Vol 3, 379–381.
84. Finney, K. N. *et al.* (2018). Post-combustion and Oxy-combustion Technologies. in *Biomass Energy with Carbon Capture and Storage (BECCS): Unlocking Negative Emissions*. 47–66. John Wiley & Sons, Ltd.
85. Gough, C. *et al.* (2018). *Biomass Energy with Carbon Capture and Storage (BECCS): Unlocking Negative Emissions*. John Wiley & Sons, Incorporated.
86. Bhave, A. *et al.* (2018). Techno-economics of Biomass-based Power Generation with CCS Technologies for Deployment in 2050. in *Biomass Energy with Carbon Capture and Storage (BECCS): Unlocking Negative Emissions*. 93–113. John Wiley & Sons, Ltd.
87. CCUS Cost Challenge Taskforce (2018). *Delivering Clean Growth*.
88. Committee on Climate Change (2018). *Net Zero: The UK's contribution to stopping global warming*.
89. Anandarajah, G. *et al.* (2018). The Future for Bioenergy Systems: The Role of BECCS? in *Biomass Energy with Carbon Capture and Storage (BECCS): Unlocking Negative Emissions*. 205–226. John Wiley & Sons, Ltd.
90. Nemet, G. F. *et al.* (2018). Negative emissions—Part 3: Innovation and upscaling. *Environ. Res. Lett.*, Vol 13, 063003.
91. Bellamy, R. (2018). Incentivize negative emissions responsibly. *Nat. Energy*, Vol 3, 532–534.
92. Thornley, P. *et al.* (2018). Policy Frameworks and Supply-Chain Accounting. in *Biomass Energy with Carbon Capture and Storage (BECCS): Unlocking Negative Emissions*. 227–250. John Wiley & Sons, Ltd.
93. Carbon Sequestration Leadership Forum (CSLF). (2018). *Technical Summary of Bioenergy Carbon Capture and Storage*.
94. Reiner, D. (2018). Investigating Moral Hazard and Other Imagined Threats of Negative Emissions Technologies.
95. Fridahl, M. (2017). Socio-political prioritization of bioenergy with carbon capture and storage. *Energy Policy*, Vol 104, 89–99.
96. BEIS (2019). *BEIS Public Attitudes Tracker (Wave 31 Key Findings).*
97. Gough, C. *et al.* (2019). Beyond social acceptability: applying lessons from CCS social science to support deployment of BECCS. *Current Sustainable/Renewable Energy Reports*, Vol 6, 116-123.
98. Bellamy, R. *et al.* (2019). Perceptions of bioenergy with carbon capture and storage in different policy scenarios. *Nat. Commun.*, Vol 10, 743.
99. Drax [online]. £5m Boost to scale up ground-breaking carbon capture pilot at Drax, UK's largest power station. Accessed 04/03/20.
100. Vivid Economics (2019). *Greenhouse Gas Removal Policy Options*.
101. BEIS (2018). *The UK Carbon Capture, Usage and Storage (CCUS) Deployment Pathway: an Action Plan*.
102. BBSRC [online]. SPF Greenhouse Gas Removal Demonstrators. Accessed 04/03/20.
103. REA (2019). *Going Negative: Policy Proposals for UK Bioenergy with Carbon Capture and Storage (BECCS)*.
104. BEIS (2019). *2018 UK Greenhouse Gas Emissions, Provisional Figures*.