The role of bioenergy with carbon capture and storage in the UK's sustainable future

Report of workshop hosted by the Royal Society and the Nature-based Solutions Initiative focusing on the sustainability of biomass supply.

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Contents

Summary

This report describes a workshop at the Royal Society that brought together a **diverse mix of experts from different sectors** to explore *The Role of Bioenergy with Carbon Capture and Storage (BECCS) in the UK's Sustainable Future*, with a focus on the potential sustainability of different feedstocks. The workshop aimed to provide an independent forum for participants to explore the key areas of agreement, disagreement and knowledge gaps across the community. This report summarises the workshop discussions but is not a detailed evidence review.

While participants offered a range of views, most agreed that BECCS has the **potential to deliver negative emissions** but that this was highly case-specific, and some were also concerned that the full life-cycle emissions and removals over time are not always clearly reported in climate models and national carbon accounting frameworks. There were mixed views on the use of **unabated bioenergy combustion for power generation,** with most agreeing that this is not a good use of limited biomass resources and should only be considered for genuine waste feedstocks with no alternative uses.

Several **significant concerns** were highlighted, mainly around the use of forest biomass, the dominant BECCS feedstock, and particularly if scaling-up led to increased extraction of biomass from biodiverse natural forests (as planned in the US and UK) rather than from plantations. Issues included the **carbon balance** (long payback periods for wood pellets from some sources), **biodiversity impacts** (including legal felling of old-growth forest for biomass), contradictory evidence on the impacts of forest biomass extraction on **fire risk**, competing uses of **land and resources** (including for higher value bioeconomy products), and **social impacts** on vulnerable local communities. Most participants viewed feedstocks such as waste and domestically produced short-rotation coppice or energy grasses such as miscanthus as potentially more sustainable, though with some questions around the impacts and feasibility of scaling-up.

As a result, **many voiced strong concerns that current evidence on sustainable biomass supply does not support BECCS deployment at the scales implied by the CCC's 6th Carbon Budget and heavily BECCS-dependent climate-economic Integrated Assessment Model (IAM) scenarios.** There were different views on whether the risks and uncertainties raised are relatively minor in the context of the need for BECCS in climate strategies, and are already being overcome; or whether they represent severe threats to biodiversity that inherently limit sustainable deployment of BECCS to low levels. A deeper exploration of systemic impacts and decision-making in the context of these far-reaching uncertainties and different priorities and concerns could be useful.

Modelling indicates that **Net Zero could in principle be achieved with lower reliance on BECCS,** through a transformational approach focussed on demand reduction. Participants' perspectives on the need for BECCS were mixed, and linked to their views on the challenge of delivering this demand reduction vs the challenge of delivering a genuinely sustainable supply of BECCS feedstocks to meet growing global demand.

Since the workshop, the UK's 7th Carbon Budget has been released, which requires 40% less BECCS than the 6th Carbon Budget and aims to phase out imported biomass feedstock by 2050. This direction of travel aligns with some of the concerns presented in this report.

1. Introduction

1.1. Aim of the workshop

The role of Bioenergy with Carbon Capture and Storage (BECCS) as a carbon dioxide removal option has become a controversial topic in recent years, particularly regarding feedstock sustainability. While previous work such as the BECCS Done Well report[1] addressed these issues to some extent, there was little input from many of those most concerned about BECCS.

The Royal Society and the Nature-based Solutions Initiative (NbSI) therefore jointly hosted a one-day workshop on 25 September 2024, to explore *The Role of BECCS in the UK's Sustainable Future*. This workshop was held as an **independent forum** for a diverse mix of participants to explore the key areas of agreement, disagreement and knowledge gaps across the community.

The workshop aimed to discuss the role and scale of BECCS in the UK's climate change mitigation pathways, as well as its opportunities and risks both locally and globally, in the context of wider cross-sectoral demands for biomass. It focused on the environmental risks and opportunities of potential sources of biomass, rather than the feasibility of carbon capture and storage technology. We hoped to identify recommendations for policymakers on how to ensure that BECCS delivers genuine benefits for climate change mitigation while also protecting biodiversity in feedstock source areas.

This report offers a summary of the discussions, but it is not a detailed evidence review. We aim to present the full range of perspectives and identify where further work could help to address areas of uncertainty and disagreement.

1.2. How the workshop was run

We aimed to invite a **broad cross-section of people** with different expertise and perspectives, all with significant prior experience and knowledge of some aspect of BECCS and/or bioenergy feedstock sourcing (see Appendix 1). These included industry representatives, researchers (in ecology, agriculture, plant science, forestry, energy, geoscience, engineering, climate science and policy, environmental science and policy, food and land use systems, economics and systems analysis), consultants and NGOs. Collectively, we aimed to achieve coverage of expertise across different feedstocks, source countries, and potential impacts on ecology, carbon and local communities. Many attendees had interdisciplinary expertise covering several of these areas, which was helpful for identifying potential synergies and trade-offs between climate, biodiversity and socio-economic goals.

To gather perspectives from other countries that are key suppliers of biomass while avoiding the climate impacts of air travel, we held three small online advance workshops for

experts from the US, Canada and Brazil. These informed a series of short presentations at the beginning of the in-person workshop.

Participants were asked to complete a survey before the workshop on the extent to which they agreed, disagreed, or were uncertain about a range of statements on the risks, challenges and opportunities of BECCS, including the different potential feedstocks. These questions aimed to stimulate thinking about different issues and gather a range of views to inform discussions.

The workshop was held under Chatham House rules with professional facilitators. The agenda (see Appendix 1) opened with a series of short presentations including a brief summary of the outcome of the BECCS Done Well report, an overview of recent systems modelling on the role for BECCS in the UK's climate pathways (see Section 3.2), and reporting back on the pre-event online workshops covering issues around forest feedstocks from North America and Brazil (see Section 3.3). This was followed by round-table discussions, firstly on the risks and opportunities of different types of feedstocks, then identifying any areas where there was a need for more work. Finally there was a Mentimeter vote on the overall level of confidence in different feedstocks, before a concluding discussion.

1.3. This workshop report

Notes of the discussions were taken by Royal Society scribes and then edited into a preliminary report which was circulated to participants for feedback. There was a round of subsequent editing and fact-checking to take account of feedback. While this is not an evidence review, it cites some references including:

- background sources used to inform the workshop presentations
- references cited by the participants during discussions
- references added by the RS and NbSI as part of fact-checking when revising the report.

In Section 2, based on the workshop discussions, we highlight key messages for policymakers where more attention is needed to ensure BECCS is deployed at a sustainable scale, with appropriate feedstocks that will avoid harm to biodiversity in a clearly verifiable way, as part of an integrated climate-nature policy framework.

Section 3 introduces the key issues that were discussed, presenting the main arguments around carbon balance, sustainability and other impacts of BECCS. Section 4 describes the discussions for each group of BECCS feedstocks, summarised in Section 5. Finally, Section 6 offers some concluding remarks and Section 7 lists key research questions. The agenda and list of participants are Appendix 1.

1.4. Background information

Here we note some key facts and figures of relevance for understanding the context of this report.

1.4.1. Role of bioenergy in the UK's energy system

- Around 15% of the UK's total energy (for heat, power and transport) is renewable (46% of electricity, 9% of heat and 6% of transport fuels).[2]
- Of this, around 8% is derived from biomass (12% of electricity generation, 5% of heat and 6% of transport fuels).
- 55% of biomass used for bioenergy is solid (providing 7% of electricity) and the rest mainly from biogas (landfill gas, anaerobic digestion) and energy-from-waste.
- 30% of biomass is imported, including 40% of solid biofuels and 70% of liquid biofuels.[3]

The 2023 UK Biomass Strategy[4] aims to transition away from unabated biomass towards use of BECCS where possible, which drives increased demand for biomass feedstock. This is expected to come both from the UK and from imports, though the strategy notes that increased global competition for biomass makes estimates uncertain, and more work is required to ensure that sourcing from forests overseas does not contribute to indirect land-use change. In the UK, although quantities of biogenic solid waste are expected to decline in line with waste reduction ambitions, the strategy anticipates greater production of perennial energy crops and scaling up extraction of biomass from UK forests, including semi-natural forests (see Section 4.2 for definition).

1.4.2. Role of BECCS in the UK's carbon budgets

CCS can in theory be applied to several forms of biomass use:

- Power generation,
- Combined heat and power generation,
- Waste-to-energy plants,
- Industrial heat plants, and
- Biohydrogen and biofuel production plants.

The **6th Carbon Budget** assumed 53 Mt CO_2 / year removed by BECCS by 2050. In the **7th Carbon Budget**, released after the workshop, this was halved to 25 Mt CO_2 / year. Of this, 10 Mt is from domestic energy crops (SRC, SRF and Miscanthus), requiring 0.7 million hectares of land, around 3% of UK land area. This represents a shift away from using imported biomass feedstock to using mainly UK energy crops and biomass residues by 2050, on the grounds that this will facilitate higher sustainability standards. BECCS is projected to provide less than 2% of electricity generation in 2040, with no large-scale unabated biomass generation at high load-factors beyond the expiry of existing contracts in 2027.

1.4.3.Current feedstocks at BECCS pilot plants

Currently, there are BECCS pilot plants at Drax in Yorkshire, a former coal-fired power station that now burns only biomass. The feedstock reported by Drax (for the whole plant, not just BECCS pilots) in 2024[5] consists of:

46% Sawmill and other wood industry residues: Woody material produced during the processing of wood at the sawmill, such as sawdust, shavings, chips, and offcuts.

31% Low-grade roundwood - material which does not satisfy the quality standards set by the timber industry and is unsuitable for use in a sawmill.

16% Thinnings - Wood from a silvicultural operation where the main objective is to reduce the density of trees in a stand, improve the quality and growth of the remaining trees and produce a saleable product.

3% Agricultural residues - Non-woody processing residues, that are not the end product that a production process directly seeks to produce

3% Branches and tops - Tops, bark and limbs of trees that have been left behind post-harvest.

1% End of life trees - Trees that are felled because they have defective stems, are ill or damaged or trees that are removed from a plantation because they have reached the end of their productive lifetime or trees that must be removed for the permitted construction of infrastructures.

Most (90%) of the feedstock is wood pellets from the US and Canada, with 5% from Latvia, 1.5% from Brazil and 1% from Portugal. Only 0.6% is from the UK, exclusively agricultural residues.

Drax is a major player in the global wood pellet industry, with capacity to produce 5Mt of pellets per year across 17 pellet plants in the USA and Canada for its own power station and for other customers in Europe and Asia. They aim to grow this side of their business and are increasing their capacity to export wood pellets from forests in British Columbia, Canada.[6]

1.4.4.Carbon accounting systems for bioenergy and BECCS

The IPCC greenhouse gas inventory accounting guidance specifies that carbon emissions from combustion of harvested biomass (from trees or energy crops) should be accounted for in the land-use sector, not in the energy sector. In practice, this means that when UK bioenergy or BECCS plants burn imported biomass, the carbon emissions are not included in the UK's carbon accounts; instead they should be included as a carbon loss in the forest sector in the country supplying the biomass. While this accounting system is useful for discouraging deforestation in source countries, critics point out that it provides an incentive for countries to burn imported biomass without considering the full carbon impacts. It could also lead to the carbon loss being effectively ignored if the source country is not signed up to the Paris Agreement. Some operators, including Drax, publish bioenergy combustion emissions for information, alongside supply chain emissions.

2. High level messages

The summary below is based on a combination of responses to the pre-workshop survey and discussions at the workshop. 'Most' indicates 50% or more of participants. Please note that the degree of agreement should not be interpreted as proof that the concept is true or false; it simply reflects the views of those present at the workshop.

Most agreed that **BECCS has the potential to deliver negative emissions**, which can help to offset emissions from hard-to-abate sectors, but this is not guaranteed. The extent and timing of net CO_2 impacts is highly dependent on the feedstock type, land management in the feedstock source area, supply chain emissions, BECCS technology, and the counterfactuals considered, including avoided emissions from alternative energy generation technologies and any alternative uses of the biomass.

There were strong views on the use of **unabated bioenergy combustion** for power generation, especially for forest feedstocks with long payback times and high supply chain emissions. As biomass produces higher combustion emissions per kWh than the current average UK electricity generation mix, most concluded that this is not a good use of limited biomass resources and should only be considered for genuine waste feedstocks with no alternative uses, though some still thought it had a role in reducing fossil fuel use.

Most agreed on the need for **full life-cycle assessment** of both biomass supply chain and combustion emissions in climate models and carbon accounting systems. In particular, many thought that the international convention of **assuming bioenergy to be carbon-neutral** and requiring carbon losses to be reported only at the point of harvest (thus ignoring combustion emissions for imported feedstocks) **may lead to flawed decision-making** when comparing bioenergy or BECCS against alternative energy technologies and climate policy options.

Participants highlighted several **significant concerns**, mainly around the use of **forest biomass**, the dominant BECCS feedstock, and particularly if scaling-up of demand for BECCS led to increased **sourcing from biodiverse natural forests** (as planned in both the US[7] and UK[8]) rather than existing managed plantations. These concerns included:

- A lack of unambiguous evidence confirming that current forest biomass harvesting practices are balanced by regrowth at the landscape scale, and disagreement over the boundaries and counterfactuals to use for these assessments.
- High scientific uncertainty on the soil carbon impacts when forests are harvested and residues removed.
- Contradictory evidence on whether forest biomass extraction increases or reduces fire risk under different circumstances.
- Significant differences in life cycle assessments of emissions of biomass feedstock production and use, depending on method and counterfactual used.
- Uncertainty over the climate risks if using forest feedstocks that may initially increase atmospheric greenhouse gas levels before ultimately reducing them. i.e. the climate implications of the 'payback period' before net carbon removals occur (this can also apply to some alternative carbon removal options such as planting trees, though carbon loss will be low unless planting on peaty soil).
- Concern over risks to nature from loss or degradation of natural ecosystems and direct or indirect land use change for new biomass plantations, especially at the higher end of BECCS deployment scenarios; this could be mitigated through freeing up marginal land via dietary change, though this land (especially rough grassland) is also needed for nature recovery.
- Concern that current forest biomass sustainability standards are not strong or clear enough to support the large-scale deployment of BECCS, with inadequate enforcement and fraudulent practices reported (by local NGOs) in the Americas (while noting a lack of peer-reviewed evidence on the extent of this issue).
- Recognition that it could be easier to ensure the sustainability of domestic biomass than for imports, but concern over conflict with land (especially rough grassland) needed for nature recovery; suggestion that land currently used for first generation biofuels (i.e. food crops) for transport could be repurposed for bioenergy crops as we transition to electric vehicles.

Modelling indicates that Net Zero can in principle be achieved with lower reliance on BECCS than currently envisaged in some international and domestic scenarios, but this would require transformative action to reduce energy demand. There were a range of views on the feasibility of this, with some concern that over-reliance on BECCS could deter investment in alternative pathways to net zero, but others convinced that BECCS was essential to meet climate targets. Caution was advised in basing targets for BECCS

deployment on global Integrated Assessment Models (IAMs), at least at present, as these currently do not have sufficient bottom-up detail needed to capture or address the concerns highlighted above and explored further below. In addition, as IAMs are not spatially explicit they do not reflect the variations in net carbon removal due to climate impacts on yield, initial soil carbon stocks, and transportation distance for feedstocks and CO_2. As such, while IAMs can reveal what may be theoretically feasible, they often overlook important production uncertainties (including those relevant to determining the full carbon balance over time) and fail to incorporate the full range of potential environmental and social impacts of biomass use**.**

Feedstocks have different opportunities and limitations. Participants were most confident about the potential sustainability of sawmill and paper industrial waste, followed by short rotation coppice (with potential wider benefits such as flood and erosion risk reduction), organic municipal and food waste, and crop residues, and were most uncertain about the sustainability of biomass from natural forests, followed by plantations, aquatic biomass and food crops (see Figure 3 for full lists). Energy grasses such as Miscanthus ranked in the middle of the list, with agreement that these could be sustainable if planted on low grade arable land to minimise competition with food production and nature recovery. While waste feedstocks were thought to be potentially more sustainable, their availability is limited and there are uncertainties over their economic and technical viability, although one pilot plant for municipal solid waste with CCS has recently started trials.

As a result of these considerations, **many concluded that current evidence on sustainable biomass supply does not support the deployment of BECCS at the scales implied by some Integrated Assessment Model (IAM) scenarios**, although **some participants strongly disagreed with this conclusion.** Views ranged from those deeply concerned about the high risks to ecological integrity and social equity posed by large-scale sourcing of certain feedstocks—who advocated greater emphasis on alternative climate-mitigation options—to those who saw BECCS as indispensable for meeting climate targets and considered other approaches unfeasible, and who therefore argued for moving ahead with implementation.

Further work is needed to address social and environmental supply chain impacts, develop more robust monitoring and enforcement strategies, understand impacts of forest biomass extraction on fire risk and ecology, explore the potential for waste feedstocks in more detail, further develop carbon accounting methodologies, and consider trade-offs with other uses of biomass and with land needed for nature recovery. However, some participants strongly advocated ‘learning by doing’, or developing new methods of decision-making to identify ‘low-regrets’ options, rather than more research aimed at ensuring supply chain sustainability.

3. Summary of key issues

This section summarises the key issues discussed at the workshop, presenting the main arguments and counter-arguments around the carbon balance of BECCS, the role of BECCS in net zero pathways, the sustainability of BECCS feedstocks, competition for resources, and other impacts. These arguments are taken from transcripts of the workshop discussions, comments submitted in the pre-event survey, information gathered during pre-workshop meetings, and the introductory presentations from the workshop.[9]

3.1. The carbon balance of BECCS

The carbon balance of BECCS depends on a range of factors:

- feedstock type and location
- feedstock characteristics (e.g. moisture and ash content)
- emissions from planting, cultivating, harvesting or collecting, processing, transport and both direct and indirect land-use change (including soil carbon changes)
- choice of baselines / counterfactuals
- assumptions on longevity of storage (though this was out of scope for the workshop).

The main area of debate is around **forest feedstocks**, especially on the appropriate counterfactual, timescale and geographic scale to consider. The arguments are complex, and there are key differences between feedstock sources (intensively managed plantations vs biodiverse natural forests) and types (clear-felled trees, thinnings, harvest residues), but can be very briefly summarised as follows:

- The fundamental argument driving use of bioenergy for climate mitigation is that it can be **carbon-neutral** over time, provided that the carbon extracted in feedstocks is replaced by new growth at landscape level, such that total carbon stored in ecosystems in the area affected by biomass extraction is stable or increasing. Hence, any long-term storage of the extracted carbon via BECCS can represent a carbon removal, provided that it is not exceeded by emissions from cultivation, harvesting, processing, transport and the CCS process. However, there is debate over the suitable area over which to measure changes in forest stocks, and the extent to which bioenergy harvesting affects total forest carbon stocks, with evidence that forest clearance is increasing around certain wood pellet plants in the USA.[10]

- The main counter-argument is that extracting and burning additional forest biomass for BECCS (i.e. if whole trees are harvested that would otherwise have been left standing) causes a loss of forest carbon stock and potential future carbon sequestration compared to a counterfactual where this extraction does not occur, regardless of what is happening in the wider landscape. However, it is also noted that the extent of foregone forest carbon sequestration is constrained by slowing down of sequestration rates as forests mature.
- There is also debate around **acceptable payback periods**. Combustion of biomass produces an immediate increase in emissions, even with carbon capture (given that less than 100% of the CO_2 is captured by the CCS process and that there are additional emissions from cultivating, harvesting, processing and transporting the biomass). While this CO_2 is gradually reabsorbed as new biomass grows, where whole trees have been harvested this can take many decades and may never be fully replaced, especially when accounting for soil carbon losses. The immediate emission increase is of particular concern if it contributes to exceeding climate 'tipping points' that breach Earth System thresholds, outweighing the potential longer-term benefits from carbon removal via BECCS. This leads some to argue that feedstocks with short payback periods should be prioritised, while others suggest that the appropriate payback period should be linked to a specific carbon budget (e.g. Net Zero by 2050).[11]

There are many additional complexities, showing that the carbon balance is highly case-specific. These include:

- **Comparison of life-cycle emissions from BECCS with alternative forms of energy generation**. For example, burning solid biomass can produce higher immediate emissions per kWh than fossil fuels due to relatively low combustion efficiency (related to ash and potassium content). While most of the CO_2 will be captured, BECCS could have slightly higher immediate emissions per kWh than fossil fuel CCS energy, and higher life-cycle emissions than wind, solar and hydropower, again depending strongly on the feedstock. For example, fitting CCS to energy-from-waste plants will have an immediate climate benefit by capturing existing emissions from waste combustion that would have occurred anyway.
- **Alternative uses of harvested biomass**, e.g. would harvest residue be left in forests (decaying partly into the soil and partly to the atmosphere) or would some be burnt in-situ (sometimes done to reduce fire risk), or collected and used for other products such as paper? Could low-grade roundwood be used for other products such as poles or chipboard? These issues are influenced by economic considerations.

- **The extent to which bioenergy feedstocks use genuine forestry by-products** or drive additional harvesting that would not otherwise have occurred, including of whole trees.
- **Whether harvesting biomass via thinning (in natural forests) can reduce risk of fire and pest damage**, or whether this increases fire risk and/or removes more carbon than would be lost to fire and pests (see section 2.3).
- **The extent to which future decarbonisation could reduce the life-cycle emissions** of harvesting, processing and transporting the biomass and powering the CCS process (including transporting the CO_2 to the disposal site).
- **Concerns over the transparency of the UNFCCC carbon accounting method** that counts carbon loss at the point of harvest, not on combustion. This means that when imported biomass is burnt in the UK, the direct combustion emissions are ignored. This can give a misleading picture of the actual impact on global CO_2 emissions when UK policymakers are deciding on support for different options.

3.2. Role of BECCS in climate mitigation targets and risk of mitigation deterrence

There is also a debate around the extent to which BECCS is needed to meet climate mitigation targets and potential impacts on funding for other GHG mitigation options. Participants expressed a wide range of views, from those who are persuaded that extensive use of BECCS is essential to those who were concerned that a large increase in biomass supply for BECCS is unsustainable and that alternative pathways had not received enough policy support.

While most Integrated Assessment Models assume that some use of BECCS is necessary, it has been argued that global scenarios indicating very high levels of carbon removal reflect the use of high discount rates and limited deployment of renewable energy and demand-side options.[12] To explore this, the seven Illustrative Mitigation Pathways presented in the IPCC's 6th Assessment Report model hypothetical scenarios that show how greenhouse gas emissions might change based on different societal choices and deployment of a range of technologies (**Figure 1**). The four scenarios that are compatible with limiting climate change to 1.5°C assume varying global deployment of BECCS, from zero in the 'Low demand' pathway (IMP-LD) to around 2 gigatonnes/year ($GtCO_2$/y) by 2100 in the 'Renewable energy' (IMP-REN) and 'Shifting to sustainability' (IMP-SP) pathways, and up to 8 $GtCO_2$/y in a scenario that envisages high overshoot of emissions targets followed by heavy reliance on Carbon Dioxide Removal technologies (IMP-Neg). However, it is argued that those scenarios may no longer apply given continuing global failure to follow the necessary emission reduction trajectory.

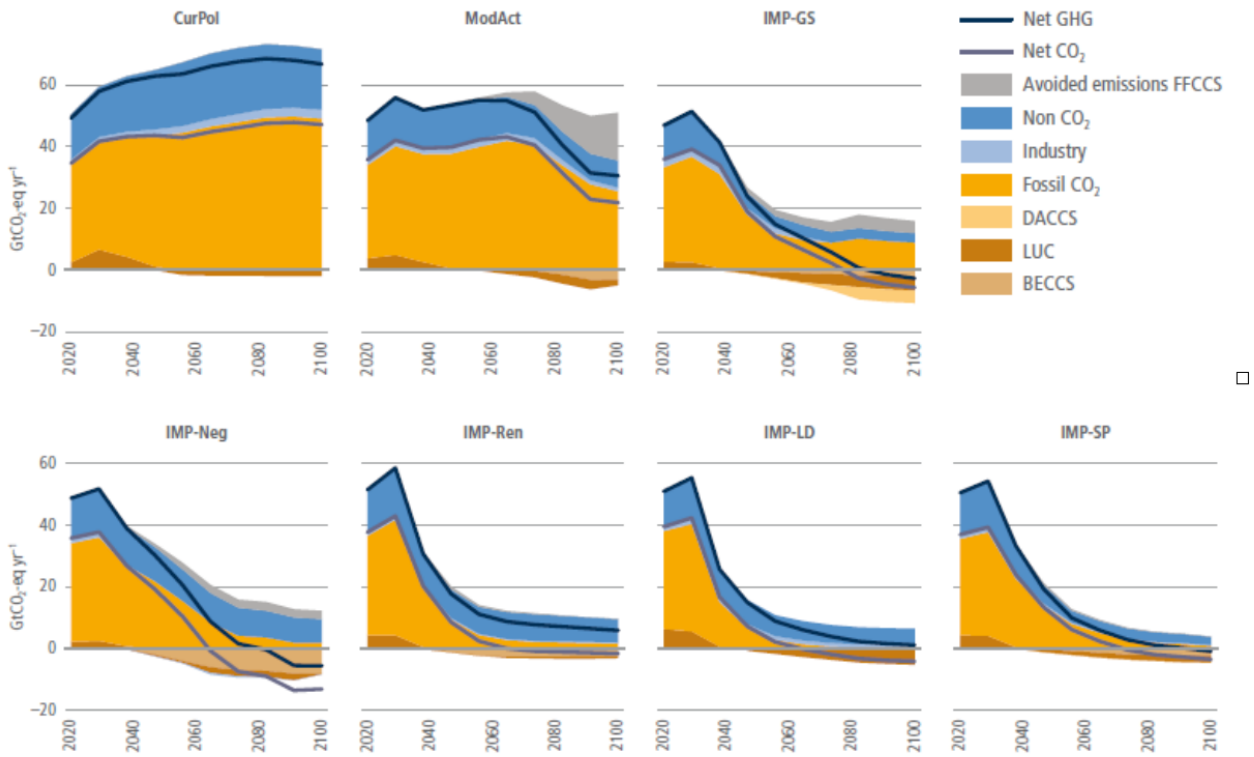


***Figure 1**. The residual fossil fuel and industry emissions, carbon dioxide removal (from land-use change (LUC), Direct air carbon capture and storage (DACCS) and BECCS), and non-CO_2 emissions for the seven illustrative mitigation pathways in the IPCC 6th assessment report.*[13]

UK-specific modelling presented at the workshop also indicates that transformative change in energy and material demand could achieve GHG targets without use of BECCS, with a 52% reduction in energy demand being possible without compromising quality of life (**Figure 2**). This would involve large-scale building retrofit, electrification of transport systems, spatial planning to reduce transport demand, renewable energy deployment, dietary change and a shift to a circular economy. Some participants were sceptical about the feasibility of achieving the necessary scale of demand reduction and argued that BECCS was essential to meet climate targets.

Others were concerned that relying on BECCS and other emission removal technologies could undermine the perceived need to invest in (and direct policies towards) efforts to reduce emissions through demand reduction and cleaner energy, which could provide additional co-benefits (such as clean air, lower energy bills, warmer homes and healthier lifestyles) and avoid some of the potential uncertainties and adverse impacts raised in relation to BECCS.

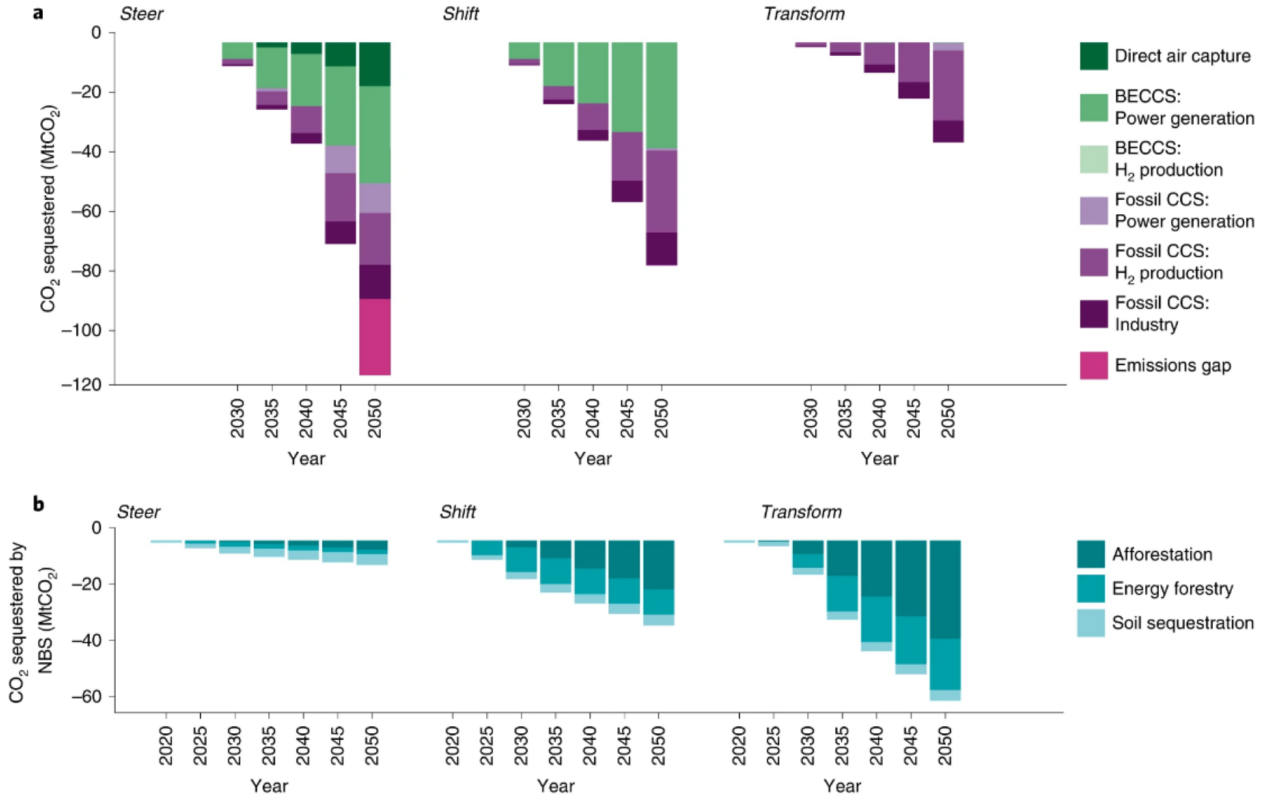


***Figure 2**. Three net zero scenarios modelled using UK-TIMES. **Steer**: current government policies as of 2018 plus energy efficiency options (31% demand reduction). **Shift**: more ambitious energy demand options with currently available technologies under current social and political framings (41% demand reduction). **Transform**: transformative change in technologies, social practices, infrastructure and institutions to deliver energy demand reductions of 52% alongside numerous co-benefits such as health, improved local environments, improved work practices, reduced investment needs and lower cumulative GHG emissions. Source: Barrett et al., 2022.* [14]

3.3. Biodiversity, pests and fires

While all participants agree that feedstocks for BECCS must be sustainable (in terms of biodiversity and carbon balance), there is debate over the extent to which this is currently being ensured, and whether or how it can be ensured in future. These issues are discussed for individual feedstocks in Section 4. Most debate centred on forest feedstocks, especially from North America, the major source for wood pellets imported to the UK (which has the highest imports of wood pellets globally), and in Brazil, a potential future source.

3.3.1.Biodiversity concerns

For forest feedstocks there is debate over biodiversity impacts, including the effectiveness of standards and monitoring. In the pre-workshop online meetings, stakeholders from the USA and Canada cited examples of clear felling in old-growth forests,[15] most of which are not legally protected,[16] and conversion of old-growth forests to plantations, which is incentivised by tax breaks[17] in North Carolina. Growing demand for wood pellets was reported to be opening up more old-growth forests for biomass harvesting.

Similarly, stakeholders in Brazil raised concerns about the risks of future tree plantation expansion encroaching on biodiversity priority areas,[18] as well as the vulnerability of eucalyptus (the major biomass tree crop in Brazil) to climate change in terms of thermal and water stress.[19] They also emphasised the potential for future wood shortages, which could drive more illegal logging. Current evidence indicates that a large portion of wood extraction in the state of Mato Grosso (Brazil's main supplier of native wood) is illegal, with significant amounts sourced from indigenous territories, giving rise to cultural impacts.[20] The need for stronger certification, monitoring and traceability of all feedstock sources was emphasised.

3.3.2.Fire risk and pests

There is intense debate over the role of forest biomass harvesting relating to fire. Policy is being driven by US Forest Service recommendations that almost all forests (including protected old growth forests) should be dramatically thinned to reduce fire risk,[21] for example removing two-thirds of the trees in Western forests,[22] with the wood used for pellet production.[23] However, other research concludes that thinning can increase fire risk by creating a hotter, drier, windier microclimate and encouraging growth of flammable grasses.[24] Critics of the thinning programme also highlight that fires are an essential part of fire-adapted forest ecosystems, and are necessary for species such as ponderosa pine and sequoia to regenerate. They also warn that the only effective way to reduce fire risk to property is to fire-harden buildings and clear vegetation immediately around habitation.

Similarly, in regard to thinning or clearance aimed at reducing pest outbreaks, species such as pine beetles are seen either as a pest, where stands with beetle damage can and should be legitimately clear-felled for bioenergy, or (at least for native 'pest' species) as an essential part of the forest ecosystem. Both fire and pests create dead wood habitat for species such as owls and woodpeckers.[25]

3.4. BECCS and competition for resources

From a wider system perspective, there are concerns that increasing demand for land[26] to grow biomass crops (including forestry plantations) will pose risks to food security and water supply, particularly in the context of already intense land-use competition (including for wind and solar power, housing, and nature recovery). While these land and water use concerns do not apply to biomass sources that are perceived as waste or by-products, further competition is highlighted between BECCS and alternative uses of biomass, such as increased utilisation of timber in buildings and other long-lived wood products, biofuels for transport (including aviation fuel) and industry (e.g. cement), or high-value bio-based alternatives to plastics and other fossil-derived commodities. On the other hand, there is scope for bioenergy and biomaterials to be produced together in forestry biorefineries.[27]

At a local level, there are concerns about social justice and equity. For example, the 'marginal and degraded land' typically targeted for biomass production by global models is often low-grade farmland that supports vulnerable social groups and marginalised communities, who may lack secure land tenure and are at risk of displacement. Similarly, there have been local protests in Brazil, India and Ghana against large-scale monoculture plantations of eucalyptus which has displaced people from their land and cut off access to water supplies.

Pre-workshop consultation with experts in Brazil highlighted that scaling-up of demand for BECCS feedstocks from the global North could exacerbate land-use pressures. They emphasised that the recovery and use of Brazil's degraded and marginal lands should be aligned to the country's own net zero commitment. These areas could support agricultural expansion while reducing the pressure on native ecosystems, helping to prevent deforestation, and enabling large-scale ecosystem restoration. In fact, nearly 80% of Brazil's net zero pledge could be met through nature-based solutions, particularly by ending deforestation and promoting large-scale ecosystems restoration.[28] Producing biomass for export to help other countries meet their net zero obligations would reduce the feasibility of this scenario.

There are also potential interactions between sectors related to biomass production. Strategic planning is needed for the sustainable production and use of biomass from tree plantations to meet diverse demands without exacerbating the risk of wood shortages, which could increase illegal deforestation of native forests. Rather than using land and valuable resources to produce cheap bioenergy feedstocks for export, local experts recommended that Brazil should maximise socio-economic benefits by producing high value-added bio-products.

Some participants made the broader point that using land for biomass production results in an 'opportunity cost' as it cannot be used to meet nature recovery targets. While forestry or biomass crops can provide ecological improvement if the land was previously used for intensive arable crops, any benefits will be low compared to specific nature restoration interventions. The balance of climatic and environmental benefits is location-specific and depends on the counterfactual (e.g. current land-use or potential ecological restoration), and the degree and permanence of environmental outcomes (including carbon storage) associated with ecological restoration.

3.5. Other impacts of BECCS

While not the focus of this workshop, other impacts raised included the following.

- Air quality and noise impacts of wood pellet processing plants, which release high levels of dust and volatile organic compounds and are often sited in communities already suffering from many other pollution sources.
- Risk of CO_2 pipeline leaks, with one pipeline rupture[29] having caused people to lose consciousness while emergency vehicles stalled due to the CO_2 levels.
- Concern that the high cost of BECCS could increase energy prices, although conversely it was also argued that BECCS would only be able to provide a small proportion of our existing energy supply due to the low efficiency of the process, which would naturally limit the impact on overall energy prices. It was noted that BECCS can be viewed primarily as a carbon removal technology with electricity as a by-product.
- Complex socio-economic impacts. For example, it was argued that production of wood pellets for BECCS can provide much-needed employment in areas faced by declining viability of the forestry industry in North America. Conversely, it was also argued that alternatives such as ecosystem restoration and regenerative agriculture can also provide employment, supported by recent evidence.[30]

4. Feedstock discussions

This section records the main points discussed for each major group of BECCS feedstocks, identifying the risks, opportunities and key uncertainties for each group.

4.1. Commercial forestry plantations

This section refers to harvesting of whole living trees and understorey for BECCS including from routine thinning to promote tree growth, thinning aimed at reducing fire risk, felling aimed at reducing pest damage, low-grade roundwood (trees harvested as part of clear-felling that are not sawmill quality) and short-rotation forestry (SRF) (purpose-grown bioenergy plantations with a 10-25 year rotation using fast-growing species such as Sitka Spruce or poplar hybrids). Use of storm-damaged wood, deadwood, bark and smaller branches is discussed in Section 3.4. Commercial forestry plantations may use either native or non-native species but tend to be even-aged monocultures with much lower biodiversity than natural / semi-natural forests.

Balance of risks and opportunities

Impacts of biomass supply from forestry plantations depend partly on whether biomass is taken from an existing plantation or whether demand drives conversion of other land to a new plantation. There was some support for use of biomass from existing forestry plantations as a BECCS feedstock, with caveats. Arguments in favour included providing a revenue stream for landowners to pay for thinning activities that increased the quality of the remaining timber. Arguments against included the risk that demand for biomass could drive conversion of natural forests to plantations, which is actively encouraged through tax breaks in some US states such as North Carolina. Participants noted that most in North America are private assets that operate within free markets, and it can be difficult to regulate, monitor and enforce standards. In addition, there were concerns over the risk that wood from old growth forests can be misclassified as plantation wood, leading to unintended consequences like ecosystem degradation. For example, as most wood is collected from the forest by private operators, there were concerns of inadequate monitoring of the source of wood entering pellet plants. Additionally, pellet production facilities were flagged for their potential local environmental impacts, such as air pollution and water use.

Participants also highlighted the EU guidance on the cascading use of biomass[31], which prioritises use of wood for material products, ideally followed by a series of stages of re-use, recycling or upcycling, before final use for energy recovery (with the opportunity for BECCS). Highest priority is the use of wood for construction or high-quality furniture, locking away forest carbon long-term while displacing energy-intensive materials such as metals and concrete, which are hard to decarbonise. Thus they identified growing potential for trade-offs between using plantation biomass directly for BECCS or as a material product, as even low-quality wood can be used for paper, particle board, laminates and other materials. However, it was recognised that if demand for timber as a low-carbon construction material

grows, this could increase the supply of biomass from thinnings and forestry residues.

There was little support for new intensively-managed forest plantations specifically for BECCS. The main arguments against this were competition with food production and space for nature, potential conversion of old growth forest to plantation to meet demand, and exacerbation of water scarcity in water-stressed areas.

Key uncertainties

The main uncertainty was around the counterfactual of what would happen to the carbon stored in a plantation if it was not harvested for BECCS. Might the forest remain unharvested, and therefore provide ongoing carbon storage (and potentially removal), or would the carbon be lost for another reason, such as harvesting (with carbon in short-lived products subsequently being lost), forest fires, burning of residues to reduce fire risk, or clearance for development? If BECCS drives additional harvesting of wood from plantations then some argued that this would increase net atmospheric CO_2 emissions (given that not all the carbon is captured, and there are supply chain emissions) compared with a scenario in which the wood was used for long-lived products or not harvested (when sequestration could continue). There was also uncertainty expressed around the supply chain emissions associated with harvesting, processing, and transportation, and the long-term impacts of biomass harvesting on soil health and biodiversity.

4.2. Semi-natural or natural forests

This section refers to extracting biomass (either as thinning or clear-felling, including on the grounds of reducing fire or windblow risk, salvage logging post-fire or post-windblow, or controlling pest outbreaks) from semi-natural or natural forests: either old-growth forests, secondary forest that has naturally regrown after felling, or deliberately restored / replanted forest using a mix of native species, not intended as a timber plantation. These forests typically support high levels of biodiversity.

Balance of risks and opportunities

Participants discussed the unique challenges and opportunities posed by using natural or semi-natural forests as a feedstock for BECCS. It was widely acknowledged that these forests offer immense biodiversity, carbon storage, and ecosystem services, which makes them valuable beyond their potential for biomass. Participants were concerned that extracting biomass from these highly biodiverse forests could have damaging impacts, and flagged the strong public desire to protect natural forests.

However, the role of thinning in these forests divided opinions. Those in favour of thinning suggested that it could improve forest health and resilience, including through reducing fire or windblow risk and controlling pest outbreaks, while also providing revenue to better support wider forest management. They also highlighted that some evidence suggests that thinning can improve carbon stock in forests through encouraging the growth of larger trees (although outcomes are mixed[32,33,34,35]). Others countered that it could result in negative ecosystem impacts, including through increasing fire risk, preventing natural

regeneration in fire-adapted forests, and reducing habitat for keystone species (see Section 3.3).

There was recognition that thinning decisions should extend beyond carbon storage to include assessment of wider impacts on natural capital and biodiversity, though valuing these services remains complex and inconsistent. It was suggested that decisions must take into account the wider landscapes and social-ecological context of individual forests, and conclusions may therefore vary on a case-by-case basis depending on the type of forest (e.g. boreal, temperate, tropical), its condition, and other local factors. However, it was also flagged that more research is required, e.g. on the impact of thinning on fire risks, before decisions are made on whether to scale up.

Concerns were raised about the effectiveness of standards for preventing logging of old growth forests for bioenergy. For example, many participants thought that current definitions of sustainable forest practices are not sufficient. Although certification schemes are intended to prevent deforestation in old growth forests, schemes have different definitions of what constitutes an old growth forest, and what is meant by sustainable/ unsustainable – including whether legal logging is permitted (the majority of old growth forests in North America are not legally protected, and logging of old-growth forests has increased in recent years). More clarity and coherence is needed across certifications. There was also discussion over whether standards are sufficiently tracked and/or enforced.

Some participants pointed out that while old-growth forests may sequester less carbon as they mature, they still provide vital ecological benefits as well as storing vast amounts of carbon. The growing demand for wood pellets also sparked debate, with questions about how it influences forestry practices, particularly in terms of the balance between maintaining forest ecosystems and meeting economic pressures. Research from tropical forests was cited, suggesting that selective logging might not be inherently bad for biodiversity, but this evidence was recognized as site-specific and not necessarily applicable to all forest types. Overall, participants were generally against the use of natural / semi-natural forests as a feedstock, however there was agreement that more evidence is required to address high uncertainty around forest management practices in the context of a changing climate and how much biomass can be ‘sustainably’ and ethically supplied. Participants emphasized the importance of sustainable practices that do not degrade forests’ ecological value or compromise biodiversity.

Key uncertainties

The discussion highlighted several uncertainties regarding the role of natural forests in BECCS. Key questions included the emissions associated with forest management, harvesting, and transportation, as well as the counterfactual scenarios for forests if BECCS demand were absent, including foregone carbon sequestration. Participants also noted the need for clear definitions of "old-growth forests" and "sustainable forest practices." The soil health and carbon impacts of repeated harvesting and the biodiversity implications of leaving or removing deadwood from forests remained contentious. Research and evidence across natural forests for BECCS was highlighted as being very mixed and site-specific, and further research needs such as quantitative research on total forest carbon, the long-term resilience of natural forests under climate change and the legitimacy of thinning practices were highlighted as requirements for better understanding of this feedstock. Examples from Scandinavia and New Zealand were cited, showcasing both positive and problematic outcomes from current forestry practices.

4.3. Short Rotation Coppice (SRC)

Balance of risks and opportunities

Short Rotation Coppice (SRC) crops, such as poplar or willow, were generally regarded as a promising feedstock for BECCS, particularly as they are purpose-grown for energy and can thrive on marginal land. Participants noted that SRC on marginal land could provide farmers with regular income through predictable harvest cycles, making it an attractive option. Some participants agreed that SRC's shorter rotation cycles set it apart from traditional forests, offering more flexibility and sustainability when managed correctly, while also potentially providing additional ecosystem services (soil carbon, nutrient regulation) compared to annual crops.

Despite these advantages, concerns emerged about land-use trade-offs. While SRC is often grown on marginal land, participants emphasized the need to ensure that this land is genuinely marginal and not displacing food production. Some attendees were surprised by the high confidence placed in SRC as a sustainable option, noting that it could still interact with the food system in the same way as herbaceous bioenergy crops [see section 4.7], while others countered that food yields on marginal land would be low and could require high use of costly and environmentally damaging inputs. In addition, marginal land often consists of biodiverse rough grassland with high existing or potential nature value. While SRC could deliver ecosystem service and biodiversity benefits relative to arable crops, even greater benefits could be delivered through restoring this land to natural ecosystems.

Key uncertainties

The classification of SRC as a "crop" rather than a "forest" sparked discussion, with participants suggesting that clearer definitions could help address differences in risks and sustainability assessments. Uncertainty also surrounded how much truly marginal land is available for SRC production in the UK and whether its cultivation could lead to unintended consequences, such as biodiversity loss or competition with food production. This is compounded by lack of a clear definition of marginal land, as land which is poor for one crop (e.g. potatoes) could be good for another (e.g. wheat). Further research was recommended to explore the best uses for SRC within the broader land-use system and its long-term sustainability in the face of increasing biomass demand.

4.4. Storm-damaged wood, deadwood, bark & small branches

Balance of risks and opportunities

Storm-damaged forestry and residual materials, such as deadwood, bark, and smaller branches, were highlighted as potentially sustainable feedstocks for BECCS, particularly as they represent by-products of natural events or forest management rather than primary forest harvesting. Some participants noted that selective harvesting of deadwood and storm-damaged material for BECCS supply chains, when done carefully, might have minimal biodiversity impacts and be less harmful than clear-cutting. However, there was caution about over-reliance on these resources, as they are inconsistent, unpredictable, and limited in supply.

Participants expressed concern that increased demand for these forestry residues could inadvertently incentivize unsustainable forestry practices, particularly if supply chains were not closely monitored. Some participants emphasised that deadwood provides vital habitats for fungi, insects, birds, bats and other species that rely on it. They voiced concern that removing it will damage forest ecosystems and expressed caution over whether it can be extracted sustainably. The benefits of leaving deadwood in place, such as improving soil health and supporting forest regeneration, were emphasized. For example, evidence from the USA shows that if fire-damaged trees are left in place, fire-adapted forests will rapidly regenerate, whereas the soil damage caused by 'salvage logging' of fire-killed trees can prevent regrowth and effectively result in deforestation. Similarly, we heard concerns from NGOs in North America (at the pre-workshop meeting) that large, misshapen ancient trees that would previously have been left standing during logging operations are now being felled, as they can be classified as 'waste' or 'low grade' wood suitable for bioenergy, despite their huge importance for biodiversity. While the bioenergy sector would not fell these ancient trees, they could be felled while clear-cutting for timber and then left in the forest if not meeting sawmill quality requirements; the bioenergy sector then takes the residues. We also heard examples of whole stands of natural forest being felled due to the presence of pests such as bark beetles, with some arguing that this is more harmful to both carbon and biodiversity than the damage caused by the beetles.

Key uncertainties

A recurring theme was the unpredictability of storm-damaged forestry as a feedstock, both in terms of availability and sustainability. There were doubts about whether deadwood harvesting could be scaled without degrading ecosystems and about how to balance the economic benefits of using these materials with their ecological importance. There were also queries over the water and dirt content of bark and branches in terms of their value for pellet production. While the impacts of deadwood removal on biodiversity are well-understood (and reflected in Sustainable Forest Management principles), some participants called for more research and better scientific understanding of the impacts on carbon balance.

4.5. By-products from timber and paper Industries

Balance of risks and opportunities

By-products from the timber and paper industries, such as sawdust, pulp waste, and wood chips, were consistently regarded as one of the most sustainable feedstock options for BECCS. Participants saw potential in using these materials to avoid waste while reducing pressure to extract biomass from forests. Additionally, some noted that by-products could complement other strategies. For example, future policy support for use of timber in construction (to store carbon in long-lived products and displace carbon-intensive materials like steel and concrete) may increase the supply of sawmill and forestry by-products.

However, participants also acknowledged challenges, particularly around the scalability of this feedstock. 'Mixed-messaging' was flagged, with the current bid to increase timber production counteracted by increasing discussions around biodiversity conservation. It was noted that expanding timber production would depend on the availability of sufficient land. In the UK in particular, domestic timber supply is falling due to historical fluctuations in planting rates and removal of plantations from peatland, bringing into question the future reliability of timber by-products as a feedstock. Participants also noted that, as for all biomass sources, it is critical to address risks of carbon "leaking" along supply chains due to emissions from processing and transport.

On current supply of by-products, participants flagged that sawmills already adopt circular principles by using sawmill residues to heat their plants, reducing the availability of by-products for BECCS. Similarly, it was noted that the EU Cascade principles promote the use of by-products for biomaterials such as particleboard, in preference to burning for energy. In the final discussion, some participants noted that the pulp and paper industry is regarded as inherently unsustainable by some, and that this could be exacerbated if these waste products are imported to the UK from other countries (as domestic supply is small). Also, it was noted that paper use could decline in a digital world, so that the supply of byproducts from this industry could also decline.

Key uncertainties

The primary uncertainties revolved around the availability of by-products for BECCS and their competing uses, such as particleboard production. Participants questioned what quantities of these materials could be sourced sustainably, especially in the UK, where domestic timber and paper production is relatively small. Although more by-products could be produced due to increased use of timber frames for housing, the scale of this increase is unclear. There was also interest in establishing clearer definitions for by-products.

4.6. Food crops

Balance of risks and opportunities

Participants discussed the use of food crops for bioenergy, such as soy, rapeseed, palm, sugarcane/beet, corn and wheat. There was general agreement that food crops are not suitable BECCS feedstocks. While food crops have the advantage of being familiar to farmers, there were strong concerns on the competition between crops for bioenergy and food production. Attendees noted that using high-quality agricultural land for energy crops could exacerbate food insecurity, and even using lower grade land could displace low-quality food production, such as forage crops for livestock. Additionally, crops like maize were seen as less sustainable options due to their high demand for fertilizers and water, which could negate their carbon savings, and their tendency to cause soil erosion.

Participants also highlighted the need to consider the carbon opportunity cost of using land for annual crops going to BECCS. Low-grade farmland could instead be used for nature recovery and carbon sequestration, either via 'land-sharing' approaches to create high nature value farmland, such as low-input, species-rich pasture, or 'land-sparing' where other policy measures free up space for ecologically focussed habitat creation.

Key uncertainties

It was questioned whether there is any viable role for food crops in BECCS, given the high use of resources and the competition with land capable of essential food provision or nature recovery.

4.7. Herbaceous non-food bioenergy crops

Balance of risks and opportunities

Herbaceous non-food bioenergy crops, such as miscanthus, switchgrass, reed canary grass and energy cane, were highlighted as promising options for BECCS. As these crops can be grown as perennials, they require fewer inputs such as fertilizers and water compared to annual crops like maize, and they can be grown on degraded or marginal lands, where they could deliver co-benefits such as soil stabilisation, water retention, and erosion prevention. Miscanthus, in particular, was noted for its relatively low input requirements, compatibility with marginal soils, and low ash production. Furthermore, it was noted that perennials were not only less damaging, but could contribute to soil restoration if grown on arable land (though not if grown on permanent semi-natural grassland). They were also perceived as less visually intrusive than large-scale tree plantations, which might help mitigate public resistance to land use change for biomass supply.

However, concerns were raised about scalability and potential conflicts with food production, with large-scale planting of bioenergy crops potentially increasing food prices, especially if planted on higher-quality agricultural land. Indirect impacts were also cited due to reduced supply of food crop residues. For example, it was said that demand for miscanthus as an energy crop could reduce the supply of straw and thus increase the price of animal bedding. It was stressed that farmers will decide what crops to grow based on maximising returns, which will depend on prices of alternative crops and availability of subsidies. The importance of robust policies, incentives, certification and clear land-use strategies was emphasized, to ensure that agricultural bioenergy crops are grown sustainably and on appropriate land, and to prevent unintended consequences.

Participants also discussed the availability of appropriate land for bioenergy crop production. Classification of low value agricultural land or degraded land as being suitable for bioenergy crop growth must be supported by adequate understanding of the true value of the land, e.g. the surrounding people, communities and biodiversity. In particular, land categorised as ‘degraded’ is often high nature value farmland or prime land for nature restoration. Planting bioenergy crops on this land could therefore have adverse impacts on biodiversity and alter the structure of local ecosystems.

Key uncertainties

The main uncertainties revolved around how much marginal land is genuinely available for herbaceous bioenergy crop production in the UK and how their large-scale cultivation might interact with other land uses such as nature recovery and food or feed production. Questions were also raised about their biomass yield relative to other feedstocks such as forest products.

4.8. Crop residues

Balance of risks and opportunities

Crop residues, such as straw, husks, and stalks, were generally regarded as a low-risk feedstock for BECCS. These materials are already produced as by-products of existing agricultural activity, making them readily available without requiring additional land use. Participants noted that crop residues are often already integrated into circular systems, such as being used for animal bedding or composting before returning nutrients to the soil. It was said that diverting some of these materials to BECCS could create additional carbon savings without significantly disrupting current practices. Participants discussed both directly diverting straw from bedding needs or using straw for animal bedding and then using it for BECCS (see section 3.11).

However, there were concerns about the potential for crop residue extraction to harm soil health. Removing too much residue could deplete soil organic matter, reduce fertility, increase soil erosion and impair the soil's ability to retain moisture. Participants also emphasized that existing uses of residues, such as for animal feed or bedding, must be considered to avoid unintended economic impacts on other sectors, e.g. using straw for bioenergy could impact supply and cost of animal bedding.

Key uncertainties

Key uncertainties included how much crop residue could be sustainably diverted to BECCS without depleting soil health or disrupting existing agricultural systems. Participants also questioned how to measure the lifecycle emissions of residue-based feedstocks, including their transportation and processing.

4.9. Organic municipal waste, food processing waste, & used cooking oil

Balance of risks and opportunities

Participants identified waste streams as one of the most promising feedstock options for BECCS due to their minimal land-use impacts. Organic municipal solid waste (MSW), food processing waste, and used cooking oil are already collected at scale, providing a consistent and predictable supply. These waste streams also align well with circular economy principles by reducing landfill use and associated methane emissions. Forthcoming bans on biodegradable municipal wastes going to landfills will also further support potential utilisation of these waste streams for BECCS. Attendees noted that retrofitting CCS to existing waste-to-energy plants offers a pathway to immediate deployment.

Participants noted that using waste streams for BECCS face technical and economic challenges, particularly in the context of CCS retrofitting, though pilot schemes are currently underway. They flagged that many waste-to-energy facilities were not designed for carbon capture, and retrofitting them may require significant investment. The economic feasibility of transporting captured CO_2 from these facilities was questioned, as there are

many widely dispersed MSW plants; this could involve storing CO_2 in tanks and transporting by truck and then by train to reach the pipeline for disposal. The high-water content of some waste streams, such as food scraps, makes them more suitable for anaerobic digestion to produce methane for subsequent use in BECCS plants rather than centralised solid biomass combustion plants. Participants also noted that while there are currently large volumes of waste, it is a policy priority to reduce this in future and/or use it for other purposes within a circular economy.

Key uncertainties

The feasibility of retrofitting existing waste-to-energy plants with CCS was a major area of uncertainty. Additional uncertainties were raised concerning the future volumes of these waste streams, given external policy pressures to reduce waste. Participants also questioned how energy-intensive processes like drying wet waste might affect the lifecycle emissions of this feedstock.

4.10. Sewage sludge & landfill gas

Balance of risks and opportunities

Sewage sludge and landfill gas were recognized as feedstocks with clear potential for BECCS due to their existing use in anaerobic digestion (AD) and methane capture systems. These feedstocks offer an opportunity to mitigate emissions from organic waste streams while providing a source of renewable energy. Participants noted that integrating CCS into these systems could enhance their carbon removal potential without requiring additional land use for feedstock cultivation.

However, concerns were raised about the scalability of these feedstocks. The total volume of sewage sludge and landfill gas available in the UK is limited. As for some of the other waste feedstocks, this means that they form only a supplementary source; they would need to be combined with other feedstocks to achieve the necessary economy of scale to make it worth constructing CCS infrastructure. Leakage risks in distributed AD systems were also flagged as a potential barrier to achieving true negative emissions. Participants also raised concerns about the cost and technical challenges of retrofitting existing AD facilities with CCS technologies, which would require significant investment and could pose a barrier to large-scale deployment.

Key uncertainties

Uncertainties included the technical challenges of integrating CCS with small-scale AD facilities and the overall scalability of sewage sludge and landfill gas as feedstocks for BECCS. Participants also questioned how these systems could be made economically viable, particularly given the dispersed nature of the resource.

4.11.Animal manure & used bedding materials

Balance of risks and opportunities

Animal manure and used bedding materials were seen as good potential additions to the BECCS feedstock portfolio, particularly when integrated with anaerobic digestion systems to produce biogas. This approach aligns with circular farming practices, offering opportunities to close nutrient loops and reduce methane emissions from manure storage. Participants also noted that processed manure (i.e. the residue from the biogas production) could improve soil health when returned as fertilizer.

However, logistical challenges emerged as a key concern. Manure and bedding materials are bulky and difficult to transport, making them less suitable for centralized BECCS systems. Participants also noted that these feedstocks might require blending with other materials, such as crop residues, to optimize their energy output, which could increase system complexity. Participants also highlighted the need for careful consideration around policy drivers and subsidies as these heavily inform farmers' decisions, which may have unintended consequences. There is the danger of subsidies creating perverse incentives that lead to poor outcomes, as was the case in Northern Ireland and Scotland where farmers responded to AD subsidies by growing grass to put straight into AD plants.

Key uncertainties

The main uncertainties revolved around the scalability of manure-based feedstocks, particularly in the context of transportation and processing costs. Participants also questioned how to balance the use of manure for BECCS with its role in maintaining soil fertility, soil carbon and soil health, though this was balanced by the potential for manure processing via AD plants, as the digestate can then be used as a soil improver.

4.12.Aquatic biomass

Balance of risks and opportunities

Aquatic biomass, such as algae and seaweed, was discussed as a potentially valuable feedstock for BECCS under the right circumstances, although it was thought that it is not yet sufficiently developed to represent a key part of the solution. Unlike terrestrial feedstocks, aquatic biomass does not compete for land resources, making it an attractive option in land-scarce regions.

Participants noted that aquatic biomass could potentially co-locate with marine infrastructure, such as offshore wind farms, to optimize resource use. Microalgae and kelp were identified as possible sources due to their scalability.

However, significant challenges were identified. Aquatic biomass has a high water content, making it energy-intensive to process and transport. Additionally, some participants noted that algae and seaweed have competing uses in higher-value sectors, such as pharmaceuticals, food and materials, which could limit their availability for BECCS. Conversely, others suggested increased algal production for these higher value sectors could lead to future waste streams for BECCS.

Participants highlighted tank-grown algae as an energy-intensive option that would be highly difficult to scale for BECCS, effectively writing it off as a viable option. Microalgae grown at sea was discussed more positively as a potential option, although is also not without its challenges. There is little research on the potential of aquatic biomass as a BECCS source, particularly in terms of sustainability and scalability, and much more evidence is required. While space for growing marine algae is less of an issue, participants raised questions around the ocean as a large, unbounded system, and the energy required to collect and dry feedstocks such as kelp. There were concerns around whether the marine organisms attracted to the kelp and using it as habitat could be destroyed when the kelp is harvested, especially if physically attached to it.

Key uncertainties

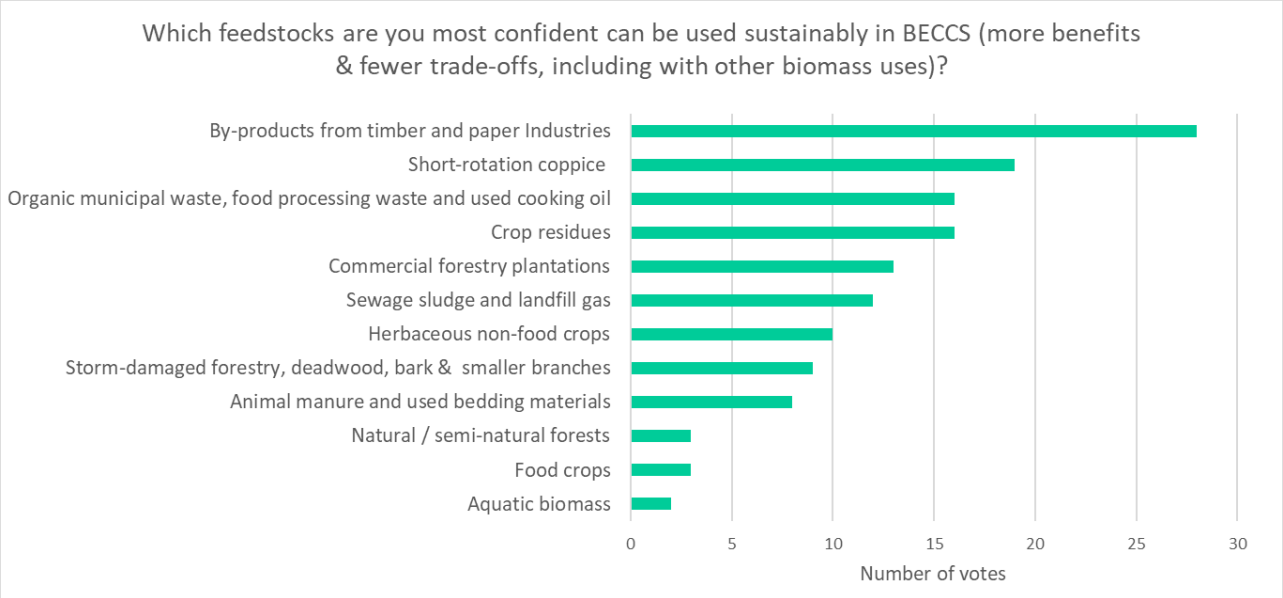
Key uncertainties included the economic and technical feasibility of processing aquatic biomass at scale and its carbon sequestration potential relative to other feedstocks. Participants also questioned how to manage competing uses for these materials and whether their cultivation could have unintended environmental impacts, especially during harvesting. Additionally, the scale and nature of the sea as an environment for growing algae was questioned as it is difficult to manage as an ecosystem, and there are serious concerns about the environmental impacts associated with commercial-scale harvesting of wild kelp.[36]

5. Summary of feedstock discussions

At the end of the workshop, participants voted for up to five feedstocks that they were most confident could be used sustainably for BECCS, with most co-benefits and fewer trade-offs, and up to five where they thought there were greater uncertainties and dependencies, and more research and debate was required (Figure 3).

The feedstocks that participants were most confident in were byproducts from timber and paper industries, short rotation coppice, organic municipal/ food waste, and crop residues. Sewage sludge/ landfill gas and plantation forests were the next most popular. Only one participant chose natural or seminatural forests, and two chose food crops.

Participants were most uncertain about the sustainability of sourcing biomass from natural/ seminatural forests, followed by plantation forests, aquatic biomass, storm damaged forestry/ deadwood/ bark/ branches, and food crops.



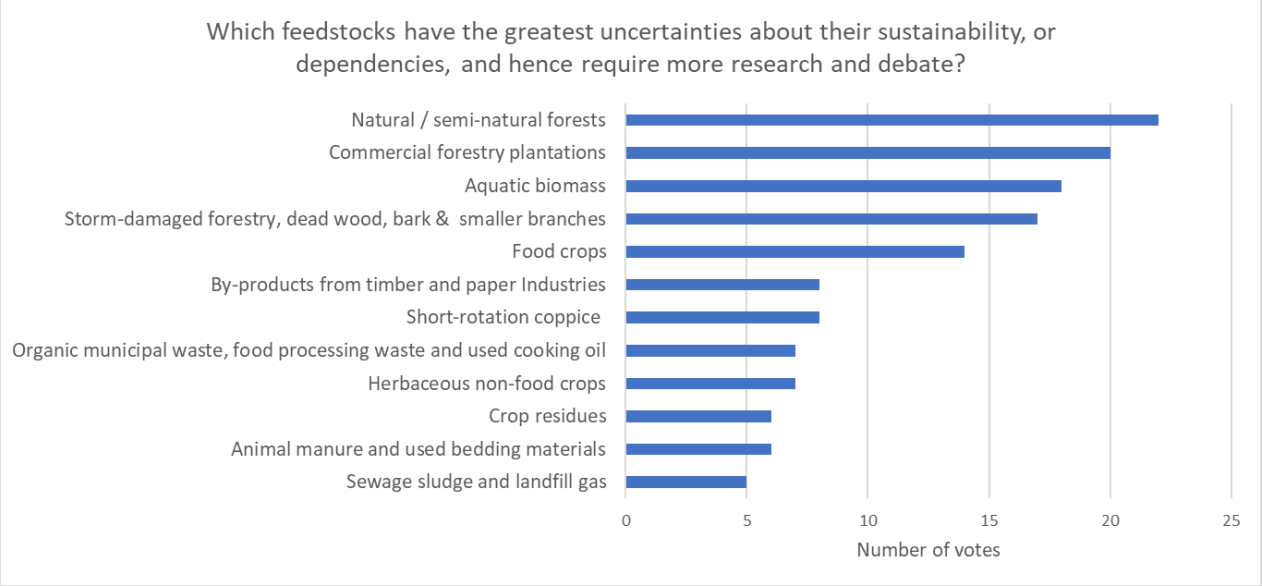


Figure 3. Outcomes of participant votes on the feedstocks with the greatest confidence in sustainability (top) and the greatest uncertainty and need for more research (bottom)

Broad groups of feedstocks each have different opportunities, risks and limitations.

Waste streams

Waste streams were often thought to have greater potential for sustainability, but there were uncertainties over the scale of the resource available, competing uses higher up the waste hierarchy, and the costs, emissions and feasibility of collecting and processing waste from multiple dispersed sources, and/or transporting captured CO_2 to the nearest disposal site.

- **Industrial and municipal waste** (sawmill waste, paper industry waste, organic municipal waste, food waste, sewage sludge, landfill gas) has the potential to be the most sustainable because it disposes of what could be a problematic waste material, does not require extra land use and has low or no impact on biodiversity, but:

    - In line with circular bioeconomy principles, it is preferable to avoid waste in the first place.
    - There are competing uses for some of these waste streams, e.g. treated sewage sludge for agricultural fertilizer; sawmill waste for particleboard; food waste for compost to be returned to the soil.
    - But there could still be a role for BECCS at end-of-life disposal after the biomass has been used in one or more products first, provided that it is not contaminated with resins, chemicals and fixings.

- **Agricultural waste** (crop residues, manure, used animal bedding) also does not require extra use of land, but there are important competing uses:

    - **Crop residues** can be left on the field, where they protect exposed soil from erosion, and gradually decay to add organic matter (and some carbon) back to the soil, supporting soil health and biodiversity.
    - **Animal manure** can be used as fertilizer, especially in organic farming systems.
    - **Used animal bedding** can also be composted and then used as a fertilizer / soil conditioner.

For all of these waste streams, there is uncertainty on the scale of waste biomass available in future, and the feasibility of fitting CCS to many small, widely dispersed MSW and landfill gas energy recovery plants and then transporting the captured CO_2 to the geological disposal site. Wet waste may be best used in Anaerobic Digesters to produce methane for use in a CCS plant elsewhere, so we also need to understand the costs, feasibility and emissions of storing and transporting the methane from multiple small sites.

Forest biomass

Forest biomass sparked the most debate. It holds the potential to provide significant quantities of biomass but with generally greater concern over sustainability, especially if scaled up. Key concerns included:

- Loopholes in standards, or standards not being rigorously enforced, leading to further loss or damage to old growth forests if extraction is scaled up.
- Contested narratives around the need for and impact of thinning of natural / seminatural forests to reduce fire and pest risks, with strong concern around ecological impacts and effectiveness.
- Potential competition with other uses of wood, such as for particleboard, and with leaving dead wood in the forest as part of the ecosystem.
- Local air pollution from wood pellet plants.

Bioenergy crops

- **Short rotation coppice** and **herbaceous non-food bioenergy crops** were regarded as potentially sustainable if planted on low grade farmland currently being used for arable crops, but still compete with food production and demand for biomaterials, and require careful land-use planning and lifecycle assessments.
- **Food crops** were thought by most participants to be unsustainable because they require high inputs (fertiliser, water) and are less suitable for marginal land, so cause more competition with food production.

Aquatic biomass

Aquatic biomass – although this avoids competition with land, there were concerns about high energy requirements for lab-grown algae, energy for processing macroalgae such as kelp, competing higher value products such as pharmaceuticals, and the impacts of harvesting on marine ecology.

6. Concluding remarks

Based on the views expressed at the workshop and in the pre-workshop meetings with overseas participants, our take-home messages are presented below.

1. Sustainable biomass availability is limited.

The workshop highlighted that most potential biomass feedstocks have alternative uses in the bioeconomy and/or compete with land for food production, nature recovery and infrastructure. Waste streams were viewed as being among the most sustainable sources, but future quantities may be limited by the need to reduce waste generation.

2. Ecosystem and biodiversity impacts must be considered in decision-making.

Potential damage to ecosystems was a recurring concern, especially for biomass extracted from natural / semi-natural forests, where the impact on fire risk is contested. Even with sustainable practices, the cumulative impacts of large-scale BECCS deployment could have adverse impacts due to indirect land-use change. Carefully planned multifunctional land use, such as targeted planting of short rotation coppice on low grade arable land, was seen as having potential to enhance ecosystem services, but the feasible scale of production was questioned. BECCS would require careful identification of feedstocks with minimal risks to nature

3. Certification and monitoring require urgent improvement.

Many participants were not confident that current sustainability certification schemes for biomass are rigorous and are always enforced as intended (although it is not clear how many participants had expert knowledge of certification schemes). They thought that key terms like "old-growth forests", "sustainable forest practices" and “marginal” or “degraded” land are ambiguously defined (though in some cases this may be partly due to the complexity of land-use). Examples (from local NGOs) of poor forest biomass sourcing practices in the Americas underscore the need for more robust, enforceable standards. Domestic supply chains are perceived as being more traceable and manageable than imports, but are unlikely to meet demand without significant reductions in biomass use in other sectors. Stronger standards and monitoring systems need to be negotiated in partnership with all stakeholders, and should take into account social and environmental impacts, tackle indirect land-use change, avoid conflicts with food production and nature recovery, prevent deforestation (including legal deforestation of unprotected forests), and avoid inappropriate afforestation of open ecosystems.

4. Counterfactuals are critical, yet under-examined

The impact of BECCS feedstocks on carbon emissions depends on counterfactual scenarios, i.e. what would happen if the feedstock were not harvested. For example, would plantation wood remain unharvested or be used for alternative purposes, and how would crop residues impact soil health and carbon if left on fields instead of used for BECCS? More local and specific data is required to fully understand the trade-offs and net carbon benefits of BECCS.

5. High uncertainty about the long-term role of BECCS in Net Zero.

While most participants agreed that BECCS has potential to deliver negative emissions, many emphasized that its role in net-zero strategies must remain conditional on reducing scientific uncertainties, improving practices, and ensuring genuine sustainability. In particular, more attention is needed on supply chain emissions and indirect land use change. Many thought that allocations for BECCS used in CCC Net Zero pathways are too high, though a few said they are too low (note: since the workshop, the 7th Carbon Budget has been released, which has 40% less BECCS than the 6th Carbon Budget and aims to phase out imported biomass). There was concern that over-reliance on BECCS could delay critical emissions reductions in other sectors and lead to unintended ecological consequences.

6. Scale and pace of BECCS deployment.

There were mixed views on whether unabated use of bioenergy (without CCS) should continue to be supported for climate mitigation purposes, with the carbon balance depending largely on the feedstocks, timescales and counterfactuals considered. There was also disagreement about the future scale and pace of BECCS deployment. Some said that BECCS deployment should be accelerated, to test assumptions, refine technologies, and better understand real-world impacts on carbon fluxes, ecosystems, and supply chains. Others said that there are already serious concerns about the social, ecological and carbon impacts of current bioenergy supply chains that need to be addressed before considering whether it is possible to scale up sustainably. As a result, **many thought that current evidence is insufficient to justify deployment of the technology at the scale envisaged in the UK's 6th Carbon Budget, although some strongly disagreed,** with the differences partly depending on assumptions about the feasibility of low-BECCS scenarios and the importance of sustainability constraints.

7. Research questions

The workshop revealed several areas where it was thought that more research is needed, in order to answer the overall question: what is the feasible scale of future UK BECCS deployment based on the sustainable supply of feedstocks that have minimal risks to biodiversity, ecosystems, and soil health?

- How do real-world BECCS supply chains compare to modelled assumptions regarding life cycle emissions, resource efficiency, and ecological impacts?
- In what circumstances is it justified to use a no-harvest counterfactual to calculate the carbon balance of forest biomass, as part of a full-carbon accounting approach that includes forgone sequestration (including for biomass sourced overseas)?
- What specific gaps in existing sustainability certification schemes limit effective monitoring and enforcement of biomass sourcing practices, especially from forests? How can these schemes better define and address ambiguities?
- How can we address the risk that greater bioenergy demand globally could drive unsustainable biomass supply including indirect land-use change?
- What are the potential impacts on forest ecology of future plans for large scale thinning of natural forests in the USA to supply wood pellet plants, and how can key uncertainties about the impact of thinning on fire risk be investigated?
- Building on the UK GBRM model,[37] what are the costs, feasibility, resource size and life cycle emissions of using UK municipal, industrial, agricultural, wastewater and food waste feedstocks for BECCS, including processing wet waste, using CCS technology with Municipal Solid Waste, landfill gas and anaerobic digestion plants, transporting the captured CO_2 from multiple dispersed sources to the disposal point, and the financial implications of declining resource size due to waste reduction policies?
- Combining existing resource assessments with detailed nature recovery priorities (e.g. the emerging Local Nature Recovery Strategies in England), what is the maximum sustainable availability of SRC, SRF and herbaceous non-food bioenergy crops that can be grown in the UK with minimal risks to biodiversity, ecosystems, soil health and food production, taking account of overlap between marginal land, high nature-value farmland and potential nature recovery networks?
- How much crop residue could be sustainably diverted to BECCS without depleting soil health or disrupting existing agricultural systems, and what are the lifecycle emissions?

- Building on the UK GBRM model, how much biomass can be sustainably sourced from paper and sawmill byproducts in the UK, and how might this change with future demand for timber in construction, and competing demands from other bioeconomy sectors?
- How can land-use planning mitigate ecosystem degradation and maximize biodiversity outcomes in BECCS projects?
- How would the absence of BECCS demand affect the management of plantation forests, crop residues, and other biomass sources?
- What are the impacts of harvesting kelp on marine ecology, including through mortality of any organisms attached to the kelp when it is harvested?

Appendix 1: Workshop agenda and participants

The workshop aims to bring together the latest evidence and enable discourse between leading experts on the role and scale of Bioenergy with Carbon Capture and Storage (BECCS) in climate change mitigation pathways, as well as its opportunities and risks both locally and globally.

This workshop will build on recent publications, including "BECCS Done Well", to better understand BECCS within the context of wider cross-sectoral demands for biomass, and to identify what the key areas of agreement, disagreement and knowledge gaps are on the future of BECCS across the community.

Professional facilitators will create a space for experts to discuss the sustainability of current BECCS targets and standards, leading to the development of recommendations to decision makers on how BECCS could be deployed in a way that ensures it:

- can align and provide synergy with the achievement of the Sustainable Development Goals
- does not undermine efforts to protect and restore nature
- does not delay or distract from the changes required to reduce ongoing damage to the climate system and biosphere

The discussions and recommendations from the workshop will be summarised within a short output targeted at decision makers.

Agenda

9.30am	**Welcome**
9.45am	**Introductory Talks** A series of short talks to set the scene for discussions
10.55am	**Tea and Coffee Break** Attendees to move to their designated tables (Session 1)
11.15am	**Discussions Part 1 – BECCS' Opportunities, Challenges and Risks** With introduction from facilitators
12.20pm	**Lunch** Attendees to move to their designated tables (Session 2)
1.10pm	**Discussions Part 2.1 – Biomass Feedstock Considerations**
2.50pm	**Tea and Coffee Break** Attendees to move to their designated tables (Session 3)
3.10pm	**Discussions Part 2.2 – Biomass Feedstock Considerations** Continued
3.30pm	**Discussions Part 2.3 – Assessing Confidence in Biomass Feedstocks** Exercise hosted by facilitators
4.15pm	**Conclusions – Developing Recommendations to Decision Makers** Whole-room exercise hosted by facilitators

Participants

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Leonardo Marioni, *The Royal Society*
Luke Reynolds, *The Royal Society*
Madeleine Quirk, *The Royal Society*
Mair Floyd-Bosley, *Culmer Raphael*
Martin Gilbraith, *Facilitator*
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