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Opportunities and challenges for Bioenergy with Carbon Capture and Storage (BECCS) systems supporting net-zero emission targets

Headlines

- Anthropogenic GHG emissions have been relentlessly growing for many decades, thus compromising attempts to avoid dangerous climate change and meet net-zero emission targets by 2050.
- BECCS technology creates a negative carbon flow from the atmosphere into storage by coupling CO_2 removal, low-carbon energy conversion routes, and carbon capture and storage technologies.
- Process modelling and life cycle assessment of the entire BECCS value chain must be implemented to determine the net-negative emission potential of this technology.
- A better understanding of the implications of large-scale BECCS deployment should be included in climate modelling methodologies such as SSPs and IAMs.
- While other renewable energies might be more cost-efficient, BECCS is the only carbon negative renewable energy approach and can provide sustainability co-benefits to various cross-cutting sectors. To enable these benefits, political intervention is needed to attract investment for long-term R&D and implementation of BECCS technologies.
- Relying on future BECCS deployment to counterbalance the current excess of CO_2 emissions only can risk sustainability benefits and would not enable the full potential and benefits of BECCS. Policy frameworks should go beyond the greenhouse gas removal potential of BECCS and integrate wider sustainability benefits whilst also considering trade-offs, for example in regard to land-use, food security, biodiversity, income opportunities, technology and infrastructure development and social justice.

Introduction

Human-induced climate change is one of the biggest challenges of our time. As a consequence of the sharp rise of the atmospheric concentrations of greenhouse gases (GHGs), the natural carbon cycle has been unbalanced and this has led to an observed temperature increase of 1.0 °C of the average global surface temperature over the last 45 years [1, 2]. Carbon dioxide (CO_2) is the major GHG contributing more than 80% of the total emissions.

The mitigation of anthropogenic impact on the global climate has become a major scientific and political concern in recent decades [3, 4]. Many countries, including the UK, have passed laws to legally establish net-zero emissions targets [5]. Consequently, much research is focused on finding efficient routes for achieving a long-term transition to an alternative economic model, and using renewable biological resources to produce materials and energy. This briefing note focuses on the energy sector, which is the highest contributing sector, producing about 70% of the global GHG emissions [6].

Since present mitigation efforts have not achieved the emission reductions that would be required to avoid dangerous climate change, net-negative emission technologies (NETs) are increasingly discussed as a way to balance GHG emission sources and sinks in the near future. Bioenergy with carbon capture and storage (BECCS) is considered as a NET technology with great potential for large scale application. Different modelling frameworks, such as the integrated assessment models (IAMs) or the shared socioeconomic pathways (SSPs), give BECCS an essential role in meeting climate change targets through the future offsetting of current GHG emissions [7].

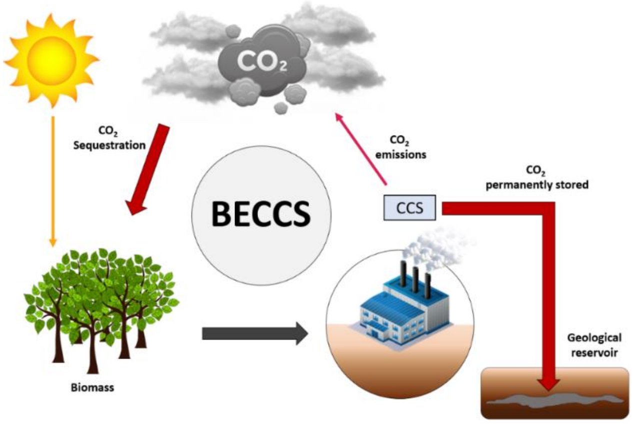


Figure 1. The carbon flow of BECCS. When BEECS systems are employed, a negative carbon flow from the atmosphere into storage is created.

What is bioenergy with carbon capture and storage (BECCS)?

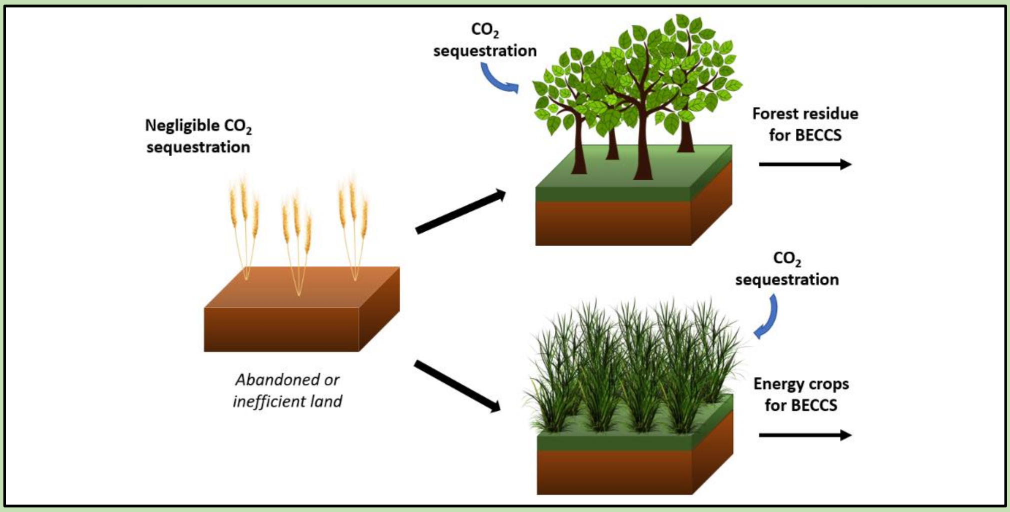
BECCS systems join CO_2 removal (CDR) methods with low-carbon energy conversion pathways (biomass-to-energy process) and carbon capture and storage (CCS) technologies. Figure 1 depicts the negative carbon flow that BECCS creates from the atmosphere into storage.

CO_2 removal methods comprising BECCS.

CDR is the basis of BECCS to achieve a negative flow of emissions. Three mechanisms for carbon removal –i.e. biological, physical, and chemical sequestration– can be identified depending on the carbon sink or reservoir where the CO_2 is stored (natural, human, in soil, ocean or plants). Those methods that could be part of BECCS systems are discussed below, while further CDR technologies are compiled and briefly described in Table 1.

Table 1. CO_2 removal (CDR) methods other than BECCS

Name	CDR type	Description	Technology status	Reference
Ocean fertilisation	Biological	Large scale anthropogenic fertilisation of the open sea, using iron or urea, to promote the growth of sea organism such as phytoplankton for CO_2 fixation.	Conceptual stage	[8]
Afforestation	Biological	Man-made establishment of new forests on treeless lands that did not previously carry forest in contemporary history	Large scale application	[9]
Ocean sequestration	Physical	Injection methods including CO_2 lake formations at the bottom of the ocean (CO_2 has higher density than sea water below 2700 m) or the dilution of dissolved CO_2 at a depth below the mixed layer	Conceptual stage	[10]
Direct air capture	Chemical / Physical	CO_2 is directly captured from the ambient air, instead from point sources, when it flows through a separation element, often a liquid or solid sorbent.	Pilot scale	[11]
Mineral carbonation (MCT)	Chemical	CO_2 is chemically reacted with calcium- and/or magnesium-containing minerals to form stable and harmless carbonate materials	Laboratory scale	[12]
Electrocatalytic reduction of CO_2	Chemical	Reduction of either gaseous or dissolved CO_2 to solid carbon products	Laboratory scale	[13]



Box 1. CO$_2$ fixation using biological sequestration means can be accelerated by promoting variations on the land use and/or agricultural practices to enhance the expansion of the previously described carbon sinks, e.g. convert abandoned, inefficient crop and livestock land into non-crop fast growing plants that can be later converted to biomass feedstocks for bioenergy production in a BECCS system. A land use change analysis (LUCA) must be, however, performed to determine the impact of anthropogenic and natural changes in the use of soil.

Biological sequestration is related to the storage of atmospheric carbon within biomass. It is primarily caused by plants that, as a result of photosynthesis, fix the carbon from sequestered CO$_2$ into their developing fibres. Woodlands, grasslands, deep soil, peatland, wetland soil, and seaweed are examples of biological sinks for anthropogenically remobilised CO$_2$. Growing biomass as feedstock is the first stage of BECCS for climate change mitigation. Alternative methods for biological carbon sequestration that are acknowledged by the IPCC are afforestation/reforestation and enhancing soil carbon in croplands and grasslands [4].

Physical sequestration comprises the last phase of carbon capture and storage (CCS) technologies comprising BECCS. The CO$_2$ captured from large emission point sources (e.g. biomass power plants) using technological means, is transported and injected into appropriate underground geological reservoirs for long-term storage. Before the storage, the CO$_2$ is compressed to supercritical fluid to increase the density and thus enhance the reservoir capacity. Sedimentary basins, saline aquifers, the ocean floor, coal seams, oil reservoirs (enhanced oil recovery) or other porous and permeable reservoir rocks (e.g. sandstone, limestone, or dolomite) overlain by an impermeable rock seal (e.g. shale or anhydrite) have been determined as a suitable geological sites for CO$_2$ storage [14].

Biomass to energy pathways for BECCS.

The main objective of BECCS is the production of bioenergy, i.e. any energy obtained from the conversion of organic matter (biomass) [15]. The main sources of biomass are organic crops, wood residues and organic wastes derived from human activities, such as agriculture, agroindustry, and organic municipal wastes. Biomass can be used directly as fuel, or alternatively it can be converted into liquid or gaseous forms through the application of heat, chemicals, microbial activity or a combination of these processes, to be used afterwards as an energy resource [16]. Depending on the predominant component of the biomass (e.g. lipids, sugars/starches or lignocellulosic materials), different biomass feedstocks are better suited to different conversion routes (see Table 2).

Table 2. Biomass conversion pathways to energy and resulting energy vectors and by-products.

Pathway	Feedstock	Pre-processing	Conversion	Primary product	Product/Energy recovery	Secondary product
Thermal & Thermochemical	Lignocellulose materials	Size reduction Moisture reduction Blending Densification	Combustion	Heat	Boiler	Electricity
			Pyrolysis	Biochar		
				Tars and Bio-oil	Extraction	Chemicals
					Upgrading	Gasoline
					Turbine	Electricity
					Boiler	Electricity
				Syngas	Synthesis	Chemicals Ammonia Methanol
					Gas turbine	Electricity
					Engine	
					Boiler	
			Gasification	Syngas		
			Carbonisation	Biochar		
			Torrefaction	Biochar		
			HTL	Bio-oil	HTG	Biogas
Biochemical	Animal manure Sewage sludge Algae		Anaerobic digestion	Biogas		
	Sugars Starch Lignocellulose	Saccharification Hydrolysis	Fermentation	Ethanol		
Chemical	Lipids		Transesterification	Biodiesel		

Carbon Capture technologies for BECCS

BECCS comprise biomass-to-energy processes that still can constitute large point sources of CO_2 emissions. The thermochemical conversion involves the thermal decomposition of biomass, so the resulting flue gas or other gaseous by-products contain great amounts of CO_2. The biogas produced in the biochemical conversion of biomass also has a high concentration of CO_2 (30–45%) that needs to be separated to upgrade the fuel quality and minimise emissions when used [17]. Only the chemical pathway is, conversely, considered carbon neutral as no CO_2 is produced in the transesterification process. Carbon capture methods, already implemented for fossil fuel power plants, could be applied in those bioenergy processes to avoid venting the generated emissions to the atmosphere.

Box 2. Despite biomass-to-energy processes involve low-carbon conversion pathways, emissions are still generated and including carbon capture and storage technologies is pivotal for BECCS systems to reach their net-negative emissions potential.

Depending on the selected biomass and conversion pathway comprising the BECCS system, different CO_2 capture methods can be applied. Four basic systems for CO_2 capturing from biomass processing are identified and briefly describe below.

Post-combustion capture

Post-combustion capture is the capture of CO_2 from the flue gases produced during the combustion of fossil fuels and biomass in air.

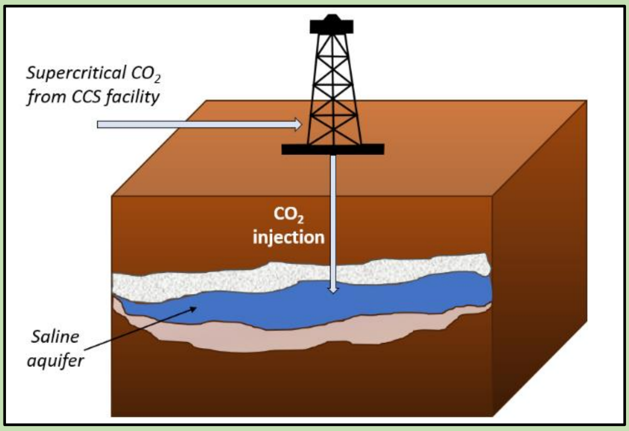
Absorption/stripping processes using chemical solvents (i.e. separation based on a chemical reaction with the absorbing medium) are currently the preferred option for acid gas treatment, since the partial pressure of flue gas is close to atmospheric and CO_2 concentrations are relatively low. Amine scrubbing processes, which use aqueous solutions of alkanolamines such as monoethanolamine (MEA), piperazine (PZ) or blends of these or other complex amines with methyldiethanolamine (MDEA), have reached commercial application. However, these processes are energy intensive. Physical processes using adsorption beds (e.g. activated carbon), membrane systems for gas separation or gas adsorption, solid sorbents (e.g. CaO), cryogenic distillation, or microalgae capture systems are alternative technologies that could compete with conventional chemical absorption for post-combustion CO_2 capture [18-20].

Oxy-fuel combustion capture

This technology uses nearly pure oxygen instead of air for biomass combustion. The oxidation reaction is enhanced due to the negligible nitrogen content, which is a temperature reducing dilutant in combustion systems with air. Combustion efficiency losses, caused by the heat absorption of nitrogen, and the production of nitrogen oxides (NO_x) are thus prevented, so the flue gas composition is mainly CO_2 and H_2O. A simple cooling can condensate water and obtain a 80%-98% CO_2 stream depending on the fuel used and the combustion conditions [21]. CO_2 can be later compressed, dried, further purified if needed (using the same processes of post-combustion capture) and delivered to storage.

Pre-combustion capture

Pre-combustion capture involves the CO_2 sequestration prior to the completion of the biomass combustion process, i.e. in the biomass gasification process for syngas (CO and H_2) or hydrogen production. Syngas conditioning using a water shift reaction stage to enhance the yield to H_2 also results in CO_2 generation. That CO_2 needs to be removed, either to purify the conditioned syngas and make it suitable for further use (e.g. combustion in gas turbines or fuel cells) or, in hydrogen production, to reduce CO_2 emissions when the H_2 is later used as a renewable fuel. Relatively high partial CO_2 pressures and concentrations are involved in pre-combustion capture. Thus, physical adsorption methods are commonly used to adsorb any gas other than H_2. This includes pressure swing adsorption (PSA) devices using switching beds of zeolites, alumina or activated carbon, and physical absorption technologies using physical solvents where the separation is based on the gas solubility on the absorbing medium (e.g. Rectisol®, Purisol® or Selexol®). PSA systems comprising multiple adsorbers are widely used in industry since they can recover a continuous flow of pure low pressure CO_2, but at a significant energy cost [22].



Box 3. Once the CO_2 is captured using any of the technologies described, the resulting CO_2 stream is compressed to reach a supercritical state and is transported for long-term storage in a geological reservoir, and therefore completing BECCS process. Geological underground storage has been already implemented at large scale, despite this, there are still major challenges and room for improvement for this technology.

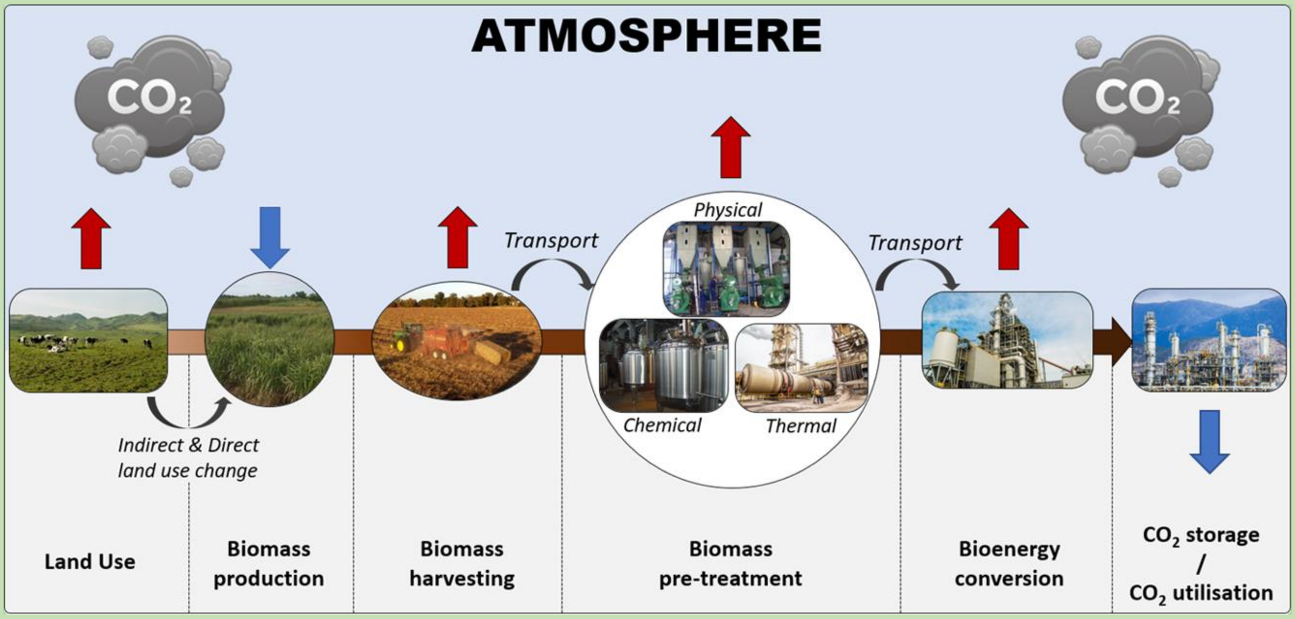
Capture from industrial process streams

Industrial applications involving non-combustion process streams that contain CO_2 also offer an opportunity to reduce GHG emissions. This includes biogas upgrading and hydrogen-containing synthesis gas purification (for ammonia or alcohol production), and these can employ similar technologies to those used in pre-combustion capture. Furthermore, post combustion capture techniques could be used to capture CO_2 produced during fermentation. [18]. Recent studies suggest that the carbon capture technologies previously described could be adapted to also operate in hard-to-decarbonise heavy industry sectors, such as steel, cement, or pulp and paper [23].

The role of BECCS in climate change mitigation

The implementation of BECCS represents a real opportunity for net-negative emission performance, but modelling frameworks must refrain from assuming the simplistic and inaccurate vision of BECCS where 1 tonne of CO_2 captured in the growth of biomass equates to 1 tonne of CO_2 sequestered geologically [24]. To determine BECCS net-negative potential with some degree of certainty it is fundamental to use a wider system boundary that includes the whole picture of BECCS, and accounts for any individual impacts associated with each stage of the value chain.

The life cycle analysis (LCA) of a BECCS supply chain shows that a carbon debt is created by the CO_2 emissions associated with land conditioning (e.g. land use change, land clearing and biomass cultivation), the supply chain emissions from biomass harvesting and pre-processing, non-captured or indirect emissions at energy conversion facilities and those emissions related to biomass storage and transportation between stages. An LCA, where all the carbon emission contributions of those CO_2 sources are deducted from the carbon sequestration achieved at the biomass growing stage, should be performed to compute the realistic net-negative emissions contribution of BECCS.



Box 4. BECCS supply chain. The CO_2 emission inflows (blue) and outflows (red) are represented:

i) ***Land use change (CO_2 source)***: existing land uses already provide carbon benefits in storage and sequestration. The initial carbon stocks can be altered by changing the land use of a certain area (e.g. forest to agricultural land) and can directly and indirectly lead to the creation of emissions.

ii) ***Biomass production (CO_2 sink)***: biological sequestration of CO_2 takes place at the biomass growing stage, as described in previous sections.

iii) ***Biomass harvesting (CO_2 source)***: the use of fossil-fuelled machinery to produce and harvest biomass contribute to the whole value chain emissions.

iv) ***Biomass pre-treatment (CO_2 source)***: biomass might not be readily available for use and often requires some form of mechanical, biological and chemical pre-treatment that is often a source of emissions

v) ***Biomass conversion (CO_2 source)***: carbon emissions are produced at the biomass-to-energy facilities even when CCS technologies are used. The efficiency of the implemented CO_2 capture technology will determine the emissions vented to the atmosphere of the conversion process.

vi) ***CO_2 storage (CO_2 sink)***: the captured and geologically stored carbon dioxide is not considered a carbon sink flow since it represents the CO_2 sequestered by the biomass and prevented to be re-released again to the atmosphere. That negative flow is already accounted in the biomass growing stage.

Barriers and challenges for BECCS deployment.

The net-negative emission potential of BECCS has been given an essential role in the transition to net zero in many of the IPCC's modelled SSPs , with the aim that this technology will compensate in the future for current emission release [25]. However, BEECS technologies are currently in developing stages and have scarcely been commercially demonstrated. There are a number of barriers and challenges that would need t be overcome for large scale BECCS deployment to be considered a realistic part of the transition to a sustainable economy:

Sustainable biomass resource

With the growing bioeconomy, there is an increasing competition for biomass resources and land. While biomass is already grown for various purposes, this will increase the pressure on sustainable biomass production and land use. As the growing biomass demand for BECCS will additionally increase and impact other sectors, sustainable management and appropriate sustainability standards for biomass are imperative. Biomass sources for BECCS should come from sources that do not have, or compete with, other markets. If grown for purpose, BECCS feedstocks should be produced on land that does not impact food production, biodiversity, soil carbon stocks or causes negative land use changes. Prioritising residue from agriculture and forestry, could not only reduce the environmental impact of the supply chain, but it could also incentivise investments and employment in this sector. In addition, a shift in use biomass feedstock production has been suggested for both abandoned land, and existing agricultural land that is inefficient for food production.

CO_2 storage and infrastructure

The CO_2 storage capacity of a country's national territory needs to be sufficient to guarantee an extended BECCS operation time. The UK has storage for emissions generated for 220 years [26, 27]. An extensive and very efficient infrastructure deployment would be necessary to reach and utilize the suitable reservoirs available (mainly saline aquifers) without causing any geological and environmental damage. Geological storage capacity is still limited, so the search of alternative CO_2 utilisation pathways (e.g. chemicals or fuel production from CO_2) seems essential to supplement storage while also creating alternative markets.

Technology readiness and commercial deployment

At present, BECCS comprise high capital-intensive and low cost-efficient technologies placed down on the technology readiness level (TRL) scale [28]. Although bioenergy processes and CCS (in the fossil-fuel sector) have been already individually demonstrated at commercial scale, to adapt conventional carbon capture to bioenergy involves challenges related to the use of biomass, such as different fuel properties and flue gas composition. The degree of technological maturity of the carbon capture technology applied will also depend on the energy conversion process. For example, capturing CO_2 in bioethanol production involves carbon capture technology at high TRL, while the TRL for technologies suitable for biomass power plants are still very low. The transportation of the captured CO_2 to storage represents an additional challenge. Underground storage is not yet a mature technology and the deployment of transportation and storage infrastructure is crucial. Economies of scale in the infrastructure cost have been already observed, which seems unfavourable for BECCS facilities of smaller scale as they are likely to be geographically scattered and use regionally sourced biomass. To implement a joint storage site seems to be a realistic approach that, nonetheless, would imply facing a challenging business model where additional uncertainties regarding co-ownership, planning and infrastructure utilisation would be incorporated to the complex large-scale implementation of BECCS.

Political-economic challenge

BECCS not only involves a high risk from a technological perspective, but it is also highly exposed to regulatory uncertainties. All these factors create an environment unattractive for funding and investment that could impede BECCS transition from the existing lab scale success to commercial application. BECCS needs to compete for investment with other cheaper renewable energy sources, like solar and wind, that also show a continuous fall in prices. However, it is advantageous over those alternatives in sustainability terms, as BECCS also encompass carbon dioxide removal. Economic and fiscal incentives are therefore required to attract investment for long-term research, development, and implementation of BECCS technologies. Increasing carbon prices or providing incentives for carbon dioxide removal are feasible political interventions that would create a market for emissions offsets and also balance, with tax revenue from emissions, the subsidies initially needed for their deployment.

Social barriers

Unquestionable social support and strong policy are commonly assumed in most IAM scenarios, but these might end constituting the hardest barriers to be overcome [29]. Strong policy is needed to implement regulatory frameworks to shape sustainable trajectories for BECCS technological development that also include social justice safeguards. The existing social reluctancy derived from the fear of this technology might spur social damage practices, such as land grabbing or compromised food security, could be therefore shift favour away from investment for large-scale BECCS implementation [30].

Conclusions

Significantly reducing the current level of GHG emissions is essential to build a long-term sustainable society. Research currently focusses on the development of sustainable low-carbon energy vectors encouraged by climate mitigation policies on those countries committed to achieve a net-zero emission performance by 2050. BECCS does not only provide low-carbon energy conversion pathways using renewable biomass, but also offers carbon dioxide removal leading to net-negative emissions properties. For this reason, IPCC modelling frameworks have high hopes for this technology to offset the present excess of GHG emissions. While modelling assessments confirm the net-negative emission potential of BECCS, more in-depth analyses for different BECCS technologies must be carried out to evaluate and specify their actual potential, impacts and trade-offs beyond a theoretical carbon balance.

It is essential to conduct emissions assessment of the entire BECCS supply chain to determine the true negative emissions performance of this technology. The negative emission potential will strongly depend on the type and location of the biomass feedstock. While prioritisation of regional residues can offer sustainability benefits and avoid land use conflicts, this might not suit the scale and location of bioenergy and CCS facilities and infrastructures. Hence, challenges associated with the potential for different steps of the supply chain from biomass production to CO_2 storages need to be overcome. To attract investment and reduce the financial risks of BECCS, policy interventions are required that support the wider environmental, technical, economic, and social benefits of BECCS. BECCS must overcome sustainability constraints of biomass availability, technical, economic, governance and perception barriers to allow a successful commercial deployment as part of the transition to a sustainable economy.

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Our research and technology capabilities include a range of advanced thermal technologies and biological conversion processes. These include gasification, pyrolysis, catalysis, and thermochemical refining of biomass, wastes and plastics to high-quality products and fuels. We also provide valuable expertise in energy systems, supply chains, techno-economic analysis, transport logistics, analytics, engines and energy systems.