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The greenhouse gas removal potential of bioenergy with carbon capture and storage (BECCS) to support the UK's net-zero emission target☆

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ABSTRACT

The UK is the first major economy to legislate the reduction of all GHG emissions to net-zero. Greenhouse gas removal (GGR) approaches are likely to be required to support the 2050 net-zero target by offsetting residual emissions from 'hard-to-abate' sectors. Bioenergy with carbon capture and storage (BECCS) is investigated as one technical solution for GGR. This research used process modelling and lifecycle assessment to identify the GGR potential of three BECCS supply chains. Results show that the BECCS supply chains have significant GGR potential with net-negative emissions as CO_2e between −647 and −1137 kg MWh^{-1}. Emissions were compared per unit energy output, biomass and area required for each supply chain to assess the GGR potential and BECCS sustainability implications. The large-scale BECCS supply chain features robust technologies with high capacity factor. It produces the greatest electricity generation and annual GGR, however, demands large amounts of biomass raising potential sustainability issues. The medium-scale (CHP) BECCS provides the greatest GGR potential per energy due to its higher energy efficiency. Limitations are a low capacity factor, energy demand-supply balance and non-existent decentralised CCS infrastructure. The (hydrogen) BECCS supply chain is more versatile, producing hydrogen with the potential to support the decarbonisation of not just power, but heat and transport sectors. The GGR potential sits in the middle and has greater benefits from a biomass sustainability perspective, yet, hydrogen infrastructure is not established, and costs remain uncertain. The relative performance of alternative BECCS supply chains should consider direct links between CO_2 removal and sustainable biomass and land use, as well as GGR potential.

1. Introduction

1.1. BECCS and greenhouse gas removal

In its fifth assessment report, the Intergovernmental Panel on Climate Change (IPCC) [1] presented modelled emission scenarios indicating that large-scale greenhouse gas removal (GGR)[1] is likely to be required to meet the 2015 Paris Agreement to limit global mean temperature rise to well below 2 °C. Attention to potential GGR mechanisms continues to grow; pursuing the targets established in the 2015 Paris Agreement without GGR, would require very steep emission reductions immediately [2]. Although methods to remove non-CO_2 greenhouse gases are being explored, such as in Jackson [3], the current focus is on approaches that could remove CO_2 from the atmosphere [4,5]; to date, Bioenergy with Carbon Capture and Storage (BECCS) and afforestation have been the dominant GGR approaches featuring in IPCC scenarios [6]. To deliver GGR or negative emissions, BECCS involves capturing CO_2 during biomass energy conversion processes for subsequent geological storage, thus enabling the long-term removal of CO_2 sequestered during biomass growth cycles. Even with GGR, reducing atmospheric greenhouse gas concentration to levels sufficient to meet the Paris goals will require ambitious reductions in all economic sectors, including so-called hard to abate sectors (e.g. aviation and agriculture) where technological options are limited and extreme demand reductions

☆ [1] The term GGR is used throughout to locate BECCS within this broad category of approaches, consistent with the terminology adopted in UK policy documents. The terms carbon dioxide removal (CDR) and negative emission technologies (NETs) are also commonly used umbrella terms.

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infeasible. GGR offers the potential to offset such residual emissions by removing equivalent amounts of CO_2 from the atmosphere [7,8].

Although other GGR approaches have been proposed [5], BECCS has a unique advantage in that it produces energy and its key components (bioenergy and CCS) are already at high technology readiness levels (TRL) [8,9]. Despite estimates of global GGR from BECCS as high as 10 Gt CO_2 per year [5], there remain significant uncertainties relating to its potential [10] and whether it can be done sustainably and in a short timescale. BECCS still faces challenges around technology costs, scaling-up, land-use competition, availability and sustainability of biomass resources, lack of strong policies and regulatory frameworks, public concerns over CO_2 leakage and ensuring that it genuinely delivers net negative emissions [11–14]. BECCS technologies have yet to be deployed commercially at scale. Several large BECCS power plants are currently planned but there are none in operation or construction [15]. The only large-scale BECCS plant in operation captures CO_2 from ethanol production (in the USA) with a capture capacity of 1 Mt per annum [16]. Further research is needed to better understand technical and non-technical barriers and hence the potential for BECCS to deliver large scale GGR [17].

In 2019, the UK committed to bringing GHG emissions to 'net-zero' by 2050, becoming the first major economy to pass legislation requiring a 100% reduction in net GHG emissions from 414 $MtCO_2e$ per year in 2020 [18]. In their sixth carbon budget, the UK's Committee on Climate Change (CCC) estimates that BECCS could facilitate CO_2 removal from the atmosphere of up to 22 $MtCO_2\ yr^{-1}$ by 2035 and 53 $MtCO_2\ yr^{-1}$ in the UK by 2050, deployed in a variety of applications (including power and hydrogen) [19]; additional engineered removals from Direct Air Capture and storage (5 $MtCO_2\ yr^{-1}$ by 2050) are also envisaged to have a role [20]. Others have estimated that the UK has a BECCS potential between 20 and 70 $MtCO_2$ removed per year [5]. BECCS in the UK is then expected to be instrumental in offsetting the remaining emissions from sectors difficult to decarbonise, potentially supporting the expansion of low-carbon electricity supply and hydrogen production [20,21]. As the technology is yet to be deployed commercially, cost estimates remain highly uncertain, the CCC estimate that BECCS costs could fall between £40–190/tCO2 by 2050 depending on the supply chain [19]. While substantial investment will be required to deliver the net-zero target, this will be offset by benefits from fuel savings, improved efficiency and cleaner technologies, and avoided climate impacts, with the CCC estimating that the overall cost will be less than 1% of GDP [19].

BECCS deployment depends on the availability of CCS infrastructure for the transport and storage of CO_2, yet to be established in the UK. The UK is well-positioned to utilise the benefits of CCS, with large offshore storage capacities in the North Sea, experience in large-scale bioenergy deployment and a strong research base on bioenergy and CCS [5,8,22–24]. Although momentum is building through the UK's Clean Growth Strategy [25] and its Industrial Decarbonisation Challenge, progress has been slow, of the 23 large-scale CCS projects operating or under construction worldwide, none is in the UK [26]. The limited commercial-scale deployment of CCS technologies is partly due to insufficient policy support and investment for technology development to date. However, with significant investment committed during 2020 and policy commitments for 4 industrial CCS clusters by 2030, the coming decade is expected to see significant progress in CCS infrastructure development in the UK [27]. Introducing biomass feedstock to CCS operations brings additional challenges, including a lack of regulatory frameworks to account for GGR and negative emissions and the challenges of sustainable biomass production and sourcing at the required scale [9,13,23,28–30].

1.2. BECCS supply chains

BECCS entails the integration of a wide range of possible biomass feedstock, (e.g. wood residues, energy crops), bioenergy technologies (e.g. combustion, gasification, fermentation), as well as, CO_2 capture and storage methods [14]. Hence, a BECCS supply chain offers different technological routes to produce electricity, heat/or biofuels. In the power sector, BECCS applications are typically categorised by one of three broad CO_2 capture methods (e.g. post-combustion, pre-combustion, oxy-combustion) which in turn depend on the bioenergy conversion technology [24].

Post-combustion capture involves the separation of CO_2 from flue gas by applying chemical absorption methods, after a fuel combustion process. It is the most mature and currently deployed technology and can be retrofitted from existing power plants [31]. Pre-combustion CO_2 capture is associated with gasification or steam methane reforming where a producer gas, comprised mainly of carbon monoxide, hydrogen, methane and CO_2 is produced and subsequently reacted with steam to produce a shifted gas containing mainly CO_2 and H_2. The CO_2 is separated from the H_2 typically using physical absorption methods [32]. Finally, oxy-combustion capture entails the CO_2 separation from flue gas (mainly composed of CO_2 and water vapour) via a condensation process. This flue gas composition results from burning fuel with oxygen and recycled CO_2 [31].

Knowledge gaps exist around what combination of biomass, energy conversion and carbon capture technologies and final energy vectors will deliver the most effective BECCS supply chains [7,8,24]. For a successful deployment of BECCS the implications of the full supply chain, from biomass production to CO_2 storage, needs to be understood from an emission, engineering, economic, social and policy point of view. The type, region and production management of biomass will have a direct impact on the CO_2 sequestration and actual GGR potential; the properties and behaviour of the biomass will influence the conversion process and efficiency. Additionally, both biomass properties and conversion process affect the quality of the flue gas, with a direct effect on the efficiency of the CO_2 separation process. BECCS offers an array of final energy vectors and energy uses that will also influence the upstream processes. Depending on the supply chain and its business model, the technical efficiency, cost and GGR potential will vary, which raises questions over the real contribution BECCS can make to attaining the net-zero target in the UK. Moreover, depending on the development and scale of other GGR approaches, the renewable energy sector and final energy demand, the future mix of BECCS applications, e.g., electricity, heat, hydrogen or transport fuels, remains open [33].

The research presented here is part of the wider NERC-funded project 'Feasibility of Afforestation and Biomass Energy with Carbon Capture and Storage for Greenhouse Gas Removal' (FAB-GGR), the primary aim of which is to better define the real-world feasibility and consequences of large-scale afforestation and BECCS approaches to GGR. Other aspects of the project are exploring the delivery of GGR assumed in assessments at national and global scales and their wider climate, environmental, social and political implications [34–36]. The research is underpinned by a strong stakeholder engagement process.

The objective of the research presented here is to investigate the GGR potential of alternative BECCS supply chains with potential for deployment in the UK and to understand how these could contribute to the UK's climate change target. Three supply chains were chosen to represent the variety of commercially available bioenergy pathways and technologies in the UK and their potential to deliver carbon dioxide removal when combined with CCS. A comparative analysis of the technical and GHG emissions performance of the relevant BECCS technologies is presented for these three supply chains. A more detailed description of the supply chain specifications can be found in Section 2.1. For each supply chain, GGR potential was evaluated using process modelling and lifecycle assessment (LCA) methods. Additionally, each bioenergy supply chain was also assessed without CCS, as a reference system, to allow comparison and provide a better understanding of the impacts on feedstock and energy demand of integrating CCS to existing bioenergy technologies.

The paper is structured as follows; Section 2 describes the methods, including the supply chain description, the process model and LCA, including the model configuration, the LCA goal and scope, system description, and lifecycle inventory. Section 3 introduces the results obtained from these analyses, first, the technical performance of the three BECCS supply chains and, second, the GHG emissions performance and potential for negative emissions of the BECCS supply chains. Section 4 discusses these results and how they inform on the BECCS role to achieve GGR and support the UK's net-zero emissions target. Finally, conclusions and recommendations are presented in Section 5.

2. Methods and materials

Three BECCS supply chains have been included in this analysis: (i) Sawmill residues to electricity with CCS; (ii) Miscanthus to CHP with CCS; (iii) Willow-BIGCC (Biomass Integrated Gasification Combined Cycle) to Electricity with CCS. The supply chain specifications were developed by the research team in consultation with stakeholders from across academic, business, industry, policy and NGO sectors. The choice of the three case study supply chains was the result of an iterative process: i) an initial set of draft supply chains were defined; ii) these were reviewed by a group of experts and practitioners at a stakeholder workshop held early in the project (see Ref. [35]) generating comments and suggestions for alternative configurations; iii) based on feedback generated during the workshop, the project team developed the following three supply chain configurations which form the basis of the analysis is described in Section 2.1 below. For each supply chain, the specification assumes a nominal location of the conversion facility in terms of distance between the biomass feedstock and CO_2 storage site.

The analysis was conducted by combining process modelling and lifecycle assessment (LCA). Through process modelling, described in Section 2.3, the technical characteristics of the bioenergy conversion, CO_2 capture and compression processes were evaluated. This included the assessment of the efficiency, process-related emissions and energy-mass balances of the biomass energy conversion, CO_2 capture and compression process. This assessment also provided detailed information on the carbon dynamics within the conversion and CCS system including the carbon embedded in the biomass entering the process, captured during CO_2 separation and its final storage. The LCA described in Section 2.4 evaluated the supply chain emissions (CO_2 and other GHG emissions) from biomass production to CO_2 storage in geological stores, including the emissions and CO_2 balance from the process modelling. This provided results for the negative and net-negative emissions and the related GGR potential for the three different supply chains.

Additionally, a set of different functional units was assessed to evaluate the absolute and net GHG emission per unit of energy produced, biomass and land required. To understand the relevance of CCS for bioenergy applications and the role of bioenergy in the transition to BECCS, the BECCS supply chains were compared with the application of the same bioenergy option without CCS. The rationale for studying the selected BECCS supply chains and a more detailed description follows.

2.1. Description of BECCS supply chains

2.1.1. Supply chain 1: Sawmill residues to electricity with CCS

The first supply chain evaluates biomass direct combustion for electricity generation, a mature technology, fitting current UK energy infrastructure; this system in combination with CCS is also included in the modelled IPCC scenarios [1]. The feedstock is sawmill residues, a potentially abundant resource, with a robust knowledge base on sustainability implications [22] and currently used in UK electricity generation [30]. Furthermore, there have been significant advances in understanding the costs, efficiencies, and challenges of biomass-fed combustion systems with carbon capture [13]. On the CCS side, post-combustion CO_2 capture technology with monoethanolamine (MEA) chemical absorbent is considered the benchmark technology and is used in several industrial applications and coal-power plants [29].

This supply chain consists of a large-scale biomass electricity plant, with a configuration based on an existing power plant facility in the UK, that integrates a post-combustion CCS unit. The supply chain encompasses the biomass production, processing, handling, transportation, energy conversion and CO_2 capture and storage stages (Fig. 1). It assumes that sawmill residues are imported from the timber industry in North America; they are pelletised and transported by ship and rail to the power plant facility in the UK [28]. The biomass power plant has a 620 MW nominal capacity and entails the wood pellets direct combustion in a subcritical pulverised fired boiler with low NOx burners to produce high-pressure steam. The steam flow is expanded in a series of steam turbines to produce electricity for the UK grid. The waste heat is used within the same plant to supply internal process demands, hence there is not heat surplus.

The CO_2 is captured from the combustion flue gas using an MEA-based chemical absorption process combined with a subsequent stripping to separate the CO_2 from the solvent. MEA (Monoethanolamine) is an amine solvent with extensive applications in post-combustion CO_2 capture and advantages over other amines in its ability to capture low CO_2 concentrations and with low heat of absorption [37]. The heat demand for solvent regeneration is obtained by drawing low-pressure steam from the power plant. The CO_2 rich gas passes through a series of compression and intercooling stages (up to a pressure of 11 MPa) and is transported through an onshore-offshore retrofitted pipeline network to storage in a former gas field in the North Sea.

2.1.2. Supply chain 2: Miscanthus to CHP with CCS

The second supply chain assesses the potential to use heat available onsite for solvent regeneration during the carbon capture process and use the biomass feedstock, Miscanthus, which has a high potential for production in the UK utilising marginal and lower-quality land [38]. Furthermore, the assessment of this supply chain explores the CCS integration to existent biomass-CHP technologies, the feasibility of medium-scale and modular systems as the majority of existing research focuses on BECCS via liquid biofuel production or biomass conversion in large-scale power plants [10]. It also investigates the potential for clustering CO_2 sources from medium-scale systems to facilitate economies of scales for CO_2 transport and storage [12].

This supply chain consists of a medium-scale biomass CHP system with the integration of a post-combustion CO_2 capture and storage unit. This supply chain also covers the stages of biomass production, processing, handling, transportation, energy conversion and CO_2 capture and storage. Fig. 2 shows a flow diagram of this supply chain. The feedstock is Miscanthus cultivated in the UK, assuming that low-quality land is converted into perennial energy crops [36]. The rotation period is 20 years, the first harvesting takes place in year 3 and is then harvested annually, yielding 12 t $ha^{-1}$of dry matter [38,39]. Miscanthus is harvested, baled, transported a maximum of 50 km by road to the plant facility and chipped at the site. The CHP plant has a net power capacity of 20 MW and a net heat generation capacity of 70 MW of heat (power to heat ratio of 1:3.7). Miscanthus chips are fired into an atmospheric air-blown circulating fluidised bed boiler for steam production. The steam flow is fed into a high-pressure turbine for electricity production and then to a backpressure turbine to extract a fraction of the steam as a heat carrier for applications such as district heating. The CO_2 capture stage is similar to the first supply chain (Sawmill residues to electricity – CCS) where a combination of MEA-based chemical absorption and stripping process is used to capture the CO_2 from the flue gas. The heat demand for the solvent regeneration, in the stripping section, is also supplied by the CHP plant. The CO_2 rich gas also passes through a series of compression and intercooling stages (up to 11 MPa of pressure) and is transported through an onshore-offshore pipeline network to the offshore storage described for the Sawmill residues to electricity with CCS.

2.1.3. Supply chain 3: Willow-BIGCC to electricity with CCS

The third BECCS supply chain considers a gasification pathway

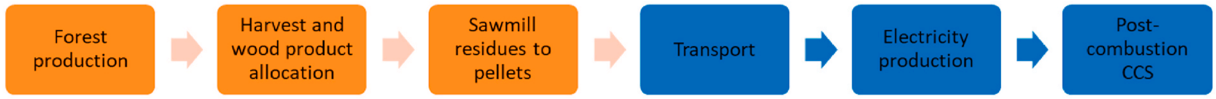

Fig. 1. Flow diagram of Sawmill residues to electricity with CCS supply chain.

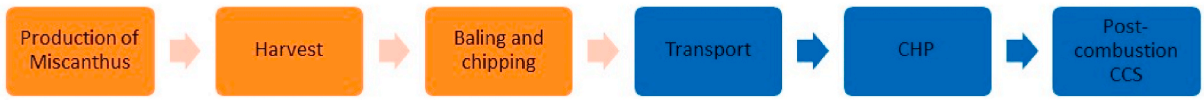

Fig. 2. Flow diagram of Miscanthus to CHP with CCS supply chain.

producing electricity from hydrogen. This biomass integrated gasification combined cycle (BIGCC) system takes Willow feedstock produced in the UK utilising marginal and lower-quality land [40,41]. The BIGCC is the most novel of the energy conversion technologies featured in the supply chains studied; pre-combustion BECCS can produce higher CO_2 reduction than post-combustion systems per unit of biomass. Research on BECCS producing hydrogen offers insights into possibly more modular applications, while past investigations mainly focus on large-scale and centralised systems. Finally, in addition to electricity generation, hydrogen can contribute to decarbonising the industry, heat and transport sectors that urgently require decarbonisation [15].

This supply chain consists of a large-scale biomass integrated gasification combined cycle with a pre-combustion CO_2 capture and storage unit including the stages of biomass production, transportation, energy conversion and carbon capture and storage (Fig. 3). The feedstock is Willow cultivated in the UK, then, harvested, bundled, chipped, and transported by road to the gasification plant facility within 50–100 km distance to the cultivation site. As for Miscanthus, the Willow is grown on lower quality land converted into perennial energy crops. The rotation period is 20 years, the first harvesting takes place in year 4 and is harvested subsequently every three years, yielding 9 t ha^{-1} of dry matter per year on average [42]. The gasification plant has a thermal capacity of 414 MW and the plant a net power capacity of 232 MW. The Willow chips are fed into a pressurised oxygen-blown circulating fluidised bed gasifier to produce a gas mixture comprised of CO, H_2, CH_4 and CO_2, the gas passes through cleaning and cooling stages, before entering the shift reactor where steam is supplied to react with the gas and convert the CO and H_2O into CO_2 and H_2. The shifted syngas goes through a scrubbing process to separate the CO_2 from the H_2 applying the commercial process Rectisol that uses chilled methanol as a physical solvent [43]. Physical solvents are more suitable for CO_2 capture when the gas has higher partial pressures of CO_2 at the inlet of the absorption process in IGCC systems. These solvents also have a higher absorption capacity, suitable for syngas containing higher CO_2 concentrations [44]. The two streams leaving the absorber are a highly pure H_2 gas and a CO_2 rich solvent. The H_2 gas is used as fuel gas in a gas turbine–steam turbine combined cycle for power generation. The power demand of the gasification and CCS plant is supplied by the same BIGCC plant. The CO_2 is stripped from the solvent in a series of flashing – intercooling stages to separate the CO_2 from the physical solvent. Finally, the pure CO_2 stream is compressed up to a pressure of 11 MPa and transported through pipelines to the offshore storage as described for the Sawmill residues to electricity with CCS supply chain.

2.2. Biomass characteristics

The biomass characteristics of the feedstock for the three supply chains are collated in Table 1 in the form of proximate and ultimate analysis. Properties on white wood pellets available in the Phyllis database [45] were used for the Sawmill residues to electricity with CCS, Miscanthus (MxG) properties reported in Ref. [46] were used for the Miscanthus to CHP with CCS supply chain and data on Willow properties presented in Ref. [47] were used for the Willow-BIGCC to Electricity with CCS supply chain. These characteristics were used to specify the

Table 1
Proximate, elemental analyses and yields of White Wood pellets, Miscanthus and Willow feedstock.

Biomass characteristics	*White wood pellets* (Sawmill residues to electricity with CCS) – Ref. [45]	*Miscanthus (MxG)* (Miscanthus to CHP with CCS) – Ref. [46]	*Willow* (Willow-BIGCC to Electricity with CCS) – Ref. [47]
Proximate analysis (dry basis mass fraction) %			
Volatile matter	82.6	81.4	78.6
Ash	0.6	2.1	5.4
Fixed carbon	16.8	16.5	16
Moisture mass fraction as received	7.8	3.7	5.7
Ultimate analysis (dry basis mass fraction) %			
Carbon	48.7	45.1	45.9
Hydrogen	6.2	5.5	5.4
Oxygen	43.4	47.2	41.5
Nitrogen	0.1	0.2	1.8
Sulphur	0.01	–	–
Ash	0.6	2	5.4
Low Heating Value$_{(d.b.)}$ (MJ kg^{-1}, dry basis)	19.3	18.6	18.2

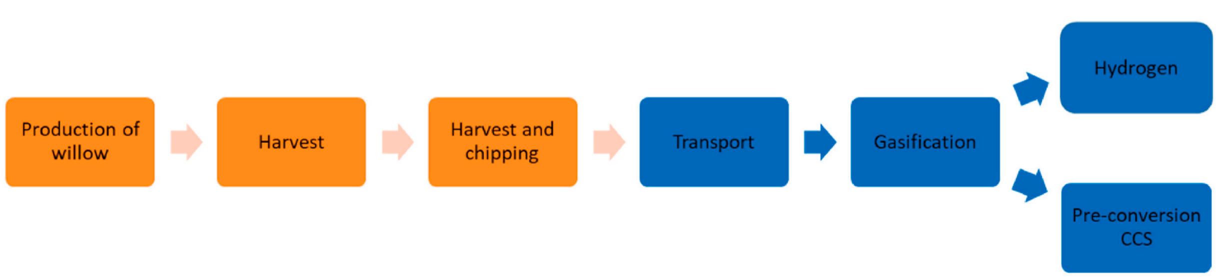

Fig. 3. Flow diagram of Willow-BIGCC to Electricity with CCS supply chain.

biomass feed together with the low heating value in the *Aspen Plus* configuration for the process modelling.

2.3. Process modelling configuration

The energy conversion processes in each supply chain were modelled following a thermodynamic equilibrium approach in the software *Aspen Plus*. This method can provide good initial estimates of the gas composition and yields, identify operating limits and allow an evaluation of the relationship between the biomass characteristics and process parameters [48]. The power generation stage was also incorporated into the *Aspen plus* model using turbines and compressors unit processes. Table 2 collates the configuration of the biomass conversion and power/CHP units in *Aspen Plus*.

For the BECCS supply chains, the CO_2 capture and compression stages were integrated into the *Aspen Plus* model and the operation of each BECCS supply chains simulated to quantify the mass and energy balances. The CO_2 capture stage of the Sawmill residues to electricity with CCS and the Miscanthus to CHP – CCS supply chains were modelled as a standard absorption-desorption process using a 30% wt. MEA (monoethanolamine) solvent, designed to capture around 90% of the CO_2 in the flue gas. The *Aspen Plus* Radfrac column model was used to model the CO_2 absorption. This modelling configuration is supported in other process modelling works of CO_2 capture systems [43,49–51]. For the CO_2 stripper, the Radfrac column model was also used, but in this case, the setup included a partial-vapour configuration for the condenser and a kettle configuration for the reboiler [43]. The heat required to regenerate the CO_2 rich solvent in the stripper was supplied through a reboiler, using the steam extracted from the steam turbine IP/LP (Intermediate pressure/Low pressure) crossover. Table 3 shows the configuration of the CO_2 capture and compression stages in Aspen Plus.

For the Willow-BIGCC to Electricity with CCS, the pre-combustion CO_2 capture stage was modelled using the Radfrac model. The CO_2 absorption process is based on the commercial Rectisol process that uses chilled methanol as a physical solvent to separate the CO_2 from the shifted gas [44]. These solvents have a higher absorption capacity, suitable for syngas containing higher CO_2 concentrations [44] compared to chemical solvents. Since a physical absorption method was used, the CO_2 stripping process was modelled with a series of flashing (i.e. pressure reduction) and cooling stages that produce a pure CO_2 stream and regenerate the rich solvent. The recovered lean solvent was recirculated to the top of the absorber. The use of the flashing steps avoids the energy penalties from the reboiler heat requirement in a conventional CO_2 stripping column. The modelling configuration of the pre-combustion CO_2 capture unit is also supported with process modelling works on BIGCC systems with CCS [32,43,52,53].

Table 2
Configuration of the biomass conversion and power generation stages of the BECCS systems.

Plant configuration	*Sawmill residues to electricity with CCS*	*Miscanthus to CHP with CCS*	*Willow-BIGCC to Electricity with CCS*
Power plant capacity (MW)	620	20	232
Heat plant capacity (MW)	NA	70	NA
Biomass feedstock	White wood pellets	Miscanthus chips	Willow chips
Biomass flow rate (t h^{-1})	320	39	132
Boiler/Gasifier technology	Subcritical pulverised fired boiler with low NOx burners	Atmospheric air-blown circulating fluidised bed boiler	Pressurised oxygen-blown circulating fluidised bed gasifier
Gas Turbine Pressure ratio	NA	NA	18
Main steam flow (t h^{-1})	1660	195	NA
High-Pressure Turbine			
Temp (°C)	570 °C	519 °C	542 °C
Pressure (MPa)	16.5 MPa	12 MPa	14 MPa

Table 3
Configuration of CO_2 capture and compression stages of the BECCS systems.

	Sawmill residues to electricity with CCS	Miscanthus to CHP with CCS	Willow-BIGCC to Electricity with CCS
Configuration of CO_2 capture stages			
Absorber configuration (Aspen model type)	RadFrac model	RadFrac model	RadFrac model
CO_2/Solvent mole ratio	30% wt. MEA	30% wt. MEA	Rectisol process Physical solvent: methanol
Solvent flow rate (t h^{-1})	9000	750	640
Lean loading (mol CO_2/mol MEA)	0.23	0.23	NA
Rich loading (mol CO_2/mol MEA)	0.46	0.46	NA
Stripper model (Aspen model type)	RadFrac model	RadFrac model	Flashing process
Configuration of compression stages			
Pressure 1 (MPa)	4	4	4
Pressure 2 (MPa)	40	40	40
Pressure 3 (MPa)	80	80	80
Pressure 4 (MPa)	110	110	110

2.4. Lifecycle assessment

An attributional LCA was conducted with the goal of evaluating the climate change impact of the three BECCS supply chains and their reference systems (bioenergy without CCS), comprising a cradle-to-grave lifecycle. An attributional approach was adequate to achieve the set goal and scope of the LCA, supporting the comparison between systems of equal functional units and the assessment of multifunctional processes [54]. Furthermore, a mid-point LCA approach was used to facilitate comparison between the supply chains and allow the LCA results to provide inputs on the climate change potential of each supply chain. The LCA followed the ISO 14040 [55] and 14044 [56] standards and used the software *Simapro* version 9.0 with the Ecoinvent 3.4 database to facilitate the construction of the lifecycle inventory and the lifecycle impact assessment of each supply chain. The calculations for the lifecycle impact assessment (LCIA) were conducted following the LCIA requirements [57]. This methodology assesses different impact categories, however, the main focus of this LCA was the climate change impact category since the aim of this research is to investigate the negative and net-negative emissions of each supply chain to evaluate the GGR potential.

The systems boundary for this LCA includes the biomass growth, sourcing and/or crop cultivation, harvest and feedstock handling, feedstock processing, transport, biomass conversion to electricity (and heat), and final CO_2 capture, compression, transportation and storage. The final use of the generated energy and other potential biomass not utilised for energy or BECCS lie outside the system boundaries. The system boundaries of the investigated BECCS supply chains and reference systems are illustrated in Fig. 4 and Fig. 5.

Table 4 collates the lifecycle inventory for biomass production, processing, handling, and transport for BECCS supply chains and reference system and CCS infrastructure for BECCS supply chains.

The unit of measurement was kg of CO_2 equivalent per MWh of

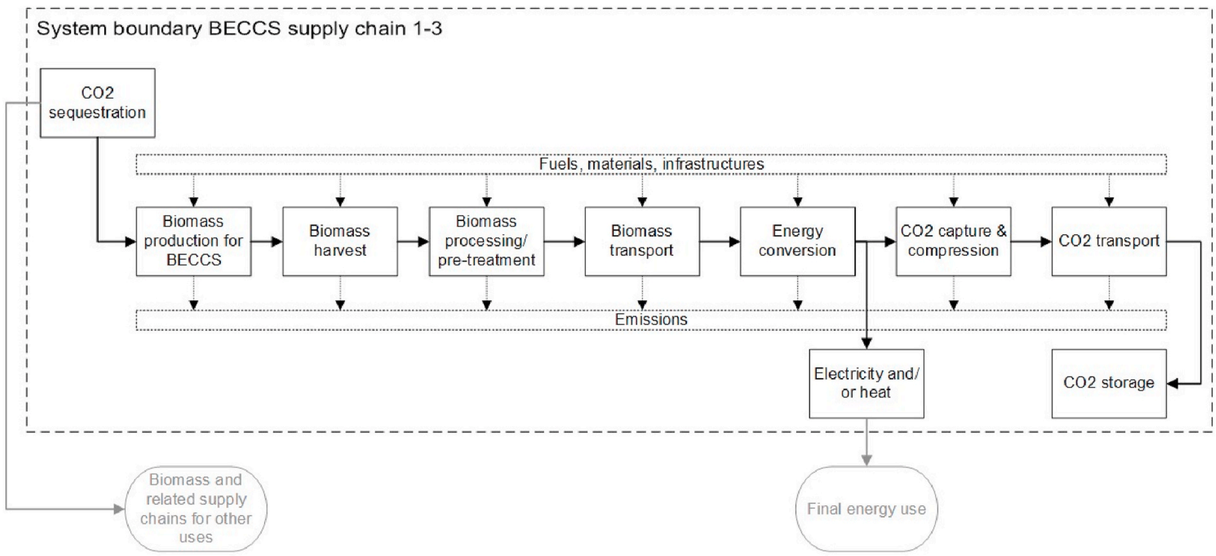

Fig. 4. System boundary for the three BECCS supply chains.

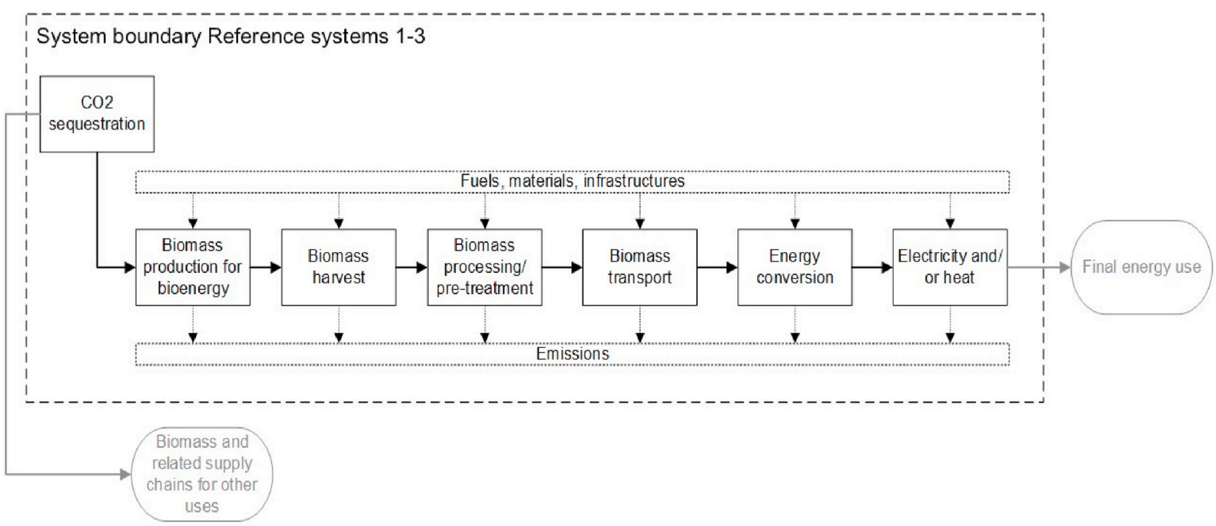

Fig. 5. System boundary for the three reference systems.

energy produced and this measurement included fossil and biogenic CO_2 emission as well as other GHGs emissions (i.e. CH_4, CO, N_2O). The functional unit was, for Sawmill residues to electricity with CCS, Willow-BIGCC to Electricity with CCS and corresponding reference systems, 1 MWh of net electricity produced. For the Miscanthus to CHP with CCS and reference system, an exergy-based allocation approach was used to account for the two energy products of the system, electricity, and heat. The procedure for the exergy allocation was taken from Njakou Djomo et al. [62], where the Carnot factor was set in $\eta_{C,el} = 1$ for electricity and $\eta_{C,th} = 0.36$ for heat. The partitioning coefficients were calculated as fractions of the exergy-based content of the electricity and heat products using the approach reported by Cherubini et al. [63] and the resulting coefficients were $\alpha_{el} = 42\%$ for electricity, and $\alpha_{th} = 58\%$ for heat. Finally, the impact indicators allocation between the electricity and heat was done using these coefficients, which allowed to have compatible functional units with the energy products of the other supply chains and reference systems.

As the focus of the research was the GGR potential of BECCS supply chains, all upstream inputs and emissions related to biomass production and sourcing were allocated by mass. The emissions related to supply chain activities are evaluated, however, related sensitivities were not evaluated as these have been reported by others [38,64–67] and were outside the scope of this study. However, the assessment of different BECCS supply chains and their reference systems provided insights into the variation of GGR potential for different applications.

While energy- and exergy-based functional units were used for the LCA, the emissions have also been converted to emissions per amount of biomass (CO_2e per tonne of biomass) and emissions per area (CO_2e per hectare). This allows the evaluation of biomass and land requirements in relation to the efficiency of the conversion and CO_2 captured. Conversion technologies with low efficiencies require larger amounts of biomass, this means more CO_2 can be captured per unit of energy than in a more efficient technology requiring less biomass per unit of energy produced. However, this also means that more biomass and larger areas of land are required to produce the same amount of energy. A comparison of energy, biomass and area related emissions provides more transparency on the actual GGR potential and possible sustainability implications of BECCS.

Soil carbon can play an important role in the carbon balance of a bioenergy system if land use change is involved in the production of biomass. There are large uncertainties related to soil carbon stock

Table 4
Lifecycle inventory for BECCS supply chains and reference systems.

Supply chain inputs (material and energy)	*White wood pellets* (Sawmill residues to electricity with CCS & ref system 1) - Ref [28]	*Miscanthus chips* (Miscanthus to CHP with CCS & ref system 2) - Ref [58]	*Willow chips* (Willow-BIGCC to Electricity with CCS & ref system 3) - Ref [59]
Biomass production			
Site establishment, diesel (L t^{-1})	1.21	0.45	2.05
Beet seed (kg t^{-1})		0.06	0.09
Agro-chemical application, diesel (L t^{-1})	1.02	0.34	0.23
Herbicide, glyphosate (g t^{-1})	3.94	11.54	8.27
Pesticide, unspecified (g t^{-1})			1.72
Pesticide, Acetamide-anillide-compound (g t^{-1})			0.69
Fertiliser, DAP (kg t^{-1})	2.97		
Fertiliser, Urea (kg t^{-1})	1.59		
Fertiliser, Phosphate rock, as P_2O_5 (kg t^{-1})		2.32	
Fertiliser, Potassium sulfate (kg t^{-1})		6.48	
Fertiliser, Magnesium oxide (kg t^{-1})		1.3	
Fertiliser, Potassium chloride, as K_2O (kg t^{-1})			2.2
Fertiliser, Lime (kg t^{-1})			27.52
Fertiliser, Nitrogen fertiliser, as N (kg t^{-1})			1.72
Mulching, diesel (L t^{-1})		0.03	0.03
Post-harvest and pre-treatment			
Harvesting, diesel (L t^{-1})	12.39	2.39 (incl. baling & chipping)	1.71 (incl. chipping)
Sawing, electricity (kWh t^{-1})	13.46		
Pelleting, electricity (kWh t^{-1})	165		
Loader, diesel (L t^{-1})	0.42	1.33	0.86
Storage pellets, electricity (kWh t^{-1})	9.1		
Transport (all as roundtrip with empty return)			
Forest to pellet mill/sawmill, truck (km)	160		
Pellet mill – U.S. port, truck (km)	300		
Transoceanic shipping, vessel (km)	13,000		
UK port to power plant (km)	348		
		4	4

Table 4 (*continued*)

Supply chain inputs (material and energy)	*White wood pellets* (Sawmill residues to electricity with CCS & ref system 1) - Ref [28]	*Miscanthus chips* (Miscanthus to CHP with CCS & ref system 2) - Ref [58]	*Willow chips* (Willow-BIGCC to Electricity with CCS & ref system 3) - Ref [59]
Field to farm, truck (km)			
Farm to power plant, truck (km)		100	100
Truck fuel use, (L/km)	0.7		
Rail fuel use, (L/km)	0.009		
Vessel fuel use, (L/km)	0.003		
CSS infrastructure (full details on energy and material demand from [60]) – BECCS supply chains only			
CO_2 transport, pipeline km (assumption)	400		
Well, storage capacity (Mt) - Ref [61]	15		
Well injection, electricity (kWh kg^{-1}) Ref [60]	0.03		
Compression every 200 km pipeline (kWh) Ref [60]	0.013		

dynamics if it is not clear what land was used for before and after growing biomass [28,68]. Moreover, if land use does not change, solid carbon stocks will plateau over time and will not have a significant impact on the overall carbon dynamics of the system [69]. In the case of the use of sawmill residues, we did not consider any land use change and assumed that soil carbon stocks in the forest plateaued [28]. In the case of Miscanthus and Willow, carbon stock changes are likely if these crops are established on land previously used differently [38]. As assumptions on the land use after the end of the rotations can vary (e.g., replanting of the same perennial, conversion to other land use), this would consequently have different effects on soil carbon stocks [68]. For this reason, solid carbon stocks have not been included in this assessment but details of the impact and scale in case of land use change have been investigated by Rowe et al. [68].

3. Results

3.1. *Technical performance of BECCS supply chains*

The technical performance of the biomass energy conversion, CO_2 capture and compression stages of the BECCS supply chains was evaluated using a set of technical parameters and benchmarked against reference systems without CCS integration. Table 5 collates the data of this technical assessment, which included the net conversion efficiency, energy penalties and CO_2 capture rates.

The Sawmill residues to electricity with CCS supply chain, generating 440 MW of electricity with a net energy efficiency of 26%, is the largest scale of the three BECCS supply chains. The energy demand of the CCS unit, deriving from the steam consumption for the solvent regeneration and the CO_2 compression stages, causes a reduction of the plant efficiency by 9% points (25% of energy penalty) compared to the reference system. This is consistent with figures of large-scale power plants with post-combustion CCS reporting energy penalties between 15 and 28% and efficiency penalties of 8–15.4% [70]. The 88% CO_2 capture rate of this supply chain is also close to the capture rate set in the configuration and the CO_2 stream is highly pure (99%) as required for

Table 5
Technical performance of BECCS supply chains and reference systems.

Performance parameters	*Sawmill residues to electricity with CCS*	*Sawmill residues to electricity – no CCS*	*Miscanthus to CHP with CCS*	*Miscanthus to CHP – no CCS*	*Willow-BIGCC to Electricity with CCS*	*Willow-BIGCC to Electricity – no CCS*
Biomass energy input (MW)	1717	1717	202	202	668	668
Net electricity output (MW)	440	590	19	28	233	276
Net heat output (MW)	–	–	71	150	–	–
Plant electricity consumption (MW)	94	29	12	3	50	32
Net energy efficiency	26%	35%	45%	88%	35%	41%
Energy penalty	25%	N/A	32% [a]	N/A	15%	N/A
Efficiency penalty	9% points	N/A	4% points [a]	N/A	6% points	N/A
CO_2 capture rate	88%	N/A	87%	N/A	94%	N/A
CO_2 concentration	99%	N/A	99%	N/A	98%	N/A
CO_2 captured per biomass (kg kg^{-1})	1.5	N/A	1.4	N/A	1.6	N/A
CO2 captured per energy (kg MWh^{-1})	1067	N/A	2827	N/A	893	N/A
CO2 emissions per energy (kg MWh^{-1})	185	904	139	345	65	757

[a] The energy penalty and efficiency penalty supply chain CHP from residues Post-CCS were calculated on an electricity basis for consistency with the other two supply chains.

the compression and transportation stages. The CO_2 captured per energy ratio (1067 kg MWh^{-1}) also falls within the range values reported by others for large-scale biomass-fired plants with CCS [51,71,72].

The Miscanthus to CHP with CCS yielded an energy conversion efficiency of 45% producing two energy products, electricity, and heat, from the biomass energy input. The proportional loss in electricity output capacity as a result of the CCS integration derived in an energy penalty of 32% and an efficiency penalty of 4% points, both on an electricity basis. Although there is no reference data for medium-scale biomass CHP with CCS systems to benchmark the results, the energy penalty is expected to increase. In the Miscanthus to CHP with CCS supply chain a larger fraction (58%) of the heat produced is used for solvent regeneration in the CO_2 capture stage. The CO_2 capture rate (87%) and CO_2 concentration (99%) result again in acceptable values for commercial CO_2 capture units [73]. The CO_2 captured ratio for this supply chain is much higher than those for the other supply chains, as this is calculated on an electricity basis (not energy) for consistency with other supply chains.

The Willow-BIGCC to Electricity with CCS supply chain combines BIGCC (Biomass Integrated Gasification Combined Cycle) and pre-combustion capture involving different bioenergy and CO_2 capture technologies compared to the other supply chains. This results in an energy conversion efficiency of 35% for the electricity generation since and IGCC system exhibit a high fuel conversion efficiency and power generation efficiency due to the use of a combined cycle, comprised of gas and steam turbines [74]. Also, the energy penalty (15%) is lower as the pre-combustion CO_2 capture with the Rectisol process significantly reduces the energy demand for the chemical solvent regeneration, using instead a series of flashing processes to separate the CO_2 from the physical solvent. These numbers evaluating the penalties on the supply chain with CCS also agree with the literature [70,75] reporting intervals between 4.9% and 20% for the energy penalty and 5–10.3% for efficiency penalty in IGCC systems with pre-combustion CCS. The CO_2 captured per energy ratio (893 kg MWh^{-1}) also compares with values reported in Refs. [71,76] for similar systems.

The energy efficiencies of the BECCS systems are lower compared to their reference systems without CCS, due to the penalty imposed by the additional energy demand of the CCS unit. The CO_2 capture and compression are the stages with the highest energy demand. The CO_2 capture stage requires heat to regenerate the amine solvent in the stripping section and the compression multi-stages also consume a large amount of electricity (43 MW, 45% of the energy demand of the plant) to raise the CO_2 gas pressure to 11 MPa. For the BECCS supply chains using post-combustion CO_2 capture, the integration of the CCS unit to the power plant more than doubles the internal power demand for the Sawmill residues to electricity - CCS and is four times higher for the Miscanthus to CHP with CCS. For the Willow-BIGCC to Electricity with CCS, the addition of the CCS plant using a pre-combustion CO_2 capture increases the plant's internal energy consumption to a lower degree as a result of the application of a physical solvent. The efficiency penalty caused by these two stages derives into an important limitation to BECCS supply chains deployment requiring more fuel input to deliver the same energy output.

The Miscanthus to CHP with CCS supply chain yields the highest energy conversion efficiency among the three BECCS supply chains, because of more effective utilisation of the biomass energy potential to produce two energy products, heat, and electricity. This system has a high heat to electricity ratio (3.7:1), as expected for CHPs using back-pressure steam turbines that use a small fraction of the steam to produce electricity and a larger fraction for process heat generation [77].

The Willow-BIGCC to Electricity with CCS has also a high conversion efficiency (35%), greater than the energy efficiency of the Sawmill residues to electricity with CCS (26%), using a conventional biomass power plant. The same occurs with their corresponding reference systems, i.e. Sawmill residues to Electricity: 35% and Willow-BIGCC to Electricity: 41%. BIGCC are cleaner and more efficient systems as a gas fuel is used instead of biomass direct combustion allowing a more efficient gas clean-up process before combustion. Also, the use of a combined power cycle (gas and steam turbines) results in a higher fuel conversion efficiency and power generation efficiency than a conventional power plant [74]. Besides, the pre-combustion CO_2 capture is less energy intensive as the CO_2 separation from the rich solvent is done through a flashing process, instead of using a stripping column that requires steam for the amine regeneration in the reboiler [31,32]. This energy-saving is, however, counteracted by the high-energy demand of the Air Separation Unit (ASU) when producing oxygen for gasification [32].

From a feedstock perspective, Sawmill residues to electricity with CCS using white wood pellets has the highest energy input per mass unit. This biomass has 19.3 MJ kg^{-1} the highest low heating value (LHV) among the three feedstocks, where the LHV of Miscanthus (18.6 MJ kg $^{-1}$) and Willow (18.2 MJ kg $^{-1}$) are similar. The high LHV of the white wood pellets responds to a lower oxygen-to-carbon (O/C) ratio among the three types of biomass [78]. The pelletisation of the sawmill residues also increases the energy density of the feedstock compared to the chipped and dried Miscanthus and Willow.

The emissions of the BECCS supply chains (CO_2 emitted per energy produced), as expected, are lower than the ones of the reference systems without CCS, despite a reduction in the net power output of the BECCS supply chains. While the BECCS supply chains capture most of the CO_2, there are still residual CO_2 emissions vented to the air, including the CO_2 not captured in the CCS unit, i.e. 87-94% of the CO_2 in flue gas or syngas streams were captured and stored.

The emissions from the energy conversion, CO_2 capture and compression (as CO_2e) are 185 kg MWh^{-1} for Sawmill residues to electricity with CCS, 139 kg MWh^{-1} for Miscanthus to CHP with CCS and 65 kg MWh^{-1} for Willow-BIGCC to Electricity with CCS. The CO_2e specific emissions of the Sawmill residues to electricity with CCS more than triple and those from the Miscanthus to CHP with CCS more than double the emissions of the Willow-BIGCC to Electricity with CCS. The Willow-BIGCC to Electricity with CCS supply chain has the lowest specific CO_2 emissions as a result of the cleaner combustion of hydrogen in the gas turbine in combination with a higher energy conversion efficiency. On the other hand, the other supply chains have higher CO_2 emissions due to the biomass direct combustion in the boilers. The CO_2 specific emissions of Miscanthus to CHP with CCS are lower than the Sawmill residues to electricity with CCS because of the significantly higher energy generation in the biomass CHP system compared to the conventional biomass power plant [77].

Among the three reference systems (no CCS integration), Miscanthus to CHP achieves the lowest CO_2e specific emissions, followed by Willow-BIGCC to Electricity and Sawmill residues to electricity with a 345 kg MWh^{-1}, 757 kg MWh^{-1} and 904 kg MWh^{-1}, respectively. The Miscanthus to CHP reports the lowest emissions due to the considerably higher energy conversion efficiency compared to the other two reference systems. The CO_2 specific emissions of Willow-BIGCC to Electricity are lower than from Sawmill residues to electricity due to the cleaner combustion of the syngas in the gas turbine and the higher energy conversion efficiency of the system.

3.2. GHG emission profiles of BECCS supply chains and reference systems

The LCA followed the method detailed in section 2.4. The results presented in this section focus on evaluating the GHG emissions performance and negative and net-negative emissions of the BECCS supply chains.

Table 6 presents the LCA results including the CO_2 sequestration during biomass growth and the supply chain emissions per unit (MWh) of energy produced and the total net emissions for the BECCS supply chains and the corresponding reference systems.

The Sawmill residues to electricity with CCS, Miscanthus to CHP with CCS and Willow-BIGCC to Electricity with CCS have total supply chain emissions as CO_2e of −647 kg MWh^{-1}, −1131 kg MWh^{-1} and -693 kg MWh^{-1}, respectively, meaning in all three cases the supply chain have net-negative emissions. With CO_2e sequestration of −1201 kg MWh^{-1} for Sawmill residues to electricity with CCS, −1568 kg MWh^{-1} for Miscanthus to CHP with CCS and −855 kg MWh^{-1} for Willow-BIGCC to Electricity with CCS, all supply chains remove more CO_2 from the atmosphere than they release along the supply chain. The CO_2e emissions from the supply chains are 557 kg MWh^{-1} for Sawmill residues to electricity with CCS, 437 kg MWh^{-1} for Miscanthus to CHP with CCS and 161 kg MWh^{-1} for Willow-BIGCC to Electricity with CCS. This was expected as most of the CO_2 from the flue gas or syngas (87%–94%) is captured and stored, leading to net-negative emissions for all three BECCS supply chains.

To complement the information presented in Table 6, Fig. 6. for Sawmill residues to electricity with CCS, Fig. 7 for Miscanthus to CHP with CCS and Fig. 8 for Willow-BIGCC to electricity with CCS illustrate the supply chain emissions, the net emissions achieved and the CO_2 storage efficiency per energy unit.

For the BECCS supply chains, the main contributions to the emission profile are related to the production and transport of biomass and the energy conversion and CO_2 capture process. The Sawmill residues to electricity with CCS has higher CO_2e emissions from biomass production and transport (323 kg MWh^{-1}) than Miscanthus to CHP with CCS and Willow-BIGCC to Electricity with CCS (with 47 kg MWh^{-1} and 40 kg MWh^{-1}, respectively) as sawmill residues require more energy for pelletising and are transported for a longer distance than the locally produced biomass chips in the other supply chains. While around 90% of the CO_2 from the flue gas or syngas is captured for the three supply chains, there are still some indirect emissions during the energy conversion and CCS process and not all CO_2 can be captured.

The Miscanthus to CHP with CCS and the Sawmill residues to electricity with CCS have higher emissions from the energy conversion and CO_2 capture process as CO_2e (344 kg MWh^{-1} and 199 kg MWh^{-1}, respectively) due to a less efficient capture process (87%–88%) in an amine-based solvent. The CHP system (with and without CCS), however, results in higher emissions as smaller biomass combustion systems tend to have less favourable emissions performance [79]. This is offset with higher energy efficiency, CO_2 sequestration ratio, and fewer emissions in the biomass production stage.

The emissions from the construction and utilisation of the CCS infrastructure are relatively low for Sawmill residues to electricity with CCS with about 7%. While the absolute CCS infrastructure CO_2e emissions are similar with 35 kg MWh^{-1} for Sawmill residues to electricity with CCS, 36 kg MWh^{-1} for Miscanthus to CHP with CCS and 29 kg MWh^{-1} for Willow-BIGCC to Electricity with CCS their relative contribution increase to 12% and 22%, respectively, with lower emissions from the other stages of the supply chains. The variations in absolute emissions of the CCS infrastructure are due to the different amounts of CO_2 transported for each supply chain, while the distance is considered the same for easier comparison.

All three BECCS supply chains have a high carbon capture efficiency; Sawmill residues to electricity with CCS has a total carbon capture efficiency of 85%, Miscanthus to CHP with CCS of 91% and Willow-BIGCC to Electricity with CCS of 92%. The higher energy efficiency of the

Table 6
CO_2 sequestration and GHG emissions of BECCS supply chains and reference systems as kg per MWh.

Supply chain	CO_2e sequestration (kg MWh^{-1})	Emissions from Biomass production & transport (kg MWh^{-1})	Emissions from Energy conversion & CO_2 capture (kg MWh^{-1})	Emissions from CCS Infrastructure (kg MWh^{-1})	Total net emissions (kg MWh^{-1})
Sawmill residues to electricity with CCS	−1201	323	199	35	−647
Sawmill residues to electricity – no CCS	−879	237	911	0	269
Miscanthus to CHP with CCS	−1568	47	344	46	−1131
Miscanthus to CHP – no CCS	−1082	32	1118	0	68
Willow-BIGCC to Electricity with CCS	−855	40	92	29	−693
Willow-BIGCC to Electricity – no CCS	−719	34	760	0	75

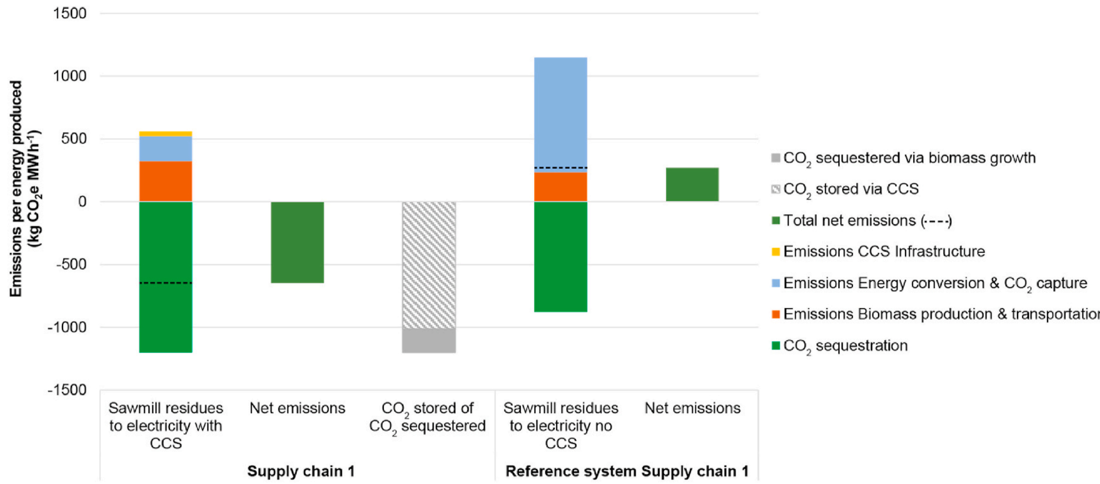

Fig. 6. GHG emissions, net emissions, and CO_2 storage efficiency per MWh of Sawmill residues to electricity with CCS s.

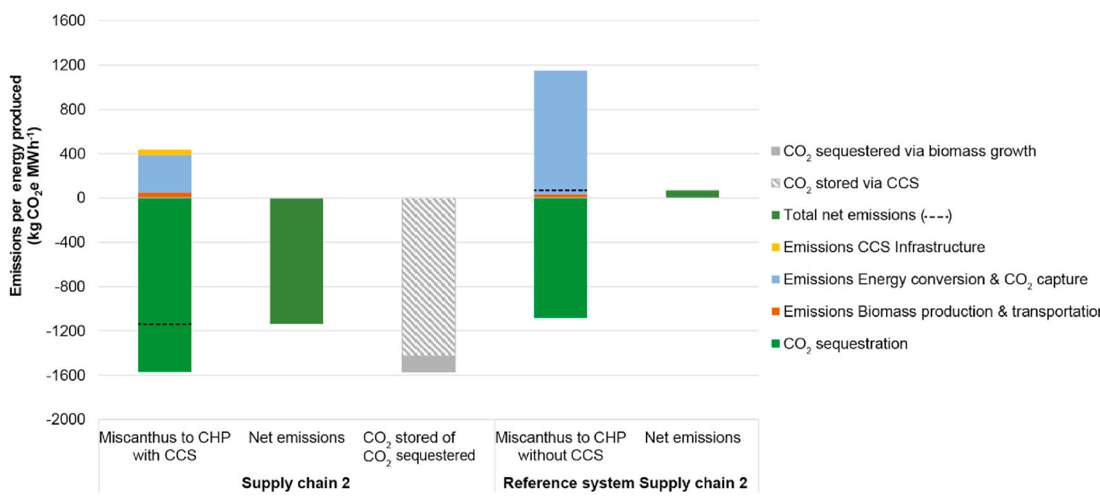

Fig. 7. GHG emissions, net emissions, and CO_2 storage efficiency per MWh of Miscanthus to CHP with CCS.

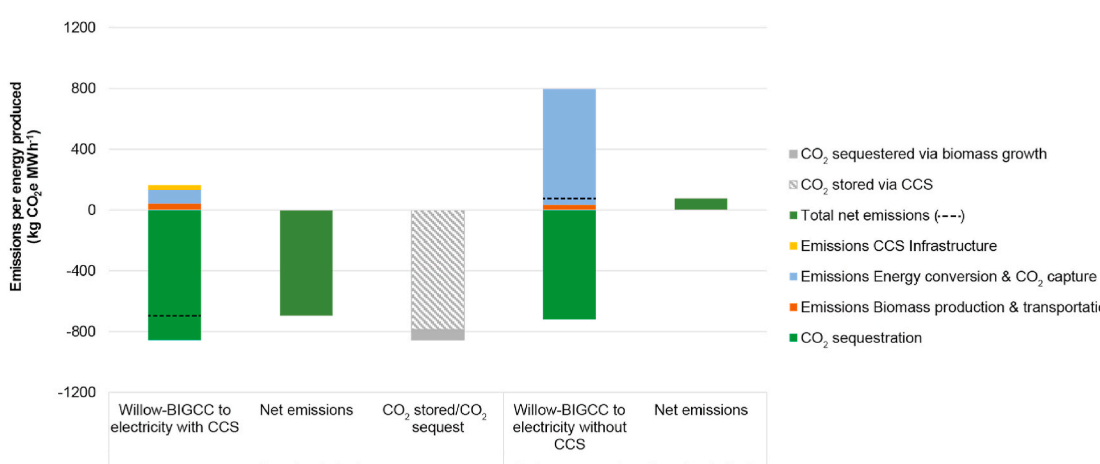

Fig. 8. GHG emissions, net emissions, and CO_2 storage efficiency per MWh of Willow-BIGCC to electricity with CCS.

Miscanthus to CHP with CCS and Willow-BIGCC to Electricity with CCS improves the overall performance of these supply chains leading to higher carbon capture efficiency compared to Sawmill residues to electricity with CCS. However, the greater amount of CO_2 captured per unit of energy in the Sawmill residues to electricity with CCS and Miscanthus to CHP with CCS supply chains relate to the higher volumetric flow of the flue gas, whereas the flow of shifted gas in the Willow-BIGCC to Electricity with CCS almost halves after the CO_2 capture stage with the physical absorbent.

The total emissions (i.e. biomass production, energy conversion and CCS infrastructure) of the Willow-BIGCC to Electricity with CCS are lower compared to the emissions of Sawmill residues to electricity with CCS and Miscanthus to CHP - CCS, due to cleaner hydrogen combustion in the gas turbines. The Willow-BIGCC to Electricity with CCS has a higher energy efficiency (35%) and CO_2 capture rate (94%) compared to Sawmill residues to electricity with CCS, hence yields more net-negative emissions. Also, the carbon storage efficiency of this system, which relates to the amount of CO_2 stored per CO_2 sequestered, is higher (92.3%) than for the other two supply chains.

Furthermore, Fig. 9 complements Table 6 comparing the net emissions per energy unit of the three BECCS supply chains and the correspondent reference systems. In the case of the reference systems, the net CO_2e emissions are 269 kg MWh^{-1}, 68 kg MWh^{-1} and 75 kg MWh^{-1}, respectively for the Sawmill residues to electricity, Miscanthus to CHP and Willow-BIGCC to Electricity. As expected, the reference systems release more CO_2 than is sequestered during plant growth as all biogenic carbon is released back to the atmosphere during the energy conversion process, in addition, to supply chain process emissions. The CO_2e emissions released during the energy conversion dominate the emission profile with a 911 kg MWh^{-1} for Sawmill residues to electricity, 1118 kg MWh^{-1} for Miscanthus to CHP and 760 kg MWh^{-1} for Willow-BIGCC to Electricity. These emissions are mainly biogenic carbon released back to the atmosphere in the flue gas.

Additionally, they included emissions related to the operation of the conversion process. As indicated above, emissions from smaller biomass combustion systems tend to be higher, hence the higher emissions for the Miscanthus to CHP reference system. Similar to the BECCSS supply chains the reference systems have emissions related to upstream supply chain processes such as biomass production, processing, and transport (Table 6). The Sawmill residues to electricity system has the highest emission of these upstream emissions due to a more energy intense pretreatment of the biomass into pellets and a longer transport distance. Overall, the upstream emissions for the reference systems are lower compared to the BECCS supply chains as less biomass is required per unit of energy produced, avoiding the energy penalty of the CCS process.

3.3. GHG emissions of BECCS supply chains and reference systems per biomass input and production area required

Table 7 and Fig. 10 collate the CO_2e emissions per biomass input (kg per tonne of biomass). The Sawmill residues to electricity with CCS, Miscanthus to CHP with CCS and Willow-BIGCC to Electricity with CCS require 0.74 t MWh^{-1}, 0.98 t MWh^{-1} and 0.54 t MWh^{-1} of biomass, respectively. There are slight variations in the amount of CO_2 sequestration due to the carbon content and properties of the different

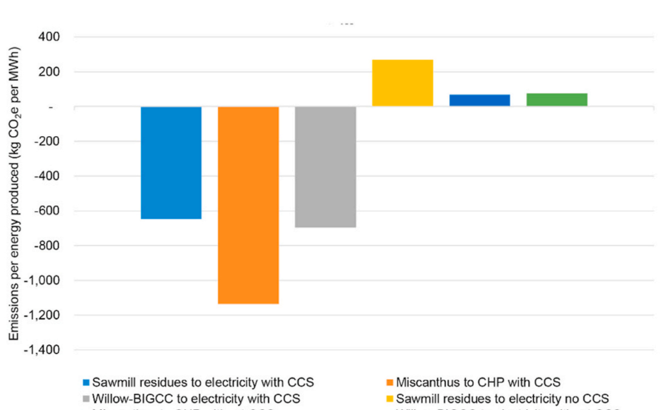

Fig. 9. Net emissions of the BECCS supply chains and references systems per unit of energy produced.

Table 7
CO_2 sequestration, supply chain emissions and total net emissions per unit of biomass.

Supply chain	*Biomass requirement* (t MWh^{-1})	*CO_2e sequestration* (kg t^{-1})	*Supply chain CO_2e emissions*[a] (kg t^{-1})	*Total Net CO_2e emissions* (kg t^{-1})
Sawmill residues to electricity with CCS	0.74	−1624	749	−875
Sawmill residues to electricity – no CCS	0.54	−1624	2122	498
Miscanthus to CHP with CCS	0.98	−1597	440	−1157
Miscanthus to CHP no CCS	0.68	−1597	1697	97
Willow-BIGCC to Electricity with CCS	0.54	−1597	269	−1301
Willow-BIGCC to Electricity – no CCS	0.45	−1597	1763	166

[a] Supply chain emissions include those from biomass production, energy conversion, CO_2 capture-storage and plant infrastructure.

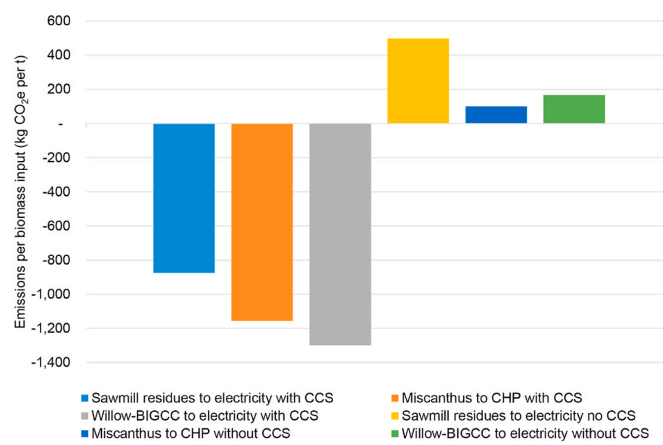

Fig. 10. Net emissions of the BECCS supply chains and reference systems per unit of biomass.

feedstock. With CO_2e emissions of 749 kg t^{-1}, Sawmill residues to electricity with CCS is the supply chain with the highest level of supply chain emissions, including biomass production, transport, energy conversion and CCS. The supply chain emissions of Miscanthus to CHP with CCS at 440 kg t^{-1} and Willow-BIGCC to Electricity with CCS at 279 kg t^{-1} are significantly lower.

The differences in the supply chain emissions are also reflected in the net emissions, with Willow-BIGCC to Electricity with CCS achieving the highest level of net-negative emission per unit of biomass followed by Miscanthus to CHP with CCS, while Sawmill residues to electricity with CCS has the lowest level of net-negative emission of the BECCS supply chains. In other words, the largest amount of CO_2 sequestered in biomass can be stored through the Willow-BIGCC to Electricity with CCS supply chain.

In relative terms, the GGR potential of Willow-BIGCC to Electricity with CCS is 12% higher than that of Miscanthus to CHP with CCS and 48% higher than the GGR potential of the Sawmill residues to electricity with CCS. The larger amount of net-negative emission in the Willow-BIGCC to Electricity with CCS supply chain is a result of lower emissions from the energy conversion process (gasification and further gas clean-up stage), cleaner combustion of hydrogen for electricity production and the high CO_2 capture rate of 94%. Similarly, the net-negative emissions of the Miscanthus to CHP with CCS are higher than the ones of Sawmill residues to electricity with CCS, due to the higher energy efficiency of the CHP system compared to the biomass direct combustion to generate electricity (only) from sawmill residues in the post-CCS supply chain.

As expected, the results for the reference systems generated net-positive emissions, meaning that bioenergy systems without CCS release more carbon to the atmosphere than the amount of CO_2 sequestered. The Sawmill residues to electricity system has the highest net CO_2e emission of the three reference systems. The Willow-BIGCC to Electricity system follows with a 166 kg t^{-1} and the Miscanthus to CHP has the lowest net CO_2e emissions with 97 kg t^{-1}. This can be explained by the significantly higher net energy efficiency of the conversion processes of 88% for Miscanthus to CHP compared to the energy efficiencies of the Sawmill residues to electricity (35%) and Willow-BIGCC to Electricity (41%).

Table 8 and Fig. 11 present the results of emissions per area. The evaluation of the net emissions per cultivated area reflects another perspective of the GHG emissions performance for the BECCS supply chains and the reference systems. The area requirement for the Sawmill residues to electricity with CCS is the lowest (431 m^2 MWh^{-1}) compared to those from the Miscanthus to CHP with CCS (819 m^2 MWh^{-1}) and Willow-BIGCC to Electricity with CCS (595 m^2 MWh^{-1}), due to a higher biomass crop yield from forest residues used to produce the wood pellets.

From the perspective of net emissions from an area requirement, results show that similar to emissions per energy, Miscanthus to CHP with CCS produces the highest net-negative emissions as CO_2e with −9.3 g m^{-2}. This is more than twice of net-negative emissions as CO_2e compared to Willow-BIGCC to Electricity with CCS -4.1 g m^{-2} and more than triple compared to Sawmill residues to electricity with CCS -28 g m^{-2}. While requiring less area, Sawmill residues to electricity with CCS supply chain has the least favourable net-emissions as it sequesters less CO_2 compared to Miscanthus to CHP with CCS and has significantly higher supply chain emissions than the Willow-BIGCC to Electricity with CCS supply chain.

Especially for the assessment of emission per area of land requirement, it must be recognised that biomass yields can vary, which would change the emissions per area. Moreover, there are large variations and uncertainties regarding the yield of residual biomass, in particular processing residues like pellets from sawmill residues. While robust and evidenced assumptions can be made on the pellet demand and its carbon content, the upstream supply chain for these type of forest residues can vary significantly and might not always be fully traceable, depending significantly on forest location, type, management and product basket of the forest [28]. Research has also shown that energy crop yields can vary significantly depending on a range of different factors, e.g., growing location, previous land use, crop management, genotype, timing of harvesting, year of growth within the rotation. For example, for England Miscanthus yields may vary between 6 and 15 tonnes per hectare depending on location and harvesting cycle [39]. Research on willow showed even larger variations of annual increments between about 3.6 and 24.7 tonnes per hectare [80]. Therefore, the results for the emissions per area must be considered carefully and are subject to uncertainties, while the emission per biomass and energy provide a more robust indication for supply chain emissions.

Table 8
CO_2 sequestration, supply chain emissions and total net emissions per unit of area.

Supply chain	*Area requirement* m^2 MWh^{-1}	*CO_{2e} sequestration* (g m^{-2})	*Supply chain CO_2e emissions** (g m^{-2})	*Total Net CO_2e emissions* (g m^{-2})
Sawmill residues to electricity with CCS	431	−5.2	2.4	−2.8
Sawmill residues to electricity – no CCS	315	−2.8	3.6	0.8
Miscanthus to CHP with CCS	819	−12.8	3.5	−9.3
Miscanthus to CHP no CCS	565	−6.1	6.5	0.4
Willow-BIGCC to Electricity with CCS	595	−5.1	0.9	−4.1
Willow-BIGCC to Electricity- no CCS	500	−3.5	3.9	0.4

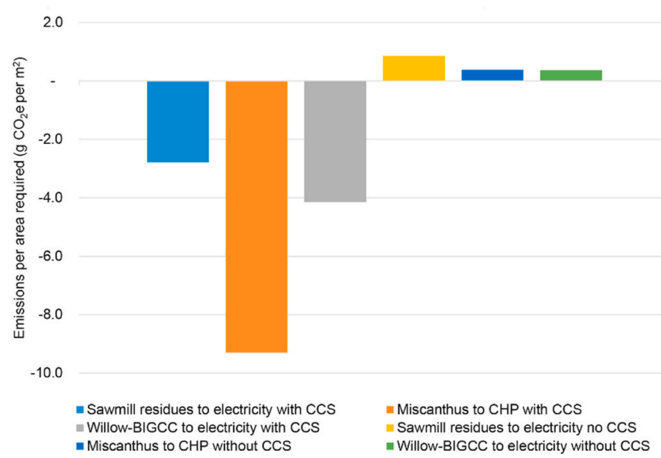

Fig. 11. Net emissions of the BECCS supply chains and reference systems per area of land requirement.

4. Discussion

4.1. Technical performance of BECCS supply chains

The results presented show the relative potential for three examples of BECCS supply chains to remove CO_2 from the atmosphere through the combination of biomass growth, bioenergy generation and CCS technologies, leading to negative emissions. Applying process modelling and LCA provides two valid methods to assess and understand the GGR potential of such BECCS supply chains.

The results from the process model are in line with previously published research. The net energy efficiency for the Sawmill residues to electricity with CCS supply chain (26%) and without CCS (35%) are comparable to values (25%–30%) reported by other authors [51,71,76,81] which evaluated the performance of large-scale biomass-power systems with post-combustion CCS. Similarly, the net efficiency for Willow-BIGCC to Electricity with CCS of 35%, also falls within the range (35%–36%) detailed in other studies investigating similar systems [71,76,82,83]. However, for Miscanthus to CHP with CCS, there is less research published on medium-scale BECCS systems as most of the existing research focuses on large-scale systems for large-scale GGR. Pröll & Zerobin [84] investigated various biomass CHP generation systems with different carbon capture approaches, including one with post-combustion capture that yielded an energy conversion efficiency of 47%, similar to the 45% efficiency obtained for the Miscanthus to CHP with CCS supply chain in this work.

Regarding the CO_2 capture performance, the three BECCS supply chains reached capture rates close to 90% or above, this is in accordance with the majority of the reviewed literature on BECCS [51,71,72,76]. The 90% capture rate has been historically fixed at this value due to associated capture costs of flue gas (or syngas) streams with relatively low CO_2 concentration [73]. Recent research [73,75] has evaluated the feasibility of reaching higher capture rates with no technical barriers to increasing this rate beyond 90%; however, further exploration of this issue is out of the scope of this paper. Among the three BECCS supply chains, the Willow-BIGCC to Electricity with CCS achieved a slightly higher CO_2 capture rate (94%) due to a higher CO_2 concentration in the shifted gas compared to the lower CO_2 concentration in the flue gas. This makes it easier to capture the CO_2 from the gas in the pre-combustion CO_2 capture setup and before its combustion.

The CO_2 concentration attained was also highly pure (above 98%) for the three supply chains. Although a high CO_2 purity demands more energy input, in both post and pre-combustion capture cases, these high concentrations are required to avoid additional expenses associated with CO_2 transportation and storage [9].

This research also identified major hotspots of (auxiliary) energy consumption and GHG emissions releases in these BECCS supply chains. The two supply chains using an amine-based CO_2 capture resulted in higher energy penalties (20%–32%) compared to the Willow-BIGCC to Electricity with CCS (15%) due to the greater energy consumption in the amine solvent regeneration during the CO_2 stripping. Mechanisms to reduce these penalties in the solvent regeneration stage have been investigated by other authors, i.e. waste heat recovery and novel and more efficient solvents [85], and process flow modifications [86,87]. Bui et al. [85] reported that an increase in the overall system efficiency of 8–9% points could be achieved by improving the post-combustion capture solvent (i.e. lower heat duty and reboiler temperature), recovering the waste heat for solvent regeneration and with 50% biomass co-firing. Consequently, the efficiency penalty could also reduce from 11.6% (conventional MEA capture) to 5% when using the before mentioned mechanisms. Research and demonstration should continue to bring these alternatives closer to commercialisation with improvements in the energy and environmental performance of these systems.

The production of hydrogen in the Willow-BIGCC to Electricity with CCS supply chain offers more versatility, as the H_2 gas could be also used as a fuel gas in heating systems and/or as biofuel for transportation. This could support further the decarbonisation of the UK energy sector, as highlighted also by the Committee on Climate Change [20]. This is not the case for the other supply chains (Sawmill residues to electricity with CCS and Miscanthus to CHP with CCS) with direct biomass combustion which produce instead a flue gas. The generation of electricity via BIGCC plants has the potential to be more efficient and environmentally benign (producing fewer contaminants) than biomass direct combustion systems [74]. However, IGCC systems have not been widely commercialized yet, requiring additional development and demonstration before widespread commercial adoption [88]. Some of the technical challenges are inherent to the biomass gasification process (scaling up, tar reduction and warm gas clean up) [74,89]. Other hurdles relate to economic competitiveness (higher capital and operating costs), availability of IGCC technologies, and complexity (integrating the GT compressor with the Air Separation Unit increases operation complexity and degrades the system's availability and reliability) [74,88,90].

4.2. GHG emissions from BECCS supply chains: uncertainties and limitations

The LCA integrated the results from the process modelling into the analysis of the GHG emissions of the whole supply chain. This reveals the emissions and CO_2 dynamics of the whole system, quantifying the overall GGR potential of the investigated supply chains. The lifecycle inventory for the upstream biomass production, processing and transport and the CCS infrastructure was based on validated and published research and were not the main focus of this research. However, research has shown that there can be variations in the lifecycle emissions depending on biomass production, management and location, biomass yields and characteristics, biomass transport and handling, pre-treatment, energy conversion and CCS technology and infrastructure [28,38,39,60,91–93]. Hence these LCA results, beyond the process modelling, can vary and will have certain levels of sensibility and uncertainty, depending on the specific supply chain upstream emissions and CCS infrastructure.

The Sawmill residues to electricity with CCS supply chain uses forestry residues rather than purpose-grown energy crop pellets and are likely to be a mix of residues from different tree species and forests with different management systems. Both factors have an impact on the temporal dynamics of the forest carbon balance and the characteristics of the biomass [28,94]. Moreover, the product basket for purpose-grown energy crops is unambiguous, as all biomass is used for energy. In the case of Sawmill residues to electricity with CCS, the destiny of the carbon embedded in the other timber products and the potential long-term storage of carbon in these products from the same forest are not necessarily clear and have not been included in this calculation. Work by others [28,94] has shown the relevance of the carbon stocks of the whole forest product basket to understand the mitigation and GGR potential of bioenergy feedstock as part of such forest systems. While the type of forest management system can have a significant impact on the timing of CO_2 sequestration and release from forest products, including timber and bioenergy feedstock [28], this assessment draws the system boundaries around the bioenergy feedstock only, to allow an easier comparison across the BECCS supply chains and a focus on the amount of CO_2 captured and stored through BECCS. To understand the full GGR potential of forests beyond BECCS, the system boundaries would need to be expanded to the whole forest basket beyond energy, which was outside the scope of this assessment and would have created a high level of uncertainty for the assessment of the Sawmill residues to electricity with CCS supply chain.

Similarly, soil carbon changes can play an important role in the case of land use change for energy crop production. Research by others has shown the effects of soil carbon when converting land for and after energy crop production as well as the role of soil types [28,38,39,95]. Again, there is a high level of uncertainty regarding the destiny of land use change, soil type and soil carbon, which are outside the scope of this assessment.

4.3. Potential of different BECCS supply chains to deliver GGR within the UK net-zero target

The results of the process modelling and LCA show that the three BECCS supply chains have a significant GGR potential with net-negative emissions as CO_2e ranging between −647 kg MWh^{-1} and -1137 kg MWh^{-1}, as Table 6 shows. While all three BECCS supply chains deliver GGR, the amounts differ.

Sawmill residues to electricity with CCS is probably the supply chain with the most robust and proven business model up to the point of energy generation and before the integration of CCS [12]. However, it is also the supply chain with the lowest GGR potential per energy produced of the three BECCS supply chains. The relatively low GGR potential can be explained by the low biomass to energy conversion efficiency and the highest supply chain lifecycle emissions, which resi-dues further the net-emissions result.

Miscanthus to CHP with CCS removes about 68% more CO_2 from the atmosphere per unit of energy produced than the Willow-BIGCC to Electricity with CCS and 76% more than the Sawmill residues to electricity with CCS. This variation in results shows that BECCS systems can achieve very different levels of GGR. While the IPPC RCP 2.6 scenarios consider centralised large-scale BECCS applications [1], this study shows that the cogeneration of electricity and heat through the direct combustion of UK grown Miscanthus in a medium-scale BECCS system provides the largest GGR benefit per unit of energy when compared with the other two BECCS supply chains. It is important to acknowledge that the Miscanthus to CHP with CCS supply chains can generate two energy vectors, power and heat, and the other two can deliver power only. Miscanthus to CHP with CCS is the supply chain with the highest amount of biomass input, hence CO_2 embedded in biomass entering the systems. It is also the supply chain with the highest energy conversion efficiency and CO_2 capture efficiency of 91%. Due to the high efficiency and supply chain activities with lower emission impacts (e.g., short transport distance, chipping of biomass), Miscanthus to CHP with CCS is the supply chain with the most favourable conditions in terms of efficiency and lifecycle emissions.

Willow-BIGCC to Electricity with CCS GGR potential per unit of energy produced exceeds that of Sawmill residues to electricity with CCS by about 7% and is 68% lower than the GGR potential of Miscanthus to CHP with CCS. However, due to its high net energy efficiency, this is also the supply chain with the lowest amount of biomass required per unit of energy produced. The combination of BIGCC with pre-combustion CCS results in a higher CO_2 capture efficiency (92%) as the CO_2 is more easily captured in a shifted syngas with its higher CO_2 concentration [32].

One could argue that the more biomass a BECCS system requires per unit of energy, the lower the net energy efficiency is and hence the more CO_2 this technology will remove from the atmosphere, an effect that has been noted previously [96]. However, sustainable biomass is limited, as is the land required to produce biomass. Making efficient use of biomass is key with an increasing demand for biomass from other sectors for the transformation to a low-carbon economy that will put more pressure on available biomass, land and other resources required to produce and process biomass.

Fig. 10 shows that the GGR potential for the three BECCS supply chains changes significantly when considering the net emissions per unit of biomass. As expected, the Willow-BIGCC to Electricity with CCS has the highest GGR potential per unit of biomass due to its higher CO_2 capture efficiency from the shifted syngas and its higher net energy efficiency converting the hydrogen-rich gas to electricity. The change in the functional unit shows the importance of seeing the wider impacts of bioenergy and BECCS and considering sustainable biomass and land use.

This issue becomes particularly important when considering the requirements and GGR potential concerning the UK's net-zero target.

Table 9
Net-negative emissions of BECCS supply chains.

	Sawmill residues to electricity with CCS	Miscanthus to CHP with CCS	Willow-BIGCC to Electricity with CCS
Net plant capacity (MW)	440 (Electricity)	20 (Electricity) 70 (Heat)	232 (Electricity)
Capacity factor (%)	85%	70%	79%
Net-negative emissions (kg CO_2e MWh^{-1})	−647	−1131	−693
Net-negative emissions (kg CO_2e t^{-1})	−875	−1157	−1226
Annual energy generation (TWh)	3.28	0.55	1.60
Annual net-negative emissions (Mt CO_2e)	−2.12	−0.63	−1.12
UK annual GGR requirement (Mt)	20	20	20
Number of facilities required for 20 Mt GGR	10	32	18
Amount of biomass required for 20 Mt GGR (Mt)	22.85	17.29	16.31
Area of land required for 20 Mt GGR (km^2)	14,432	14,405	18,126

Table 9 summarises the GGR potential for the three BECCS systems. Due to its BECCS facility characteristics (i.e. large-scale plant with high capacity factor), Sawmill residues to electricity with CCS produces the largest amount of energy per year, about twice as much as the Willow-BIGCC to Electricity with CCS and six times as much as the Miscanthus to CHP with CCS. This is reflected in the annual net-negative emissions; the amount of net-negative emissions from Sawmill residues to electricity with CCS is about twice that of Willow-BIGCC to Electricity with CCS and over three times as much of Miscanthus to CHP with CCS. Hence, in terms of energy and annual GGR provision Sawmill residues to electricity with CCS would provide the biggest benefit and Miscanthus to CHP with CCS the lowest, and Willow-BIGCC to Electricity with CCS sitting in the middle. To achieve an annual GGR of 20 Mt CO_2e to support the UK's net-zero emission target, 10, 32 or 18 facilities equivalent to the Sawmill residues to electricity with CCS, Miscanthus to CHP with CCS, and Willow-BIGCC to Electricity with CCS supply chains respectively would be required.

Although the research presented here compares the GGR potential of three different BECCS supply chains, it is worth noting that BECCS has not yet been deployed on a commercial scale. The assessment of the reference systems however provides some insight on how bioenergy applications could perform within the UK's climate mitigation requirements and that in the long term BECCS could potentially deliver GGR and eventually contribute to the UK's net-zero emission targets.

Additionally, they included emissions related to the operation of the conversion process. As indicated above, emissions from smaller biomass combustion systems tend to be higher, hence the higher emissions for the Miscanthus to CHP reference system. Similar to the BECCSS supply chains the reference systems have emissions related to upstream supply chain processes such as biomass production, processing, and transport. The Sawmill residues to electricity system has the highest emission of these upstream emissions due to a more energy intense pre-treatment of the biomass into pellets and a longer transport distance. Overall, the upstream emissions for the reference systems are lower compared to the BECCS supply chains as less biomass is required per unit of energy produced, avoiding the energy penalty of the CCS process.

The Sawmill residues to electricity system using imported sawmill residues could contribute to low-carbon electricity. With a carbon intensity (as CO_2e) of 220 kg MWh^{-1}, this system is in line with the current carbon intensity of the UK electricity mix of 227 kg MWh^{-1}. The integration of post-combustion CCS to this system could deliver net-negative emissions with a carbon capture efficiency of 88%. The Sawmill residues to electricity with CCS supply chain could justify bioenergy generation in the long term when a decrease in the UK electricity carbon intensity from further integration of other renewables energies is expected.

The supply chains Miscanthus to CHP with CCS and Willow-BIGCC to Electricity with CCS utilising UK-grown feedstock such as Miscanthus in CHP (68 kg MWh^{-1}) and Willow in BIGCC (75 kg MWh^{-1}) systems would result in CO_2e specific emissions well below the current carbon intensity of the UK electricity mix helping to further decarbonise the energy sector.

Further work is needed to investigate the implications of scaling up BECCS supply chains to deliver GGR at the levels reported by the Committee on Climate Change [19] and this would include a more detailed analysis of the specific locations of supply chain elements and their implications, alongside a more detailed analysis of the non-CO_2 implications of BECCS technologies. The UK has adopted a cluster approach to developing CCS infrastructure around areas with a high concentration of industrial emitters and linked to key offshore storage locations; a more detailed analysis relating to these specific locations will provide opportunities for developing operational data across the BECCS supply chain.

5. Conclusions

This study evaluated the GGR potential of three BECCS case study supply chains and their feasibility to support the UK's net-zero emission targets. The results show that the investigated BECCS supply chains can deliver effective GGR at a significant level. The results also show that supply chain evaluation must go beyond carbon performance alone. With direct links between CO_2 removal, sustainable biomass production and land use; sustainability and feasibility depend on more than simply maximising GGR potential. Nevertheless, the assessment showed that the GGR potential of different BECCS supply chains can vary significantly and each presents its own challenges. As with conventional bioenergy, there is a vast array of pathways for BECCS, each facing context-specific engineering, economic, social and policy challenges and trade-offs. The Sawmill residues to electricity with CCS supply chain provides the most robust and tested business model but requires high investment and reliable long-term supply chains to provide enough sustainable and cost-effective biomass. While providing the potential to deliver significant GGR levels, a reliance on imported feedstocks to supply the necessary inputs for such a large-scale facility not only impacts the efficiency of the process but introduces additional non-technical complexities.

In terms of efficiency and GGR potential per unit of energy produced, while Miscanthus to CHP with CCS performs best, as a medium-scale operation its relatively low capacity factor compared to large-scale systems could limit the overall GGR potential. The analysis considered that this supply chain would be linked to centralised CCS infrastructure, this is may not be the case in practice. The power and heat cogeneration would need to match the energy demand for heat and electricity (i.e. industrial process or district heating) to sustain a feasible operation with a viable capacity factor. Should a more distributed CO_2 transport network (whether using pipelines, rail or truck) be needed to access larger transport and storage hubs the overall lifecycle emissions would be affected. The most novel of the three supply chains, Willow-BIGCC to Electricity with CCS, generates Hydrogen which could alternatively be used in other applications and could facilitate the decarbonisation of challenging sectors such as transport and industry within a net-zero pathway.

This analysis shows that BECCS has the potential to provide significant GGR alongside additional services for energy and transport. With investment decisions set to establish operational CCS infrastructure in the mid-2020s, concentrated in industrial clusters, the UK is on track to establish the necessary transport and storage infrastructure over the coming decade. Our research makes a case for the early demonstration of BECCS technologies within the clusters, and beyond, in order to realise the potential for BECCS within the UK's wider net-zero strategy.

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