Hydrogen production via gasification with carbon capture utilisation and storage

Case Study Report United Kingdom

IEA Bioenergy: Task 33 Gasification

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The Wolfson Centre for Low Carbon Hydrogen. Photo: EBRI Energy and Bioproducts Research Institute

Hydrogen production via gasification with carbon capture utilisation and storage

WP3 Case Study Report

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Contribution of IEA Bioenergy Task 33 to
Strategic Inter-Task Project Management of biogenic CO_2: BECCUS Phase 2

IEA Bioenergy: Task 33

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Preface

Bioenergy combined with carbon capture and utilisation or storage, also known as bio-CCUS or BECCUS is a concept that has been discussed in climate change mitigation research for quite some time. However, implementation has only become the subject of serious consideration within governments and private actors within the last 5 years. The reasons for this are largely related to four factors that are somewhat entwined: a) an emerging awareness of the need for BECCS and other negative emissions technologies in order for governments to reach net-zero targets, b) increased interest in buying carbon negative or neutral products and value of biogenic CO_2, c) rising CO_2 prices, and d) the rapidly decreasing costs of electricity generation from solar & wind (and expectations of similar developments for electrolysers) that have made BECCU options based on power-to-X technologies more cost-effective.

In light of this, identifying and implementing approaches for how BECCUS systems can be deployed and integrated in ways that maximise benefits in terms of climate change mitigation - as well as in terms of energy system integration and sustainability ambitions more broadly - is highly important.

THE IEA BIOENERGY STRATEGIC PROJECT ON BECCUS

In 2019 the IEA Bioenergy TCP initiated a strategic project on bioenergy carbon capture, utilisation and storage (BECCUS) in order to understand the concept and opportunities for deployment. The project involves several of the IEA Bioenergy Tasks and is led by Task 40 (Deployment of biogenic value chains and carbon management)[1]. The project has evolved to a multi-annual research project, in which the findings of each project phase led to new research question for a next phase. Details on the project focus in the different phases are presented below, and more information on the BECCUS project can be found on Task 40's website.[2]

Phase I (2019- 2021)

During the 2019-2021 triennium, IEA Bioenergy Task 40 worked together with Task 36 (Material and Energy valorisation of waste in a Circular Economy), Task 44 (Flexible Bioenergy and System Integration) and Task 45 (Climate and Sustainability Effects of Bioenergy within the Circular Bioeconomy) on a strategic project called *Deployment of BECCUS value chains* that focused on understanding the opportunities for, and obstacles to, deployment of BECCUS in different sectors. Focus was on trying to cut across the full set of factors that determine successful deployment, from technology readiness, to business model viability and design of policy and regulatory frameworks.

Phase I findings

Factors determining successful deployment of BECUSS include technology readiness, business model viability, upstream supply chain set up, and current and expected public policy design. The investigations indicate that while the majority of the required individual BECUSS technology components can largely be considered proven, there is still R&D needed into finding models for on-the-ground deployment. Supply chain set up and possibly alterations of existing supply chain concepts are important. Many concepts are looking for viable business

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[1] An overview of all Tasks of IEA Bioenergy TCP is found here: https://www.ieabioenergy.com/our-work-tasks/

[2] https://task40.ieabioenergy.com/inter-task-project-bioenergy-with-carbon-capture-storage/.

models for the captured carbon. Thus far, the focus is on utilising rather storing the carbon. Lack of governance with corresponding support measures and regulations for carbon storage pose a challenge. A synthesis report summarising phase I findings (Olsson, et al., 2022), as well as publications covering case studies topical reports, and system studies can be found on the IEA bioenergy, Deployment of BECCUS value chains website.[3]

Phase I suggestions for further work

Research and development are still required to identify models of on-the-ground deployment that make the most sense from techno-economic and climate perspectives. This includes aspects such as specific designs, deployment scales and choice of site locations. In addition, there are many questions remaining when it comes to process and supply chain integration as well as policy design and implementation. Answers to the above questions can assist in addressing key and most complex questions, i.e., *in a given situation should biogenic CO_2 be sequestered, or utilised? Which type of facilities (i.e., bioenergy installations) shall best provide BECCS and/or BECCUS under certain criteria (economics, CO_2 emissions mitigation potential etc.)? What are the main challenges for commercialising BECCUS projects and the lessons learnt thus far? How to monetise the carbon negative products that bioenergy can deliver? How to govern the different energy system services when targeting a high level of CO_2 emissions mitigation? And related to this, what factors and parameters should guide this decision-making process?*

Phase II

Phase II of the BECCUS project is more diverse in its scope, with a stronger emphasis on cross-sector and cross-country learning about implementation of BECCUS projects using different energy conversion processes. A further goal is to shed some light on the effects of the integration of BECCUS facilities and systems within the overall energy system and its interaction with other energy system services. In addition, although we tend to refer to “BECCUS” as a unified concept, we also emphasise and analyse the important differences between BECCS and BECCU, not least from the perspective of potential business models and policy development. An understanding of the impacts of BECCUS on overall climate system in terms of potential for CO_2 mitigation is addressed and all different aspects covered are analysed jointly and policy recommendations provided. This approach allows for a systemic consideration of how to take different BECCUS applications to deployment, thereby building upon, but going beyond, Phase I. In this second phase of the BECCUS project, besides the Tasks already participating in Phase 1, Tasks focused on conversion technologies become involved as well: Task 32 (Biomass Combustion), Task 33 (Biomass Gasification) and Task 34 (Direct Thermal Liquefaction).

Phase III (2025-2027)

While the current report is part of the Phase II work, preparations for Phase III have been initiated. Overall biochar, biorefineries, first-of-its-kind projects, permanence of storage and the BECCS/BECCU potential and financing are foreseen as central themes. Further examples for case studies look to potentially include: BECCUS for biogas installations, BECCUS with novel capture technologies e.g. oxyfuel, H_2 from biomass with CCS, BECCS with decentralised storage solutions, BECCUS with mixed feedstocks, CCU from the chemical industry, and further small- to medium scale BECCS installations.

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[3] https://www.ieabioenergy.com/blog/task/deployment-of-beccus-value-chains/

SUMMARY

This report presents an in-depth analysis of a decentralised bioenergy installation with carbon capture, utilisation, and storage (BECCUS) system for hydrogen production via gasification, using sawmill residue-derived wood pellets as the feedstock. The study aims to assess the potential of such a system to contribute to the United Kingdom's net-zero emissions targets by delivering net-negative carbon dioxide (CO_2) emissions while producing low-carbon hydrogen.

Through a combination of process modelling, life cycle assessment (LCA), and the Bioeconomy Sustainability Indicator Model (BSIM), this case study evaluates the technical, environmental, and sustainability aspects of the proposed BECCUS pathway. The analysis reveals a CO_2 capture rate of 98%, with a carbon removal of −859 kg CO_2e per MWh of hydrogen produced. The system demonstrates 27% energy efficiency and produces high-purity hydrogen suitable for fuel cell applications. The integration of carbon capture significantly enhances carbon removal performance while remaining relatively energy efficient.

The BSIM assessment highlights notable sustainability benefits in the categories of Climate Change and Emissions and Natural Systems, with the system contributing positively to multiple UN Sustainable Development Goals (SDGs), including SDGs 3 on good health, 7 on affordable and clean energy, 8 on economic growth, 9 on sustainable industrialisation, 11 on sustainable cities, 12 on sustainable production and consumption, 13 on climate action, and 15 on protecting ecosystems. However, challenges remain in infrastructure requirements and economic viability, underlining the need for supportive policy frameworks and investment mechanisms.

Key messages:

- Sustainable biomass gasification with carbon capture can simultaneously deliver low-carbon hydrogen and durable carbon removals, demonstrating a pathway that supports both industrial decarbonisation and net zero objectives.
- Prioritising waste and residual biomass feedstocks can maximise climate benefits while reducing risks associated with land use change, biodiversity impacts and competition for resources.
- The key barriers are no longer technical capability but investment certainty, CO_2 transport and storage infrastructure, and route-to-market arrangements for low-carbon hydrogen and carbon removals.
- Recognising and rewarding carbon removals alongside low-carbon hydrogen production could strengthen project economics and support investment in early commercial-scale biohydrogen with CCS facilities.

BACKGROUND

As we address the pressing challenge of climate change induced by human activities, the accelerated rise in greenhouse gas emissions presents significant and far-reaching impacts on our planet. At the heart of this issue is carbon dioxide (CO_2), which makes up more than 80% of these emissions. In response, countries like the United Kingdom have set ambitious net-zero emissions targets, aiming to keep global warming from increasing less than 2°C relative to pre-industrial era levels. But simply reducing emissions isn't enough. We need to take bolder steps. This has led to the exploration of net-negative emission technologies (NETs), which offer a hopeful solution. These technologies could help us not just stop the rise of CO_2 emissions, but reverse it, giving us a fighting chance to protect our world for future generations (Almena, et al., 2022).

Among the array of NETs, bioenergy with carbon capture and storage (BECCS) stands out as a dual-purpose marvel, capable of generating negative emissions while simultaneously producing renewable energy (see Figure 1) (Almena, et al., 2022). BECCS operates like a symphony of nature and technology, orchestrating a harmonious balance in the carbon cycle. It begins with the humble growth of plants, which absorb CO_2 from the atmosphere like green sentinels. Once mature, this biomass is harnessed to produce energy. During this process, the CO_2 released is not left to wander back into the air. Instead, it is meticulously captured and stored deep underground, creating a negative carbon flow. This ingenious system ensures that more CO_2 is removed from the atmosphere than is emitted, offering a powerful tool in our quest to restore environmental balance. Figure 1 illustrates a conceptual framework for integrating bioenergy with carbon capture, utilisation, and storage (BECCUS) as a sustainable carbon management approach. It depicts the process beginning with solar energy driving photosynthesis, enabling trees and biomass to absorb carbon dioxide (CO_2) from the atmosphere. The harvested biomass is utilised in bioenergy facilities to produce energy, during which CO_2 emissions are captured through carbon capture technologies. The captured CO_2 is either permanently stored in geological formations or utilised in various industrial processes, such as the production of fuels, chemicals, and materials, contributing to a circular carbon economy. This integration of BECCUS demonstrates its potential to mitigate climate change by achieving negative emissions, promoting renewable energy production, and/or supporting sustainable industrial practices.

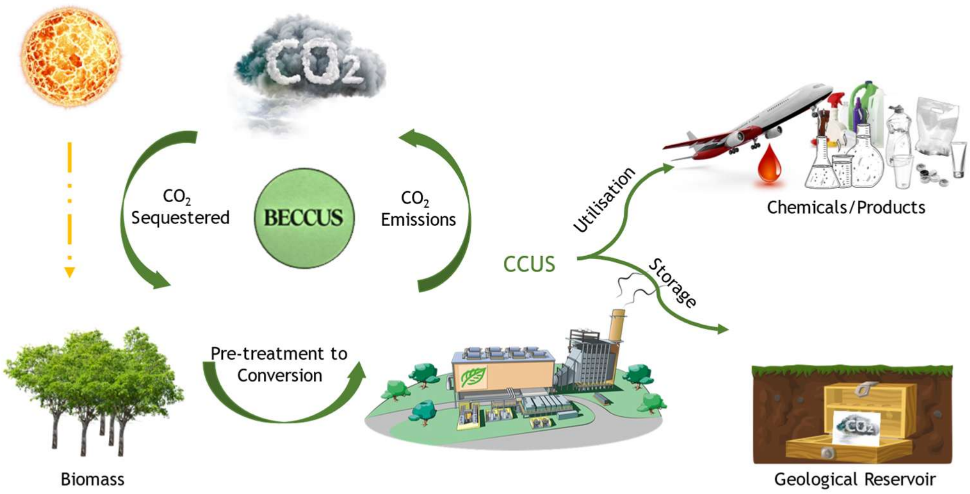

Figure 1: The carbon flow of BECCUS – sequestration and/or utilisation of biogenic CO_2.

This case study (called Case H_2 in this report) investigates the carbon dioxide removal (CDR) potential of decentralised utilisation BECCUS systems, specifically focusing on hydrogen production in small-scale gasifiers using waste wood via gasification with carbon capture, utilisation and storage. Through process modelling and lifecycle assessment, the study evaluates the flexibility, scalability, and immediate applicability of this BECCUS pathway with the aim of quantifying its CDR potential and assessing its contribution to the UK's net-zero targets. To understand the potential for Carbon Dioxide Removal (CDR) and net emissions of Bioenergy with BECCUS, we need to look at the entire supply chain. This includes everything from growing and sourcing the biomass to how the captured CO_2 is stored or used.

This case study also highlights the importance of policy frameworks that prioritise carbon efficiencies, which can influence operational decisions and impact the overall performance of BECCUS systems. This includes the biogenic CO_2 contained in the biomass and captured during conversion, as well as all emissions associated with land, crop, or forest management, harvesting, biomass processing, storage, and transport at every stage of the supply chain. Additionally, it encompasses emissions from the biomass-to-energy conversion and CO_2 capture processes, as well as any emissions related to the transport, storage, or use of the captured CO_2. Details on the process approach studied are given below.

Moreover, the case study was analysed using the Bioeconomy Sustainability Indicator Model (BSIM)[4]. This model provided a structured framework to evaluate sustainability across multiple dimensions, including People, Development, Natural Systems, and Climate Change & Emissions. The BSIM revealed significant areas of both risks and benefits. On the one hand, it identified substantial climate benefits, such as reductions in emissions and the replacement of fossil fuels with low-carbon hydrogen. On the other hand, it highlighted key development-related risks, including the challenges posed by infrastructure requirements, feedstock mobilisation, and techno-economic feasibility. The model's adaptability enabled it to capture these complex dynamics, providing valuable insights into potential trade-offs and helping to inform policy and investment decisions to optimise sustainability outcomes.

TECHNOLOGY AND CONCEPT DESCRIPTION

This case study focuses on hydrogen production via gasification with CO_2 capture, using white wood pellets derived from sawmill residues. Hydrogen is essential for the UK's industrial and transport decarbonisation strategies to meet net-zero targets by 2050. However, most hydrogen production processes generate CO_2, with 96% of hydrogen currently produced from fossil fuels, and gasification of coal and oil accounting for 48% of global hydrogen production. Biomass gasification offers a viable alternative to fossil fuel-based hydrogen production.

To mitigate land-use impact, the study chose residual feedstock, specifically white wood pellets from sawmill residues, which are widely available. The UK has an estimated annual availability of 16.8 million cubic meters of wood over the 50 years 2013-2061, with 30% being sawdust,

[4] The Bioeconomy Sustainability Indicator Model (BSIM) has been developed by the UK Supergen Bioenergy Hub. Further information on the Model can be found here: Welfle, A., & Roeder, M. (2022). Bioeconomy Sustainability Indicator Model (BSIM): Guidance Manual. UK Supergen Bioenergy Hub; https://research.manchester.ac.uk/en/publications/bioeconomy-sustainability-indicator-model-bsim-guidance-manual/

offcuts, and chips suitable for wood pellet production.

The study considered a facility with a 1 MW bubbling fluidised bed (BFB) gasifier and a feed rate of 300 kg/h of wood pellets, producing hydrogen suitable for fuel cell operations. The BFB gasifier was operated at 800 ◦C and atmospheric pressure. The thermo-chemical conversion of biomass with a gasifying agent produces syngas, primarily containing carbon monoxide, hydrogen, methane, and CO_2. For tar removal, the process included a catalytic bed material (e.g., dolomite) and an oil scrubber, with ceramic filters to remove fines from the raw syngas. Hydrogen concentration in the syngas was maximised using two downstream water-gas shift (WGS) reactors, which also increased CO_2 generation, necessitating a capture system to prevent venting acid gases. Physical absorption methods, using methanol as a solvent, were preferred due to high CO_2 concentration and minimal impact on hydrogen yield, following the Rectisol process for capture.

The hydrogen produced would be distributed as fuel for vehicles and stationary applications, requiring a minimum purity of 99.97% H_2 according to ISO 14687:2019. Therefore, a membrane system was necessary to meet fuel cell specifications, and metal hydride technology was suggested for hydrogen storage. The captured CO_2 would be compressed to a liquid for market use or to a supercritical fluid for underground transport and sequestration. Figure 2 shows a block diagram representing the case study assessed within this work, as discussed above.

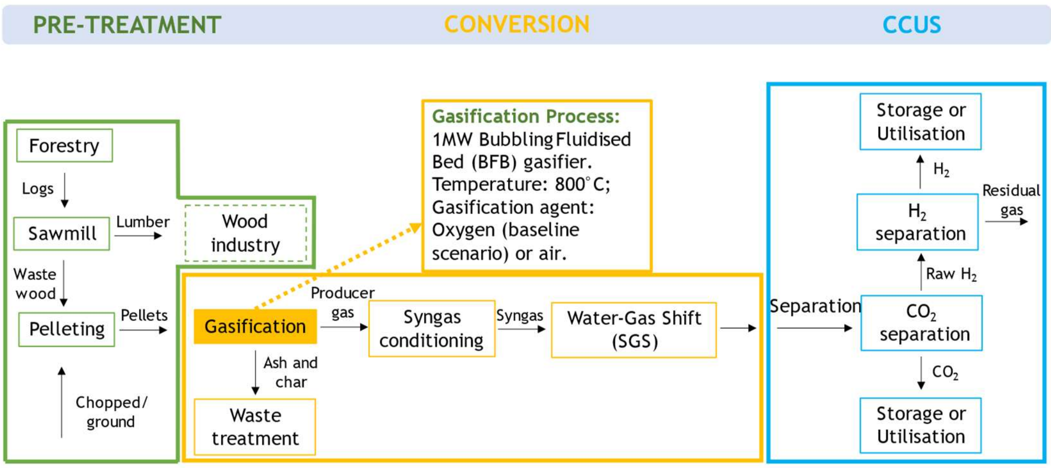

Figure 2: Overview of BECCUS Case Study: H_2 production.

Bioenergy Technology

An overview of the BECCUS Case Study H_2 is provided in Table 1, outlining the technology and feedstock used, main application, and the assumptions adopted for this study.

Table 1: Overview data bioenergy technology

Designation	Data
Developer/Promoter/Project	Process model case H_2: Hydrogen production via gasification with pre-combustion capture. The model replicated the existing gasification pilot plant at the Energy and Bioproducts Research Institute (EBRI) at Aston University
Conversion technology	Bubbling fluidised bed (BFB) gasification
Feeding System	Direct feeding of wood pellets from sawmill residues
Principal Feedstock(s)	White wood pellets (sawmill residues)
Principal Application(s)	Hydrogen production for use in fuel cells (minimum fuel index with 99.97% H2 purity is required) (ISO, 2019)
Scale	A facility featuring a 1 MW bubbling fluidized bed (BFB) gasifier and a wood pellet feed rate of 300 kg per hour was evaluated. 1 MW facility (pilot-scale)
Development Status	Pilot scale integrated demonstration Kew Technologies; commercially demonstrated components (pretreatment and gasification)
Other relevant info	Utilises sawmill residue feedstock to minimise land-use impact, producing fuel-cell-grade hydrogen.

BECCUS Concept

The BECCUS project, as outlined in Case H_2, presents an innovative approach to hydrogen production through the gasification of residual biomass, specifically wood pellets sourced from sawmill residues. Using advanced pressurised fluidised bed gasification technology, the process generates hydrogen alongside a carbon capture system. By capturing CO_2, the process enables the carbon to be either stored in geological formations or utilised in various industrial applications, such as materials and polymer synthesis. This dual-purpose system – producing clean hydrogen while removing CO_2 from the atmosphere – directly contributes to the creation of negative emissions, a key strategy in combating climate change.

Situated at the intersection of renewable energy and hydrogen production, BECCUS in Case H_2 focuses on harnessing biomass for hydrogen generation while integrating carbon capture technology to significantly reduce CO_2 emissions. This represents a cutting-edge solution for producing low-carbon hydrogen, a fuel poised to play a crucial role in the decarbonisation of hard-to-abate sectors such as industry and transport.

The BECCUS business model centres on the production of clean hydrogen as a sustainable energy source, with an additional revenue stream generated through the sale of captured CO_2 for industrial use or its storage in underground reservoirs. The project's financial sustainability is enhanced by policy mechanisms that incentivise low-carbon hydrogen production, such as negative emissions trading, carbon pricing, and potential feed-in tariffs tied to carbon removal. By capitalising on these incentives, BECCUS aligns itself with the emerging frameworks of a low-carbon economy, positioning the project as both environmentally and economically viable. The academic origins of this case study, developed by Aston University, indicate likely collaboration between academic institutions, government bodies, and private sector entities. This reflects the public-private partnerships common in research-driven initiatives of this nature. Interest in BECCUS is fuelled by the political and environmental agenda, particularly the UK's commitment to achieving net-zero emissions by 2050. Hydrogen is increasingly recognised as a pivotal enabler of decarbonisation across key sectors, and integrating BECCUS technology within this framework provides a clear pathway to achieving negative emissions while generating energy.

The CO_2 captured in the BECCUS process is intended to be compressed into a supercritical state for storage in geological formations or sold to industrial customers. Additionally, Case H_2 could potentially join a CO_2 capture cluster if suitable industrial partners are located nearby, fostering synergies that allow for cost-effective CO_2 transportation and infrastructure sharing. Although the project explores both the utilisation and storage of captured CO_2, its primary goal remains the long-term sequestration of carbon in geological reservoirs, ensuring the achievement of negative emissions. However, selling captured CO_2 for industrial applications remains a secondary, albeit feasible, option depending on market demand.

The BECCUS project offers significant technological advantages, particularly for hard-to-abate industries such as steel, cement, and chemicals. Its combination of gasification and carbon capture supports the production of high-purity hydrogen, suitable for fuel cells, while the carbon capture system enhances overall process efficiency.

In conclusion, Case H_2 within the BECCUS framework represents a comprehensive and forward-thinking strategy for producing clean hydrogen while capturing carbon emissions. It holds significant potential for contributing to the UK's ambitious climate targets while enabling the decarbonisation of key industrial sectors. By supporting the transition to a low-carbon future, BECCUS positions itself as a crucial player in the fight against climate change, driving the innovations necessary to achieve a sustainable energy landscape.

METHODOLOGY

The methodology of this study involves a combination of process modelling and life cycle assessment (LCA) to evaluate the carbon dioxide removal (CDR) potential of the BECCUS case study. Subsequently, following the results obtained from the LCA captured within the first part, the Bioeconomy Sustainability Indicator Model (BSIM) has been applied to analyse the sustainability of this case study. The BSIM has been designed to provide a flexible tool to map the sustainability of biomass resource, supply chain, technologies, and/or whole bioenergy value chains. Figure 3 schematically shows the methodology of the present case study.

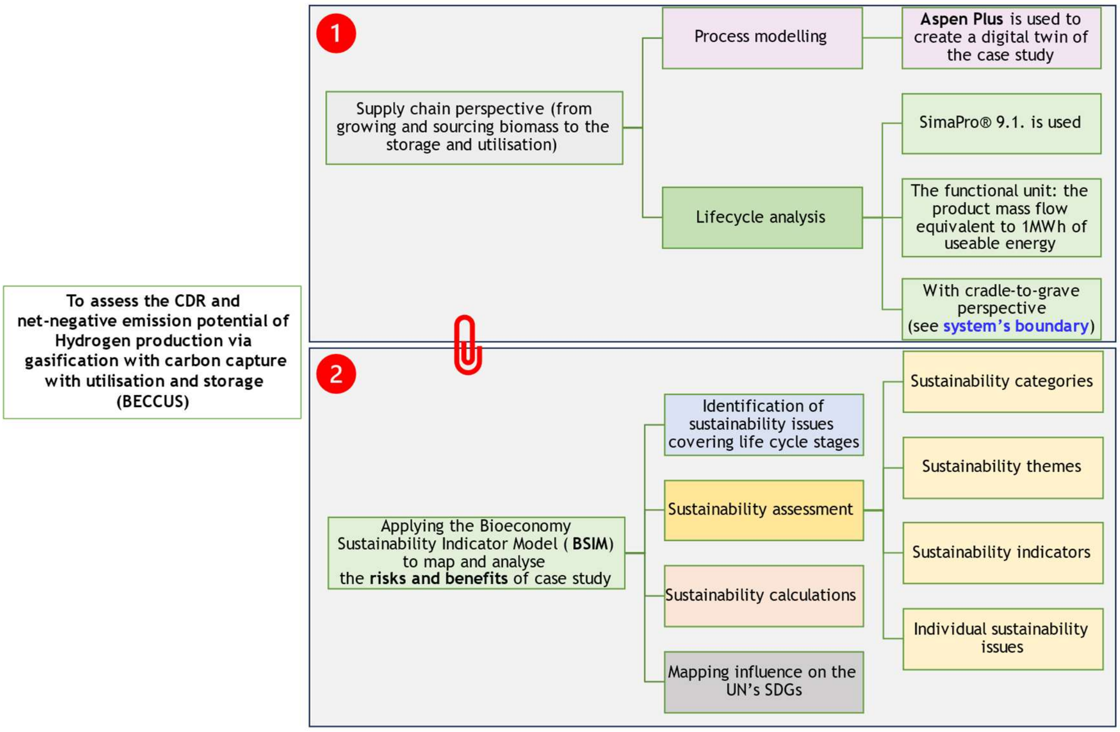

Figure 3: Methodology of the Case study.

The system boundary for the BECCUS supply chain within this study is illustrated in Figure 4. The system boundaries encompassed the entire supply chain, incorporating biomass production, harvesting, transportation, feedstock pre-treatment, biomass-to-energy conversion, carbon dioxide (CO_2) capture, transportation, and storage (the system boundary is illustrated within the red dashed rectangle). However, the emissions resulting from the utilisation of the captured CO_2 were excluded from the scope of this study.

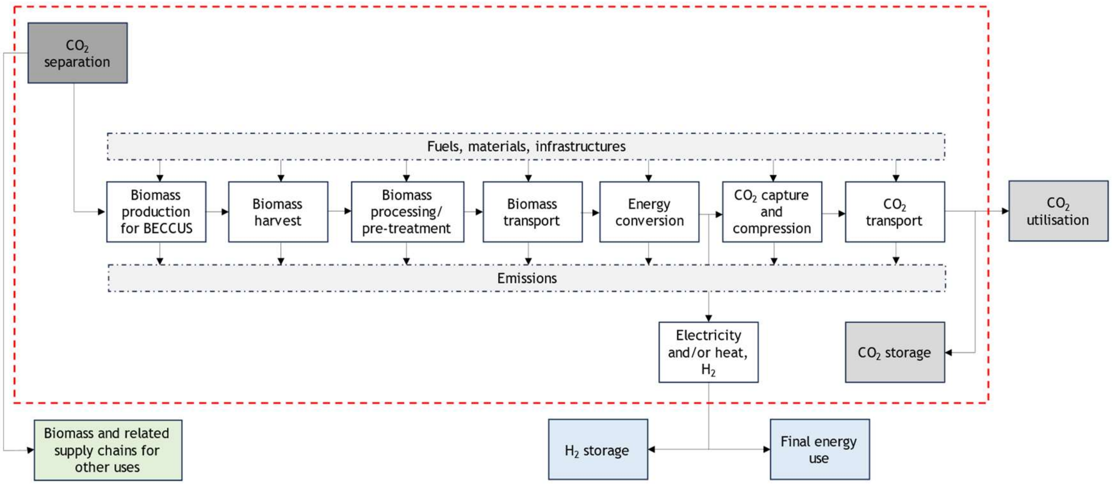

Figure 4: System boundary for BECCUS supply chain within this study.

The goal of the Life Cycle Assessment (LCA) was to assess the climate change impacts, specifically focusing on CO_2 and CO_2-equivalent emissions, associated with the analysed case study. The functional unit was defined as "1 MWh of energy delivered by the process". For the hydrogen production process, the assessment accounted for the product mass flow corresponding to 1 MWh of usable energy. To achieve this, the hydrogen's free Gibbs energy (33.33 kWh per kg) – representing the maximum usable energy released when hydrogen reacts with oxygen – was utilised to convert the hydrogen mass flow into an energy-equivalent value. Accordingly, the emissions were expressed as kilograms of CO_2-equivalents per MWh of energy produced.

In accordance with the outlined methodology, the LCA results illustrate the net greenhouse gas (GHG) emissions, expressed as mass equivalents of carbon dioxide per unit of energy (kg CO_2e MWh^{-1}), for the case study. Emissions throughout the supply chain have been aggregated and categorised into four groups: CO_2 uptake during biomass growth, CO_2 emissions from the bioenergy feedstock supply chain, emissions from the bioenergy conversion process integrated with a carbon capture (CC) facility, and the operation of the carbon capture and storage (CCS) infrastructure.

The findings indicate that the supply chain in Case H_2 achieved net-negative emissions. For every 1 MWh of hydrogen produced by the BECCS system, 859 kg of atmospheric CO_2 were taken out. Figure 5 illustrates the emission profile, net emissions, and carbon dioxide removal (CDR) potential per unit of energy for Case H_2. In this scenario, the conversion stage (red/brown colour) is the largest contributor to the emission profile, generating more than twice the emissions compared to the feedstock supply chain (blue colour). The emissions contributions from the CCS infrastructure (yellow colour) were one order of magnitude lower than feedstock and energy conversion results for the H_2 case study. Process modelling indicates that carbon capture and storage (CCS) in Case H_2 achieves a CO_2 capture rate of 81%. Additionally, the energy efficiency of Case H_2 stands at 27%. The biomass requirement for producing 1 MWh of energy in Case H_2 is 0.71 tonnes of wood pellets.

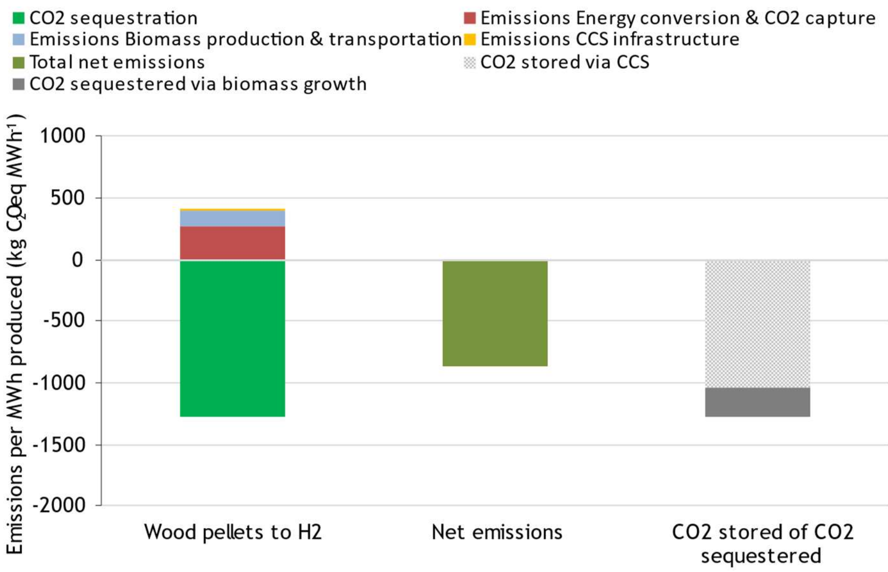

Figure 5: GHG emissions, net emissions and CO_2 storage efficiency per MWh of energy produced for the gasification (Case H_2).

Table 2 and Table 3 summarise the results: (a) carbon attribution per stage for the H_2 case study, (b) the outputs of different aspects assessed including some of the inputs used in the process as well as the major outputs and results obtained.

Table 2: Summary of the results.

Case H_2: Wood pallets to H_2 with CCS	
CO_2 biological sequestration (kg CO_2e MWh^{-1})	-1277
Emissions - Biomass supply chain (kg CO_2e MWh^{-1})	123
Emissions - Bioenergy conversion (kg CO_2e MWh^{-1})	275
Emissions - CCS Infrastructure (kg CO_2e MWh^{-1})	20
Net emissions (kg CO_2e MWh^{-1})	-859

Table 3: Summary of the outputs of different aspects assessed.

Aspect	Case H_2
Biomass feedstock	White wood pellets
Technology used	Hydrogen production via gasification
CO_2 capture method	Pre-combustion capture
CO_2 capture rate	98%
Net CO_2 removal	81%
CO_2 captured per unit of energy produced	1033 kg CO_2/MWh^{-1}
Net emissions (kg CO_2e MWh^{-1})	-859
Biomass input rate	300 kg/h
Energy efficiency	27%
Internal power supply	0.23 Mwe
Internal heat supply	0.43 MW
Captured CO_2 concentration	99.00%
Post-processing CO_2 use	Compressed to supercritical fluid for storage or utilisation

Highlights from LCA:

- **BECCUS shows a 27% biomass-to-energy conversion efficiency.**
- **99.0% pure CO_2: suitable for both storage and various industrial utilisation pathways.**
- **CO_2 capture rate (98%) makes the system efficient for negative emissions, reducing atmospheric emissions to 181 kg CO_2/MWh^{-1}.**
- **The process results in net-negative (−859 kg CO_2e per MWh^{-1} of energy produced), meaning it actively removes more CO_2 than it emits.**

Bioeconomy Sustainability Indicator Model (BSIM)

The Bioeconomy Sustainability Indicator Model (BSIM[5]) is a tool developed by the UK Supergen Bioenergy Hub to assess and map the sustainability of bioeconomy projects (Welfle & Roeder, 2022). The BSIM analyses various sustainability aspects of bioenergy systems, allowing for both risks and benefits to be quantified across a project's lifecycle. It identifies relevant sustainability issues by dividing them into categories, themes, indicators, and issues, and then assesses these issues based on impact and weight. The tool also provides sustainability scores, enabling comparisons across different projects.

For the present Case in the study, the focus is on the gasification of forestry and agricultural residues to produce hydrogen for fuel cell technologies. The process involves using sawmill residues that are dried and pelletised to create a uniform feedstock for gasification, which in turn generates hydrogen-rich syngas. The sustainability assessment of this case covers all steps of the process, from the raw feedstock's preparation to the energy applications of the hydrogen produced. Importantly, CO_2 captured during the process is utilised or stored, adding to the sustainability potential of the system.

The application of BSIM allows for a detailed mapping of sustainability, accounting for the impacts on people (e.g., jobs, livelihoods), development (e.g., energy access, infrastructure), natural systems (e.g., land use, water quality), and climate change (e.g., carbon emissions, renewable energy generation). In the present case study, the model evaluates both the environmental benefits of using bio-based residues for energy generation and the economic viability of producing hydrogen as a clean energy source, focusing on the development and climate change sustainability indicators. The BSIM thus provides a holistic assessment of the bioenergy system, identifying areas where sustainability benefits can be maximised, and risks mitigated. Table 4presents the details of the sustainability indicators used in BSIM for the present case study.

Table 4: Details of the sustainability indicators used in BSIM.

Categories	Themes	Indicators	Issues	Sustainability Issue Scores		
				Applicability	*IS^r*	*IS^b*
Development	Economy	Economic Performance	Gross Domestic Product	*No*	*0*	*0*
			Influence on Wider Sectors	*No*	*0*	*0*
			International Trade	*No*	*0*	*0*
			Financial Capacity to Adopt Bioenergy	*No*	*0*	*0*
		Economic Stimulation	Increased Sustainable Energy Generation	*Yes*	*4*	*8*
			Economic Support Mechanisms	*Yes*	*8*	*8*
	Infrastructure	Infrastructure Requirements	Existing Infrastructure - Availability	*Yes*	*10*	*4*
			Existing Infrastructure - Capacity	*Yes*	*10*	*4*
			New Infrastructure Capacity	*Yes*	*10*	*10*

[5] https://research.manchester.ac.uk/en/publications/bioeconomy-sustainability-indicator-model-bsim-guidance-manual

Categories	Themes	Indicators	Issues	Sustainability Issue Scores		
				Applicability	*IS^r^*	*IS^b^*
	Feedstock Production/ Mobilisation/ Distribution	Production Processes	Chemical Agro-Chemicals (fertiliser + pesticide)	*No*	*0*	*0*
			Use of Genetically Modified Materials	*No*	*0*	*0*
			Feedstock Production Strategy	*No*	*0*	*0*
			Land Use Productivity	*No*	*0*	*0*
		Mobilisation	Resource Mobilisation	*Yes*	*4*	*4*
			Competition for Resources	*Yes*	*10*	*2*
		Distribution	Spatial Distribution of Resources	*No*	*0*	*0*
			Resource Transportation	*No*	*0*	*0*
	Technology	Innovation	TRL Development	*Yes*	*6*	*8*
			Intellectual Property	*No*	*0*	*0*
		Efficiencies	Processing Efficiencies	*Yes*	*8*	*10*
			Supply Chain Efficiencies	*Yes*	*4*	*6*
		Techno-Economics	CAPEX - Direct Fixed Capital Cost	*No*	*0*	*0*
			CAPEX - Indirect Fixed Capital Cost	*No*	*0*	*0*
			OPEX - Fixed Operational Costs	*No*	*0*	*0*
			OPEX - Variable Operational Costs	*No*	*0*	*0*
			Biomass Feedstock Costs	*No*	*0*	*0*
			Reliance on Economic Support Measures	*No*	*0*	*0*
	Energy Sector	Bioenergy	Infrastructure Alignment	*Yes*	*4*	*4*
			Bio-Product Flexibility (energy)	*Yes*	*2*	*8*
			Bio-Product Flexibility (non-energy)	*No*	*0*	*0*
			Bioenergy Vector Distribution	*Yes*	*8*	*8*
			Bioenergy Vector Affordability	*Yes*	*10*	*8*
		Energy System Performances	Input Energy Requirements	*No*	*0*	*0*
			Influences on Energy System Resilience	*No*	*0*	*0*
			Accessibility to Wider Input Energy	*No*	*0*	*0*
	Bioeconomy	Added Value Products	Bio-Chemicals	*No*	*0*	*0*
			Bio-Products	*No*	*0*	*0*
		Bioenergy Complementing Wider Sectors	Agriculture	*Yes*	*0*	*8*
			Chemical	*No*	*0*	*0*
			Waste	*No*	*0*	*0*
			Construction	*No*	*0*	*0*

Categories	Themes	Indicators	Issues	Sustainability Issue Scores		
				Applicability	IS^r	IS^b
			Transport	*Yes*	*2*	*8*
			Services	*No*	*0*	*0*
			Manufacturing	*No*	*0*	*0*
	Land Utilisation	Land Characteristics	Topography - Influencing Access	*No*	*0*	*0*
			Location - Influencing Distribution & Connectivity	*No*	*0*	*0*
			Use of Contaminated Lands	*No*	*0*	*0*
			Potential for Phytoremediation	*No*	*0*	*0*
Climate Change	Governance	Climate Action	Targets, Legislation & Regulations	*Yes*	*6*	*10*
			Awareness	*Yes*	*6*	*6*
		Standards	Fuel Standards	*Yes*	*2*	*8*
			Technical Standards	*No*	*0*	*0*
			Supply Chain of Custody Processes	*No*	*0*	*0*
	Carbon & Emissions	Whole Life Cycle Emissions	Energy Conversion	*Yes*	*2*	*10*
			Feedstock Sources	*Yes*	*2*	*8*
			Transport	*Yes*	*2*	*8*
			Processing & Pre-treatment	*Yes*	*4*	*8*
		Land & Carbon Stocks	Direct Land Use Change	*No*	*0*	*0*
			Indirect Land Use Change	*No*	*0*	*0*
			Changes in Carbon Stocks	*No*	*0*	*0*
		Counterfactual Considerations	Land Use Counterfactuals	*No*	*0*	*0*
			Resource Use Counterfactuals	*Yes*	*8*	*8*
	Energy System	Replaced Fuels	Substitution of Fossil Fuels	*Yes*	*2*	*10*
			Substitution of Traditional Bioenergy	*No*	*0*	*0*

Blue colour: for Development indicators

Orange colour: for Climate Change & Emissions indicators

Grey colour: reflects indicators which are not assessed within the case study.

Following Table 4, Figure 6 below provides a detailed sustainability assessment of a bioenergy case study. The figure offers a key that categorises each of the 38 sustainability indicators used in the analysis, grouping them into four major categories: People Sustainability Indicators, Development Sustainability Indicators, Natural System Sustainability Indicators, and Climate Change and Emissions Sustainability Indicators. As can be seen, the Development and the Climate Change and Emissions indicators have been considered for the present case study. The indicators are further colour-coded to signify areas of sustainability benefit (in green) and sustainability risk (in red), while grey represents indicators that were not included in this particular assessment. This structured categorisation allows for a comprehensive and nuanced view of the environmental, economic, and social impacts associated with the case study, providing a framework for interpreting the project's sustainability performance.

Key		
Sustainability Benefit	Sustainability Risk	Indicators not Included in Sustainability Assessment

People Sustainability Indicators		Development Sustainability Indicators		Natural System Sustainability Indicators		Climate Change & Emissions Sustainability Indicators	
1	Health & Wellbeing	11	Economic Performance	26	Ecosystems	33	Climate Action
2	Food Systems	12	Economic Stimulation	27	PM Pollutants	34	Standards
3	Land Management	13	Infrastructure Requirements	28	Oxide Pollutants	35	Whole Life Cycle Emissions
4	Decent Work	14	Production Processes	29	Heavy Metals	36	Land & Carbon Stocks
5	Jobs & Skills	15	Mobilisation	30	Water Use & Efficiency	37	Counterfactual Considerations
6	Change in income	16	Distribution	31	Water Quality	38	Replaced Fuels
7	Equality	17	Innovation	32	Water Systems		
8	Strong Institutions	18	Supply & System Efficiencies				
9	Partnerships	19	Techno-Economics				
10	Energy Access	20	Bioenergy				
		21	Energy System Performances				
		22	Added Value Products				
		23	Complementing Wider Sectors				
		24	Land Characteristics				
		25	Soil				

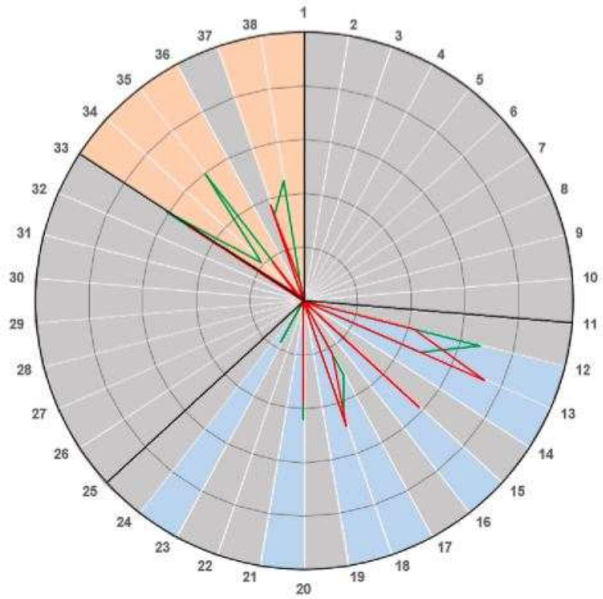

Figure 6: Radar Graph for the Bioenergy Case Study, Mapping the Risks & Benefits across the 38 Bioenergy Sustainability Indicators of the BSIM. The figure presents the Sustainability Performance Score (SPS) values from the BSIM at the sustainability Indicator resolution. Radar graph is shaded to delineate the different sustainability Categories of the BSIM: 'blue' for Development Indicators; 'green' for Natural Systems and 'orange' for Climate Change & Emissions. 'Grey' segments of the graphs reflect Indicators not assessed within the Case Study.

Moreover, the radar plot displays the indicators as segments along the perimeter, with benefits extending outward in green lines and risks shown in red. Sustainability benefits are most prominent in the Climate Change and Emissions and Natural Systems categories, where the case study exhibits a strong performance in indicators like Climate Action (indicator 33) and Whole Life Cycle Emissions (indicator 35), both of which reflect the project's substantial contribution to reducing greenhouse gas emissions. Additionally, the project shows environmental benefits under Ecosystems (indicator 26) and Water Use and Efficiency (indicator 30) within the Natural Systems category, highlighting its minimal impact on land and water resources by using residual biomass instead of dedicated energy crops. However, the radar plot also reveals sustainability risks in the Development category, particularly concerning Economic Performance (indicator

11) and Infrastructure Requirements (indicator 13). These areas are flagged in red, indicating potential challenges due to the high capital and operational costs associated with setting up and running a bioenergy system that integrates hydrogen production with CCS.

Interpreting these results, the case study demonstrates a promising sustainability profile, especially in its environmental and emissions-related aspects. The project's use of residual biomass for hydrogen production coupled with CO_2 capture significantly reduces its carbon footprint, positioning it as a valuable technology for climate mitigation. The ability of the case study to capture CO_2 before it is emitted into the atmosphere aligns with net-negative emissions goals, making it a strong candidate for inclusion in decarbonisation strategies. Moreover, the low impact on land use and water resources supports biodiversity and conserves natural resources, making the project environmentally sound. By avoiding dedicated crop cultivation, the case study reduces the risks of land competition, which is a common concern in bioenergy projects. These environmental benefits align well with global sustainability goals, particularly in contributing to emissions reductions and promoting sustainable resource use.

However, the economic aspects of the case study pose challenges that could affect its scalability and feasibility. The radar plot highlights economic risks for the gasification infrastructure, CO_2 capture technology, and hydrogen storage and distribution systems. These costs could be prohibitive without external financial support, such as grants, subsidies, or carbon credits, which are often necessary to make such advanced bioenergy systems economically viable. The infrastructure required to support the capture, transport, and storage of CO_2, as well as the distribution of hydrogen, demands substantial investment, which may limit the project's deployment in regions without existing support infrastructure. Additionally, the economic risk indicators underscore the importance of policy frameworks that can incentivise low-carbon hydrogen production, thereby improving the project's financial attractiveness. If supported through mechanisms such as carbon pricing, negative emissions trading, or dedicated subsidies for green hydrogen, the case study could become more feasible and play a critical role in the hydrogen economy.

Mapping the potential impact of the case study on the SDGs:

Figure 7 illustrates the outputs of the BSIM, highlighting the potential impact of the case study on each of the 17 Sustainable Development Goals (SDGs). Since each SDG is composed of multiple individual sustainability targets, the project has the potential to exert both positive and negative influences on an SDG, depending on its effect on these specific targets. The BSIM maps the potential connections between the 126 issues outlined in its Sustainability Assessment Framework and the individual targets of the SDGs (Welfle & Roeder, 2022).

When a potential sustainability benefit or risk is identified for a particular issue, the BSIM's methodology assumes a corresponding benefit or risk in achieving the SDG targets linked to that issue. For each SDG, two Sustainability Index values are generated: the Sustainability Benefit Index (SBI), which quantifies the extent to which a project may positively contribute to achieving the SDG, and the Sustainability Risk Index (SRI), which reflects potential risks. These indices are calculated by tallying the number of BSIM issues identified as having either a positive or negative impact on each SDG.

For instance, if 10 sustainability issues are recognised as having a positive effect on the targets of a particular SDG, the project's SBI for that SDG will be 10. Figure 7 indicates that the case study has the potential to exert both positive and negative impacts across the 17 SDGs.
In present case study, SDG 3 (ensure healthy lives and promote well-being for all at all ages),

SDG 7 (ensure access to affordable, reliable, sustainable and modern energy for all), SDG 8 (promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all), SDG 9 (build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation), SDG 11 (make cities and human settlements inclusive, safe, resilient and sustainable), SDG 12 (ensure sustainable consumption and production patterns), SDG 13 (take urgent action to combat climate change and its impacts), and SDG 15 (Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss) have been covered.

Figure 7: Mapping the potential influence of the case study on the SDGs.

ASSESSMENT ACCORDING TO SELECTED ASPECTS

The following section reflects on key technological, system and environmental aspects of the case study. The aspects presented have been selected in order to allow for comparison of results across the various case studies undertaken within the BECCUS Inter-Task Project.

Technology related

- Resources efficiency (total efficiency of the technology/concept)
  - Resource efficiency is achieved by converting residual biomass (white wood pellets from sawmill residues) into hydrogen with integrated CO_2 capture, supporting low-carbon hydrogen production and maximising the use of available biomass resources.
- Technical effort required for integrating CO_2 capture (CO_2 in the gas)
  - Technical effort is required for CO_2 capture, benefiting from the high CO_2 concentration in the syngas. This setup uses methanol-based physical absorption (Rectisol process), which is efficient for high CO_2 concentrations.
- Removal capacity of the individual technology (kt CO_2 per year)
  - The removal capacity depends on operational scale and feedstock availability. For a pilot-scale 1 MW facility, CO_2 removal could be in the range of hundreds of tonnes annually, but larger-scale operations would contribute significantly to national CO_2 reduction targets

- Additional energy demand for CO_2 capture (share/percentage of product energy)
    - CO_2 capture in this setup requires approximately 10-15% of the total energy produced, making it relatively efficient and less energy-intensive.
- % of CO_2 capture
    - The system captures a high percentage of CO_2, typically around 85%, due to the efficient capture process that removes CO_2 before combustion, ensuring substantial carbon reduction.

System related

- Infrastructure development need
    - Requires infrastructure for biomass feedstock supply, hydrogen storage and distribution, and CO_2 transport for storage or utilisation. Additional infrastructure for CO_2 compression and storage facilities would be beneficial
- Negative emissions possible with BECCS
    - Negative emissions are achievable as the system captures a substantial portion of CO_2 produced during gasification. This contributes to carbon reduction targets when the CO_2 is permanently stored or utilised
- Optimise on CO_2 capture or electricity/heat/process heat etc. value?
    - The system is optimised for CO_2 capture and hydrogen production, prioritising carbon capture efficiency while producing fuel-grade hydrogen. There is flexibility to adjust capture efficiency depending on economic or policy incentives for CO_2 reduction
- Multiple products (heat electricity fuel materials)
    - Primarily produces hydrogen as fuel. CO_2 captured can serve as an additional product for utilisation or storage.
- Infrastructure for products available
    - Infrastructure for hydrogen storage and distribution is still developing. CO_2 infrastructure, such as pipelines or transport for storage sites, is also necessary but may require further investment depending on location and integration with existing facilities
- Other energy system services (integration of VRE)
    - Could potentially produce PtX fuels onsite, or supply CO_2 to such production

Environmental related

- Carbon foot-print data
    - The carbon footprint of hydrogen production in this BECCS system is significantly reduced due to CO_2 capture. For example, CO_2 capture efficiency is around 85%, and this can reduce emissions by approximately 0.8 to 1.4 tonnes of CO_2 per tonne of biomass used.
- LCA data
    - The LCA data includes a link to CCS/CCU, assessing the emissions impact of CO_2 capture, compression, and storage or utilisation. This link provides a comprehensive view of the carbon reduction potential through BECCS and its contribution to negative emissions targets.

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