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Discussion Paper

Challenges and Opportunities for Sustainable Deployment of Bioenergy with Carbon Capture and Storage Pathways (BECCS) Globally

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Abstract

Countries are exploring various options to achieve net-zero emissions, including bioenergy with carbon capture and storage (BECCS), which is the process of capturing and storing carbon dioxide (CO_2) from processes that utilize bioenergy to produce heat, electricity or biofuels. However, this technology faces sustainability concerns, an unclear public perception and has complex value chains for its emissions. Adding to this complexity, the literature presents two opposing views regarding the potential of BECCS to achieve negative emissions. This paper analyzes in detail a wide range of BECCS pathways in terms of their ability to achieve negative emissions and their associated costs. Out of the seven assessed pathways, our analysis shows that the corn-to-ethanol and biomethane-production-from-maize BECCS pathways in the U.S., along with biomethane production from wet manure in Europe and baling of straw pellets with trans-Atlantic shipment, can achieve negative emissions at a cost of 50, 108, 159 and 232 dollars per ton of CO_2 ($/t$CO_2$), respectively. Other technologies, such as poplar pellets, forest residue and agricultural residue with trans-Atlantic shipments, are not able to achieve negative emissions.

Keywords: Bioenergy, Biomass, BECCS, CCS, Sustainability, Emissions, Net Zero

Highlights

- The life-cycle emissions and costs of each pathway are calculated, and the associated socioeconomic implications of each path are analyzed. We conclude that not all pathways are net-negative and that these technologies are highly contextual (i.e., country-specific).
- For example, we find that locally cultivated energy crops can achieve negative emissions at a relatively low cost with positive socioeconomic implications, provided risks are mitigated in terms of competing with food production and land use change. Furthermore, biomethane from wet manure can achieve significantly higher negative emissions at a medium-cost range while concurrently contributing positively to socioeconomic aspects, with the lack of economies of scale being a bottleneck.
- On the other hand, dedicated land-based pathways with trans-Atlantic shipments are unable to achieve negative emissions; these pathways also fail to contribute positively to socioeconomic objectives. Only the straw pellets BECCS pathway with trans-Atlantic shipment could achieve net negative emissions due to relatively low upstream and midstream emissions.

1. Introduction

Global warming is one of the most significant challenges facing the world in the 21st century. To address this issue, world leaders reached the Paris Agreement in 2015 (United Nations 2015), wherein all countries committed to reducing their emissions and working cooperatively to adapt to the impacts of climate change. The agreement outlines a pathway for developed nations to assist developing nations in their climate mitigation efforts and establishes a framework for the transparent monitoring and reporting of countries' climate goals. According to the International Energy Agency (IEA), global energy-related carbon dioxide (CO_2) emissions rose to a record level of 36.3 billion tons in 2021 (IEA 2022). Consequently, countries are exploring various options to reduce emissions and/or achieve net-zero emissions.

Among the technologies contributing to a more sustainable future is bioenergy with carbon capture and storage (BECCS), which has been proposed and adopted in various modeling efforts. In essence, BECCS is a process of capturing and storing CO_2 from a bioenergy conversion process that uses biomass feedstock to produce heat, electricity or biofuels. Bioenergy conversion processes include combustion, anaerobic digestion and fermentation. One advantage of BECCS, compared to other technologies like fossil carbon capture and storage (CCS), is that it can remove CO_2 already present in the atmosphere, whereas fossil CCS only prevents new CO_2 from entering the atmosphere (EBA 2022). Another benefit of BECCS is that it provides firm, dispatchable renewable energy, while other negative emission technologies consume energy (IPCC 2022). Therefore, BECCS can be viewed as reducing the net cost of carbon removal compared to other technologies (The Economist 2022).

Despite the benefits that BECCS offers, uncertainty surrounds its global potential. According to the Climate Change Committee (CCC) (The CCC 2020), there is little consensus on precisely which set of biomass feedstocks, conversion techniques and carbon capture techniques can definitively be labeled as BECCS. There is also little agreement on whether a project must be carbon-neutral or carbon-negative to qualify as a BECCS project. These and other aspects complicate the analysis and make the categorization of BECCS processes and projects more challenging (The CCC 2020). In this regard, the IEA (2017) has identified a need for further research and clarification.

Additionally, there are no clear and transparent deployment criteria being followed by countries before choosing a specific pathway for BECCS. Since BECCS involves several processes and products, some BECCS pathways are highly dependent on a global value chain; therefore, their implications and potential should be viewed holistically. This complexity makes accounting for greenhouse gas (GHG) emissions and other techno-socioeconomic parameters complicated. According to a European Commission report (Bogaert et al. 2017), unsustainable use of biomass can adversely impact biodiversity, soil and water, particularly in relation to biomass production. Currently, the literature on BECCS is dominated by land-based pathways — other pathways remain underexplored.

In light of the above, this paper analyzes various BECCS pathways in terms of their social, economic and environmental aspects. This analysis aims to bring transparency and clarity concerning the basis by which a specific BECCS pathway is chosen. Following this, we conduct a detailed numerical analysis to assess the emission reduction potential of various BECCS pathways and their associated costs.

2. Literature Review and Research Gap

2.1. BECCS Overview

2.1.1. BECCS Definition

Several organizations have provided definitions for BECCS. Below is a summary of some of these definitions:

- The IEA (2023) defines BECCS as the process of capturing and storing CO_2 from processes that use biomass feedstocks to produce heat, electricity or biofuels (e.g., in biomass combustion, gasification, biogas plants, ethanol plants and pulp mills for paper production; lime kilns for cement production; and biorefineries).
- The BECCS task force of the Carbon Sequestration Leadership Forum defines BECCS as the concept of combining bioenergy applications, including all forms of power, heat and fuel production, with CCS (Netherlands Environmental Assessment Agency 2022).
- The U.K. CCC defines BECCS as technologies that convert biomass, biogas and biogenic wastes into power, heat, fuel or methane while capturing biogenic CO_2 and storing it in geological locations (The CCC 2020).
- In some studies, BECCS is presented in terms of specific pathways, such as BECCS Stockholm, where BECCS refers to the process in which biogenic CO_2 is separated from the flue gases in the combustion of biofuels and then permanently stored (BECCS SE 2023).
- The World Biogas Association defines BECCS as the combination of energy generation with CCS, in which organic waste is fed into a digester and CO_2 is captured (World Biogas Association 2021).
- The Innovation for Cool Earth Forum proposed using the term Biomass Carbon Removal and Storage (BICRS), as some processes that use biomass to remove CO_2 do not involve bioenergy, and, additionally, biomass has a high carbon value but poor energy value (ICEF 2020).

From the above definitions, it is evident that the scope covered by BECCS is well described. However, these definitions also highlight that several technologies are considered to come under the BECCS category, with each technology representing a separate pathway. It is also important to note that not all pathways would necessarily result in a negative-emissions (i.e., carbon sink) scenario or even a net-zero scenario. These pathways are discussed in more detail in the following sections.

2.1.2. BECCS Technologies and Pathways

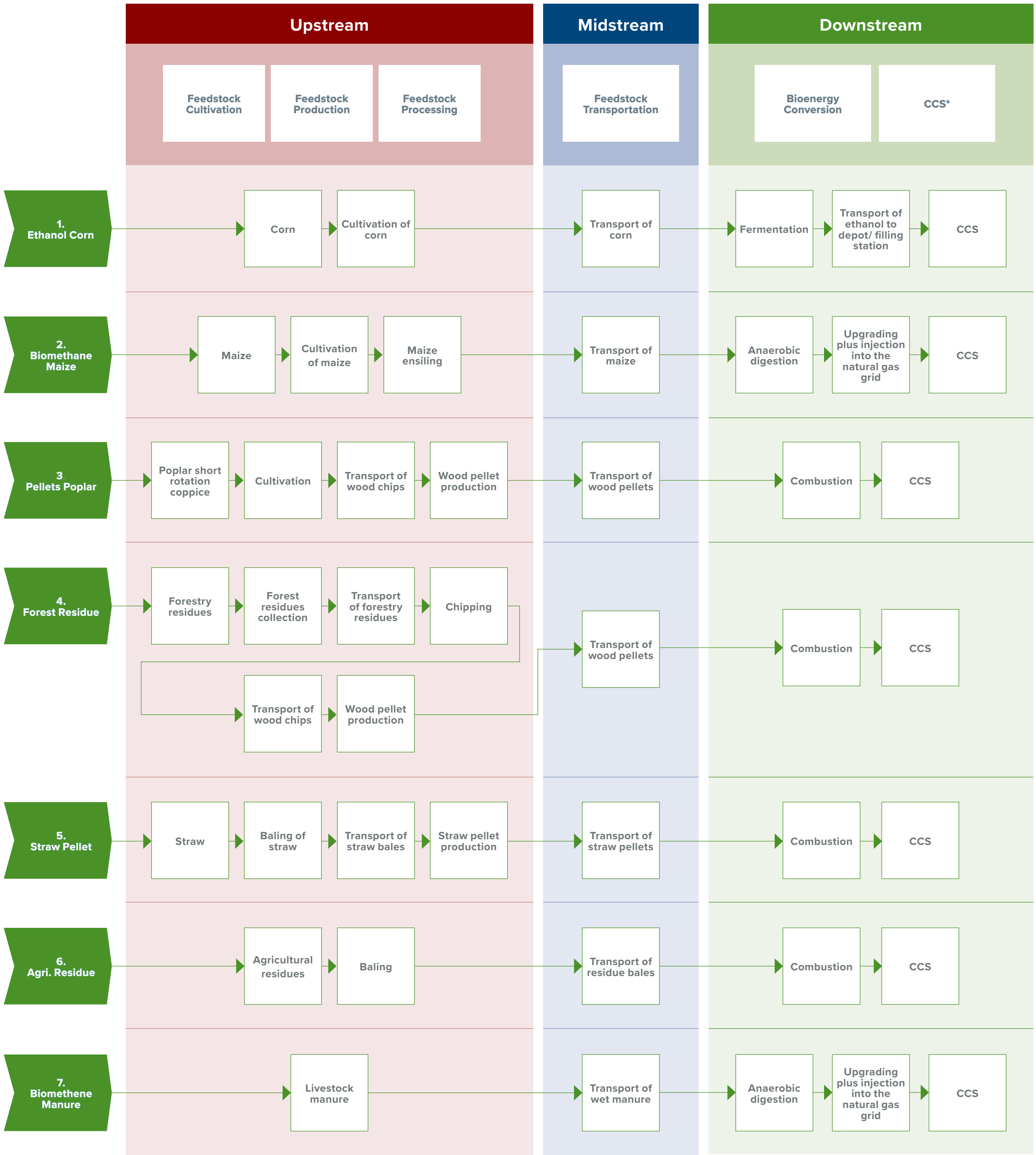
The BECCS pathways encompass a complex set of processes and products. As depicted in Fig. 1, a typical BECCS value chain can be divided into three segments: upstream, which includes the cultivation, production and processing of feedstock; midstream, which involves the transportation of feedstock; and downstream, which includes bioenergy conversion, carbon capture, transport and storage.

Bioenergy with carbon capture and storage feedstock can be derived from various sources, such as woody biomass grown on dedicated land, agricultural waste, forestry waste or livestock manure. Notably, woody biomass products can vary significantly in their supply chain carbon intensity, as they can be procured from a multitude of suppliers and sources (García-Freites, Gough, and Röder 2021). Bioenergy-dedicated crops, such as sugar cane and corn, can also serve as feedstock for BECCS, yielding a variety of products (Synhelion 2023). Regarding livestock manure, cattle in a biogenic cycle consume carbon from plants, which capture CO_2 through photosynthesis (University of California 2021). The collection and digestion of manure in an anaerobic digester considerably reduces GHG emissions from the manure while generating energy that can be used onsite or exported (World Biogas Association 2018). Microalgae, one of the most efficient photosynthetic organisms in nature, can be cultivated on land unsuitable for agriculture, such as deserts, while biomass can also be harvested from macroalgae (seaweed) grown in oceans or lakes (Energy Transition Commission 2021). Nonetheless, this paper does not further explore using algae as a feedstock for BECCS due to its low technology readiness level and lack of available data. The midstream transportation of feedstock, as depicted in the blue (middle) section of Fig. 1, can be conducted using trucks, rail or ships, depending on the distance and type of feedstock.

The final segment of the BECCS pathway involves bioenergy conversion coupled with CCS. Various types of bioenergy conversion technologies are illustrated in Fig. 1. The thermochemical conversion process for BECCS can include combustion, gasification, pyrolysis and liquefaction (Shahbaz et al. 2021). Among these, combustion is the most prevalent, with methods such as direct combustion power generation, co-firing of biomass and fossil fuel and combined heat (Huang et al. 2020). In combustion, CCS can occur either before or after the process. Post-combustion capture involves removing CO_2 from the power station flue gas using a capture medium, often a liquid that absorbs CO_2. Pre-combustion technology is not anticipated to be available in the near term. Non-thermochemical processes include fermentation using feedstock like corn or anaerobic digestion using waste as feedstock (UK Department for Business, Energy & Industrial Strategy 2021). Biomethane capture technology is mature and is implemented in nearly 1,000 biomethane production units across Europe. These biogas plants, considerably smaller than biomass power plants, can be geographically widely distributed (European Biogas Association 2022). The captured biogenic CO_2 from the biogas upgrading process can be utilized in various applications, such as dry ice production, beverage carbonation, or the transportation of perishable goods (Biogas Pentair 2023). Additionally, some biofuel production plants capture CO_2, which would have otherwise been emitted, and sell it for various applications (e.g., beverages).

It is important to note the challenges associated with transporting carbon dioxide, including costs and logistics. However, by strategically co-locating sequestration sites, some of the challenges related to CO_2 transport can be mitigated, subsequently reducing the costs of sequestration, monitoring and verification (IEA 2021; SEAI 2022; Shahbaz et al. 2021; Wong et al. 2022). In the context of CCS, considerations such as CO_2 transport pipelines, well storage, well injection and compression possibilities are crucial. The relevance of the CCS pipeline and infrastructure in finding optimal CCS clusters and aligning them with the CO_2 capture site is essential to minimize cost and inefficiencies during transportation across different segments of BECCS pathways.

Figure 1. BECCS selected pathways flow chart (detailed steps adopted from the Biograce GHG calculation tool).



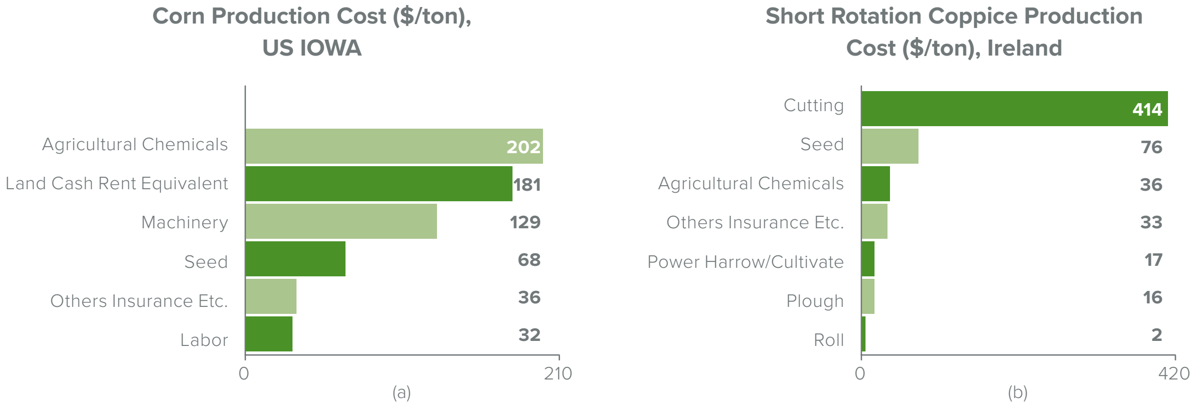
** CCS: Carbon capture, transport, and storage*

2.1.3. Costs

As explained above, the first segment of any BECCS pathway is the sourcing of feedstock, which is sector-, space- and time-of-year specific. The BECCS value chain for plant-based biomass involves site establishment, dependent on fuel price (primarily diesel) and GHG emissions during production, harvesting, treatment and transport (Netherlands Environmental Assessment Agency 2022; García-Freites, Gough, and Röder 2021; Cumicheo, Mac Dowell, and Shah 2019; IPCC 2019). Woody biomass, such as eucalyptus and poplar, is one of the major feedstocks for BECCS. It gained prominence in the U.S. when coal-fired stations were converted into biomass power stations. Woody biomass initially received subsidies when it was cheaper than renewables such as wind and solar (Huang et al. 2020). However, due to rising demand and stricter sustainability criteria, the price of wood pellets has increased globally (Global Status Report for Renewable Energy 2022). Prices may escalate further if more countries begin retrofitting coal-fired plants into biomass.

To illustrate the specificity of the costs related to feedstocks, Fig. 2 summarizes the production costs of corn in Iowa, U.S. (Ag Decision Maker 2023), and the production costs of short rotation coppice (a fast-growing genus of trees in the willow family that can be harvested on a short rotation) in Ireland (Agriculture and Food Development Authority 2015). Fig. 2 demonstrates how costs are highly sensitive to both the type of feedstock and the location where it is grown. For instance, in the case of corn from the U.S., agricultural chemicals are the most significant cost element, which is over five times higher than the corresponding element for short rotation coppice. It is also noteworthy that agricultural chemicals lead to indirect emissions associated with their manufacturing. Subsequently, land rent is the second-highest cost in corn production, which comes with socioeconomic implications. For short rotation coppice, however, seed is the second-highest cost element. It is also noted that for short rotation coppice in Ireland, the dominant cost is cutting, which is driven by labor costs, given its labor-intensive nature.

Figure 2. Upstream production costs of (a) corn production in Iowa, U.S. (Ag Decision Maker 2023), and (b) short rotation coppice production in Ireland (Agriculture and Food Development Authority 2015).



The feedstock transportation cost is mainly influenced by the calorific value of the feedstock (measured in MJ/kg), as shown in Table A1. The costs of transporting feedstock via truck, rail or ship, depending on the distance and type of feedstock, are detailed in Tables A2-A4. In general, feedstock with low combustion energy and high bulk attracts elevated transportation and handling costs. Bioenergy conversion costs, presented in Table A5, are generally not context-specific. Countries with existing conversion technologies are more likely to leverage experience and economies of scale. Processes such as combustion release energy and do not require energy for the conversion process. However, conversion from anaerobic digestion is resource intensive, requiring electricity and heat, thus increasing costs. In some BECCS pathways, carbon capture occurs automatically as part of the processing, while in others, it must be performed as a separate process by capturing emissions. For instance, in post-combustion capture, CCS is a separate process, whereas, in the case of corn ethanol, capture can be integrated into the process. Direct combustion to power is the most established technology, having the lowest capital cost as well as a relatively low electricity cost. Oxy combustion is an emerging option, but its capital and operating costs remain high. In the case of biogas, relatively small and scattered biogas plants contribute to increased costs due to the lack of economies of scale (IEA 2019). The most widely used carbon capture method, currently available at a relatively low cost, is corn ethanol fermentation, as shown in Table A6. Regarding combustion, post-combustion has the lowest cost, with oxy-fuel capture emerging as the most efficient.

The last segment of the BECCS value chain is the downstream segment, where CO_2 is transported and stored. The CO_2 transport cost is strongly impacted by pipeline capacity and the distance covered by the pipeline. As indicated in Table 1, tripling the pipeline transport distance can result in an approximately threefold increase in carbon transport costs while maintaining constant pipeline capacity. Conversely, doubling the pipeline capacity can decrease the cost by around 45%, assuming the same transportation distance. Therefore, clustering the CO_2 transport network over short distances while increasing its capacity can significantly save costs. Carbon dioxide storage primarily depends on the depth and thickness of the CO_2 storage well, as shown in Table A7.

Cost estimates for the BECCS value chain cover a broad range due to the diversity of BECCS pathways and variations in the boundaries of both cost and CO_2 balance (UK Energy Research Centre 2020). Current estimates for BECCS carbon removal costs differ widely, ranging from 30 to 400 \$/tCO_2; estimates vary based on different feedstocks, conversion and capture technologies and system configurations (Fuss et al. 2018), as detailed above.

Table 1. Cost of carbon for CO_2 transport (\$/tCO_2) based on different annual pipeline capacities (MtCO_2) and transportation distances (miles), as sourced from Bloomberg NEF CO_2 transport and storage 2023.

Annual Pipeline Capacity (MtCO_2)	Transportation Distance (miles)						
	25	35	45	55	65	75	85
0.25	13.91	19.43	24.25	29.07	34.58	39.4	44.23
0.5	7.51	10.15	12.78	15.41	18.05	21.29	23.92
1	4.1	5.56	7.01	8.46	9.92	11.94	13.4
2	2.49	3.33	4.3	5.2	6.1	7.01	7.91
5	1.34	1.84	2.26	2.83	3.33	3.82	4.79
10	0.86	1.19	1.51	1.84	2.16	3.02	3.35
20	0.56	0.77	1.31	1.59	1.88	2.15	2.36

2.2. Research Gap

As previously explained, BECCS encompasses several pathways, with processes and products that make accounting for GHG emissions and other techno-economic parameters challenging (CCC 2020). Due to this complexity, the amount of carbon removed from the atmosphere over the life of a BECCS project is highly circumstantial and depends on several factors, such as geography, land-use change, feedstock characteristics, energy conversion technology and the CCS approach.

In addition to this complexity, two predominant views regarding BECCS emissions potential are generally found in the literature. One view posits that biomass (plant-based) BECCS can achieve negative emissions, with studies projecting that high volumes of negative emissions can be realized. In contrast, the other view considers dedicated land-based BECCS (including plant-based BECCS), as having limited potential and cautions against over-reliance on this method. Table 2 provides a sample of papers from both schools of thought.

Table 2. Review of studies on the projected potential of BECCS.

Sample of studies with the view that land-based BECCS has high negative emission potential	Sample of studies with a view that land-based BECCS has low negative emission potential
IPCC 2018	ICEF 2020
Cumicheo, Mac Dowell, and Shah 2019	Kemper 2015
Selosse and Ricci 2014	Bui 2021
Ball-Burack, Salas, and Mercure 2022	Bogaert et al. 2017
Weng, Cai, and Wang 2021	Emenike et al. 2020
	Quiggin 2021
	Kreuter and Lederer 2021

Some dedicated land-based BECCS studies have projected significant CO_2 emission mitigation potential for biomass-based BECCS. For instance, in the pathway limiting global warming to 1.5°C, BECCS deployment is projected to reach up to 5 $GtCO_2$ per year by 2050 (IPCC 2018). Similarly, Cumicheo, Mac Dowell, and Shah (2019) projected that BECCS has the potential to offset 18 Mt/year of industrial CO_2 emissions in the U.K. and suggested that global sustainable biomass is sufficient to meet the fuel requirement for 3,000 BECCS plants of 500 MW capacity each. However, the figures presented for supply chain emissions were simplistic, and no calculation details were provided. Selosse and Ricci (2014) evaluated the role of power generation from BECCS and projected that 50% of CCS deployed globally would be associated with BECCS by 2050. Moreover, Ball-Burack, Salas, and Mercure (2022) conclude that biomass availability for BECCS plays a pivotal role in enabling net negative emissions in the power sector and could significantly contribute to achieving 48 $MtCO_2$/year net negative power sector emissions as aimed by the CCC by 2050 in the U.K. (Ball-Burack, Salas, and Mercure 2022). In the context of China, Weng, Cai, and Wang (2021) evaluated the use of BECCS and afforestation under China's carbon-neutral target for 2060 and concluded that in 2060, biomass-based BECCS combined with afforestation would capture 2.91 $GtCO_2$ per year.

On the other hand, various studies have raised concerns about plant-based BECCS (Table 2). For instance, the Innovation for Cool Earth Forum, in its Biomass Carbon Removal and Storage Roadmap, suggests that several models have allocated very large and unrealistic amounts of carbon removal to BECCS (ICEF 2020). Similarly, Kemper (2015) has raised concerns that BECCS would interfere with food production, lead to monoculture, increase pressure on water/land reserves, impact small-scale farmers and elevate the use of fertilizers. Additionally, Bui (2021) viewed the sustainability of biomass as a major concern and proposed that limited biomass resources should be prioritized for the most valuable end products to render carbon removal economically viable. Moreover, according to a report by the European Commission (Bogaert et al. 2017), certain bio-energy pathways result in insufficient negative GHG emissions. As suggested by Emenike et al. (2020), the energy used in the harvesting and processing of biomass can significantly affect overall emissions. Likewise, Chatham House has warned against an overreliance on BECCS (Quiggin 2021), while Kreuter and Lederer (2021) have referred to BECCS as a speculative technology.

To complement the above observations, it is important to mention that some studies have suggested alternative, underexplored pathways for BECCS. For example, the American University (2020) and the IEA (2018) have recommended that agricultural and forestry residues, along with industrial/municipal wastes, have the lowest impact on land-use change and are more sustainable pathways for BECCS. Additionally, Pour et al. (2018), discussing the opportunities of BECCS in the Australian power sector, chose to avoid using BECCS with dedicated energy crops due to the ecological uncertainties and social challenges associated with it and instead considered feedstock options of organic waste from the municipal, agricultural and forestry sectors only. Similarly, Wong et al. (2022), who studied the BECCS potential for California, considered biomass residues (feedstock), municipal solid waste, crop residues and manure as feedstock and concluded that together, these sources could achieve five million tons of carbon sequestration per year, which is less than 5% of California's CO_2 emissions. It should also be noted that even if the feedstock is waste and residue, the projected potential should be based on what can be sustainably achieved. For example, as stated by Quiggin (2021), if 100% of U.K. feedstock were to be provided by domestically grown wheat straw residue for BECCS-to-power pathways by 2050, an 83% increase in current wheat production would be required, which could have implications on food prices.

In terms of the scope of previous studies around BECCS, examples such as Negri et al. (2021), García-Freites, Gough, and Röder (2021) and Cabral, Bui, and Mac Dowell (2019) have conducted techno-economic and life-cycle assessments of BECCS pathways from the perspective of achieving negative emissions. However, these studies have not assessed wider socioeconomic implications. Other studies primarily focused on either the upstream segment, such as Kato and Yamagata (2014), or the downstream aspects, such as Bennett et al. (2021), but not on both. There are also studies (Cumicheo, Mac Dowell, and Shah 2019; Wong et al. 2022) that have only evaluated a specific BECCS pathway. From the above review, we can conclude that there is a lack of studies in the literature related to the assessment of the potential of BECCS, considering the entire BECCS value chain and simultaneously addressing socio-environmental-economic implications.

Indeed, assessing the potential of BECCS requires further scrutiny, without which we will not be able to attain reasonable projections on the future capabilities of this technology. In addition to the potential of each BECCS pathway, it is important to view BECCS deployment from multiple perspectives. While reducing emissions is certainly an important aspect, other aspects, including social and economic ones, are also vital. One distinguishing aspect of this paper is that it assesses the emissions of several BECCS pathways, considering their entire life cycle. Furthermore, it provides a detailed assessment of the costs associated with these pathways.

3. Analysis, Results and Discussion

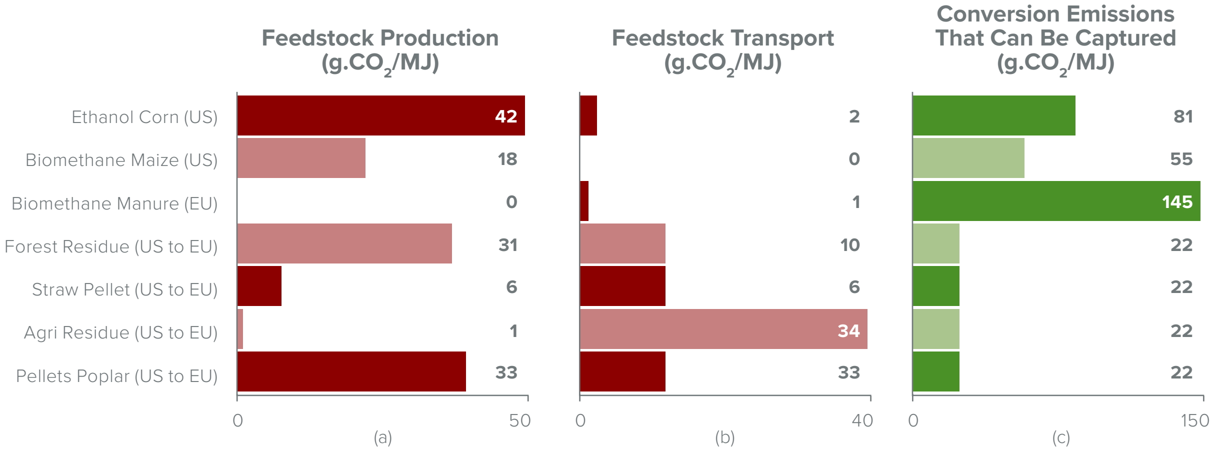
To explore a wide range of possible processes and products of BECCS, seven pathways (as outlined in Section 2.1.2) were selected. We calculated the life-cycle emissions and costs of each pathway at the upstream (cultivation, production and processing), midstream (transportation) and downstream (bioenergy conversion and CCS) segments. Additionally, we highlighted the bottlenecks and opportunities associated with each pathway. Our analysis primarily utilizes data from the Biograce GHG emissions tool, which was developed for calculating GHG emissions from bioenergy pathways in Europe. This tool or its data has been employed for calculating GHG emissions of various bioenergy pathways in several studies, including Hennecke et al. (2013), IEA Bioenergy (2019) and Berger et al. (2023). All associated assumptions are included in the "Appendix."

3.1. Emissions of Pathways

Generally, there are two possible methods for calculating the life-cycle GHG emissions associated with BECCS. The first is based on calculating the upstream and midstream emissions by mass (i.e., in terms of kilograms of CO_2 per ton of biomass [kg.CO_2/tbm]). However, the limitation of this approach is that mass is not necessarily a true reflection of energy output, as there can be varying energy densities for different types of feedstock. The alternative method involves the calculation of life-cycle emissions based on calorific value, which is a better representation of the emission intensity of various BECCS pathways. Therefore, in this paper, the life-cycle emissions analysis is based on the equivalent gram of CO_2eq emissions produced per MJ of energy produced (gCO_2eq/MJ). Furthermore, CO_2eq emission quantities include various GHG emissions, such as CH_4 and N_2O emissions.

Fig. 3 summarizes the emissions associated with each segment: (a) upstream feedstock production and processing emissions, (b) midstream feedstock transportation emissions and (c) downstream bioenergy conversion emissions for the seven selected pathways. Fig. 3(a) illustrates the upstream positive emissions related to biomass cultivation, production and processing for various BECCS pathways. These emissions are associated with diesel consumption, agrochemical consumption and electricity consumption for the cultivation of feedstock. Another significant component of emissions is associated with pellet production for some pathways. As observed, upstream emissions are in the high range (31 to 42 gCO_2eq/MJ) for corn ethanol, poplar and forest residue. In the case of corn ethanol, emissions are mainly driven by resource-intensive cultivation, while for poplar and forest residue, emissions are primarily driven by resource-intensive pellet production. These upstream emissions are around the medium range for maize. For pellet straw and agricultural residue, upstream emissions are the lowest since the feedstock is residue. There are no upstream emissions in the case of wet manure.
In the midstream feedstock transportation segment,

Figure 3. depicts emissions associated with several BECCS pathways: (a) shows feedstock production and processing emissions in terms of equivalent CO_2 emissions in grams per MJ of energy produced (gCO_2eq/MJ), (b) illustrates feedstock transport emissions generated (gCO_2eq/MJ), and (c) presents bioenergy conversion emissions that can be captured (gCO_2eq/MJ). Note that in (a) and (b), we use a red bar to indicate that CO_2 is emitted, while the bars are green in (c) to denote that emissions here can be captured. Data were calculated via the Biograce GHG calculation tool, and inputs can be found in Tables A1 and A2.



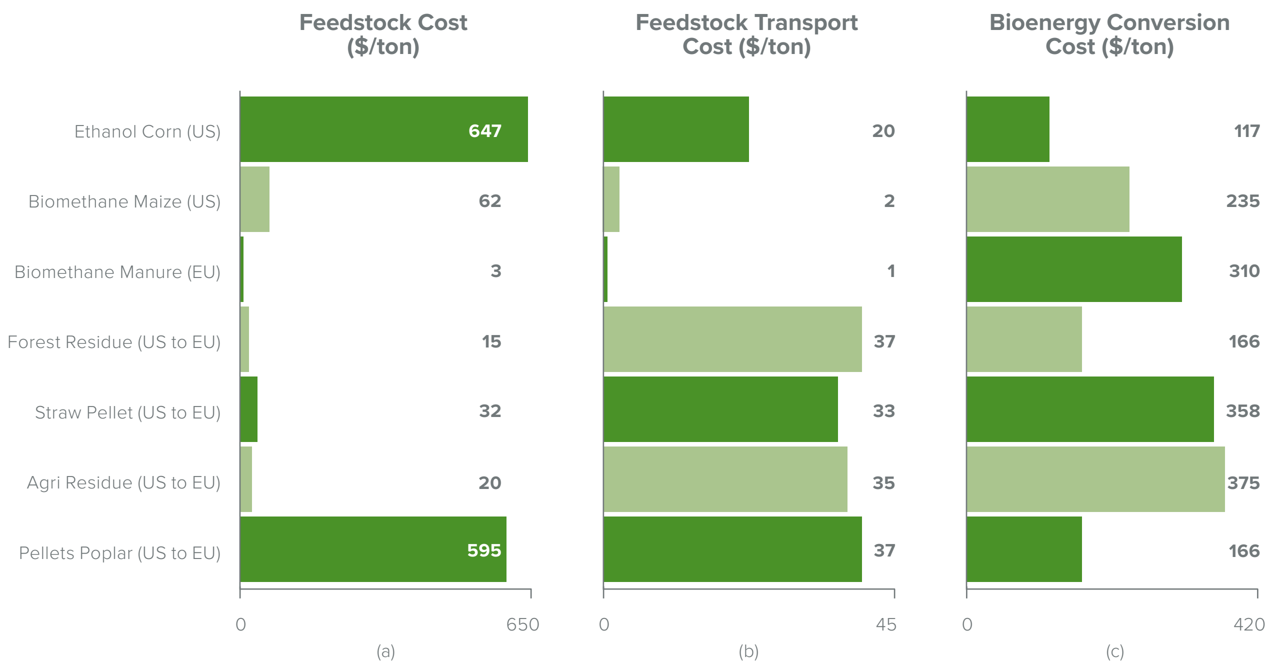
as depicted in Fig. 3(b), the assumed feedstock transportation distances and types for various BECCS pathways are summarized in Table A2. Fig. 3(b) shows that positive transportation emissions for agricultural residue are more than 300% when compared with pellet transportation for the same distance. This is primarily due to the bulkiness and low energy density of the residue bales. In the case of local transportation, these emissions are minimal, which also presents an opportunity for economic growth by fostering local jobs. International transportation comes with the additional added complexity of GHG emissions accounting, monitoring, compliance and verification.

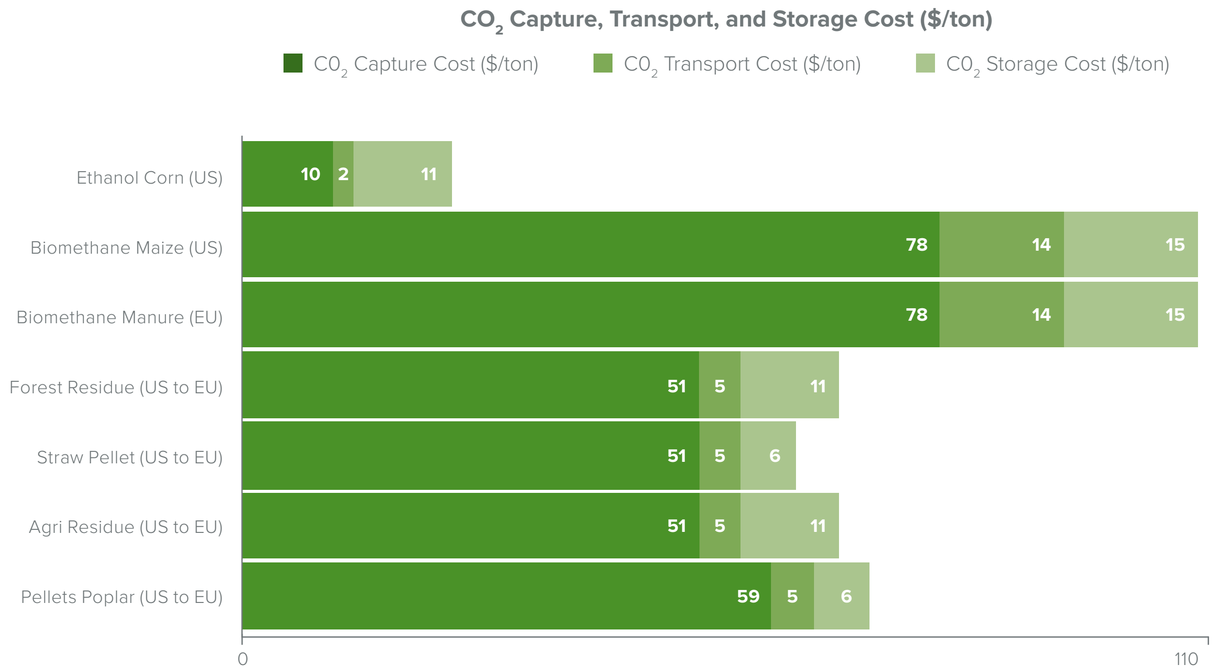
Fig. 3(c) demonstrates the downstream emissions from the bioenergy conversion process, depicted with green bars to signify the opportunity to capture those emissions in this segment. The production of biomethane from wet manure has the highest emissions at 145 gCO_2eq/MJ, presenting an opportunity to capture highly concentrated carbon. Post-combustion emissions are low compared to fermentation and anaerobic digestion processes. Based on the Biograce GHG calculation tool, we find that emissions from bioenergy conversion from maize, corn and wet manure are approximately 200%, 300% and 600% higher than emissions from the combustion process, respectively. Here, we note that Cannell (2003) makes simplified assumptions that all the carbon captured during photosynthesis is released during the biomass conversion process. However, depending on the bioenergy conversion process, there can be significant variations in the emissions that can be captured. Therefore, downstream, higher concentrated CO_2 emissions indicate the opportunity to capture more emissions with an increased likelihood of achieving net-negative emissions. In this analysis, selected BECCS pathways are able to achieve negative emissions when captured and stored biogenic CO_2 is greater than the BECCS value chain emissions. It is also assumed that land-use change does not occur for the selected BECCS pathways with the sustainable growth of biomass and bioenergy crops, whereas this parameter is not relevant for the pathways using waste or residue as feedstock.

3.2. Costs of Pathways

This section quantifies the costs associated with different segments of the BECCS pathways (Fig. 4). The feedstock production cost is depicted in Fig. 4(a) in dollars per ton ($/t) and is calculated based on agricultural chemical use, land rent, machinery, seed and labor costs and other miscellaneous costs. As discussed in Section 2.1.3, these costs are highly contextual; that is, they are country-specific and vary based on the type of feedstock. The costs for corn ethanol and poplar are extremely high in terms of upstream costs since these pathways are resource-intensive, requiring considerable energy, land and labor. When sourced locally, as in the case of corn ethanol, this presents an opportunity for economic growth. However, in the case of poplar, which is sourced internationally, it does not positively impact local economic growth. For all other pathways, the cost of feedstock is relatively low.

Figure 4. Cost associated with several BECCS Pathways: (a) feedstock production cost in ($/ton), (b) feedstock transport cost in ($/ton), (c) bioenergy conversion cost ($/ton eq) (Shahbaz et al. 2021), and (d) detailed carbon capture, transport, and storage ($/t$CO_2$). Data were calculated via the Biograce GHG calculation tool, and inputs can be found in Tables A1 to A7.





(d)

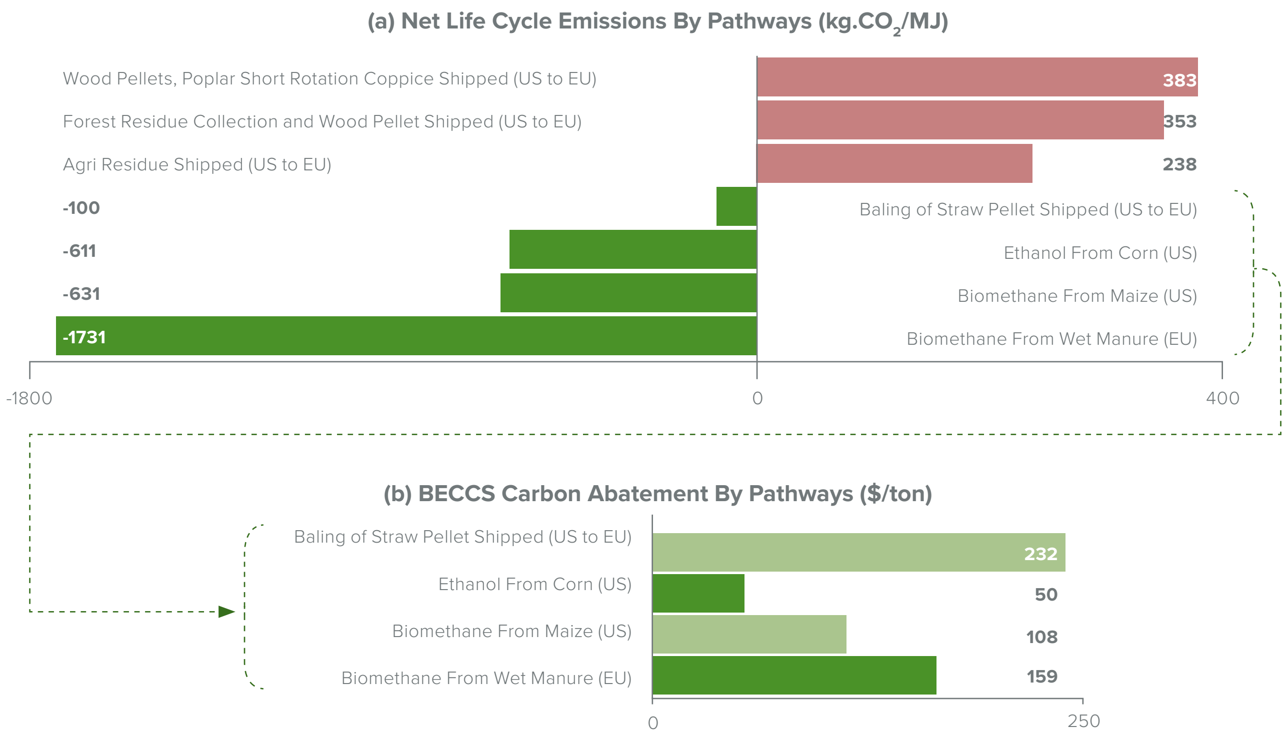
Fig. 4(b) illustrates the transportation cost of feedstock in dollars per ton ($/t). As expected, this cost is significantly higher for the pathways involving trans-Atlantic shipment. Fig. 4(c) displays the calculated bioenergy conversion cost based on the type of conversion technology employed. To make it pathway-specific, an adjustment factor based on calorific value is applied (see Table A1). In terms of bioenergy conversion cost, corn ethanol and poplar wood pellet BECCS pathways are the least costly. Fig. 4(d) demonstrates the cost of capturing, transporting and storing CO_2 for each pathway. The pathway-specific CO_2 transport and storage costs are derived from Tables 1 and A6, respectively, assuming the typical size of plants and capture capability for the selected BECCS pathways. As seen in Fig. 4(d), the 'capture step' is the costliest in all cases, except for ethanol.

3.3. Results and Discussion: Value Chain Analysis of Pathways

With the calculations presented in the previous sections, it is now possible to derive insights related to the life-cycle emissions of each BECCS pathway. The reader is reminded that the upstream and midstream segments result in positive emissions, whereas the downstream segment results in negative emissions. Ideally, the specific BECCS pathway should yield the highest possible net negative emissions at the lowest possible costs.

The results for the life-cycle emissions of the chosen pathways are depicted in Fig. 5. As shown in Fig. 5(a), wood pellets and forestry residues, both with trans-Atlantic shipment and CCS, are unable to achieve negative emissions due to high emission intensity, mainly stemming from upstream activities. Similarly, agricultural residue with trans-Atlantic shipment also fails to achieve negative emissions due to high midstream transportation emissions, attributed to the bulkiness of the feedstock. However, these pathways can have a positive impact in terms of energy security and cost reduction in power generation.

Figure 5. illustrates the life cycle analysis of emissions for BECCS pathways: Fig. 5(a) displays the net life-cycle emissions of various BECCS pathways, while Fig. 5(b) depicts the BECCS carbon abatement (captured, transported, and stored) cost for pathways that could achieve negative emissions. The data was calculated via the Biograce GHG calculation tool, and the inputs can be found in Tables A6 to A7.



On the other hand, four technologies have been shown to achieve negative emissions, as illustrated in Fig. 5(a); these include straw pellets, ethanol from corn, biomethane from maize and biomethane from manure. The corresponding costs associated with each technology to achieve these negative emissions are depicted in Fig. 5(b). For instance, straw pellets with trans-Atlantic shipment for direct combustion to power with CCS can achieve relatively low negative emissions of 100 kg per ton of feedstock (Fig. 5(a)) at a high cost of 232 $/ton of CO_2 captured, transported and stored, as shown in Fig. 5(b). The performance of the straw pellet pathway on socioeconomic measures is consistent with that of the forestry residue pathway discussed above, with the added benefit that this pathway is relatively more sustainable and can achieve net negative emissions. Biomethane-production-from-maize and corn-to-ethanol BECCS pathways in the U.S. are both able to achieve significant negative emissions of more than 600 $kgCO_2eq$/ton of feedstock at a cost of 159 and 50 $/ton, respectively, as shown in Fig. 5(b). This pathway can have a positive impact on energy security and green fuel provision and can stimulate economic growth by encouraging local jobs, provided it is sourced sustainably and does not compete with the food industry. The carbon abatement costs calculated in this paper are within the range of cost estimates from other studies, such as EFI (2022), and they align closely with the ethanol pathway in the study by EFI (2023).

The highest net negative emissions in Europe are achieved through biomethane production from wet manure with CCS. This pathway can provide a net negative emission of more than 1,700 kg per ton of feedstock at a cost of 108 $/ton. It can have a positive impact in terms of energy security, offering renewable gas, and can significantly boost economic growth by creating local jobs. However, the higher costs for anaerobic digestion and upgrading to natural gas, coupled with the lack of economies of scale, present challenges for this pathway.

Based on the calculations above, it is evident that dedicated land-based biomass with trans-Atlantic shipment is unable to achieve negative emissions. While this result was anticipated, the scale of this difficulty is demonstrated by quantifying the life-cycle emissions for this scenario, which reach nearly 383 $kgCO_2$/MJ. Nevertheless, the straw pellet-based feedstock with trans-Atlantic shipment can achieve a negative emission of 100 kg per ton of feedstock at an abatement cost of 232 $/$tCO_2$. Generally, such pathways with imported feedstock typically require government support to operate as a viable business and may not contribute significantly to local economic growth. This pathway remains a preferred option for some countries, such as the U.K., as it can mitigate the risk of stranded coal-fired plants and provide long-term energy security while reducing emissions compared to coal-fired power plants.

In the case of energy crop pathways, such as corn to ethanol and biomethane production from maize, this pathway presents a favorable opportunity to achieve higher negative emissions at a relatively reasonable cost. It could positively contribute to economic growth, provided that the risks associated with land use and food security are mitigated. Such a pathway has been successfully adopted by countries such as the U.S., leveraging the opportunity for local bioenergy potential.

Biomethane from wet manure can achieve significantly higher negative emissions, with a carbon abatement cost of 159 $/$tCO_2$. This pathway can make a positive contribution to local economic growth. However, the anaerobic digestion pathway is resource intensive, requiring substantial amounts of electricity and natural gas for the process. These pathways currently lack economies of scale, a challenge that could be overcome by establishing CCS clusters at suitable locations. This approach has been successfully implemented in several European countries.

Various studies have projected the potential of BECCS, as outlined in Section 2.2. After the detailed analysis provided in this section, a brief commentary on these studies is warranted. For instance, Weng, Cai, and Wang (2021) projected the negative emission potential of BECCS in China to be 2.61 $GtCO_2$ by 2060. Given China's significant bioenergy potential, it is reasonable to assume that BECCS can play a key role in achieving net-zero emissions in the power sector in China. Conversely, the projected BECCS potential in the U.K., amounting to up to 48 $MtCO_2$/year of net negative emission in the power sector (Ball-Burack, Salas, and Mercure 2022), warrants careful consideration due to the limited indigenous biomass potential and the need for imported feedstock. Pour, Webley, and Cook (2018) projected a negative emission potential of around 25 $MtCO_2$ per year for Australia; this estimate seems reasonable, considering landfill, forest residue and municipal solid waste as feedstock in the Australian context.

In addition to analyzing emission potentials, the studied pathways also addressed socioeconomic aspects. Selosse and Ricci (2014) evaluated the global potential of BECCS and projected the role of power generation from BECCS; they estimated that 50% of CCS deployed globally would be associated with BECCS by 2050. However, such projections at the global level can be overly simplistic and may not accurately represent the realistic, sustainable potential of BECCS. As life-cycle assessments of BECCS pathways show that not all pathways are net negative, it is crucial to conduct contextual and country-specific research before extrapolating domestic experiences to the rest of the world.

4. Conclusion

Bioenergy with carbon capture and storage is a technology comprising a complex array of processes, products and pathways and is considered by many net zero studies as a viable contender for achieving negative emissions. However, some studies in the literature view these same BECCS technologies as less promising, thus warranting additional scrutiny of the definitions and assumptions.

The emissions and costs of the BECCS pathways were calculated using a Biograce calculator. The analysis conducted was a life-cycle analysis that included the upstream (cultivation, production and processing), midstream (transportation) and downstream (bioenergy conversion and CCS) segments. The BECCS pathways found capable of achieving negative emissions were corn-to-ethanol and biomethane-production-from-maize pathways in the U.S., biomethane production from wet manure in Europe, and baling of straw pellets with trans-Atlantic shipment at a cost of 50, 108, 159 and 232 $/tCO_2$, respectively. Other pathways, including poplar pellets, forest residue and agricultural residue with trans-Atlantic shipment, were unable to achieve negative emissions.

The emission and cost findings mentioned above result from the type of feedstock and the associated processes for cultivation and processing. In instances where biomass resources are not available locally, they may need to be imported, adding complexity and associated emissions from midstream transportation. In such cases, balancing socio-enviro-economic objectives becomes challenging. Fortunately, upstream emissions can be substantially reduced when residue and waste feedstock are used. However, midstream transportation emissions can increase due to the bulkiness and/or low energy density of the residue and waste feedstock. Downstream bioenergy conversion emissions intensity and concentration present an opportunity to capture emissions efficiently to achieve net negative overall emissions. Governments can play a pivotal role in the downstream segment of the transportation and storage of CO_2 by establishing CCS clusters at suitable locations. This analysis demonstrates that BECCS technologies do not always result in negative emissions; in cases where negative emissions are achieved, they can come at a substantial cost. Governments should focus on the pathways that offer the most “value” within their specific context. Evaluating emission potential and the possible socioeconomic benefits provided by the specific BECCS pathway is a crucial step for countries aiming to choose more sustainable pathways. This assists in initiating a dialogue on global biomass governance and establishing sustainability criteria for the BECCS value chain.

5. Appendix A

Table A1. Net combustion energy for each pathway (Biograce GHG calculation tool). This Table is used as an input to Fig. 3, Fig. 4, and Fig. 5.

Pathways	Net Combustion Energy (MJ/kg)
Pellets Poplar U.S. to EU	19
Agri. Residue U.S. to EU	18
Straw Pellet U.S. to EU	17.2
Forest Residue U.S. to EU	19
Biomethane Manure EU	12
Biomethane Maize U.S.	16.9
Ethanol Corn U.S.	16.19

Table A2. Feedstock transportation distances for selected BECCS pathways (Biograce GHG calculation tool). The feedstock transport emissions shown in Fig. 3(b) are based on the distances shown in this table.

Feedstock Type	Transportation Distance (km)	Type of Transport
Trans-Atlantic shipment of wood pellets/ agri. residue	19,800	Handymax Ship
Local transport of maize	20	Truck
Local transport of corn and ethanol	200	Truck
Local transport of wet manure	5	Truck

Table A3. Ship transport costs of wood pellets (analysis of biomass prices). As shown in the Table, there can be some variation in shipping costs based on capacity. This study assumes transatlantic shipping costs based on Handymax.

Wood Pellets	Handymax	Panamax	Chip Carrier
Cargo Wood Pellets (tons)	42,466	52,318	45,394
Cargo Wood Pellets (GJ)	721,920	889,407	791,231
Ship Transport Costs (USD/GJ/1,000 km)	0.0978	0.0934	0.1416

Table A4. Truck and rail unit costs for the transportation of feedstock (Stolaroff et al. 2021). There are both truck and rail options; however, this study only assumes truck transport prices locally due to the very short distance involved in some pathways.

Feedstock Transport	Cost ($/t-km)
Truck	0.101
Rail	0.044

Table A5. Biomass conversion electricity costs for each technology (Shahbaz et al. 2021). The bioenergy conversion cost in ($/ton) shown in Fig. 4(c) is calculated based on the net combustion energy (MJ/kg) in Table A1, converting it to equivalent (kWh/ton) as 1 MJ = 0.2777 kWh, and then calculating ($/ton) using Table A5.

Biomass Conversion Technologies	Electricity Cost (US $/kWh)
Oxy Combustion	0.175
Pulverized Coal Biomass Co-fired	0.0315
Direct Combustion to Power	0.075
Anaerobic Digestion	0.093

Table A6. Carbon capture costs for each technology (CSL Forum 2018). These costs are shown in Fig. 4(d).

CO_2 Capture Technology	CO_2 Capture Cost ($/t$CO_2$)
Post-Combustion CO_2 Capture	51
Oxy-Fuel Capture	59
Corn-Ethanol Plants	10
Anaerobic Digestion	78

Table A7. Carbon storage costs based on CO_2 storage well depth and thickness (Bloomberg NEF CO_2 transport and storage 2023). This table is used in Fig. 4(d), with storage cost for each BECCS pathway applied based on the typical size of bioenergy plants and capture capability.

CO_2 Storage Cost ($)	Depth (m)	Thickness (m)
6	1,551.432	276.4536
11	1,749.552	215.4936
15	1,978.152	196.596
20	2,039.112	140.208

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Notes

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Amro is the acting program director of Utilities and Renewables at the King Abdullah Petroleum Studies and Research Center (KAPSARC), Riyadh, Saudi Arabia, and possesses 20+ years of experience in energy and technology garnered on three continents. His expertise includes renewable energy policy, electricity sector regulation, power systems modeling, and hybrid microgrid design and optimization. He has led and executed several national modeling initiatives both at the distributed and utility scales, and he is listed among the top 2% of scientists globally as per Elsevier. Some aspects of his research have been adopted by BP in creating their seminal annual statistical review. Credited with 50+ papers and patents, Dr. Elshurafa holds a Ph.D. in electrical engineering complemented thereafter with an MBA in finance.

About the Project

This study falls under the project "Innovations in Market Design, Network Regulations, Low-carbon Investments and Technologies" within KAPSARC's Utilities and Renewables program. The study assesses the challenges and opportunities for sustainable deployment of bioenergy with carbon capture and storage (BECCS) pathways. Moreover, this study analyzes in detail a wide range of BECCS pathways in terms of their ability to achieve negative emissions and their associated costs. The study's findings provide insights for exploring sustainable BECCS pathway in Saudi Arabia.

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