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DEEP DECARBONIZATION: BECCS (P PATRIZIO AND N MAC DOWELL, SECTION EDITORS)

Decarbonising Industry via BECCS: Promising Sectors, Challenges, and Techno-economic Limits of Negative Emissions

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Abstract

Purpose of Review This paper reviews recent literature on the combined use of bioenergy with carbon capture and storage (BECCS) in the industries of steel, cement, paper, ethanol, and chemicals, focusing on estimates of potential costs and the possibility of achieving "negative emissions".

Recent Findings Bioethanol is seen as a potential near-term source of negative emissions, with CO_2 transport as the main cost limitation. The paper industry is a current source of biogenic CO_2, but complex CO_2 capture configurations raise costs and limit BECCS potential. Remuneration for stored biogenic CO_2 is needed to incentivise BECCS in these sectors. BECCS could also be used for carbon–neutral production of steel, cement, and chemicals, but these will likely require substantial incentives to become cost-competitive. While negative emissions may be possible from all industries considered, the overall CO_2 balance is highly sensitive to biomass supply chains. Furthermore, the resource intensity of biomass cultivation and energy production for CO_2 capture risks burden-shifting to other environmental impacts.

Summary Research on BECCS-in-industry is limited but growing, and estimates of costs and environmental impacts vary widely. While negative emissions are possible, transparent presentation of assumptions, system boundaries, and results is needed to increase comparability. In particular, the mixing of avoided emissions and physical storage of atmospheric CO_2 creates confusion of whether physical negative emissions occur. More attention is needed to the geographic context of BECCS-in-industry outside of Europe, the USA, and Brazil, taking into account local biomass supply chains and CO_2 storage siting, and minimise burden-shifting.

Keywords BECCS · Negative emissions · Steel · Cement · Ethanol · Paper · CO_2 capture

Introduction

We emitted 59 billion tonnes (CO_2eq) of greenhouse gases in 2019 [1], yet limiting catastrophic climate change requires global emissions to be net-zero within the next few decades. Results from integrated assessment models (IAMs) indicate that, beyond rapidly reducing emissions, this transition will require permanently removing greenhouse gases (GHGs) from the atmosphere, or "negative emissions", to compensate for residual or historic emissions [2]. One of the most studied potential negative emission technologies is bioenergy with carbon capture and storage (BECCS). In a BECCS system, CO_2 is removed from the atmosphere via biomass, which is then combusted for energy. The resulting biogenic CO_2 is captured and permanently stored, such as in a geologic formation, and the biomass is regrown. BECCS can result in negative emissions—that is, a decrease in atmospheric CO_2—if, and only if, more biogenic CO_2 is permanently stored than CO_2 is emitted throughout the supply chains of biomass cultivation and use and of CO_2 capture and storage [3•].[1]

IAMs typically assume BECCS deployment in the power sector and/or for biofuel production [2, 4]. However, the

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[1] BECCS systems do not necessarily result in negative emissions. Thorough cradle-to-grave accounting of GHG emissions and removals is a critical step to determine whether net removal actually occurs.

Table 1 Overview of major CO_2-emitting industries and their current use of bioenergy and CO_2 capture [5, 6, 8, 9]

Industry	Direct CO_2 emissions (2019, global)	Status of biomass use	Status of CO_2 capture
Cement	2300 Mt fossil 30–80 Mt biogenic[1]	Commercial, with individual kilns firing up to 35–40% biomass, typically wastes [11]	Demonstration, up to 75 kt/year
Steel	2100 Mt fossil	Commercial partial replacement of coal with charcoal. Primarily used in small-scale production in Brazil	Demonstration for blast furnace steelmaking. Commercial for direct reduced iron steelmaking
Petrochemical refining	1400 Mt fossil	Early commercialisation for methanol (1 facility) and biomass-to-liquids from biowastes (multiple facilities under construction)	Commercial for methanol and coal-to-liquids, up to 100 kt/year
Paper	200 Mt fossil 700–800 Mt biogenic[2]	Commercial. Process is inherently biobased. Residues used for cogeneration of heat and electricity	Demonstration, 11 kt/year [16]
Ethanol	82 Mt biogenic[3]	Commercial. Process is inherently biobased, with maize and sugarcane as primary feedstocks. Sugarcane bagasse is used for cogeneration of heat and electricity. Early commercialisation of fermentation of cellulosic biomass	Commercial for capture of high-purity fermentation CO_2, including 1 Mt/year to dedicated storage

[1]Three to six percent of biogenic fuel mix [10, 11], assuming 0.8–1.1 t CO_2/GJ [12]

[2]For an approximate global production of 400 Mt pulp [13], assuming an average biogenic CO_2 intensity of 1.9 t CO_2/t pulp [14, 15]

[3]Stoichiometrically, 82 Mt CO_2 from the fermentation of 86 Mt of ethanol in 2019 [17]

industrial sector, responsible for 20% of global GHG emissions [1], including 8.5 Gt of CO_2/year [5], is a stronger candidate for near-term deployment. Currently, industry's bioenergy use is more than double that of power [6], and, so far, 95% of the CO_2 stored from large-scale CCS operations has been from industry [7]. Furthermore, industry is the expected source of many residual emissions in a net-zero society, as industry uses carbon as a feedstock, reducing agent, or other stoichiometric necessity, and while the use of bioenergy or CCS alone can significantly decrease CO_2 emissions, only in combination can they result in negative emissions.

In the past five years, 50 peer-reviewed papers[2] considered the combined use of biomass and CO_2 capture in the five largest CO_2-emitting industries: iron steel, cement, paper, platform chemicals, and transport fuels, whose CO_2 emissions and current status of biomass and CO_2 capture are summarised in Table 1.[3] The papers reviewed broadly fall into three categories:

1. Retrofitting CCS into existing biomass-based industries as an early opportunity for negative emissions, compensating for CO_2 emitted elsewhere in society.
2. Retrofitting BECCS into carbon-intensive heavy industry, compensating for CO_2 emitted during production.
3. Integrating CCS into novel biobased production pathways for carbon-based chemicals (e.g. fuels, olefins), compensating for CO_2 emitted during product use or disposal.

In this work, we review the proposed configurations and challenges for BECCS-in-industry reported in these papers. We then discuss estimated costs and environmental impacts, focusing on the potential of negative emissions via BECCS-in-industry.

CCS for Existing Biogenic Industries

Some industries already use biomass as a feedstock and emit biogenic CO_2 during production. Notably, the production of bioethanol and paper emit over 800 Mt of biogenic CO_2 per year, not including CO_2 embodied in products. As such, the addition of CCS to these industries may by itself be sufficient to result in negative emissions.

The most discussed industry in the recent literature is bioethanol, often highlighted as a "low-hanging fruit" for BECCS [18–20, 21•, 22–30]. As the CO_2 released from ethanol fermentation is nearly pure (> 98 vol% [27]), it could be prepared for transport and storage via compression alone. Currently, 1 Mt/year of ethanol fermentation CO_2 is injected into dedicated geologic storage in Illinois and three more CCS projects are under development [8].

[2] See supplementary information for search queries used and descriptions of all literature reviewed.

[3] While transport fuels are often assigned the energy sector, they are included here as manufactured energy storage products are distinct from the on-demand provision of energy. Due to space constraints, smaller industries, such as beverage manufacturing and ceramic and glass production, were excluded, as were industry-generic BECCS options, such as BECCS-hydrogen, BECCS-boilers, and CHP.

Bioethanol is typically produced from maize, sugarcane, or other starchy food crops. Alternatively, cellulosic biomass, such as grasses and coppice wood grown on less-arable land or agricultural wastes, can also be fermented. Currently, only a few ethanol distilleries produce cellulosic bioethanol, primarily from maize and sugarcane residues [31, 32]. However, several recent BECCS-in-ethanol studies envision dedicated facilities fermenting corn stover [33•, 34], switchgrass [33•, 34, 35], miscanthus [33•, 36], and wood [33•, 37•], with captured CO_2 sent to dedicated geologic storage.

Not all CO_2 from bioethanol production is as easy to capture as the high-purity CO_2 from fermentation. In Brazilian distilleries, sugarcane residues are combusted to cogenerate heat and electricity, producing up to 90% of total distillery CO_2 in dilute flue gas streams, the capture of which was explored by [19, 20, 21•, 26], all assuming post-combustion amine-based capture, whose energy demand was estimated to reduce distillery electricity exports by 50–75% [19, 20, 26].

Pulp and paper mills also cogenerate heat and electricity, and the biogenic CO_2 from the combustion of process wastes typically accounts for over 75% of on-site emissions [38, 39]. Flue gases are typically less than 20% CO_2 and distributed between several point sources [38, 40, 41, 42•, 43, 44]. Some studies estimated that energy demand of full CO_2 capture can switch paper mills from being net energy exporters to energy importers [43] or require supplemental fuel [42•, 45]. If only on-site energy is used, estimates of capturable CO_2 ranged from less than 30% in [42•, 44], to 90% (with an 80% reduction in electricity exports) in [45], for post-combustion amine-based capture. Two studies [39, 43] considered the integration of a calcium looping CO_2 capture unit[4] into the lime kiln[5] of a pulp mill, which could lower the net energy intensity of CO_2 capture.

Despite these challenges, BECCS-in-paper could be particularly significant in the USA, whose mills produce a quarter of the world's paper [13], with biogenic CO_2 accounting for over 115 Mt CO_2/year [42•] and in countries like Sweden, where pulp and paper mills account for over 60% (ca. 20 Mt CO_2/year) of large-scale CO_2 emitters [40, 46].

Retrofitting BECCS Into Carbon-Intensive Industries

BECCS could also be used in industries that are large CO_2 emitters but are not currently major biomass consumers, such as steel and cement, which together emitted 5.0 Gt CO_2 in 2018 [6]. While low-carbon production technologies are under development, they will not be available on a large scale for a few decades [6]. Retrofitting BECCS could allow existing steel mills and cement plants to continue operating at or near carbon neutrality.

Globally, over 70% of steel is produced in blast furnace mills [47] that use high-grade coal as a fuel and reducing agent, emitting around 2–3 t CO_2/t steel [48•, 49, 50] from the blast furnace and associated energy production. CO_2 capture in steel has been considered by a number of studies (e.g. [27, 51–53]) and demonstration facilities [8], and the use of charcoal as a partial coal replacement is common in Brazil [6, 54]. However, as blast furnaces rely on the mechanical properties of coal as a process control mechanism, biomass replacement is likely limited to around 30% of coal use in current large blast furnaces [49, 55].

Only five studies of the fifty studies reviewed considered BECCS for blast furnace steelmaking [48•, 50, 56, 57, 58•]. They estimated that partial charcoal use with full CCS could reduce steel mill emissions over 80% but was unlikely to compensate for emissions from charcoal production or CO_2 transport and storage to allow for negative emissions. Still, BECCS deployment at 30 EU steel mills could mitigate up to 200 Mt CO_2 per year [56]. However, this requires capturing CO_2 from most point sources within the mill. If capture is limited to the largest CO_2 source, the blast furnace itself, BECCS has the potential to reduce direct CO_2 emissions by approximately 50% [50, 56].

Other steelmaking methods are more amenable to BECCS. Direct reduction of iron (DRI), which accounts for 7% of global steelmaking [47], typically uses natural gas or gasified coal to reduce iron, and CO_2 capture can be integrated into reducing gas preparation. This is already the case at Emirates Steel in Abu Dhabi, where 0.8 Mt CO_2/year is captured for use in enhanced oil recovery (EOR) [8]. Combined with CCS, a biogenic reducing gas [59, 60] could theoretically allow for "carbon negative" DRI steel [48•, 50]. Similarly, BECCS in smelt reduction steelmaking routes, such as Corex and the under-development HIsarna process, which are also more fuel-flexible than blast furnace steelmaking, could also allow for carbon–neutral or -negative steel [50, 58•].

Like steel, cement production is also CO_2 intensive. At a cement plant, roughly 60% of the CO_2 emitted results from the calcination of limestone. This fossil CO_2 is stoichiometrically unavoidable and BECCS may be the only path to CO_2-neutral cement production [61, 62•].

CO_2 capture at cement plants currently operates on scales of 50–75 kt CO_2/year [6], and demonstration plants capturing 400–600 kt CO_2/year are under development [8]. Furthermore, cement kilns already partially co-fire biomass or biogenic wastes. An estimated 3–6% of global kiln fuel is

[4] Calcium looping CO_2 capture works by cycling carbonation ($CaO+CO_2 \rightarrow CaCO_3$+heat) and calcination ($CaCO_3$+heat$\rightarrow CaO+CO_2$) to first remove CO_2 from a gas stream, and then, in an oxygen environment, release a pure stream of CO_2 for capture.

[5] Used to regenerate paper-making process chemicals.

Table 2 CO_2 abatement cost estimates of BECCS-in-industry, compared to cost estimates for CCS-in-industry, $€_{2020}$/t CO_2.[1] Values in parentheses refer to cost of CO_2 capture only

	BECCS, this review (CO_2 capture cost only)		BECCS [75]	CCS only [76]	CCS only [58•]	CCS only [51]	CCS only [27]	CCS only [77]
Ethanol, fermentation CO_2 only	22–388 (11–31)	[20, 21•, 22–24, 29, 78] ([18, 21•, 27, 28])	20–180	–	–	–	13	–
Ethanol, fermentation and cogeneration CO_2	47–120 (13–115)	[20, 21•, 34, 78] ([21•, 34, 78])	–	–	–	–	–	–
Paper	82–95 (41–110)	[40, 58•] ([38, 40, 41, 42•, 43, 46])	20–70	55–87	26–91	56–58	–	–
Steel	61–200	[48•, 56, 58•]	–	62–69	26–193	10–118	30–34	35–60
Cement	55–88	[58•]	–	55–110	10–132	17–163	25–40	30–65
Drop-in transport fuels	68	[65]	20–40	–	–	–	–	–
Olefins and mixed chemicals	13–102	[58•, 74]	–	153–200	23–230	28–247	96	35

[1]Costs have been standardised to $€_{2020}$ by first adjusting for inflation in the source currency and then converting to Euros. If no basis-year was provided, the annual average for the year preceding the publication year was assumed

biogenic, with individual kilns co-firing up to 37% biomass [10, 11].

Despite this, only four studies in the past 5 years explicitly consider BECCS-in-cement [58•, 61, 62•, 63]. Tanzer et al. concluded that CO_2-negative cement and concrete are plausible via fully charcoal-fired cement kiln with post-combustion CCS [62•]. Two other studies concluded that partial biomass use with CCS can reduce emissions over 70% [58•, 61].

BECCS-Integrated Biochemical Production

The chemical sector emitted 1.4 Gt CO_2 in 2018 from direct energy use and process emissions [6], but half of its carbon inputs leaves as products, such as fuels, fertilisers, and olefins, which then release CO_2 during use or disposal. Both CCS integration and biobased production are under development to reduce the net CO_2 of chemical production [6], and some biobased production pathways also integrate CCS into their designs, aiming for carbon–neutral [58•, 64•] or carbon-negative [65–71] production.

The majority of these studies focus on biomass gasification technologies [58•, 64•, 66–68, 72–74]. Biomass gasification breaks the biomass into its component parts (H_2, H_2O, CO, CO_2), followed by catalytic processes to reassemble these components into the desired hydrocarbons, such as diesel and kerosene [73] or methanol and olefins [67–69, 73]. As CO_2 removal is typically a necessary step before catalytic reassembly, capturing the CO_2 for storage represents a relatively minor addition to the proposed process. Two studies did not consider gasification, but used hydrogen separated from biogenic process gases, requiring CO_2 removal [65, 70]. Most of these technologies are generally at an early stage of development, though currently two plants gasify biomass into methanol, and fossil-based CO_2 capture is commercialised in methanol production [6].

Costs of BECCS-in-Industry

Cost estimates from BECCS literature are difficult to compare, as they embody widely varying assumptions regarding technical performance, technology maturity, system boundaries, financing, commodity pricing, coproduct sales, and carbon taxation.[6] Table 2 summarises the abatement costs of BECCS-in-industry from the reviewed studies, in comparison with literature on CCS alone. When possible, costs of CO_2 capture were separated, but cost estimates were often not broken down into their components. Only one study [58•] estimated costs across multiple industries. Their estimates for BECCS integration into steel, cement, transport fuels, and pulp ranged between 50 and 90$€_{2020}$/t CO_2 avoided. However, underlining the difficulty of direct comparison, their CO_2 abated includes emissions from

[6] A breakdown of what each study's cost estimates include is available in the ESI.

upstream fossil and bioenergy supply chains, unlike most other studies, but did not include distance-specific transport costs.

The wide uncertainty in cost estimates is also a function of sparsity of BECCS-in-industry studies as well as the need to incorporate multiple system changes—bioenergy use, CO_2 capture, and CO_2 transport and storage—whose individual uncertainty is compounded by their interaction. Nevertheless, we can discuss the influential cost components seen in the recent literature.

Biomass Price

Wood-based biomass was used in 30 of the 41 studies that were not about sugarcane or maize ethanol. Prices ranged from 0 to 8.6€$_{2020}$/GJ for forestry and mill residues [30, 42•, 56, 65, 66, 72], 1.9 to 7.5€$_{2020}$/GJ for wood chips and stem wood [30, 38, 43, 59, 64•, 67, 70, 73], and 7.2 to 15.4€$_{2020}$/GJ for charcoal and torrefied wood [48•, 58•, 74, 79]. Currently, global export prices of wood chips are 4–8€$_{2020}$/GJ [13], and biomass pellet prices in the USA and EU are 10–22€$_{2020}$/GJ [80, 81]. As biomass demand increases, however, prices of sustainably produced biomass are likely to increase.

CO_2 Capture

Capture costs typically include the cost of equipment, labour, chemicals, and energy to capture and compress CO_2 so that it is transport-ready. Capture costs ranged from 3 to 30€$_{2020}$/t CO_2 [18, 22–24, 27–29, 34] for near-pure fermentation CO_2 and 42 to 110€$_{2020}$/t CO_2 for complex configurations that use amine-based solvents to capture CO_2 from multiple dilute streams, such as in paper mills [40].

CO_2 Transport

In papers that assumed fixed CO_2 transport costs, those values ranged from 5 to 17€$_{2020}$/t CO_2 [38, 40, 43, 58•, 64•, 74, 78]. In studies that calculated transport costs on volume and distance, the range was much wider: 5–380€$_{2020}$/t CO_2 [20, 21•, 22–24, 29, 34, 42•, 46, 56], varyingly accounting for topography, existing land use, compression boosting, seasonality of biomass, shared pipelines, or multi-modal transport. However, in only four of these studies, all on Brazilian bioethanol production, was it possible to decompose costs by distance, with average costs typically between 0.2 and 0.4€$_{2020}$/tkm CO_2, with higher costs typically the result of low volumes transported over long distances [20, 21•, 22, 23]. The use of intermediate pipeline hubs [21•, 22, 23], short-distance truck transport for low-volume distilleries [22], and shared capacity with CO_2 captured from fossil sources [21•] all led to lower transport cost estimates.

Tax on Fossil Carbon

Beyond absolute costs, an important factor is the cost of BECCS relative to the cost of fossil-based production. In several studies [46, 61, 73, 82, 83], an estimated 70€$_{2020}$/t CO_2 tax on fossil emissions was necessary for BECCS processes to be considered cost-competitive with fossil ones. Alternatively, several BECCS studies on drop-in biofuels [64•, 66, 70, 72] estimated the crude oil price necessary for the biofuels to break even, typically between 120 and 180€$_{2020}$/bbl.

Credits for Stored (Biogenic) CO_2

Existing biobased industries may not emit enough fossil CO_2 to be financially impacted by a fossil carbon tax. Therefore, several studies considered compensation for stored CO_2. One proposal is tradable "negative emission credits" [34, 38, 43] for stored biogenic CO_2, which can be sold to CO_2 emitters as offsets on emission trading networks. Another option is subsidies for stored CO_2, such as the 45Q scheme in the USA, which provides up to $50/t CO_2 stored, regardless of CO_2 origin. Sanchez et al. [28] estimated that a $50/t CO_2 credit would be sufficient to incentivise the storage of 20–25 Mt/year of CO_2 from bioethanol distilleries, but for most distilleries an additional $20–40/t CO_2 credit would be necessary to cover transport costs [29, 42•]. Higher credits would be needed to incentivise many US paper mills as $50/t CO_2 may be insufficient to cover even the costs of CO_2 capture alone [42•].

Achieving Negative Emissions via BECCS-in-Industry

Thirty-eight of the BECCS-in-industry studies claimed their system could result in negative emissions, but few provided sufficient detail to estimate if negative emissions occur. As negative emissions are intended to physically decrease GHGs in the atmosphere [2], they require that, as stated in [3•]:

1. *Physical greenhouse gases are removed from the atmosphere.*
2. *The removed gases are stored out of the atmosphere in a manner intended to be permanent.*
3. *Upstream and downstream greenhouse gas emissions associated with the removal and storage process, such as biomass origin, energy use, gas fate, and co-product fate, are comprehensively estimated and included in the emission balance.*

4. *The total quantity of atmospheric greenhouse gases removed and permanently stored is greater than the total quantity of greenhouse gases emitted to the atmosphere*.

Estimating negative emissions requires scrutinising the complete systems of biomass production and use and carbon capture and storage. Only 9 of the BECCS-in-industry papers performed cradle-to-grave life cycle assessment [3•, 34, 36, 37•, 62•, 63, 64•, 66, 70], though a further 9 considered a "cradle-to-gate" system, including impacts of upstream biomass and energy production, but not end of product life or CO_2 transport and storage [33•, 35, 48•, 58•, 65, 67, 68, 74, 78].

Many of the BECCS-in-industry studies that claimed to result in negative emissions added together estimates of net permanent storage of atmospheric CO_2 with estimates of avoided emissions from BECCS products replacing fossil-based production [33•, 34, 35, 58•, 63, 64•, 66, 70, 71, 74]. However, avoided emissions refer to an assumed relative change in emissions from one system to another, while negative emissions are an absolute reduction in CO_2 in the atmosphere via the physical removal and permanent storage of atmospheric CO_2. Caution is needed when interpreting such negative numbers to determine whether they actually represent net physical removal of atmospheric CO_2.

Estimates of GHG emissions from biomass supply chains ranged from 32 to 173 kg CO_2eq/t biomass and varied with biomass type, cultivation technique, transport method and distance, and greenhouse gases considered [3•, 19, 37•, 48•, 58•, 62•, 64•, 66, 67, 70, 74], with the lowest emissions for residual biomass and the highest for charcoal or torrefied pellets. Biomass system emissions are also challenging to estimate due to the variability of land use change and change in soil carbon stocks, which few studies included. In Field et al., converting forest to switchgrass production for cellulosic bioethanol released CO_2 both from the destruction of forest and loss of soil carbon, resulting in higher CO_2 emissions than uninterrupted forest growth [35]. However, in the BECCS system, the estimated biogenic CO_2 stored via CCS was more than double the total carbon storage of continued forest growth, even when considering indirect land use change. In Gelfand et al., replanting marginal land with native grasses for use in BECCS ethanol or electricity production was estimated to result in net carbon storage from both CCS and from increased soil carbon stocks [33•]. In contrast, in Fan and Friedmann, the inclusion of land use CO_2 emissions nearly negated the original estimated decarbonisation of BECCS-in-steel [48•].

With regard to downstream impacts, in the studies that separated emissions from CO_2 transport and storage [3•, 62•, 66, 70], estimates ranged from 5 to 20 kg/t CO_2 for pipeline transport to dedicated geologic storage and were not a major contributor to total emissions. However, not all studies assumed that the CO_2 was sent to dedicated geologic storage. Several studies assumed that the CO_2 would be used in enhanced oil recovery [19, 21•, 22, 26, 30, 64•]. While EOR does lead to geologic storage of injected CO_2, it also leads to CO_2 emissions from the extracted oil, which was not considered in any of the studies. While it is possible for EOR systems to store more CO_2 than is emitted by the recovered oil, if the system is designed to maximise permanent CO_2 injection [84], that is not typically the case [85–87], and CO_2 emitted by recovered CO_2 would mute the potential "negative emissions" from BECCS systems.

Geologic storage of CO_2 is likely to store CO_2 for millennia [88] and can be considered effectively permanent. Carbon storage in concrete [62•] or buried biochar [79] may also result in long-term storage, though biochar carbon may be partially re-released over time, and carbon storage in concrete is dependent on how the concrete is disposed. In contrast, carbon in short-lived products such as urea, paper products, or olefins, as considered in [44, 59, 67–69], will re-release CO_2 during use or disposal, and thus, carbon in these products should not be counted towards negative emissions.

Timing of CO_2 storage and emissions is also relevant to upstream biomass cultivation. Biomass for bioenergy is typically combusted shortly after harvest, and CO_2 is then reabsorbed by replacement biomass, allowing CO_2 from biomass combustion to be part of the short-term carbon cycle. However, while biomass regrowth can be 1–2 years for grasses or 5–10 years for coppiced or fast-growing tree species such as eucalyptus or poplar, common boreal species such as Scots pine or Norwegian spruce take 50–100 years to mature, and CO_2 emitted from their combustion contributes to global warming for decades [89, 90]. In Tanzer et al.'s models of BECCS-in-concrete, the BECCS systems resulted in higher atmospheric CO_2 than a fossil-based CCS system for up to a third of the biomass's rotation period and carbon-negativity was not reached until the after the biomass had been regrown (and CO_2 was reabsorbed by concrete), 50 years after the concrete was produced [62•].

Beyond global warming, in the four studies that look at other environmental impacts [25, 36, 37•, 63], the BECCS system resulted in higher acidification, human toxicity, ecosystem toxicity, water depletion, eutrophication, and ozone depletion compared to fossil-based production. These higher impacts resulted from the land and water use of bioenergy production, particulate matter and NO_X formation of biomass combustion, and the energy use of CO_2 capture. However, these studies only considered variations in the industrial production system; options for decreasing burden-shifting in the bioenergy or CCS systems were not considered.

Conclusions

As both bioenergy and CCS are more developed in industry, industry is a likely candidate for near-term BECCS implementation. In particular, bioethanol is a potential early source of negative emissions, as fermentation CO_2 can be cheaply captured. However, when bioethanol plants are far from geologic storage, transport network design is of crucial concern to costs. Pulp and paper mills represent the other major existing biogenic industry, but CO_2 capture is likely to be costly due to the complex configuration to capture multiple point-sources of dilute CO_2. BECCS could also be retrofitted into the carbon-intensive production of steel or cement while low-carbon production technologies are developed. CCS integration into novel biobased chemical production pathways also allows for carbon neutral production of short-lived carbon-based products, such as olefins or transport fuels.

Many uncertainties remain about BECCS-in-industry, which is predominantly a prospective technology. However, interest is growing, with 16 studies published in 2020 alone, the same as in 2016–2018. From the studies available, it is clear that BECCS-based production will require fossil carbon taxes as well as incentives for biogenic stored CO_2 to be cost-competitive on the global market. Furthermore, while BECCS can reduce GHG emissions, achieving negative emissions is sensitive to specific system configurations and assumptions, and requires thorough and accurate assessment of emissions across the biomass and CCS supply chains.

While ongoing research on separate CCS and bioenergy use in industry and on BECCS-in-power will benefit BECCS-in-industry, we emphasise the following research needs for BECCS-in-industry:

- Life cycle assessment of BECCS-in-industry configurations outside of Europe and the Americas, and particularly in centres of industrial production in China and India, that take into account local availability of biomass and CO_2 storage.
- Evaluation of the logistical impacts of retrofitting both combined biomass and CO_2 capture at industrial facilities, particularly on space demand, heat recovery, and siting relative to both biomass and CO_2 storage.
- System designs that incorporate optimisation of both biomass production and CCS supply chains to minimise environmental burden-shifting.
- Interactions and optimisation between BECCS and other decarbonisation options available to industry, taking into account the timing of investment decisions, technological change, and received benefit.
- The incorporation of BECCS-in-industry into IAMs, using industry and geography-specific parameters and limitations.

As estimates of costs and environmental impacts of BECCS systems are highly sensitive to studies' assumptions, it is crucial that these assumptions as well as system boundaries are clearly documented. BECCS-in-industry studies should ensure that they account for all carbon in their system and refrain from estimating negative emissions without a cradle-to-grave life cycle assessment. Avoided CO_2 should be accounted for separately from CO_2 that is physically and permanently removed the atmosphere. Furthermore, CO_2 avoidance cost estimates explicitly state both what costs and CO_2 emissions are included, and provide clearly decomposed costs of CO_2 capture, transport, and storage to facilitate comparisons between studies. Finally, environmental impacts beyond GHG emissions need more attention, taking into account the local context of biomass cultivation and CO_2 fate.

BECCS is not a substitute for immediate and rapid decarbonisation of industry via increased efficiency, novel production methods, and, above all, reduced consumption and waste. Rather, the judicious use of BECCS can allow for limited continued use of fossil carbon or limited removal of historical CO_2 from the atmosphere. With or without BECCS, the transition to a "net-zero" society requires confronting the hard limits of our resource-constrained world.

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Compliance with Ethical Standards

Conflict of Interest The authors declare no competing interests.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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• Of importance

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