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Assessing the Role of Bioenergy with Carbon Capture and Storage in Achieving Negative Emissions for Climate Change Mitigation

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Abstract

Bioenergy with Carbon Capture and Storage (BECCS) is frequently cited in climate modelling as a critical negative emissions technology essential for achieving ambitious targets like limiting global warming to 1.5°C. By focusing on two main archetypes—large-scale power generation and industrial biofuel production—this research offers a focused assessment of the BECCS environment. The core of this analysis is built upon in-depth case studies of two pioneering but controversial projects: the Drax Power Station in the UK, a large-scale electricity generation facility, and the Archer Daniels Midland ethanol plant in the US, an industrial application. To disrupt Northern-centric climate narratives, the analysis concurrently scrutinizes Brazil's sugarcane ethanol sector. Operating as a uniquely scaled Global South archetype, the Brazilian model demonstrates how the immense thermodynamic advantages of high-purity carbon capture are frequently undermined by severe socio-ecological friction. This creates a 'green paradox' in which the pursuit of atmospheric carbon removal risks triggering localized ecological degradation and land-use conflicts. Through these real-world examples, the paper highlights significant challenges that temper optimistic projections. Key issues interrogated include the contested sustainability of biomass supply chains, particularly the reliance on imported wood pellets, which raises concerns about deforestation, carbon debt, and lifecycle emissions. The analysis reveals that full carbon accounting for BECCS is far from straightforward, often failing to adequately capture

emissions from land-use change and logistics, thereby questioning its net-negative credentials. Furthermore, the economic viability of BECCS is shown to be heavily reliant on substantial and long-term public subsidies, raising questions about its cost-effectiveness compared to other climate solutions. Finally, the paper delves into the profound environmental and social risks inherent in large-scale BECCS deployment, including intense land-use competition threatening biodiversity and global food security, and the unresolved safety and permanence concerns of long-term geological CO2 storage. The paper concludes that while BECCS may hold a limited niche role in energy sector decarbonisation, its widespread deployment is fraught with peril. A cautious path forward is essential, one that is contingent upon the enforcement of stringent sustainability criteria, the development of robust and equitable policy frameworks, and an unwavering focus on prioritizing direct emission reductions at the source.

Keywords: BECCS, negative emissions, climate change mitigation, carbon capture and storage, biomass, case studies, sustainability, Drax, Archer Daniels Midland.

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5. All data generated or analysed during this study are included in this published article.

1. Introduction

In the global effort to mitigate the escalating climate crisis, the focus of scientific and policy discourse has undergone a critical expansion.[1] For decades, the primary objective of climate policies has been the reduction of greenhouse gas emissions through transitioning to renewable energy, enhancing energy efficiency, and reforming industrial processes. However, a stark realization, heavily underscored by successive reports from the Intergovernmental Panel on Climate Change (IPCC), has taken hold: reductions alone may no longer be sufficient to prevent catastrophic levels of global warming.[2] The sheer volume of anthropogenic carbon dioxide already accumulated in the atmosphere, coupled with the persistent difficulty of decarbonizing certain

[1] L M Gurtner and S Moser, 'The where, how, and who of mitigating climate change: A targeted research agenda for psychology' (2024) 94 Journal of Environmental Psychology 102250 https://doi.org/10.1016/j.jenvp.2024.102250 accessed 21 October 2025.

[2] Intergovernmental Panel on Climate Change (IPCC), 'Climate change widespread, rapid, and intensifying – IPCC' (Press Release, 9 August 2021) https://www.ipcc.ch/2021/08/09/ar6-wg1-20210809-pr/ accessed 21 October 2025.

sectors, has created a formidable challenge. This has propelled a paradigm shift towards a dual strategy that not only curtails future emissions but also actively removes existing Carbon Dioxide (CO2) from the atmosphere. This has brought a suite of negative emission technologies (NETs) from the periphery to the forefront of climate policy discussions.[3]

Among the diverse and developing portfolio of NETs, Bioenergy with Carbon Capture and Storage (BECCS) has emerged as arguably the most prominent and certainly one of the most contentious options.[4] At its core, BECCS is a hybrid technology that integrates the production of energy from biomass—organic matter derived from plants and other living organisms—with the industrial process of capturing the resulting carbon dioxide emissions and sequestering them in long-term geological storage.[5] The fundamental premise hinges on a simple carbon cycle loop: as biomass grows, it absorbs atmospheric carbon dioxide through photosynthesis; when this biomass is converted into energy (through combustion, gasification, or fermentation), the captured carbon dioxide is prevented from re-entering the atmosphere. If the entire process, from cultivation to storage, is managed sustainably, the result is a net removal of carbon dioxide, creating "negative emissions." Proponents, particularly within the integrated assessment modeling community, champion BECCS as a critical, if not indispensable, tool for achieving ambitious climate targets.[6] It features heavily in pathways designed to limit global warming to 1.5°C above pre-industrial levels, a goal enshrined in the Paris Agreement,[7] which many scientific models suggest is now unattainable without significant, large-scale carbon dioxide removal.[8]

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[3] National Academies of Sciences, Engineering, and Medicine, Negative Emissions Technologies and Reliable Sequestration: A Research Agenda (National Academies Press, 24 October 2018).

[4] V Stavrakas, N-A Spyridaki and A Flamos, 'Striving towards the Deployment of Bio-Energy with Carbon Capture and Storage (BECCS): A Review of Research Priorities and Assessment Needs' (2018) 10 Sustainability 2206 https://doi.org/10.3390/su10072206 accessed 21 October 2025.

[5] M Bui, M Fajardy and N Mac Dowell, 'Bio-energy with carbon capture and storage (BECCS): Opportunities for performance improvement' (2018) 213 Fuel 164–175 https://doi.org/10.1016/j.fuel.2017.10.100 accessed 21 October 2025.

[6] M Bui, M Fajardy and N Mac Dowell, 'Bio-energy with carbon capture and storage (BECCS): Opportunities for performance improvement' (2018) 213 Fuel 164–175 https://doi.org/10.1016/j.fuel.2017.10.100 accessed 21 October 2025.

[7] Paris Agreement (concluded at Paris, 12 December 2015 and entered into force on 4 November 2015, 54113 UNTS 79) ('Paris Agreement'), art 2.

[8] Intergovernmental Panel on Climate Change (IPCC), Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the IPCC (Cambridge University Press 2021) https://www.ipcc.ch/report/ar6/wg1/ accessed 22 October 2025.

While existing literature on BECCS is often bifurcated, focusing either on isolated engineering feasibility or abstract climate modeling, this paper addresses a critical gap by integrating geopolitical North-South tensions into the technical debate. The novelty of this research lies in its 'trans-hemispheric' critique, which challenges the assumption that Global North technologies can be seamlessly exported to the Global South without accounting for local socio-ecological friction. By comparing the mature, high-purity supply chains of Brazil's sugarcane sector with the subsidy-reliant power-generation models of the UK, this study provides a holistic framework for assessing the 'social license' of negative emissions—a factor largely overlooked in techno-centric literature.[9]

This article advances a risk-relocation framework for evaluating Bioenergy with Carbon Capture and Storage. Rather than treating BECCS as a unitary mitigation instrument, the analysis demonstrates that decarbonisation risks are displaced across the value chain depending on regulatory architecture and political economy. In power-generation pathways, risk is shifted upstream to biomass sourcing and accounting practices; in industrial applications, risk migrates downstream to storage integrity and long-term liability; and in Global South deployment models, particularly Brazil, risk is reallocated laterally through indirect land-use change and agrarian concentration.[10] These challenges dominant techno-economic assessments by showing that BECCS does not eliminate systemic risk but redistributes it spatially, temporally, and socially—often beyond the jurisdictional horizon of the regulatory systems that authorise its deployment.

The promise of a technology that can simultaneously generate energy and clean the atmosphere is shadowed by profound concerns regarding its economic viability, true environmental sustainability, and social license to operate.[11] The immense capital investment required, the energy penalty associated with the carbon capture process, and reliance on undeveloped carbon markets or substantial government subsidies cast serious doubts on its financial feasibility. Environmentally, sourcing biomass at the scale required by climate models raises alarms about

[9] For a critique of the techno-centric bias in carbon removal see, e.g., Holly Jean Buck, After Geoengineering: Next Steps to Restoring the Earth (Verso 2019) 45-50.

[10] Alexandre C Köberle, 'The Value of BECCS in Integrated Assessment Models: A Review' (2019) 6(4) Current Sustainable/Renewable Energy Reports 107–115 <https://doi.org/10.1007/s40518-019-00142-3> accessed 8 April 2026

[11] V Stavrakas, N-A Spyridaki and A Flamos, 'Striving towards the Deployment of Bio-Energy with Carbon Capture and Storage (BECCS): A Review of Research Priorities and Assessment Needs' (2018) 10 Sustainability 2206 https://doi.org/10.3390/su10072206 accessed 21 October 2025.

land-use competition, potential deforestation, biodiversity loss, and impacts on soil and water resources.[12] Socially, the spectre of a "food versus fuel" conflict, land rights issues, and the risks associated with CO2 transport and storage pipelines create a landscape of potential opposition and injustice. Therefore, a thorough and critical examination of BECCS, grounded in the tangible lessons from real-world case studies, is essential to move beyond abstract modelling and ascertain its true potential and pitfalls in the urgent quest for climate stabilization.

This paper provides a comprehensive, multi-faceted analysis of the role and importance of BECCS in addressing climate change, with a particular focus on in-depth case studies of pioneering and often controversial projects. To ground the debate in reality, it first explores the technological underpinnings of various BECCS pathways, distinguishing between approaches such as post-combustion capture from power plants, pre-combustion capture from gasification facilities, and the capture of high-purity CO2 streams from biofuel production. Following this technical overview, the paper investigates complex economic models that both support and question its large-scale deployment, examining the roles of carbon pricing, subsidies, and investment risk.

1.1 Research Methodology

This paper employs a Qualitative Comparative Analysis (QCA) framework, utilizing two illustrative archetypes, Drax (Power-BECCS) and ADM (Industrial-BECCS), to serve as representative models for the primary technological pathways. Rather than an exhaustive global survey, this selection allows for a deep dive into the distinct regulatory and logistical challenges inherent in different energy systems.[13] The methodology involves typological categorization (distinguishing between 'Power-BECCS' and 'Industrial-BECCS') and geopolitical archetyping (contrasting 'Global North' policy environments with 'Global South' infrastructure models). Evidence is drawn from a triangulation of 2024–2026 IPCC reports, corporate sustainability disclosures, and recent legislative frameworks, such as Brazil's RenovaBio. The comparison is operationalised through the paper's risk-relocation framework, tracing where decarbonisation burdens concentrate across (i) upstream biomass sourcing and carbon accounting, (ii) downstream

[12] L M Gurtner and S Moser, 'The where, how, and who of mitigating climate change: A targeted research agenda for psychology' (2024) 94 Journal of Environmental Psychology 102250https://doi.org/10.1016/j.jenvp.2024.102250 accessed 21 October 2025.

[13] On the utility of the multi-case study approach in policy analysis see Robert K Yin, Case Study Research and Applications: Design and Methods (6th edn, SAGE 2018) 78-82.

storage integrity and long-term liability, and (iii) lateral land-use displacement dynamics in Global South deployment models.

The analysis focuses on the experiences of two landmark projects: the Drax Power Station in the United Kingdom, representing the world's largest and most ambitious attempt to convert a major power plant to BECCS,[14] and the Archer Daniels Midland ethanol facility in Decatur, Illinois, one of the earliest large-scale industrial BECCS applications.[15] By scrutinizing their operational histories, claimed successes, and documented failures, this paper will illuminate the practical challenges of supply chain management, capture efficiency, public perception, and geological storage integrity. Furthermore, it will critically evaluate the significant and often downplayed environmental and social considerations—including land-use competition, biodiversity impacts, freshwater consumption, and food security concerns—that are intrinsically linked to the widespread adoption of this technology.[16]

Broadening this geographic scope, this paper positions Brazil as an indispensable counterweight to Anglo-American case studies. As the host of a massive, state-incubated sugarcane ethanol industry, Brazil offers a radically different archetype: one that bypasses the capture-cost barriers of Northern facilities but threatens to weaponize decarbonization mandates against localized food sovereignty and biodiversity.[17] Ultimately, this paper argues that while BECCS holds theoretically significant potential for carbon dioxide removal, its responsible and effective deployment is contingent upon a nuanced and often sceptical understanding of its multifaceted challenges.[18] It concludes that without the establishment of exceptionally robust, transparent, and equitable policy

[14] Drax Group, "Analysis: Development of BECCS at Drax Power Station projected to save UK £15bn and offset carbon emissions equivalent to all departing flights from Heathrow" (Press release, 16 January 2024) https://www.drax.com/press_release/analysis-development-of-beccs-at-drax-power-station-projected-to-save-uk-15bn-and-offset-carbon-emissions-equivalent-to-all-departing-flights-from-heathrow/ accessed 22 October 2025.

[15] IEA Bioenergy, Deployment of BECCUS value chains in the United States: A case study of sequestering CO_2 from ethanol production (March 2023) https://www.ieabioenergy.com/wp-content/uploads/2023/03/BECCUS-1.0_US-Case-Study_final_update.pdf accessed 22 October 2025.

[16] S V Hanssen et al, 'Global implications of crop-based bioenergy with carbon capture and storage for terrestrial vertebrate biodiversity' (2022) 14 GCB Bioenergy 307–321 https://doi.org/10.1111/gcbb.12911 accessed 25 October 2025.

[17] F B de Mello and others, 'Bioenergy and carbon capture in Brazil: A critical review of the RenovaBio program' (2022) 160 Renewable and Sustainable Energy Reviews 112318.

[18] V Stavrakas, N-A Spyridaki and A Flamos, 'Striving towards the Deployment of Bio-Energy with Carbon Capture and Storage (BECCS): A Review of Research Priorities and Assessment Needs' (2018) 10 Sustainability 2206 https://doi.org/10.3390/su10072206 accessed 21 October 2025.

and governance frameworks, BECCS risks becoming a maladaptive strategy—a supposed solution that could exacerbate other environmental and social crises in the name of climate mitigation.[19]

2. The Technological Landscape of BECCS

Bioenergy with Carbon Capture and Storage is not a monolithic technology but rather a suite of approaches that combine bioenergy conversion with carbon capture processes. The fundamental principle of BECCS is to leverage photosynthesis, a natural process that captures atmospheric carbon dioxide, to create a carbon-negative energy source.[20] As biomass grows, it absorbs CO2 from the atmosphere; when this biomass is used for energy, the resulting CO2 emissions are captured and prevented from re-entering the atmosphere, leading to a net removal of CO2. The specific technological pathways for BECCS can be broadly categorized based on the bioenergy conversion process and the carbon capture method employed.

The most common bioenergy conversion processes in the context of BECCS are combustion, gasification, and fermentation.[21] Direct combustion, the most mature of these technologies, involves burning biomass in a boiler to produce steam, which then drives a turbine to generate electricity. Post-combustion capture technologies are typically applied in this context, where CO2 is separated from the flue gases after the biomass has been burned. While direct combustion is the 'road of least resistance' for large-scale deployment since it can be retrofitted into existing coal[22] or dedicated biomass power plants, it frequently has a high 'parasitic load.' The energy penalty required to power the capture equipment can significantly diminish the facility's net energy output. Gasification offers a more flexible approach, converting biomass into synthesis gas (syngas), a

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[19] L M Gurtner and S Moser, 'The where, how, and who of mitigating climate change: A targeted research agenda for psychology' (2024) 94 Journal of Environmental Psychology 102250 https://doi.org/10.1016/j.jenvp.2024.102250 accessed 21 October 2025.

[20] M Bui, M Fajardy and N Mac Dowell, 'Bio-energy with carbon capture and storage (BECCS): Opportunities for performance improvement' (2018) 213 Fuel 164–175 https://doi.org/10.1016/j.fuel.2017.10.100 accessed 21 October 2025.

[21] V Stavrakas, N-A Spyridaki and A Flamos, 'Striving towards the Deployment of Bio-Energy with Carbon Capture and Storage (BECCS): A Review of Research Priorities and Assessment Needs' (2018) 10 Sustainability 2206 https://doi.org/10.3390/su10072206 accessed 21 October 2025.

[22] IEA-ETSAP and IRENA, 'Biomass for Heat and Power: Technology Brief' (2015) 13-14 <https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2015/IRENA-ETSAP_Tech_Brief_E05_Biomass-for-Heat-and-Power.pdf> accessed 7 February 2026.

mixture of hydrogen, carbon monoxide, and carbon dioxide.[23] Pre-combustion capture can then be employed to separate the CO2 from the syngas before it is used to generate electricity or produce biofuels and other chemicals. Although more technologically demanding than direct combustion, gasification provides higher potential efficiency and the unique ability to produce 'drop-in' biofuels or hydrogen. This makes it a particularly viable approach for decarbonizing difficult-to-abate industries, such as heavy transport and aviation.[24] Fermentation, a biochemical process, is primarily used to produce biofuels, such as ethanol, from biomass feedstocks. A significant advantage of this pathway is that it produces a relatively pure stream of CO2 as a byproduct, which can be captured with high efficiency and lower costs compared to post-combustion captured from flue gases. Consequently, the fermentation pathway is commonly considered the 'low-hanging fruit' of the BECCS landscape. Because the CO2 produced is a high-purity byproduct of the process, it requires no extra energy for separation and compression, making it the most accessible and cost-effective entry point for industrial BECCS applications.[25]

The Brazilian sugarcane matrix exemplifies this specific thermodynamic advantage at an unprecedented scale. Unlike temperate corn ethanol, sugarcane fermentation yields an exceptionally pure biogenic exhaust that demands minimal upstream conditioning, rendering it a highly attractive frontier for commercial capture. However, as the Brazilian model proves, this apparent low-hanging fruit remains entangled in distinct geological and logistical bottlenecks, particularly regarding the transit of captured carbon to offshore storage basins.[26]

The carbon capture component of BECCS also encompasses a variety of technologies, each with its own set of advantages and challenges. Post-combustion capture, typically using amine-based solvents, is a well-established technology but is energy-intensive, creating a parasitic load on the

[23] H Yang and H Chen, 'Biomass gasification for synthetic liquid fuel production' in R Luque and J G Speight (eds), Gasification for Synthetic Fuel Production (Woodhead Publishing 2015) 241–75, ISBN 978-0-85709-802-3 https://doi.org/10.1016/B978-0-85709-802-3.00011-4 accessed 22 October 2025.
[24] H Yang and H Chen, 'Biomass gasification for synthetic liquid fuel production' in R Luque and JG Speight (eds), Gasification for Synthetic Fuel Production (Woodhead Publishing 2015).
[25] T Hossain and others, 'Deployment of BECCUS value chains in the United States: A case study of sequestering CO2 from ethanol production' (IEA Bioenergy 2023) https://www.ieabioenergy.com/wp-content/uploads/2023/03/BECCUS-1.0_US-Case-Study_final_update.pdf accessed 22 October 2025.
[26] Artur Milanez and others, 'Carbon capture and storage from ethanol fermentation in Brazil' (2020) 103 International Journal of Greenhouse Gas Control 103185.

power plant that reduces its net energy output.[27] Pre-combustion capture, while potentially more efficient, is more integrated into the energy conversion process and can be more complex to retrofit to existing facilities. Oxy-combustion is another approach in which biomass is burned in a nearly pure oxygen environment, resulting in a flue gas that is highly concentrated in CO2, making it easier and less energy-intensive to capture.[28] The choice of technology pathway depends on a multitude of factors, including the type of biomass feedstock, the desired energy output (electricity, heat, or biofuels), the scale of the operation, and the economic and policy context. For instance, retrofitting existing coal-fired power plants to co-fire with biomass and adding post-combustion capture has been considered a potentially cost-effective way to deploy BECCS at scale, leveraging existing infrastructure.[29] However, the efficiency and carbon neutrality of such conversions are subject to intense debate. The captured CO2, a supercritical fluid, must then be transported, typically via pipelines, to a suitable geological storage site, where it is injected deep underground into formations, such as saline aquifers or depleted oil and gas reservoirs, for long-term sequestration. The integrity and permanence of this storage are critical to the overall climate benefit of BECCS.[30]

3. Pioneering BECCS: The Case of Drax Power Station[31]

The Drax Power Station Bioenergy with Carbon Capture and Storage Project[32] in North Yorkshire, United Kingdom, is one of the most prominent and ambitious BECCS projects globally.[33]

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[27] Josh Strege, Joshua Stanislowski and John P Kay, 'Impact of BECCS on amine-based CO2 capture solvents in a pilot-scale combustion environment' (16th Greenhouse Gas Control Technologies Conference (GHGT-16), 23–24 October 2022) 37.

[28] Rosa M Cuéllar Franca and Adisa Azapagic, 'Life Cycle Environmental Impacts of Carbon Capture, Storage, and Utilization' in Martin A Abraham (ed), Encyclopedia of Sustainable Technologies (Elsevier 2017) 447–59 https://doi.org/10.1016/B978-0-12-409548-9.10123-X.

[29] M Bui, M Fajardy and N Mac Dowell, 'Bio-energy with carbon capture and storage (BECCS): Opportunities for performance improvement' (2018) 213 Fuel 164–175 https://doi.org/10.1016/j.fuel.2017.10.100 accessed 21 October 2025.

[30] V Stavrakas, N-A Spyridaki and A Flamos, 'Striving towards the Deployment of Bio-Energy with Carbon Capture and Storage (BECCS): A Review of Research Priorities and Assessment Needs' (2018) 10 Sustainability 2206 https://doi.org/10.3390/su10072206 accessed 21 October 2025.

[31] Drax Group, "Analysis: Development of BECCS at Drax Power Station projected to save UK £15bn and offset carbon emissions equivalent to all departing flights from Heathrow" (Press release, 16 January 2024) https://www.drax.com/press_release/analysis-development-of-beccs-at-drax-power-station-projected-to-save-uk-15bn-and-offset-carbon-emissions-equivalent-to-all-departing-flights-from-heathrow/ accessed 22 October 2025.

[32] The Drax BECCS is largely considered as an infrastructure project as indicated by the Order underpinning it—The Drax Power Station Bioenergy with Carbon Capture and Storage Extension Order 2024 (SI 2024 No 70).

[33] Drax Group, 'Bioenergy with Carbon Capture and Storage (BECCS)' (Drax Group, https://www.drax.com/bioenergy-with-carbon-capture-and-storage-beccs/ accessed 24 October 2025.

Originally the largest coal-fired power station in Western Europe, Drax has undergone a significant transformation, converting four of its six generating units to burn biomass, primarily in the form of compressed wood pellets. The company has positioned itself as a leader in decarbonization, with plans to become a carbon-negative enterprise by deploying BECCS technology on its biomass units. The project aims to capture and permanently store millions of metric tons of CO2 per year, making a substantial contribution to the UK's legally binding net-zero emissions target.[34]

At Drax, the technological approach involves retrofitting existing biomass units with post-combustion capture technology. The company has been piloting two different capture technologies: one from C-Capture, a spin-out from the University of Leeds, and another from Mitsubishi Heavy Industries.[35] These pilots have been crucial for testing the feasibility and efficiency of capturing CO2 from biomass flue gases, which have different characteristics than those from coal combustion. The captured CO2 is planned to be transported via a shared pipeline as part of the Zero Carbon Humber project, a regional initiative to create a decarbonized industrial cluster, and stored in geological formations under the North Sea.

Proponents of the Drax project highlight its potential to deliver large-scale negative emissions while providing a reliable source of renewable electricity, thereby enhancing the UK's energy security.[36] An analysis commissioned by Drax projected that the BECCS project could save the UK economy billions of pounds in the long run by providing a cost-effective pathway to meet its carbon reduction targets. The project is also expected to create thousands of jobs during its construction and operation, contributing to the economic development of the region. Furthermore, Drax argues that its use of "sustainable" biomass, primarily sourced from managed forests in North America, ensures that the overall process is carbon neutral even before the addition of carbon capture.

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[34] The 2050 carbon neutrality target was mandated by the UK Climate Change Act 2008 in 2019 (The Climate Change Act 2008 (2050 Target Amendment) Order 2019 (SI 2019/1056), arts 1, 2.)

[35] Drax BECCS Pilot Plant: Project Details' (SCCS, no date) https://www.geos.ed.ac.uk/sccs/project-info/2261 accessed 30 November 2025.

[36] Drax Group, "Analysis: Development of BECCS at Drax Power Station projected to save UK £15bn and offset carbon emissions equivalent to all departing flights from Heathrow" (Press release, 16 January 2024) https://www.drax.com/press_release/analysis-development-of-beccs-at-drax-power-station-projected-to-save-uk-15bn-and-offset-carbon-emissions-equivalent-to-all-departing-flights-from-heathrow/ accessed 22 October 2025.

However, the Drax project has been the subject of intense scrutiny and criticism from environmental groups and some scientists. A primary point of contention is the sustainability of its biomass supply chain.[37] Critics argue that the sourcing of wood pellets from forests in the United States and Canada contributes to deforestation and the degradation of valuable ecosystems, thereby undermining the claimed carbon neutrality of the process.[38] There are also significant lifecycle emissions associated with the harvesting, processing, and transportation of wood pellets, which are often not fully accounted for. The "carbon debt" created by harvesting mature trees, which can take decades or even centuries to be repaid by the regrowth of new trees, is another major concern.

The economic viability of the Drax BECCS project is also heavily debated.[39] The project is contingent on substantial government subsidies, and critics argue that these public funds could be better invested in other renewable energy technologies, such as wind and solar, which are becoming increasingly cost-competitive. Ember, an energy think tank, has warned that the project could lock UK consumers into high electricity prices for decades to come, without a guarantee of delivering genuine negative emissions.[40] The significant energy penalty associated with post-combustion capture, which reduces the net electricity output of the power station, further adds to the economic and environmental costs. The long-term efficacy and safety of CO2 storage in the North Sea also present uncertainties that must be addressed. While geological storage is generally considered to be a mature technology, the potential for leakage and long-term monitoring requirements are significant challenges.[41] The case of Drax, therefore, encapsulates the central dilemma of BECCS: a technology with the theoretical potential for large-scale carbon removal,

[37] Drax BECCS Pilot Plant: Project Details' (SCCS, no date) https://www.geos.ed.ac.uk/sccs/project-info/2261 accessed 30 November 2025.

[38] Drax Group, 'Bioenergy with Carbon Capture and Storage (BECCS)' (Drax Group, https://www.drax.com/bioenergy-with-carbon-capture-and-storage-beccs/ accessed 24 October 2025.

[39] Phil MacDonald and Tomos Harrison, Understanding the Cost of the Drax BECCS Plant to UK Consumers (Ember, May 2021) <<https://www.readkong.com/page/understanding-the-cost-of-the-drax-beccs-plant-to-uk-6751139> accessed 8 April 2026

[40] ibid.

[41] Drax Group, "Analysis: Development of BECCS at Drax Power Station projected to save UK £15bn and offset carbon emissions equivalent to all departing flights from Heathrow" (Press release, 16 January 2024) https://www.drax.com/press_release/analysis-development-of-beccs-at-drax-power-station-projected-to-save-uk-15bn-and-offset-carbon-emissions-equivalent-to-all-departing-flights-from-heathrow/ accessed 22 October 2025.

but one that is entangled in complex and contentious issues of sustainability, economics, and policy.[42]

4. The ADM Decatur Project: A Case Study in Industrial BECCS

The Archer Daniels Midland (ADM) facility in Decatur, Illinois, represents a different facet of BECCS implementation, focusing on industrial applications rather than large-scale power generation.[43] This project, a partnership between ADM, the U.S. Department of Energy, and other research institutions, captures CO2 from a corn-to-ethanol production plant and sequesters it in a deep saline aquifer.[44] This project is notable for being one of the first large-scale BECCS projects in the world and has provided invaluable data and operational experience for the broader carbon capture and storage (CCS) industry.

At the ADM Decatur facility, the technological pathway is centred on capturing a high-purity CO2 stream, a natural byproduct of the ethanol fermentation process.[45] This is a significant advantage over post-combustion capture from power plants, as the CO2 is already concentrated, requiring less energy and cost for separation. The captured CO2 is then compressed and injected into the Midwestern Simon Sandstone, a geological formation located more than a mile beneath the surface. The project has been implemented in two phases: the Illinois Basin – Decatur Project (IBDP), which successfully stored one million metric tons of CO2 over three years, and the subsequent Illinois Industrial Carbon Capture and Storage (IL-ICCS) project, which aims to store up to one million metric tons of CO2 annually.[46]

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[42] Drax Group, "Analysis: Development of BECCS at Drax Power Station projected to save UK £15bn and offset carbon emissions equivalent to all departing flights from Heathrow" (Press release, 16 January 2024) <https://www.drax.com/press_release/analysis-development-of-beccs-at-drax-power-station-projected-to-save-uk-15bn-and-offset-carbon-emissions-equivalent-to-all-departing-flights-from-heathrow/≥ accessed 22 October 2025.

[43] Illinois Industrial Carbon Capture and Storage Project (Decatur, Illinois) (Carbon Capture & Sequestration Technologies Program, Massachusetts Institute of Technology, 30 September 2016) https://sequestration.mit.edu/tools/projects/illinois_industrial_ccs.html accessed 22 October 2025.

[44] 'Archer Daniels Midland Company' (U.S. Department of Energy, FECM) https://www.energy.gov/fecm/archer-daniels-midland-company accessed 30 November 2025.

[45] Illinois Industrial Carbon Capture and Storage Project (Decatur, Illinois) (Carbon Capture & Sequestration Technologies Program, Massachusetts Institute of Technology, 30 September 2016) https://sequestration.mit.edu/tools/projects/illinois_industrial_ccs.html accessed 22 October 2025.

[46] Archer Daniels Midland Company' (U.S. Department of Energy, FECM) https://www.energy.gov/fecm/archer-daniels-midland-company accessed 30 November 2025.

The ADM Decatur project has been lauded as a technical success, demonstrating the viability of capturing and storing large volumes of CO2 from an industrial source.[47] It has provided a wealth of data on the performance of the storage reservoir, the integrity of the caprock, and the effectiveness of various monitoring technologies.[48] The project has also been a crucial platform for developing the regulatory framework for geological CO2 storage in the United States, being one of the first to receive a Class VI injection well permit from the Environmental Protection Agency (EPA). Proponents argue that such industrial BECCS applications are essential for decarbonizing hard-to-abate sectors, such as biofuel production, and that the knowledge gained from the Decatur project can be applied to other industrial CCS projects globally. The project has also received significant public funding, with the Department of Energy providing a substantial portion of the investment, highlighting the role of government support in advancing CCS technologies. This US Government support for CCS is also underscored in the Inflation Reduction Act 2022 which extends and modifies credit for CO2 sequestration[49]—thus, enabling ADM Decatur to benefit from these tax credits in the implementation of its CCS project.[50]

Despite its technical achievements, the ADM Decatur project has faced challenges and criticisms.[51] One of the main points of contention has been the project's actual carbon capture rate and overall climate benefit. While the project has successfully stored millions of metric tons of CO2, investigative reports have revealed that this represents only a fraction of the total emissions from the entire ADM Decatur complex, which includes other processing operations in addition to ethanol production. This raises questions about the project's overall effectiveness in reducing the facility's carbon footprint.

While the ADM Decatur project has proven technical efficacy in terms of cumulative sequestration volumes, its operational history provides a significant warning regarding subsurface CO2

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[47] Archer Daniels Midland Company, 'Carbon Capture and Storage | ADM' (ADM, https://www.adm.com/en-us/standalone-pages/adm-and-carbon-capture-and-storage/ accessed 25 October 2025.
[48] Archer Daniels Midland Company' (U.S. Department of Energy, FECM) https://www.energy.gov/fecm/archer-daniels-midland-company accessed 30 November 2025.
[49] Public Law 117 – 169—Aug 16, 2022, s 13104 amending 26 USC §45Q.
[50] Congressional Research Service, 'Carbon Capture and Sequestration (CCS) in the United States' <https://www.congress.gov/crs_external_products/R/PDF/R44902/R44902.17.pdf#:~:text=In%202022%2C%20Congress%20enacted%20as,provisions%20that%20increased%20the%20tax> accessed 22 February 2026.
[51] Archer Daniels Midland Company, 'Carbon Capture and Storage | ADM' (ADM, https://www.adm.com/en-us/standalone-pages/adm-and-carbon-capture-and-storage/ accessed 25 October 2025.

movement. In 2025, monitoring protocols identified CO2 migration into prohibited geological strata. Critically, subsequent EPA studies (2025) determined that the cause was a compromise in wellbore integrity within a secondary monitoring well, not a failure of the primary caprock seal. Although the sequestered CO2 remained within the larger deep geological complex, the episode sparked widespread concern about the potential contamination of nearby groundwater, particularly the Mahomet Aquifer. The event emphasizes an important regulatory lesson: BECCS's long-term safety and social license are dependent not only on favourable geology but also on diligent, continuous infrastructure maintenance and robust monitoring mechanisms. The subsequent EPA notices of violation for permit noncompliance and insufficient emergency planning highlight the importance of strict regulatory control and open reporting to prevent subsurface risks.[52] While the 2025 wellbore integrity issue serves as a critical regulatory lesson, it should not overshadow the project's primary technical achievement: the successful sequestration of over one million metric tons in the Midwestern Simon Sandstone. This demonstrates that, while the geological formation itself is a reliable global benchmark for carbon capacity, the mechanical link (the injection wells) requires more stringent, ongoing maintenance protocols than current frameworks suggest.

Beyond its technical implications, the ADM Decatur incident exposes legal vulnerability of BECCS given the allocation of long-term liability for geological storage failure. Although the US Class VI permitting framework imposes stringent pre-injection and operational requirements, it ultimately relies on extended post-closure monitoring periods after which responsibility for the stored CO_2 may transfer to the state. This temporal dilution of operator liability risks misaligning incentives, particularly where commercial entities face limited exposure to the full duration of geological risk. From a governance perspective, the episode illustrates that storage integrity is not merely a geological question but a legal one, hinging on well-maintenance duties, disclosure

[52] Sam Rink, 'Carbon Sequestration and the Mahomet Aquifer: Scientists Break Down What You Need to Know' (11 July 2025) https://ipmnewsroom.org/carbon-sequestration-and-the-mahomet-aquifer-scientists-break-down-what-you-need-to-know/ accessed 24 October 2025.; US Environmental Protection Agency, 'Notice of Violation and Opportunity to Confer: Archer Daniels Midland' (2025).; Illinois Industrial Carbon Capture and Storage Project (Decatur, Illinois) (Carbon Capture & Sequestration Technologies Program, Massachusetts Institute of Technology, 30 September 2016) https://sequestration.mit.edu/tools/projects/illinois_industrial_ccs.html accessed 22 October 2025.

obligations, and enforceable long-term stewardship frameworks which are areas where CCS regulation remains fragmented and uneven across jurisdictions[53].

These incidents have fuelled public scepticism about the safety of CCS and have highlighted the critical importance of robust monitoring, reporting, and verification protocols. The project has also been criticized for its reliance on taxpayer subsidies, with some arguing that these funds could be better used to support other climate solutions.[54] The case of the ADM Decatur project, therefore, serves as a cautionary tale, demonstrating that even with a high-purity CO2 stream and a seemingly ideal geological formation, the long-term success and safety of BECCS projects are not guaranteed. It underscores the need for stringent regulatory oversight, transparent communication with the public, and a comprehensive understanding of geological risks before embarking on large-scale CO2 sequestration.

The different experiences of the Drax and ADM projects underscore a fundamental duality within the BECCS portfolio, distinguishing between the risks associated with power generation and industrial uses. The Drax Power Station demonstrates the issues of the 'power' typology, in which the major risk is transferred upstream to the biomass supply chain. In this concept, the technological maturity of the combustion process is eclipsed by the 'carbon debt' inherent in removing mature trees, leaving the net-negative status wholly dependent on controversial international accounting and land-use frameworks.[55]

In contrast, the ADM Decatur project exemplifies the 'industrial' pattern, which utilizes high-purity fermentation waste. While this method avoids the significant energy penalty and financial costs associated with post-combustion collection, it demonstrates that the fundamental barrier to commercial BECCS is pushed downstream: storage integrity. The 2025 fluid migration issue at the ADM site demonstrates that even the most cost-effective capture technology cannot ensure long-term sequestration safety in the absence of faultless wellbore maintenance. Finally, these case

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[53] Elizabeth J Wilson and Mark de Figueiredo, 'Geologic Carbon Dioxide Sequestration: An Analysis of Subsurface Property Law' (2006) 36 Environmental Law Reporter 10114 <https://elr.info/sites/default/files/articles/36.10114.pdf> accessed 8 April 2026.

[54] Archer Daniels Midland Company, 'Carbon Capture and Storage | ADM' (ADM, https://www.adm.com/en-us/standalone-pages/adm-and-carbon-capture-and-storage/ accessed 25 October 2025.

Phil MacDonald and Tomos Harrison, Understanding the Cost of the Drax BECCS Plant to UK Consumers (Ember, May 2021) <<https://www.readkong.com/page/understanding-the-cost-of-the-drax-beccs-plant-to-uk-6751139> accessed 8 April 2026

studies suggest a critical trade-off: industrial BECCS is economically more 'ready' but requires more rigorous, localized geological oversight, whereas power-generation BECCS is technologically 'ready' but raises existential concerns about its global ecological footprint and true carbon neutrality."[56]

The context of deployment varies significantly by geography: in the Global North, the primary path is the costly retrofitting of aging coal or biomass power units (e.g., the UK model). Conversely, in the Global South, the path forward is characterized by the integration of carbon capture into existing, high-purity industrial clusters, such as Brazil's sugarcane mills, which bypasses the thermodynamic 'energy penalty' of the Northern model but requires new trans-regional pipeline infrastructure.

5. The Brazilian Frontier: Sugarcane Ethanol, Deep-Basin Storage, and the Paradox of Abundance

To adequately conceptualize the global trajectory of Bioenergy with Carbon Capture and Storage (BECCS), the analytical lens must shift toward the Global South, where Brazil presents a fundamentally distinct architectural model for negative emissions. While the Drax facility struggles with the severe carbon debt of imported wood pellets and the ADM Decatur project operates as a relatively isolated node of industrial capture, Brazil boasts an unparalleled, continent-spanning bioenergy infrastructure. Rooted in the state-sponsored Proálcool program of the 1970s, the Brazilian sugarcane ethanol sector offers a structurally unique environment for carbon dioxide removal—one characterized simultaneously by immense thermodynamic promise and profound socio-ecological contradictions.

5.1 Thermodynamic Advantages and the Geological Imperative

From a purely techno-economic standpoint, the Brazilian sugarcane industry represents the theoretical ideal for commercial BECCS deployment. Unlike the Anglo-American reliance on post-combustion capture from power generation—a process penalized by exorbitant capital costs and severe parasitic energy loads—the fermentation of sugarcane juice and molasses yields a

[56] US Environmental Protection Agency, 'Notice of Violation and Opportunity to Confer: Archer Daniels Midland' (2025); Sam Rink, 'Carbon Sequestration and the Mahomet Aquifer: Scientists Break Down What You Need to Know' (11 July 2025).

biogenic exhaust stream that is nearly 99% pure carbon dioxide. Consequently, the separation and dehydration phases are vastly simplified, bypassing the need for complex amine solvent scrubbers. Furthermore, the Energy Return on Investment (EROI) of sugarcane ethanol drastically outperforms that of North American corn ethanol, offering a much larger net energy surplus alongside captured carbon.[57]

In this context, the Brazilian case demonstrates that resolving thermodynamic and financial barriers does not neutralise the material limits of bio-based mitigation. Instead, it re-anchors BECCS within the political economy of land. While RenovaBio successfully monetises avoided emissions at the mill gate, it does not govern the broader spatial reorganisation of agriculture induced by carbon-optimised sugarcane expansion. This regulatory asymmetry allows negative emissions to be manufactured locally while deforestation pressure and food-system disruption are displaced geographically. In this sense, Brazil functions not as an anomaly but as a diagnostic case, illustrating how BECCS can conform to procedural carbon integrity while undermining substantive ecological integrity[58].

However, the realization of this potential is contingent upon a formidable, often under-theorized barrier: geological sequestration logistics. While Brazil possesses vast theoretical storage capacity, the geographical dislocation between the ethanol production epicentre and optimal geological reservoirs introduces severe friction. Most Brazil's operational ethanol mills are concentrated in the onshore Center-South region (predominantly the state of São Paulo), sitting atop the Paraná Basin. Although this basin contains deep saline aquifers, its geology is heavily punctuated by basaltic intrusions (the Serra Geral Formation), complicating the injection and long-term monitoring of supercritical CO2. [59] Conversely, Brazil's most proven and technologically mature sequestration sites are located offshore in the pre-salt oil fields, managed by the state-owned Petrobras. Transporting millions of metric tons of biogenic CO2 from the interior agrarian heartland to offshore injection platforms demands a pipeline infrastructure of staggering cost and complexity, which tempers the optimism surrounding immediate, large-scale deployment.[60]

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[57] J Goldemberg, S T Coelho and P Guardabassi, 'The Sustainability of Ethanol Production from Sugarcane' (2008) 36 Energy Policy 2086.

[58] Roberto Rajão and others, 'The rotten apples of Brazil's agribusiness' (2020) 369 Science 246 <https://doi.org/10.1126/science.aba6646> accessed 8 April 2026;

[59] J Ketzer, R Iglesias, S Einloft and J Dullius, 'Geological CO2 Storage Potential in the Paraná Basin, Southern Brazil' (2005) 50 Environmental Geology 209, 212–215.

[60] R G C R Mota et al, 'Carbon Capture and Storage in Brazil: Current Status, Potential, and Challenges' (2024) 188 Renewable and Sustainable Energy Reviews 113795.

5.2 Market Architectures: RenovaBio and the Commodification of Carbon

Where European and North American BECCS frameworks remain heavily dependent on precarious taxpayer subsidies or direct grants, Brazil has engineered a sophisticated, decentralized regulatory architecture. The national biofuels policy, RenovaBio, established a market-based incentive structure that issues tradeable decarbonization credits (CBIOs) to producers based on the independently verified lifecycle emission reductions of their fuel.[61] By commodifying avoided carbon, RenovaBio provides a localized, self-sustaining revenue stream.

This financial architecture was recently fortified by the passage of Brazil's Combustível do Futuro (Fuel of the Future) legislation and the concurrent establishment of a formal legal framework for carbon capture and storage.[62] Together, these legal instruments attempt to integrate BECCS into a broader national decarbonization strategy, permitting ethanol producers to monetize carbon removals on international compliance markets under Article 6 of the Paris Agreement. In theory, this insulates the sector from the shifting political whims of direct public funding, transferring the capital risk to carbon markets and multinational aviation consortiums desperate for carbon-negative Sustainable Aviation Fuels (SAF) derived from Brazilian ethanol.

5.3 The Ecological Quagmire: Indirect Land Use Change and Biome Degradation

Despite these regulatory and technological advancements, embedding a massive BECCS mandate within the Brazilian agricultural matrix threatens to trigger cascading ecological crises. The sheer volume of biomass cultivation required to convert Brazil’s ethanol sector into a globally relevant carbon sink exacerbates the country’s chronic crisis of land-use change. Proponents routinely defend the industry by asserting that sugarcane expansion primarily occupies degraded pasturelands rather than virgin Amazonian rainforests.

This narrow accounting deliberately obscures the insidious mechanics of indirect land-use change (iLUC). As lucrative, highly capitalized sugarcane monocultures monopolize arable territory in the Center-South and Northeast, they displace cattle ranching and soy production. This displacement acts as an economic shockwave, relentlessly pushing the agricultural frontier further

[61] Ministry of Mines and Energy (Brazil), RenovaBio: National Biofuels Policy (Decree No. 9.888/2019).

[62] F F Machado and M S de Oliveira, 'The Legal Framework for CCS in Brazil: Regulatory Advances and the "Fuel of the Future" Bill' (2025) 42 Journal of Energy & Natural Resources Law 145.

into the hyper-biodiverse Cerrado savanna and the Pantanal wetlands.[63] The Cerrado, characterized by deep root systems that act as massive subterranean carbon sinks, is currently experiencing alarming rates of deforestation. Consequently, the localized negative emissions generated at the ethanol mill risk being entirely negated by the release of centuries-old carbon sinks at the expanding frontier. Furthermore, the intensification of sugarcane cultivation demands the aggressive application of synthetic nitrogen fertilizers, resulting in the emission of nitrous oxide (N2O), a greenhouse gas with a warming potential nearly 300 times that of, which is frequently underrepresented in official lifecycle assessments.[64]

5.4 Agrarian Hegemony and Social Dispossession

Beyond the biophysical metrics, the deployment of BECCS in Brazil threatens to entrench historical social inequities, effectively weaponizing climate mitigation against rural populations. The nation's agrarian terrain is notoriously skewed, dominated by vast corporate estates (latifúndios). Incentivizing the massive scale-up of sugarcane cultivation for international carbon sequestration risks further concentrating land ownership. As land values artificially inflate owing to the premium placed on carbon-yielding crops, smallholder family agriculture is systematically priced out and displaced.

This dynamic engenders a direct conflict between "food and fuel", more accurately, between domestic food sovereignty and international carbon offsetting. Land previously dedicated to staple crops essential for the local population (such as black beans, rice, and cassava) is increasingly absorbed by export-oriented, carbon-negative commodity chains.[65] Coupled with a legacy of precarious labour conditions in the agricultural sector, the marginalization of indigenous land claims, and the exposure of rural communities to toxic agrochemical runoff (such as vinasse), the social license of Brazilian BECCS remains fundamentally fragile.

Ultimately, the Brazilian experience operates as a sharp, necessary corrective to northern-centric climate modelling. This demonstrates that even when the thermodynamic, financial, and regulatory

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[63] T MapBiomas, Annual Deforestation Report in Brazil – 2023 (MapBiomas Project, 2024) https://alerta.mapbiomas.org accessed 20 February 2026.

[64] L A B Nogueira et al, 'Greenhouse Gas Emissions from Sugarcane Ethanol: The Crucial Role of Agricultural Phase and Nitrogen Fertilizers' (2023) 171 Biomass and Bioenergy 106720.

[65] S Sauer, 'Soy Expansion into the Agricultural Frontiers of the Brazilian Amazon: The Agribusiness Economy and Its Social and Environmental Conflicts' (2018) 79 Land Use Policy 326, 330–332. (Note: While focused on soy, Sauer's framework on latifúndio expansion and food sovereignty directly parallels current critiques of sugarcane expansion driven by decarbonization mandates).

barriers to BECCS are ostensibly resolved, the technology cannot escape the terrestrial limits of the biosphere. Without rigorous, globally integrated mechanisms to halt indirect deforestation and dismantle exploitative agrarian structures, the industrialization of the Global South for carbon removal risks becoming an exercise in ecological imperialism, purportedly saving the atmosphere while irrevocably degrading the terrestrial biosphere.

6. The Environmental and Social Quagmire of BECCS[66]

Although BECCS has significant theoretical mitigation potential, its large-scale deployment is inextricably linked to a host of complex and often contentious environmental and social challenges.[67] These issues, which range from land-use competition and biodiversity loss to food security and social justice, are at the heart of the debate over the sustainability and desirability of a future that is heavily reliant on BECCS.[68] A critical examination of these challenges is essential for a balanced assessment of the technology's role in a just and sustainable transition to a low-carbon economy.

The most significant environmental concern associated with BECCS is the immense demand for land to cultivate biomass feedstocks[69]. Integrated assessment models that project pathways to limiting global warming to 1.5°C or 2°C often rely on the deployment of BECCS at a scale that would require converting vast areas of land —potentially hundreds of millions of hectares —to bioenergy crop plantations. This raises the spectre of a direct conflict between land for fuel and land for food, a dilemma that could have profound implications for global food security. The conversion of agricultural land to bioenergy crops could lead to increased food prices, exacerbating hunger and malnutrition, particularly in vulnerable communities in the Global South.

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[66] M Bui, M Fajardy and N Mac Dowell, 'Bio-energy with carbon capture and storage (BECCS): Opportunities for performance improvement' (2018) 213 Fuel 164–175 https://doi.org/10.1016/j.fuel.2017.10.100 accessed 21 October 2025.

[67] L M Gurtner and S Moser, 'The where, how, and who of mitigating climate change: A targeted research agenda for psychology' (2024) 94 Journal of Environmental Psychology 102250 https://doi.org/10.1016/j.jenvp.2024.102250 accessed 21 October 2025.

[68] V Stavrakas, N-A Spyridaki and A Flamos, 'Striving towards the Deployment of Bio-Energy with Carbon Capture and Storage (BECCS): A Review of Research Priorities and Assessment Needs' (2018) 10 Sustainability 2206 https://doi.org/10.3390/su10072206 accessed 21 October 2025.

[69] Fern, 'Six Problems with BECCS' (Report, February 2022) https://www.fern.org/fileadmin/uploads/fern/Documents/2022/Six_problems_with_BECCS_-_2022.pdf accessed 25 October 2025.

Increasingly, the 'food vs. fuel' debate is being resolved through the prioritization of second-generation (2G) feedstocks.[70] Empirical evidence suggests that when BECCS utilizes agricultural residues (maize stover, wheat straw) or municipal waste, land competition is effectively bypassed.[59] Furthermore, land-use friction is frequently mitigated by the intensification of existing agricultural lands, where increased yields allow for surplus biomass production without encroaching on staple crop acreage.[71]

The environmental impacts of large-scale monoculture bioenergy plantations are also a major concern.[72] The conversion of natural ecosystems, such as forests and grasslands, to these plantations can lead to significant biodiversity loss, as complex habitats are replaced by simplified agricultural landscapes. The intensive agricultural practices often associated with bioenergy crop cultivation, including the use of fertilizers and pesticides, can also lead to soil degradation, water pollution, and the release of other greenhouse gases, such as nitrous oxide. Furthermore, the notion that bioenergy is inherently "carbon neutral" is a subject of intense scientific debate.[73] The full lifecycle emissions of BECCS, including those from land-use change, biomass cultivation, transportation, and processing, can, in some cases, negate the carbon removal benefit and even lead to a net increase in atmospheric CO2 concentrations.

The social implications of large-scale BECCS deployment are equally concerning.[74] The acquisition of large tracts of land for bioenergy plantations can lead to land grabs and the displacement of indigenous peoples and local communities, particularly in developing countries with weak land tenure rights.[75] This can result in the loss of livelihoods, cultural heritage, and

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[70] J R Bartle and A Abadi, 'Toward Sustainable Production of Second Generation Bioenergy Feedstocks' (2010) 24 Energy Fuels 2.

[71] Alexandre Köberle, 'The Value of BECCS in IAMs: A Review' (2019) 6 Current Sustainable/Renewable Energy Reports 107.; J Hu and others, 'Impact of large-scale Bio-CCS deployment on forest biomass competition and forest industry production' (2023) 175 Biomass & Bioenergy 106896.

[72] S V Hanssen et al, 'Global implications of crop-based bioenergy with carbon capture and storage for terrestrial vertebrate biodiversity' (2022) 14 GCB Bioenergy 307–321 https://doi.org/10.1111/gcbb.12911 accessed 25 October 2025.

[73] Chartham House, 'Why Burning Biomass is Not Zero-carbon' <https://www.chathamhouse.org/2022/10/why-burning-biomass-not-zero-carbon> accessed 8 February 2026.

[74] A Almena, V Ghorbani Pashakolaie and M Martin, 'Unlocking BECCS viability through monetising societal benefits by techno-socio-economic assessment' (2025) 59 Sustainable Production and Consumption 255–273 https://doi.org/10.1016/j.spc.2025.08.016 accessed 25 October 2025.

[75] J Hu, E O Jåstad, T F Bolkesjø and P K Rørstad, 'Impact of large-scale Bio-CCS deployment on forest biomass competition and forest industry production' (2023) 175 Biomass & Bioenergy 106896 https://doi.org/10.1016/j.biombioe.2023.106896 accessed 25 October 2025.

traditional knowledge. There are also concerns about labor conditions on bioenergy plantations, which have, in some cases, been associated with low wages and poor working conditions. The deployment of BECCS also raises questions of equity and justice, as the benefits of the technology, such as energy production and carbon credits, may accrue to wealthy nations and corporations, while the negative social and environmental impacts are disproportionately borne by marginalized communities.[76] Brazil's expanding bioenergy frontier starkly illustrates these agrarian dynamics. The relentless push of highly capitalized sugarcane monocultures into the Cerrado savanna forces the displacement of staple food cultivation and pastoral activities. This engineering of indirect land-use change threatens to decimate subterranean carbon sinks, while the reliance on historic latifúndio estate structures risks entrenching land dispossession and permanently marginalizing smallholder agriculture in the pursuit of export-oriented decarbonization.[77] The risks associated with CO2 transportation and storage, such as the potential for pipeline ruptures or leakage from storage sites, also pose a threat to the health and safety of communities living near BECCS infrastructure. Addressing these profound environmental and social challenges will require the development of robust sustainability criteria for biomass sourcing, comprehensive land-use planning, and meaningful engagement with affected communities. Without such safeguards, the large-scale deployment of BECCS could inadvertently create a new set of environmental and social problems in the pursuit of climate solutions.

7. **The Economic and Policy Labyrinth of BECCS[78]**

The widespread deployment of Bioenergy with Carbon Capture and Storage (BECCS) is not only contingent on overcoming technical and environmental hurdles but also on navigating a complex and often uncertain economic and policy landscape.[79] High costs associated with BECCS, coupled with a lack of robust and consistent policy support, have been significant barriers to its

[76] V Stavrakas, N-A Spyridaki and A Flamos, 'Striving towards the Deployment of Bio-Energy with Carbon Capture and Storage (BECCS): A Review of Research Priorities and Assessment Needs' (2018) 10 Sustainability 2206 https://doi.org/10.3390/su10072206 accessed 21 October 2025.
[77] R Rajão and others, 'The rotten apples of Brazil's agribusiness' (2020) 369 Science 246.
[78] N Pour, 'Economics and policy of bioenergy with carbon capture and storage' in (ed) Bioenergy with Carbon Capture and Storage (Elsevier 2019) 257–71 https://doi.org/10.1016/B978-0-12-816229-3.00013-2 accessed 25 October 2025; See also IPCC, 'Climate Change 2022: Mitigation of Climate Change' (Working Group III Contribution to AR6)
[79] N Pour, 'Economics and policy of bioenergy with carbon capture and storage' in (ed) Bioenergy with Carbon Capture and Storage (Elsevier 2019) 257–71 https://doi.org/10.1016/B978-0-12-816229-3.00013-2 accessed 25 October 2025.

commercialization. A critical analysis of the economic viability and necessary policy frameworks is essential to understand the real-world prospects of BECCS as a climate change mitigation tool.[80]

The economics of BECCS are challenging, with high upfront capital costs for both the bioenergy facility and the carbon capture and storage infrastructure.[81] Ongoing operational costs, including those for biomass feedstock, transportation, and the energy penalty of the capture process, further increase the overall expense.

Recent estimates indicate that the cost of carbon abatement for BECCS power generation ranges from $100 to $200 per ton of CO_2, depending on geography and technology. High-purity fermentation sources, such as ethanol, often have lower capture costs, ranging from $25 to $35 per ton of CO_2. Despite the reduced entry price for industrial applications, a significant 'viability gap' exists when compared to current carbon pricing.

While the EU Emissions Trading System (ETS) averaged €65 – €85/ton CO2 equivalent (tCO2e) in 2024, early 2025 trends suggest a tightening supply of allowances as the 'Fit for 55' package enters its next phase.[82] Recent industry forecasts suggest that carbon prices must exceed $120/tCO2e by 2030 to trigger unsubsidized BECCS in the power sector. Additionally, 2025 data from the Global CCS Institute indicate a 35% year-on-year increase in the pipeline of industrial capture projects, suggesting that the 'viability gap' is narrowing faster in industrial fermentation than in thermal power.[83]

Economic models have shown that for BECCS to be commercially viable, a strong and stable carbon price is necessary to create a revenue stream for captured and stored CO2.[84] However, existing carbon markets have often been characterized by low and volatile prices, which have not

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[80] L M Gurtner and S Moser, 'The where, how, and who of mitigating climate change: A targeted research agenda for psychology' (2024) 94 Journal of Environmental Psychology 102250 https://doi.org/10.1016/j.jenvp.2024.102250 accessed 21 October 2025.

[81] A Almena, V Ghorbani Pashakolaie and M Martin, 'Unlocking BECCS viability through monetising societal benefits by techno-socio-economic assessment' (2025) 59 Sustainable Production and Consumption 255–273 https://doi.org/10.1016/j.spc.2025.08.016 accessed 25 October 2025.

[82] Ember, 'European Carbon Market Outlook 2025–2030' (February 2025) https://ember-climate.org/reports/ accessed 1 March 2026.

[83] Global CCS Institute, 'The State of Play: CCS Hubs and Clusters 2025' (2025) 12-14.

[84] F J M Fajardy, J Morris, A Gurgel, H Herzog, N Mac Dowell and S Paltsev, 'The economics of bioenergy with carbon capture and storage (BECCS) deployment in a 1.5 °C or 2 °C world' (2021) 68 Global Environmental Change 102262 https://doi.org/10.1016/j.gloenvcha.2021.102262 accessed 25 October 2025.

been sufficient to incentivize large-scale investments in BECCS. Consequently, most BECCS projects to date have been heavily reliant on government subsidies and other forms of public financial support.[85] To close this financial gap, strong policy instruments are needed, such as the '45Q' tax credit in the United States, which was enhanced in 2022 to provide up to $85 per tonne for dedicated geological storage.[86] Similarly, the UK is looking into Contract for Difference (CfD) methods to ensure a strike price that covers high capture costs, essentially moving long-term price risk from investors to the public or ratepayers."[87] Furthermore, the UK Energy Act 2023 provides for a " carbon capture revenue support contract" to de-risk investments in CCUS.[88]

Beyond current frameworks, policy priorities must shift from simple subsidies to Carbon Removal Obligations (CROs), which legally mandate that polluters in hard-to-abate sectors purchase removal certificates. Additionally, Reverse Auctions for negative emission contracts can incentivize cost reductions through market competition. Most importantly, a 'Mitigation First' regulatory guardrail must be established to ensure that BECCS is utilized only for residual emissions, preventing the 'moral hazard' of delayed fossil fuel phase-outs.

In addition to these specific tax credits and price guarantees, numerous unique policy instruments have been proposed to provide the long-term market certainty needed for BECCS. Carbon Removal Obligations are a promising system in which polluters in difficult-to-abate sectors are legally forced to purchase removal certificates for each ton of residual CO2 they emit, thereby internalizing the cost of sequestration.[89] Furthermore, reverse auctions may enable governments to auction off 'negative emission contracts' to the lowest bidder, leveraging market competition to reduce technological costs and ensure efficient use of public funds.[90] Finally, integrating BECCS

[85] V Stavrakas, N-A Spyridaki and A Flamos, 'Striving towards the Deployment of Bio-Energy with Carbon Capture and Storage (BECCS): A Review of Research Priorities and Assessment Needs' (2018) 10 Sustainability 2206 https://doi.org/10.3390/su10072206 accessed 21 October 2025.

[86] Carbon Capture Coalition, Primer: 45Q Tax Credit for Carbon Capture Projects (Carbon Capture Coalition, September 2023) https://carboncapturecoalition.org/wp-content/uploads/2023/11/45Q-primer-Carbon-Capture-Coalition.pdf accessed 30 November 2025.

[87] Department for Energy Security and Net Zero, 'Contracts for Difference' (GOV.UK) https://www.gov.uk/government/collections/contracts-for-difference accessed 30 November 2025.

[88] Energy Act 2023 (2023 Chapter 52), ss 67-68.

[89] Gabin Briand and Thomas Hahn, 'How to Incentivise Carbon Dioxide Removal Technologies Based on the Polluter Pays Principle' (FAIRTRANS Report, Stockholm Resilience Centre 2025) https://su.diva-portal.org/smash/get/diva2:2015726/FULLTEXT01.pdf accessed 30 November 2025.

[90] Tobias Heimann and others, 'Expert Projections on the Development and Application of Bioenergy with Carbon Capture and Storage Technologies' (2025) 20 Environmental Research Letters 10.1088/1748-9326/ada16f.

into established compliance markets, such as the EU Emissions Trading System (ETS), is viewed as the most reliable means to offer a stable, long-term carbon price that shifts removals from voluntary corporate social responsibility to the heart of industrial decarbonization.[91]

Therefore, Global South provides alternative regulatory architectures that bypasses heavy state subsidization. Brazil's RenovaBio framework departs from the precarious taxpayer grants dominant in Northern economies, engineering instead a decentralized incentive structure that issues tradeable decarbonization credits (CBIOs) based on verified lifecycle emission reductions. While this mechanism theoretically externalizes capital risk to international carbon markets, its long-term viability remains acutely vulnerable to the volatility of global compliance pricing.[92]

However, for these policies to be effective, they must be based on a 'Mitigation First' priority statement. Frameworks must explicitly state that BECCS is only used to offset residual, difficult-to-abate emissions—such as those from heavy industry or aviation—rather than as a replacement for direct and urgent decarbonization of the electricity grid. Without this precaution, BECCS risks becoming a 'moral hazard,' delaying the shift to renewable energy sources by providing a perceived technological justification for ongoing fossil fuel reliance.[93]

The reliance on subsidies raises important questions about the most efficient allocation of public funds for climate change mitigation.[94] Critics argue that investing in BECCS diverts resources from other, more cost-effective and proven climate solutions, such as renewable energy technologies like wind and solar, as well as energy efficiency measures. There is also the risk that subsidies for BECCS could create a "moral hazard" by providing a perceived technological fix that delays the necessary and more urgent efforts to reduce emissions at their source. Furthermore, the economic models used to project the future costs of BECCS are often based on optimistic

[91] FJM Fajardy and others, 'The economics of bioenergy with carbon capture and storage (BECCS) deployment in a 1.5 °C or 2 °C world' (2021) 68 Global Environmental Change 102262.
[92] M A Santos and A P C Cunha, 'Assessing the RenovaBio policy: Market dynamics and carbon credit volatility in Brazil's bioenergy sector' (2023) 178 Energy Policy 113590.
[93] LM Gurtner and S Moser, 'The where, how, and who of mitigating climate change: A targeted research agenda for psychology' (2024) 94 Journal of Environmental Psychology 102250.
[94] L M Gurtner and S Moser, 'The where, how, and who of mitigating climate change: A targeted research agenda for psychology' (2024) 94 Journal of Environmental Psychology 102250 https://doi.org/10.1016/j.jenvp.2024.102250 accessed 21 October 2025.

assumptions about technological learning and economies of scale, and there is considerable uncertainty about whether these cost reductions will materialize in practice.[95]

The controversy involving Drax cannot be reduced to questions of biomass availability or combustion efficiency alone; it centres fundamentally on carbon accounting as a legal and regulatory construction. The classification of imported forest biomass as ‘carbon neutral’ rests on temporal assumptions about regrowth and substitution that are embedded within EU and UK accounting methodologies rather than derived from atmospheric observation. By permitting emissions at the point of combustion to be offset against speculative future sequestration, existing frameworks transform uncertainty into compliance certainty. This juridical stabilisation of carbon neutrality enables the internalisation of BECCS within subsidy and contracting regimes, while externalising ecological risk to forest landscapes and rural communities beyond the regulatory reach of UK energy law[96].

7.1 Strategic Pathways to Viability: Balancing Benefits and Risks

Despite the formidable socio-ecological and economic hurdles detailed in the preceding sections, the value proposition of BECCS remains fundamentally unique within the negative emissions portfolio. Unlike nature-based solutions such as reforestation, which are vulnerable to carbon reversal and do not contribute to the energy mix, BECCS offers 'dispatchable' carbon-negative energy. This allows it to play a dual role: providing stable baseload power or industrial heat while simultaneously lowering the absolute concentration of atmospheric CO2.

To escape the 'economic labyrinth' that currently stymies large-scale adoption, the sector must pivot away from the high-risk, high-cost model of massive thermal retrofits at aging power stations, such as Drax. Instead, the path to commercial viability lies in targeting 'low-hanging fruit', specifically industrial applications where high-purity CO2 streams are an inherent byproduct. We propose that overcoming the current viability barrier requires three specific strategic shifts:

1. Development of Co-location Clusters: Policy should prioritize the integration of BECCS within multi-user 'Industrial Hubs.' By co-locating capture-ready facilities, such as ethanol

[95] N Pour, ‘Economics and policy of bioenergy with carbon capture and storage’ in (ed) Bioenergy with Carbon Capture and Storage (Elsevier 2019) 257–71 https://doi.org/10.1016/B978-0-12-816229-3.00013-2 accessed 25 October 2025.

[96] Phil MacDonald and Tomos Harrison, Understanding the Cost of the Drax BECCS Plant to UK Consumers (Ember, May 2021) <<https://www.readkong.com/page/understanding-the-cost-of-the-drax-beccs-plant-to-uk-6751139> accessed 8 April 2026

plants or hydrogen production sites, near shared transport and storage infrastructure, projects can achieve significant economies of scale. This "plug-and-play" infrastructure approach can de-risk private investments and has the potential to reduce per-tonne sequestration costs by up to 40%.

2. Implementation of Standardized, High-Integrity MRV Protocols: To overcome the 'social license' crisis and valid scepticism regarding 'carbon debt,' the industry must adopt rigorous, blockchain-verified Monitoring, Reporting, and Verification (MRV) systems. These protocols must provide a transparent, end-to-end accounting of the supply chain—from the soil-carbon impacts of biomass cultivation to the long-term integrity of geological storage—ensuring that carbon credits are only issued for high-integrity, net-negative removals.
1. A Shift Toward Modular and Scalable Technology: Rather than focusing on bespoke, billion-dollar engineering projects, the industry should move toward modular, containerized carbon capture units. These standardized units can be mass-produced at lower costs, thereby dramatically reducing Capital Expenditure (CAPEX) for smaller biofuel producers. This shift is particularly critical for the Global South, as it allows smaller sugarcane mills or agricultural cooperatives to participate in carbon markets without the need for massive state subsidies, as required by Northern 'Power-BECCS' models.[97]

The development of a supportive and coherent policy framework is therefore crucial for the responsible deployment of BECCS. This includes not only providing financial incentives but also establishing clear and robust regulations for the entire BECCS value chain, from sustainable biomass sourcing to long-term monitoring and verification of CO2 storage. The accounting of negative emissions from BECCS within national and international climate frameworks is another complex policy challenge that must be addressed. There is a need for internationally agreed-upon methodologies to ensure that the claimed carbon removals are real, permanent, and additional. The development of such a comprehensive policy framework is further complicated by the fact that BECCS intersects with a wide range of policy domains, including energy, agriculture, forestry, and land use, each with its own set of competing interests and objectives. The lack of a clear and consistent policy signal has created a significant level of investment risk for the private sector,

[97] Department for Energy Security and Net Zero, 'Update on the UK Cluster Sequencing Process' (January 2025)

which has been a major impediment to the deployment of BECCS at a scale that would be meaningful for climate change mitigation.[98] Ultimately, the future of BECCS will depend not only on technological innovation but also on the political will to create a policy environment that can effectively and equitably manage the complex trade-offs inherent in this technology.[99]

8. BECCS in Context: A Comparative Analysis of Alternative Negative Emissions Technologies[100]

While bioenergy with carbon capture and storage (BECCS) features prominently in many decarbonization pathways, it is crucial to recognize that it is not a monolithic solution and does not exist in a vacuum.[101] It is one of several Negative Emissions Technologies (NETs) being proposed to draw down atmospheric CO2 actively.[102] A comprehensive evaluation of BECCS's role and importance necessitates a comparative analysis against other leading NETs, primarily nature-based solutions, such as Afforestation and Reforestation (A/R), and purely technological approaches, such as Direct Air Capture with Carbon Storage (DACCS).[103] By weighing these alternatives across key metrics, such as land and resource footprint, cost, permanence of storage, scalability, and technological readiness—we can better situate BECCS within a realistic and responsible climate mitigation portfolio, understanding its unique trade-offs rather than viewing it as a standalone panacea.[104]

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[98] L M Gurtner and S Moser, 'The where, how, and who of mitigating climate change: A targeted research agenda for psychology' (2024) 94 Journal of Environmental Psychology 102250 https://doi.org/10.1016/j.jenvp.2024.102250 accessed 21 October 2025.

[99] A Almena, V Ghorbani Pashakolaie and M Martin, 'Unlocking BECCS viability through monetising societal benefits by techno-socio-economic assessment' (2025) 59 Sustainable Production and Consumption 255–273 https://doi.org/10.1016/j.spc.2025.08.016 accessed 25 October 2025.

[100] National Academies of Sciences, Engineering, and Medicine, Negative Emissions Technologies and Reliable Sequestration: A Research Agenda (National Academies Press, 24 October 2018).

[101] V Stavrakas, N-A Spyridaki and A Flamos, 'Striving towards the Deployment of Bio-Energy with Carbon Capture and Storage (BECCS): A Review of Research Priorities and Assessment Needs' (2018) 10 Sustainability 2206 https://doi.org/10.3390/su10072206 accessed 21 October 2025.

[102] National Academies of Sciences, Engineering, and Medicine, Negative Emissions Technologies and Reliable Sequestration: A Research Agenda (National Academies Press, 24 October 2018).

[103] P Ganeshan, V V S, S C Gowd, R Mishra, E Singh, A Kumar, S Kumar, A Pugazhendhi and K Rajendran, 'Bioenergy with carbon capture, storage and utilization: Potential technologies to mitigate climate change' (2023) 177 Biomass & Bioenergy 106941 https://doi.org/10.1016/j.biombioe.2023.106941 accessed 25 October 2025.

[104] L M Gurtner and S Moser, 'The where, how, and who of mitigating climate change: A targeted research agenda for psychology' (2024) 94 Journal of Environmental Psychology 102250 https://doi.org/10.1016/j.jenvp.2024.102250 accessed 21 October 2025.

Afforestation and Reforestation (A/R) represent the most intuitive and widely supported forms of carbon dioxide removal. Similar to BECCS, A/R leverages the power of photosynthesis to capture atmospheric CO2 and store it in biomass and soils. Its advantages are significant and multifaceted.[105] Technologically, it is simple, relying on well-understood ecological principles. Economically, it is often among the least expensive methods of carbon removal per ton. Crucially, A/R can deliver a wealth of co-benefits that BECCS typically lacks, such as enhancing biodiversity, improving soil health, regulating local water cycles, and providing recreational and cultural value. Public perception is overwhelmingly positive, making it a politically feasible option. However, A/R is not without its limitations; the most significant of which is the non-permanence of carbon storage. Forests are vulnerable to reversal events, such as wildfires, disease, pest outbreaks, and illegal logging, which can release decades of stored carbon back into the atmosphere in a short period. Furthermore, forests have a finite capacity for carbon sequestration; as they mature, their net rate of CO2 uptake slows, eventually reaching an equilibrium. Finally, like BECCS, large-scale A/R programs require vast tracts of land, placing them in direct competition with agriculture and other essential land uses, a challenge that is often underestimated in ambitious planting pledges.

BECCS is often presented as a technological enhancement of this biological process, designed to overcome the permanence issue.[106] By harvesting biomass and sequestering the resulting CO2 in deep geological formations, BECCS aims to provide permanent carbon removal, locked away for millennia rather than centuries. In doing so, it also generates dispatchable energy in the form of electricity, heat, or biofuels—a direct economic product that A/R does not offer. However, this purported advantage comes at a steep price. The industrial infrastructure required for BECCS, power plants, capture facilities, pipelines, and injection wells, is vastly more complex and expensive than planting trees. More fundamentally, the BECCS model disrupts the ecological co-benefits associated with natural forests. It often favors fast-growing monoculture plantations that can degrade soil quality, consume large amounts of water, and offer little in the way of habitat for

[105] P Ganeshan, V V S, S C Gowd, R Mishra, E Singh, A Kumar, S Kumar, A Pugazhendhi and K Rajendran, 'Bioenergy with carbon capture, storage and utilization: Potential technologies to mitigate climate change' (2023) 177 Biomass & Bioenergy 106941 https://doi.org/10.1016/j.biombioe.2023.106941 accessed 25 October 2025.
[106] V Stavrakas, N-A Spyridaki and A Flamos, 'Striving towards the Deployment of Bio-Energy with Carbon Capture and Storage (BECCS): A Review of Research Priorities and Assessment Needs' (2018) 10 Sustainability 2206 https://doi.org/10.3390/su10072206 accessed 21 October 2025.

biodiversity. The continuous cycle of harvesting and regrowth in a BECCS system is fundamentally different from the ecological development of a mature forest ecosystem, trading holistic environmental benefits for the singular goal of quantifiable, permanent carbon removal.

At the opposite end of the technological spectrum lies Direct Air Capture with Carbon Storage (DACCS).[107] This is a purely engineering-based solution that uses chemical and physical processes to scrub CO2 directly from the ambient air. Once captured, the CO2 is compressed and, similar to BECCS, injected into geological formations for permanent storage. The most profound advantage of DACCS over any land-based NET is its remarkably small land footprint.[108] DACCS plants can be built on non-arable land, in deserts, or co-located with industrial facilities, thereby completely avoiding the contentious land-use trade-offs that plague both BECCS and A/R. This decoupling of carbon removal from the agricultural and forestry sectors is a powerful argument in its favor, as it sidesteps the complex and often unverifiable accounting of land-use emissions and removes the direct threat to food security and natural ecosystems. DACCS offers a clear, verifiable, and permanent method of CO2 removal.

However, the current drawbacks of DACCS are formidable, centring primarily on its enormous energy requirements and prohibitive costs.[109] The laws of thermodynamics dictate that capturing CO2 from a dilute atmosphere (around 420 parts per million) is significantly more energy-intensive than capturing it from a concentrated flue gas stream (as in BECCS).[110] For DACCS to be truly carbon-negative, this substantial energy input must come from a dedicated low-carbon source, adding another layer of infrastructure and cost. Consequently, current estimates place the cost per ton of CO2 removed via DACCS several times higher than even the most optimistic projections for BECCS. While proponents argue that costs will decline with technological learning and economies of scale, much like solar panels and wind turbines, it remains a nascent and

[107] Institute for Carbon Removal Law & Policy, Direct Air Capture with Carbon Storage (DACCS): Carbon Removal Fact Sheet (American University, Washington DC, October 2018) https://www.american.edu/sis/centers/carbon-removal/upload/icrlp_fact_sheet_daccs_181005.pdf accessed 25 October 2025.
[108] National Academies of Sciences, Engineering, and Medicine, Negative Emissions Technologies and Reliable Sequestration: A Research Agenda (National Academies Press, 24 October 2018).
[109] Institute for Carbon Removal Law & Policy, Direct Air Capture with Carbon Storage (DACCS): Carbon Removal Fact Sheet (American University, Washington DC, October 2018) https://www.american.edu/sis/centers/carbon-removal/upload/icrlp_fact_sheet_daccs_181005.pdf accessed 25 October 2025.
[110] F Sher, S Hameed, N Smječanin Omerbegović, B Wang, I Ul Hai, T Rashid, YH Teoh and MJ Yildiz, 'Bioenergy with carbon capture and storage technology to achieve net zero emissions – A review' (2025) 210 Renewable and Sustainable Energy Reviews 115229 https://doi.org/10.1016/j.rser.2024.115229 accessed 25 October 2025.

exceptionally expensive technology today. In this comparison, BECCS occupies a challenging middle ground.[111] While nature-based alternatives, such as afforestation, can enable removal at less than 50 per ton, and current DACCS implementation frequently surpasses 600 per ton, BECCS presents a technically mature option in the 100-200 per ton range.[112] It is less expensive and more technologically mature than DACCS but carries an immense environmental and social baggage that DACCS avoids. It offers more permanent storage than A/R but sacrifices nearly all associated ecological co-benefits.

Ultimately, this comparative analysis reveals that there is no "silver bullet" among negative emissions technologies.[113] A portfolio approach is almost certainly necessary, in which different NETs are deployed strategically based on regional context,[114] available resources, and desired outcomes. A/R is a vital, low-cost strategy that should be pursued for its climate and ecological benefits, with the understanding that its storage is non-permanent. DACCS represents a crucial long-term technological hedge and a potentially scalable solution for a world with constrained land resources, provided its cost and energy challenges can be overcome. [115]BECCS, however, emerges as a particularly high-risk option. It attempts to merge a biological process with an industrial one but arguably inherits the most significant drawbacks of both: the massive land and resource footprint of large-scale bioenergy, and the high cost and technical risk of carbon capture and storage. Its narrow pathway to genuine sustainability likely lies not in the large-scale deployment envisioned in climate models, but in niche applications utilizing non-dedicated feedstocks, such as agricultural residues, forestry waste, or municipal solid waste, which would avoid the perilous trade-offs with land, food, and biodiversity.

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[111] V Stavrakas, N-A Spyridaki and A Flamos, 'Striving towards the Deployment of Bio-Energy with Carbon Capture and Storage (BECCS): A Review of Research Priorities and Assessment Needs' (2018) 10 Sustainability 2206 https://doi.org/10.3390/su10072206 accessed 21 October 2025.

[112] Haris Ishaq and Curran Crawford, 'Negative Emission Technologies: A Way Forward?' (2025) 3 RSC Sustainability 3652–3680 https://doi.org/10.1039/D5SU0016

[113] National Academies of Sciences, Engineering, and Medicine, Negative Emissions Technologies and Reliable Sequestration: A Research Agenda (National Academies Press, 24 October 2018).

[114] National Academies of Sciences, Engineering, and Medicine, Negative Emissions Technologies and Reliable Sequestration: A Research Agenda (National Academies Press, 24 October 2018).

[115] D Garza, P Dargusch and D Wadley, 'A Technological Review of Direct Air Carbon Capture and Storage (DACCS): Global Standing and Potential Application in Australia' (2023) 16 Energies 4090 https://doi.org/10.3390/en16104090 accessed 25 October 2025.

9. Conclusion: A Cautious Path Forward for BECCS[116]

Bioenergy with Carbon Capture and Storage occupies a complex and contested space in the portfolio of climate change mitigation strategies.[117] On the one hand, it offers the tantalizing prospect of large-scale negative emissions, a capability that many climate models suggest is indispensable for achieving the ambitious goals of the Paris Agreement.[118] The technological pathways for BECCS are diverse and evolving, and pioneering projects, such as the Drax Power Station and the ADM Decatur facility, have provided invaluable, albeit mixed, real-world experience. On the other hand, the deployment of BECCS is fraught with profound challenges that cast a long shadow over its potential.[119] The case studies examined in this paper have illuminated the multifaceted nature of these challenges, which span the technical, economic, environmental, and social domains. These cases show that BECCS rarely eliminates systemic risk; instead, it redistributes it—upstream into biomass governance and accounting, downstream into storage stewardship and liability, and laterally into land-use displacement pressures that sit beyond the immediate regulatory horizon.

The Drax Power Station, with its ambitious plans for carbon-negative power generation, has become a lightning rod for debate over the sustainability of biomass sourcing and the true lifecycle emissions of BECCS.[120] The project's reliance on imported wood pellets has raised legitimate concerns about deforestation, biodiversity loss, and the carbon debt of forest harvesting, questioning the foundation of its claimed climate benefits. Similarly, the ADM Decatur project, although technically successful in many respects, has been plagued by issues of storage integrity

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[116] V Stavrakas, N-A Spyridaki and A Flamos, 'Striving towards the Deployment of Bio-Energy with Carbon Capture and Storage (BECCS): A Review of Research Priorities and Assessment Needs' (2018) 10 Sustainability 2206 https://doi.org/10.3390/su10072206 accessed 21 October 2025.

[117] L M Gurtner and S Moser, 'The where, how, and who of mitigating climate change: A targeted research agenda for psychology' (2024) 94 Journal of Environmental Psychology 102250 https://doi.org/10.1016/j.jenvp.2024.102250 accessed 21 October 2025.

[118] Intergovernmental Panel on Climate Change (IPCC), Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the IPCC (Cambridge University Press 2021) https://www.ipcc.ch/report/ar6/wg1/ accessed 22 October 2025.

[119] Illinois Industrial Carbon Capture and Storage Project (Decatur, Illinois) (Carbon Capture & Sequestration Technologies Program, Massachusetts Institute of Technology, 30 September 2016) https://sequestration.mit.edu/tools/projects/illinois_industrial_ccs.html accessed 22 October 2025.

[120] Drax Group, "Analysis: Development of BECCS at Drax Power Station projected to save UK £15bn and offset carbon emissions equivalent to all departing flights from Heathrow" (Press release, 16 January 2024) https://www.drax.com/press_release/analysis-development-of-beccs-at-drax-power-station-projected-to-save-uk-15bn-and-offset-carbon-emissions-equivalent-to-all-departing-flights-from-heathrow/ accessed 22 October 2025.

and transparency, highlighting the significant risks and uncertainties associated with the long-term geological sequestration of CO2. These case studies underscore a crucial point: the theoretical potential of BECCS is far from guaranteed reality.[121]

Adding the Brazilian experience to this matrix shatters the illusion of a geographically uniform BECCS rollout. While Brazil successfully circumvents the prohibitive capture costs plaguing Northern facilities via cheap sugarcane fermentation, its trajectory confirms a sobering reality: resolving thermodynamic and economic friction does not neutralize the terrestrial limits of the biosphere. Instead, it merely displaces the crisis, substituting technological hurdles for severe indirect land-use change and the entrenchment of agrarian inequalities.[122]

The environmental and social quagmire of BECCS, particularly the immense land-use requirements and the potential for conflict with food security and biodiversity, remains a formidable obstacle.[123] The prospect of converting vast swathes of land to monoculture bioenergy plantations, with all the attendant ecological and social consequences, cannot be taken lightly. The economic viability of BECCS is also highly questionable, with its heavy reliance on public subsidies and the lack of a strong and stable carbon price, creating a significant investment barrier. The policy labyrinth surrounding BECCS, with its fragmented and often contradictory signals, further complicates the path forward.

Considering these profound challenges, a cautious and discerning approach to the future of BECCS is warranted. BECCS should not be viewed as a silver bullet solution to the climate crisis, nor should it be allowed to detract from the urgent and primary task of reducing greenhouse gas emissions at their source. The promise of future negative emissions must not be used as an excuse for inaction in the present. However, to dismiss BECCS entirely would be to ignore its potential role, albeit a potentially limited and conditional one, in a comprehensive climate change mitigation

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[121] V Stavrakas, N-A Spyridaki and A Flamos, 'Striving towards the Deployment of Bio-Energy with Carbon Capture and Storage (BECCS): A Review of Research Priorities and Assessment Needs' (2018) 10 Sustainability 2206 https://doi.org/10.3390/su10072206 accessed 21 October 2025.

[122] L F de Almeida and J A C de Oliveira, 'The political ecology of BECCS in the Global South: Lessons from the Brazilian sugarcane frontier' (2024) 81 Global Environmental Change 102715.

[123] S V Hanssen et al, 'Global implications of crop-based bioenergy with carbon capture and storage for terrestrial vertebrate biodiversity' (2022) 14 GCB Bioenergy 307–321 https://doi.org/10.1111/gcbb.12911 accessed 25 October 2025.

strategy.[124] There may be specific niches where BECCS can be deployed in a genuinely sustainable and beneficial manner, such as by utilizing waste biomass streams that do not compete with food production or require additional land conversion.[125]

The path forward for BECCS, if it is to have one, must be guided by a set of stringent and non-negotiable principles.[126] First and foremost is the imperative of sustainable and verifiable biomass sourcing, with a clear and scientifically robust accounting of lifecycle emissions. Second is the need for a comprehensive and participatory approach to land-use planning that prioritizes food security, biodiversity, and the rights of local communities. Third is the development of a coherent and equitable policy framework that provides a level playing field for all climate solutions and ensures that the costs and benefits of BECCS are distributed fairly. Finally, there must be a commitment to ongoing research and development to improve efficiency and reduce the costs of BECCS technologies, as well as to enhance our understanding of the long-term risks and impacts of CO2 storage.[127] It should be noted that biomass governance and lifecycle accounting that does not convert temporal uncertainty into regulatory certainty. Second is land-use planning that can prevent indirect displacement and protecting food security and biodiversity. Third is a coherent policy framework that provides incentives with durable stewardship and liability arrangements for long-term storage integrity. Finally, ongoing research and development remains essential to reduce costs and improve monitoring, verification, and permanence,

In conclusion, the importance of BECCS in addressing climate change is not a given but a question that can only be answered through a rigorous and honest assessment of its potential and its perils. The case studies of Drax[128] and ADM Decatur offer a sobering glimpse into the complexities of

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[124] L M Gurtner and S Moser, 'The where, how, and who of mitigating climate change: A targeted research agenda for psychology' (2024) 94 Journal of Environmental Psychology 102250 https://doi.org/10.1016/j.jenvp.2024.102250 accessed 21 October 2025.

[125] A Köberle, 'The Value of BECCS in IAMs: A Review' (2019) 6 Current Sustainable/Renewable Energy Reports 107–115 https://doi.org/10.1007/s40518-019-00142-3 accessed 25 October 2025.

[126] V Stavrakas, N-A Spyridaki and A Flamos, 'Striving towards the Deployment of Bio-Energy with Carbon Capture and Storage (BECCS): A Review of Research Priorities and Assessment Needs' (2018) 10 Sustainability 2206 https://doi.org/10.3390/su10072206 accessed 21 October 2025.

[127] S V Hanssen et al, 'Global implications of crop-based bioenergy with carbon capture and storage for terrestrial vertebrate biodiversity' (2022) 14 GCB Bioenergy 307–321 https://doi.org/10.1111/gcbb.12911 accessed 25 October 2025.

[128] Drax Group, "Analysis: Development of BECCS at Drax Power Station projected to save UK £15bn and offset carbon emissions equivalent to all departing flights from Heathrow" (Press release, 16 January 2024) https://www.drax.com/press_release/analysis-development-of-beccs-at-drax-power-station-projected-to-save-uk-15bn-and-offset-carbon-emissions-equivalent-to-all-departing-flights-from-heathrow/ accessed 22 October 2025.

translating the theoretical promise of BECCS into a practical and sustainable reality.[129] Although the allure of negative emissions is strong, the path to achieving them through BECCS is fraught with challenges that demand our utmost caution and diligence. The future of BECCS, if it is to be a part of a just and sustainable future, will depend not on wishful thinking but on a clear-eyed and evidence-based approach that prioritizes the well-being of people and the planet.

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