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Energy Transition in Brazil and the Role of Bioenergy with Carbon Capture and Storage

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Abstract

Climate change demands robust measures to mitigate greenhouse gas (GHG) emissions. Among carbon dioxide removal approaches assessed in the literature, Bioenergy with Carbon Capture and Storage (BECCS) has received particular attention. This study conducted a narrative literature review of an exploratory and descriptive nature, based on 16 unique articles selected from the ScienceDirect database. The objective was to analyze the role attributed to BECCS technology in the scientific literature within the context of Brazil's energy transition. The results indicate that Brazil has favorable conditions for BECCS deployment, including extensive bioenergy production, especially ethanol, and geological storage potential. However, the literature also identifies high costs, regulatory barriers, infrastructure constraints, and ecological risks associated with biomass cultivation. Scenario studies reviewed here indicate that BECCS may provide negative emissions that compensate for residual emissions in hard-to-abate sectors and, in some modeled pathways, permit continued partial fossil-fuel use. Accordingly, the possibility that BECCS could be invoked to support continued oil and gas production is treated in this article as a governance risk rather than as an inevitable outcome. Net-negative performance remains conditional on sustainable biomass supply, lifecycle emissions, capture-energy requirements, transport emissions, and durable geological storage.

Keywords

Bioenergy with Carbon Capture and Storage (BECCS), Energy Transition, Carbon Dioxide Removal (CDR), Negative Emissions, Bioenergy, Brazil

1. Introduction

The Sixth Assessment Report of the Intergovernmental Panel on Climate Change

(IPCC, 2021b) scientifically confirms that global warming is due to human influence. Global greenhouse gas emissions have unequivocally caused global warming (IPCC, 2023), and such emissions continue to grow, driven by unsustainable energy use, land-use changes, lifestyles, and consumption and production patterns, varying between regions, countries, and individuals (IPCC, 2023).

The Paris Agreement is an international milestone established within the framework of the United Nations Framework Convention on Climate Change (UNFCCC), adopted on December 12, 2015, during the 21st Conference of the Parties on Climate Change (COP21). The main objective of the Paris Agreement is to limit the increase in the average global temperature to below 2˚C above pre-industrial levels, with efforts to restrict warming to 1.5˚C. One of the main objectives in terms of mitigation is to reduce greenhouse gas emissions through Nationally Determined Contributions (NDCs), which are spontaneous expressions of commitments by member countries to achieve the objectives of the agreement, with NDCs being updated every five years (UN, 2015).

According to the first global assessment, the NDCs of the countries participating in the Paris Agreement contributed to a reduction in the projected global temperature, which was 4˚C, to a range of 2.1 to 2.8˚C, if the NDCs are fully implemented. However, a warning was issued about the shortfall in actions to align global emissions to limit warming to 1.5˚C (UNFCCC, 2023), given that the projected global temperature remained above this limit.

According to the Summary for Policymakers document, published by the IPCC in 2018, all pathways to limit global warming to 1.5˚C, with little or no overshoot, foresee the use of carbon dioxide removal (CDR) between 100 and 1000 $GtCO_2$ throughout the 21st century. CDRs would be used to offset residual emissions and, in most cases, achieve net negative emissions to return global warming to 1.5˚C after the peak that exceeds the limit (IPCC, 2018a).

Although the Brazilian energy matrix is above the world average in terms of domestic energy supply from renewable sources (EPE, 2023), meeting the growing energy needs of the Brazilian economy with low-carbon sources seems inevitable, and BECCS technology can play a central role in this process (Lap et al., 2023).

The current version of Brazil's NDC, presented in November 2024, foresees the expansion of biofuel production associated with carbon capture and storage for the energy sector as a way to meet the demand for negative greenhouse gas emissions (Brasil, 2024b).

Therefore, investigating the role of BECCS in the energy transition is relevant, since the technology has increasingly featured in important references on the world stage.

The objective of this article was a narrative literature review that aimed to analyze the role attributed by the scientific literature to BECCS in the energy transition scenario in Brazil.

2. Methodology

The proposed methodology for the development of this work consists of a narrative bibliographic review of scientific literature of an exploratory nature and descriptive approach.

According to Botelho et al. (2011: p. 125), "the narrative review is used to describe the state of the art of a specific subject, from a theoretical or contextual point of view." Furthermore, according to Cavalcante and Oliveira (2020), "this type of method allows a broad description of the subject, but does not exhaust all sources of information, since its realization is not done through systematic search and analysis of data." In this context, the present research presents the state of the art on the energy transition in Brazil and the role of BECCS.

The bibliographic material was collected through a search in the ScienceDirect digital repository using the terms "energy transition," "BECCS," and "Brazil" in October 2024, considering articles published in any year. The initial search returned 103 records. Abstracts were screened using explicit relevance criteria: studies were retained when they i) addressed BECCS, bioenergy combined with carbon capture, or a directly relevant CCS/CDR application; and ii) provided evidence relevant to Brazil's energy transition, including Brazilian applications, bioenergy systems, carbon-removal pathways, deployment barriers, or scenario implications. Records focused on unrelated technologies, regions or applications without transferable relevance to the research question were excluded. After the application of these criteria, 16 unique articles were selected for full-text reading and analysis.

The 16 unique articles selected for full-text analysis are listed in **Table 1** below.

All 16 selected articles were read in full to answer the central research question: what role is attributed to BECCS technology in the context of the energy transition in Brazil? The analysis used a qualitative thematic coding framework. For each study, the authors identified whether BECCS was framed primarily as i) carbon dioxide removal through net-negative emissions, ii) mitigation or compensation for residual emissions in hard-to-abate sectors, iii) support for bioenergy and low-carbon fuel systems, and/or iv) an offset that creates room for continued fossil-fuel use in modeled pathways. Ecological, technological, social, economic, and regulatory conditions affecting these roles were also recorded. The synthesis then distinguished statements explicitly supported by the reviewed studies from the authors' interpretive discussion of policy and governance implications.

The analysis of the collected data was conducted in a descriptive and critical manner, allowing the construction of an articulated, up-to-date, and systematic understanding of the topic. It is worth emphasizing that most of the articles analyzed were published in 2024, which reinforces the timeliness of the discussion.

In addition, the subjects addressed in this research have been the object of constant research and improvement, so that the literature review presents an updated and systematized view of the main advances. The importance of this research is highlighted, since no recent studies were identified that gave identical treatment to the topic, reinforcing its academic pertinence and scientific relevance.

Table 1. Articles selected for analysis.

Heading	Year	Authors
BECCS potential in Brazil: Achieving negative emissions in ethanol and electricity production based on sugar cane bagasse and other residues	2016	José Roberto Moreira, Viviane Romeiro, Sabine Fuss, Florian Kraxner, Sérgio A. Pacca
Carbon capture potential and costs in Brazil	2016	Pedro R.R. Rochedo, Isabella V.L. Costa, Mariana Imperio, Bettina Susanne Hoffmann, Paulo Roberto de C. Merschmann, Camilla C.N. Oliveira, Alexandre Szklo, Roberto Schaeffer
Bioenergy with carbon capture and storage (BECCS): Global potential, investment preferences, and deployment barriers	2018	Mathias Fridahl, Mariliis Lehtveer
CO_2 capture in ethanol distilleries in Brazil: Designing the optimum carbon transportation network by integrating hubs, pipelines and trucks	2018	Fabio T.F. da Silva, Francielle M. Carvalho, Jorge Luiz G. Corrêa Jr., Paulo R. de C. Merschmann, Isabela S. Tagomori, Alexandre Szklo, Roberto Schaeffer
The post-carbon society: Rethinking the international governance of negative emissions	2018	Espen Moe, Jo-Kristian S. Røttereng
A first look at social factors driving CCS perception in Brazil: A case study in the Recôncavo Basin	2020	Anna Luisa Abreu Netto, George Câmara, Expedito Rocha, Aldo Luiz Silva, José Célio Silveira Andrade, Drielli Peyerl, Paulo Rocha
The role of biomass gasification and methanisation in the decarbonisation strategies	2020	Gabin Mantulet, Adrien Bidaud, Silvana Mima
Bioenergy with carbon capture and utilization: A review on the potential deployment towards a European circular bioeconomy	2021	E.I. Koytsoumpa, D. Magiri-Skouloudi, S. Karellas, E. Kakaras
Costs and benefits of Brazil's climate policies on CCUS business: governmental cases of how institutional changes can shape the agent's behavior	2021	Israel Lacerda de Araújo, Danilo Perecin, Isabela Morbach Machado e Silva, Hirdan Katarina de Medeiros Costa and Zen Makucha
Potential and challenges of bioenergy with carbon capture and storage as a carbon-negative energy source: A review	2021	Alexandre Babin, C´eline Vaneeckhaute, Maria C. Iliuta
Regional energy diversity and sovereignty in different 2 C and 1.5 C pathways	2022	A.F. Hof, K. Esmeijer, H.S. de Boer, V. Daioglou, J.C. Doelman, M.G.J. den Elzen, D.E.H.J. Gernaat, D.P. van Vuuren
BECCS as climate mitigation option in a Brazilian low carbon energy system: Estimating potential and effect of gigatonne scale CO_2 storage	2023	Tjerk Lap, René Benders, Floor van der Hilst, André Faaij
Climate strategies for oil and gas production under the lens of an Integrated Assessment Model: The case of Brazil	2024	Leticia C. Coutinho, Mariana Império, Gerd Angelkorte, Gabriela N. da Silva, Clarissa Bergman-Fonte, Rebecca Draeger, Bruno S.L. Cunha, Pedro R.R. Rochedo, Alexandre Szklo, Roberto Schaeffer
Emerging bio-capture strategies for greenhouse gas reduction: Navigating challenges towards carbon neutrality	2024	Tanmay Tiwari, Gun Anit Kaur, Pravin Kumar Singh, Sapna Balayan, Anshuman Mishra, Ashutosh Tiwari
Life cycle assessment of bioenergy with carbon capture and storage: A review	2024	D.A. Salas, A.J. Boero, A.D. Ramirez
The role of bioenergy in Brazil's low-carbon future	2024	Matheus Poggio, Mariana Império, Luiz Bernardo Baptista, Roberto Schaeffer, André F.P. Lucena, Alexandre Szklo, Pedro R.R. Rochedo, Nathan Hultman, Haewon McJeon, Leon Clar

3. Discussion and Results

3.1. Energy Transition

The energy transition is essential to limit the increase in global temperature to 1.5°C above pre-industrial levels, which requires rapid decarbonization of energy systems and the adoption of existing and emerging technologies (IPCC, 2023).

The energy transition represents the need to adapt energy systems to models that emit fewer greenhouse gases compared to fossil fuels, which are responsible for 81% to 91% of global GHG emissions from total anthropogenic emissions (IPCC, 2021a).

The National Energy Plan 2050 (MME/EPE, 2020: p. 34) states the following on the subject:

The concept of energy transition is associated with significant changes in the structure of the world's primary energy matrix. Characteristically, energy transitions are complex processes, with variations in the stage and pace of transformation in different countries, regions, or localities. In other words, it is generally not a linear, disruptive process, but rather a long coexistence between the source that characterizes it and the sources that are progressively replaced. Factors involving the transition of energy production, transport, and utilization infrastructure are some that explain the slow transition of energy systems worldwide. The current energy transition process has been underpinned by conditions such as sustainable development, climate change, and technological innovations associated with electronics and the entry into the digital age.

As discussed in the National Energy Plan 2050 (MME/EPE, 2020), the energy transition goes beyond changes in the primary energy matrix, encompassing profound alterations in conversion technologies, consumption patterns, and socioeconomic and environmental relations. These transformations also affect the geopolitics of energy and bring regulatory and market opportunities. The new Brazilian energy transition, based on renewable electrification, biofuels, energy efficiency, and natural gas, integrates fossil and renewable fuels, with emphasis on green hydrogen and batteries, essential for decarbonizing the energy system and meeting climate goals.

According to Lima and Hamzagic (2022), the current energy transition is a phenomenon in response to the need to seek energy sources that generate lower greenhouse gas (GHG) emissions into the atmosphere. Similarly, the National Energy Plan 2050 (MME/EPE, 2020) argues that the current energy transition highlights the shift towards more sustainable energy sources, intending to achieve an energy matrix that reduces greenhouse gas emissions.

However, according to Rifkin (2012), who associates industrial revolutions with transformations in energy and communication sources, this is not the first energy transition the world has experienced.

The First Industrial Revolution, which began in the 18th century, was marked by the exploitation of coal and the invention of the steam engine. This combination enabled a significant transformation in the economy, shifting from agricultural systems to mechanized industries, and allowed for the expansion of railway infrastructure, increasing the capacity to transport goods and people. The new energy matrix brought unprecedented productivity, but also consolidated centralized structures of power and production (Rifkin, 2012).

The second Industrial Revolution, in the late 19th and early 20th centuries, was driven by the introduction of fossil fuels, especially oil and natural gas, as well as electrification. The internal combustion engine, along with the growth of electrical grids, enabled advances in transportation, communications, and manufacturing. This transition shaped modern capitalism, but was responsible for high environmental costs, including significant greenhouse gas emissions and socioeconomic inequalities between nations (Rifkin, 2012).

The third industrial revolution, which we are currently experiencing, is marked by a transformation of the energy sector and characterized by decentralization and sustainability. The use of renewable sources, such as solar, wind, and biomass, combined with the technological possibilities of digitalization and smart grids, is transforming the way society relates to energy (Rifkin, 2012).

The energy transition, according to the National Energy Plan (MME/EPE, 2020), integrates a set of fundamental policies for the energy sector and for the socioeconomic development of the country. Among the main challenges of this transformation are the reconciliation between job creation, income generation, social inclusion, combating inequalities, improving the quality of life of the population, reindustrialization, preservation of biodiversity and environmental quality, among other essential aspects.

Therefore, the energy transition is not just a moment of transformation of energy sources, but also an opportunity for a more inclusive and just society.

The current energy transition represents a process of structural transformation in the energy sector, aiming to replace fossil fuel energy sources with renewable and sustainable sources. This movement is not only an environmental necessity but also a socio-economic imperative, given its potential to drive sustainable development and promote social justice (Rogelj et al., 2018).

However, the energy transition also presents challenges, such as high initial costs and the need for effective public policies that promote both decarbonization and social inclusion. The conservation of biodiversity and the reduction of negative socio-environmental impacts are central points that must be considered in formulating strategies for expanding renewable sources, such as solar, wind, and biomass (IPCC, 2022).

The history of the Brazilian energy transition reveals a country that is highlighted by its already highly renewable electricity and energy matrix (EPE, 2024), which followed peculiar paths marked by energy supply crises that led to energy policies of source diversification.

For example, in the 2000s, Brazil faced electricity supply crises that accelerated investments in alternative sources, such as natural gas and biomass thermal plants, reducing the country's dependence on hydroelectric power. Nuclear energy was also incorporated into the energy mix with the Angra 1 and Angra 2 plants, which together accounted for about 2% of the electricity supply in 2020. In that same year, biomass, especially sugarcane bagasse, already accounted for 9% of the national electricity matrix (EPE, 2024).

However, despite having a domestic energy supply composition above the world average in terms of renewable energy share, Brazil is still a major emitter of greenhouse gases worldwide (WRI, 2026).

In August 2024 (EPE, 2024), the National Energy Transition Plan was released, which aims to structure long-term actions to direct efforts towards a more sustainable energy matrix with low carbon emissions.

Regarding the domestic supply of energy from biomass, according to the 2024 National Energy Balance (EPE, 2024), approximately 32.7% of the domestic energy supply comes from biomass, with 16.9% derived from sugarcane, 8.6% from firewood and charcoal, and 7.2% from other renewable sources, including black liquor, biodiesel, other biomass (such as rice husks, elephant grass, and vegetable oils), biogas, and industrial gas from charcoal.

Nevertheless, the significant percentage of sugarcane derivatives in the energy mix stems from past policies that sought to reduce national dependence on oil in the face of international crises, such as Proálcool, from 1975, Proinfa, from 2002, the technology of flex-fuel vehicles, as well as the use of waste from the sugar and alcohol industry.

Law No. 13,576, of December 26, 2017, which provides for the National Biofuels Policy (RenovaBio), seeks to consolidate previous biofuel policies (Grangeia et al., 2022) and establishes the objective of contributing to the fulfillment of the country's commitments under the Paris Agreement under the United Nations Framework Convention on Climate Change.

Similarly, the Brazilian Center for International Relations, the Inter-American Development Bank, the Energy Research Company, and the Center for Energy and Environmental Economics (Cebri et al., 2023), when addressing carbon neutrality within the Energy Transition Program, point to a growth in the use of biomass-derived energy as the main exponent in the three scenarios outlined for 2050, followed by solar and wind sources. This report not only highlights the importance of biomass in reducing emissions from the transport sector, but also as an instrument for achieving negative emissions through bioenergy technology combined with carbon capture and storage (BECCS). Therefore, biofuels are seen as a strategic option for the country.

Along the same lines, the study developed by Mantulet et al. (2020) indicates that there will be global growth in biomass consumption in climate policy scenarios, especially second-generation ones, but with very different patterns according to the functions and specificities of the countries where they are implemented.

In reality, there is growing evidence indicating that the most effective paths to transitioning to a carbon-neutral energy system involve a diversified portfolio of low-carbon energy sources, including renewables, nuclear energy, carbon capture and storage (CCS), and bioenergy (Babin et al., 2021; Kriegler et al., 2014; Krey et al., 2014; Williams et al., 2012; Mileva et al., 2016; Brick & Thernstrom, 2016; Hof et al., 2022).

It is worth highlighting that of the scenarios from the Intergovernmental Panel on Climate Change that show more than a 50% probability of achieving the 2˚C target, 87% assume the widespread adoption of negative emissions (Moe & Røttereng, 2018; IPCC, 2014).

The Brazilian Nationally Determined Contribution, released in November 2024, explicitly includes carbon capture, use, and storage technologies in bioenergy production among national mitigation actions, indicating a policy-relevant role for BECCS while not determining the scale or conditions of its future deployment (Brasil, 2024b: p. 19):

Leveraging innovative low-carbon solutions in national production and developing carbon capture, use, and storage technologies in bioenergy production and fossil fuel sectors.

Therefore, BECCS is expressly contemplated within Brazil's national mitigation objectives, although its effective contribution will depend on deployment scale, lifecycle performance, costs, infrastructure, and the permanence of CO_2 storage.

3.2. Carbon Dioxide Removal Technologies

According to the IPCC (2023), Carbon Dioxide Removal (CDR) technologies are anthropogenic activities that remove carbon dioxide (CO_2) from the atmosphere and store it sustainably in geological, terrestrial, or oceanic reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical CO_2 sinks and direct air capture and storage (DACCS), but excludes natural CO_2 absorption not directly caused by human activities.

Current and potential CDR measures include afforestation and reforestation, land restoration and soil carbon sequestration, BECCS, direct air carbon capture and storage (DACCS), intensified weathering, and ocean alkalization. These technologies vary widely in terms of maturity, potential, costs, risks, collateral benefits, and trade-offs (IPCC, 2018b).

According to the IPCC (2023), carbon capture and storage (CCS) can be defined as a process in which a relatively pure stream of carbon dioxide (CO_2) from industrial and energy-related sources is separated (captured), conditioned, compressed, and transported to a storage location for long-term isolation from the atmosphere.

EPE (2023) advocates CCS as a fundamental strategy for the energy transition in Brazil, especially in the context of the oil and gas sector, in line with global climate goals. Given the projected increase in hydrocarbon production, CCS emerges as a solution to mitigate greenhouse gas (GHG) emissions while maintaining energy security. The technology encompasses three main stages: capture, transport, and storage of carbon dioxide (CO_2), with potential applications also in enhanced oil recovery (EOR).

Brazil already applies advanced CCS techniques, such as in the pre-salt layer, and is discussing regulatory frameworks to promote the sector, including Bill No. 1425/2022 (Brasil, 2022) and Law No. 14,993/2024 (Brasil, 2024a), which regulates the storage of CO_2 in geological reservoirs.

According to Gaspar (2014), carbon capture and storage (CCS) is an essential technology for mitigating greenhouse gas emissions, with the capacity to capture up to 90% of the CO_2 emitted by industrial and energy sources, storing it safely in deep geological formations.

Recognized by the International Energy Agency (IEA) (IEA, 2020a) as a key tool for achieving emissions cuts, carbon capture, utilization, and storage (CCUS) can be adapted to existing industrial and power plants, allowing for their continued operation. It can address emissions in sectors that are difficult to reduce, particularly heavy industries such as cement, steel, or chemicals.

According to Daniels (2023), CCS plays a crucial role in industries that are difficult to decarbonize, in the production of low-carbon hydrogen, and in the supply of dispatchable energy with reduced emissions. Although implementation costs vary by sector (US$ 20 - 150/ton), the adoption of hub and cluster models with shared infrastructure has significantly reduced costs. Regional initiatives in the European Union, North America, and Asia-Pacific demonstrate the progress of the technology, but advancement depends on clear policies, specific regulations, and financial incentives that enable investments in the sector.

The International Energy Agency (IEA, 2020b) points to the increased global interest in CCUS, with more than 30 projects announced since 2017, which could triple global capture capacity to around 130 million tons of CO_2 per year. Despite this, investments remain below what is needed. To accelerate implementation, the report suggests incentive policies, the development of industrial hubs with shared infrastructure, and the promotion of technological innovation. Without the CCUS, global climate goals, such as those established by the Paris Agreement, are, according to the document, unattainable.

The CCS Institute (2016) highlights that Brazil has a theoretical storage potential of approximately 2.030 gigatons of CO_2, mainly in deep saline formations and depleted oil and gas fields. Although the country has begun to explore this technology, it still faces challenges in terms of policies, regulations, and large-scale CCS projects.

Petrobras is a global leader in carbon capture, utilization, and geological storage (CCS), operating the world's largest program in terms of CO_2 reinjected annually, and is also a pioneer in ultra-deep waters. In 2022, the company achieved a world record, with 10.6 million tons of CO_2 reinjected, equivalent to 5.8 billion m^3, representing about 25% of the total reinjected by the global industry, according to (Petrobras, 2023b).

The main challenges for the implementation of Carbon Capture and Storage (CCS) technologies in Brazil include the absence of a consolidated regulatory framework, the high costs associated with the development of the necessary infrastructure, and the identification of suitable areas for the geological storage of CO_2.

Despite being partially foreseen in Law No. 14,993 of October 8, 2024 (Brasil, 2024a), regulatory gaps still exist on the part of the ANP (National Agency of Petroleum, Natural Gas and Biofuels). In addition, it is necessary to attract investments and promote economic incentives that enable the expansion of this technology. These challenges demand coordinated actions between the public and private sectors so that the country can take advantage of its storage potential and contribute to the sustainable energy transition (EPE, 2023).

Law No. Law 14,993 of October 8, 2024 (Brasil, 2024a), the so-called "future fuel law," deals with carbon capture and storage, defining carbon dioxide capture as a physical-chemical or biological process of removing carbon dioxide from the atmosphere and from stationary emission sources.

According to the aforementioned law:

Article 27. The execution of carbon dioxide capture activities for geological storage purposes and their storage must observe the following guidelines:

I - economic efficiency and sustainability;

II - adoption of methods, techniques, and processes that consider local and regional peculiarities and industry best practices; and

III - integration of infrastructures, services, and geological and geophysical information for efficient management of the natural resources involved in the development of the activity.

However, the law assigns to the ANP (National Agency of Petroleum, Natural Gas and Biofuels) the responsibility of regulating carbon dioxide capture activities, as per article 28 (Brasil, 2024a).

Nevertheless, Bill No. 1,425/2022 (Brasil, 2022), which regulates the exploitation of the activity of permanent CO_2 storage in geological or temporary reservoirs, and its subsequent reuse, is currently being processed in the National Congress.

The regulatory framework for CCS in Brazil is an important step towards expanding the activity, which has already proven solid in past experiences such as those in the Santos Basin (Petrobras, 2023a).

According to EPE (2023: p. 1):

In Brazil, the expected growth in hydrocarbon production over the decade is confronted with the challenges to the sustainability of the energy sector in the face of pressures imposed by climate change already observed. In this context, Carbon Capture and Storage (CCS) technologies emerge as key elements for meeting the goals defined in international environmental agreements, while alternatives related to renewable sources can, while maintaining energy security, expand their reach in society, increasing their participation in the energy matrix.

Therefore, it is clear that CCS technology has been gaining support and importance over time in the Brazilian context, where growth in the oil and fossil fuel industry is foreseen, which needs to be aligned with the objectives and commitments assumed internationally by the country.

In a similar situation, Beck (2020) points out that most carbon capture technology in the United States is used in ethanol production, enhanced oil recovery, and underground storage in deep rock formations. Currently, the country has about 10 facilities in operation, which together capture approximately 25 million tons of CO_2 per year. Such international experiences can serve as a learning experience for the development of technology in Brazil.

3.3. BECCS

BECCS (bioenergy with carbon capture and storage) technology corresponds to carbon capture and storage (CCS) associated with bioenergy (Ketzer et al., 2016) and consists of a series of processes that capture the carbon dioxide produced during the use of biomass for energy generation and store it in suitable geological formations (Kemper, 2015).

The IPCC (2023) report defines Bioenergy with Carbon Capture and Storage (BECCS) as carbon capture and storage (CCS) technology applied to a bioenergy facility. It should be noted that, depending on the total emissions of the BECCS supply chain, carbon dioxide (CO_2) can be removed from the atmosphere.

The process consists of the stages of capture, transport, and storage, but each of these stages corresponds to a range of possibilities to be executed, so that BECCS corresponds to a variety of possible applications (Silveira, 2023).

The capture stage may be associated with biomass combustion for energy generation or the production of biofuels, during fermentation or anaerobic digestion (Silveira, 2023). After CO_2 capture, it is separated from other gases and compressed until it reaches a supercritical state for transport and injection (Silveira, 2023; Kemper, 2015; Ketzer et al., 2016). After transport, which can be done by pipelines, trucks, or ships, storage occurs, which must be carried out in geological formations with appropriate conditions. According to Ketzer et al. (2016), the reservoir must have a minimum depth of 800m and suitable porosity and permeability properties. Depleted oil and natural gas fields, deep saline formations, and coal seams are examples of formations with storage potential (Ketzer et al., 2016; Silveira, 2023).

According to Ketzer et al. (2016), bioenergy with carbon capture and storage represents a promising option among strategies for reducing greenhouse gas emissions.

BECCS, BECCU, CCS, and CCUS are related but distinct concepts. CCS refers to the capture of CO_2 from industrial or energy-related sources followed by transport and long-term geological storage. CCUS is a broader category that also includes pathways in which captured CO_2 is utilized. When CCS is applied to bioenergy, it is referred to as BECCS; when biogenic CO_2 is captured and used in products or processes, it may be described as BECCU. Carbon utilization does not necessarily constitute durable atmospheric carbon removal because the CO_2 may be re-released depending on the product and its lifetime. Accordingly, the negative-emissions conclusions of this article refer specifically to BECCS pathways in which biogenic CO_2 is permanently stored in geological formations and lifecycle emissions remain lower than the amount durably stored (Koytsoumpa et al., 2021).

This is largely due to the potential of BECCS technology for negative emissions, which occurs through the double capture of carbon, whether in bioenergy production or in combination with carbon capture and storage (CCS) technology. In other words, adding BECCS technology to bioenergy production, whose raw material, biomass, has low emissions, can result in negative emissions (Moreira et al., 2016).

Compared with CCS applied to fossil sources, BECCS can generate net-negative emissions only under specific lifecycle conditions. The carbon removed through biomass growth must exceed emissions associated with cultivation and land-use change, biomass processing and transport, capture energy demand, CO_2 transport, injection, monitoring, and any leakage. Sustainable feedstocks and durable geological storage are therefore prerequisites for treating BECCS as carbon dioxide removal rather than merely as an emissions-reduction technology (Moreira et al., 2016; Salas et al., 2024).

According to Rochedo et al. (2016), the extensive use of biofuels in Brazil, especially ethanol—whose CO_2 capture can be carried out during the fermentation process—combined with the large-scale oil production in sedimentary basins that allow the use of CO_2 for enhanced recovery, gives the country a high potential for both carbon capture and storage. Since this research does not address the issue of transport between biorefineries (where CO_2 would be captured) and oil production fields (where CO_2 would be used for EOR), a gap remains for feasibility analysis.

Several technological approaches to BECCS are being explored globally, and one alternative that deserves highlighting is the application of this technology in energy production from sugarcane. One of the main benefits of this approach is the conversion of part of the primary energy into ethanol through fermentation, a process that generates a relatively pure CO_2 flow. Capturing CO_2 at this stage represents a viable opportunity to achieve negative emissions, making this technology a promising option for mitigating emissions in Brazil (Moreira et al., 2016).

BECCS was indicated by the Intergovernmental Panel on Climate Change as a mitigation strategy compatible with limiting global warming to 1.5˚C, initially proposed as the main alternative to achieve decarbonization targets through negative emissions (IPCC, 2018b).

Fuss et al. (2018) estimated that the decarbonization potential of BECCS is between 0.5 and 5 gigatons of CO_2 per year by 2050, values that are considered high compared to other negative emission technologies.

In Brazil, BECCS technology gained new momentum after the publication of the new Brazilian NDC in November 2024 (Brasil, 2024b: p. 20), where its role is explicitly highlighted:

In the energy sector, where the country already stands out for the high participation of renewable sources in its energy matrix—89.2% electricity mix and 49.1% energy mix—Brazil will seek to expand electricity generation by increasing the participation of clean technology and sources, a considerable challenge given the significant share of these resources in the national electricity matrix. In the medium and long term, it will seek the gradual replacement of the use of fossil fuels with electrification solutions and advanced biofuels—including Sustainable Aviation Fuels—as well as the expansion of biofuel production associated with carbon capture and storage to meet the demand for negative greenhouse gas emissions (Brasil, 2024b).

Thus, within the Brazilian context, one option that deserves special attention is BECCS technology applied to sugarcane-based energy production, since fermentation releases a relatively pure CO_2 stream (Moreira et al., 2016). Therefore, the relatively low cost of capturing the carbon produced during the alcoholic fermentation process and the potential for storage in mature oil fields in the country show an opportunity for BECCS to achieve internationally assumed goals (Silva et al., 2017).

The bioethanol production industry is one of the most indicated by recent literature as a great opportunity for BECCS (Tanzer, Blok, & Ramírez, 2021). Despite this, there is only one BECCS plant in the country in the study and evaluation phase (CCS Institute, 2025). However, despite being considered a low-hanging fruit (Moreira, 2016), BECCS technology also faces a number of challenges. The articles studied indicated ecological, technical, regulatory, and social challenges that need to be overcome for its emissions mitigation potential to be fully realized.

Technologies such as BECCS are still under development and are considered a potential solution for mitigating climate change, but they still present some challenges related to cost, scalability, and environmental impacts (Tiwari et al., 2024).

3.3.1. Ecological Challenges

The implementation of Bioenergy with Carbon Capture and Storage (BECCS) technology faces a series of ecological, technical, and regulatory challenges.

One of the main obstacles is the availability of sustainable biomass. For the use of biomass not to generate adverse environmental impacts, such as deforestation or soil degradation, it is necessary to ensure that its origin is certified and environmentally responsible (Tiwari et al., 2024).

Land-use change is evaluated by several studies, and its large-scale effect calls into question the very suitability of BECCS as a measure to generate negative emissions (Babin, Vaneeckhaute, & Iliuta, 2021) due to the emissions caused by land-use change.

The expansion of biomass production for energy purposes may compete with food production, affect biodiversity, and even cause an increase in greenhouse gas emissions associated with land-use changes. Furthermore, the installation of BECCS plants in ecologically sensitive areas can generate cross-contamination between the natural environment and the biological material used (Tiwari et al., 2024).

In addition, one of the possible impacts of the expansion of monocultures aimed at bioenergy is the conversion or elimination of native vegetation and natural habitats. In addition to altering or losing these habitats, this expansion can also cause changes in the diversity, abundance, composition, and distribution of species (Babin et al., 2021).

One of the proposals to minimize the land-use impacts associated with the expansion of bioenergy is to carry out its production in degraded areas. This approach seeks to take advantage of land that is no longer suitable for food agriculture or wildlife, enabling the expansion of energy biomass cultivation with reduced impacts on food production, biodiversity, and greenhouse gas emissions (Babin et al., 2021; Nijsen et al., 2012).

Another important factor to be evaluated is the amount of water required for biomass production (Babin et al., 2021). In addition, the carbon capture and storage stage also increase the water consumption of a power generation plant by about 20% to 60% (Magneschi et al., 2017).

The energy efficiency of the process is another limiting factor, since the chain involving the production, transport of biomass, conversion into energy, and subsequent capture and storage of carbon consumes significant energy. To mitigate losses and costs, it is recommended that biofuel production units be located close to processing and capture plants (Tiwari et al., 2024).

Considering the energy, water, carbon, and land-use requirements involved in cultivating, harvesting, processing, drying, pelletizing, and transporting biomass, there is a possibility that BECCS may, under certain circumstances, have a negative energy balance, that is, consume more energy than it produces (Babin et al., 2021).

However, the study conducted by Salas et al. (2024), which carried out a systematic review of approximately 47 scientific articles addressing the capabilities of BECCS according to LCA (life cycle assessment), found that the results are consistent with respect to negative GWP (global warming potential) or carbon neutrality for BECCS. Still, the study warns that the current evidence is not sufficient to confirm that BECCS is a fully sustainable solution for the global energy transition and decarbonization.

Therefore, the implementation of BECCS should be targeted, prioritizing applications where it brings the most significant benefits, and limited to avoid harmful effects on other dimensions of sustainability (Smith et al., 2023; Tiwari et al., 2024).

3.3.2. Technological Challenges

Beyond the need for sustainable biomass, the success of BECCS implementation is also contingent on the viability of Carbon Capture and Storage (CCS) technology. Carbon capture imposes a high energy penalty, and regarding storage, there are physical limitations arising from the available geological capacity, as well as challenges associated with transport logistics. Additionally, the risks and potential consequences of CO_2 leakage may compromise the adoption of CCS due to environmental, social, and economic concerns. Therefore, it is essential to assess the environmental impacts of carbon storage to ensure its safety and thus enable the advancement of CCS. It is also worth noting that the full utilization of BECCS potential requires substantial investments in adequate infrastructure for CO_2 transport (Salas et al., 2024).

With regard to carbon storage, the viability of the technology depends on the identification and use of suitable and safe geological formations for the confinement of captured CO_2. These locations are not always close to the plants, which increases costs and logistical challenges (Tiwari et al., 2024).

The high cost is, in itself, a significant obstacle. The implementation of carbon capture and storage technology requires substantial initial investments, which makes BECCS economically unviable without robust subsidies or incentives (Tiwari et al., 2024).

Considering the survey conducted by Rochedo et al. (2016), as many ethanol plants in Brazil have reduced capacities and are unevenly distributed, predominantly in the Southeast region, the main implementation challenge may not be in the capture unit itself, but in the logistics required to establish a carbon transport hub capable of bringing together all individual emissions.

CO_2 is mainly transported by onshore pipelines, which are mostly used for enhanced oil recovery (EOR) in the context of carbon capture and storage (CCS). CO_2 can also be transported by trucks, railways, and ships. However, transport by trucks and road vehicles is considered unfavorable in terms of capacity and cost, making pipelines the only viable option for large-scale, long-distance onshore transport (Babin et al., 2021).

CO_2 capture demands high energy consumption and facilities with high costs and, in certain situations, can result in the transfer of impact to other forms of environmental damage (Salas et al., 2024).

3.3.3. Social Challenges

Social perception is another important challenge for BECCS. Research shows that the public generally demonstrates greater support for climate change mitigation strategies that are better known, such as the use of renewable energy sources—hydroelectric, wind, and solar—and energy efficiency measures (Babin et al., 2021).

Furthermore, Carbon Capture and Storage (CCS) technology faces resistance, mainly due to its strong association with the fossil fuel industry, which raises concerns about the possibility of prolonging these fuels as the main source of energy (Babin et al., 2021).

Fridahl and Lehtveer (2018) discuss bioenergy technology with carbon capture and storage (BECCS) and explore its global potential, investment preferences, and obstacles to its implementation. The research was based on questionnaires applied at UN climate conferences, analyzing the perceptions of different governmental, non-governmental, and expert actors on the viability of BECCS as a climate mitigation tool. The results point to low interest in investing in BECCS, mainly due to socio-political and economic barriers, such as a lack of political incentives and low social acceptance, which affect the technology's viability. The study highlights the importance of political incentives and social acceptance for BECCS to be implemented on a large scale and questions the viability of climate scenarios that assume the massive use of this technology without considering these obstacles.

Social perception is a relevant factor for the development of CCS projects, and research indicates a low level of public knowledge about the subject and the risks involved, although these are considered low (Netto et al., 2020).

Raising awareness about the potential of BECCS not only to help overcome the fossil fuel lock-in, but also to provide more effective mitigation than fossil fuels with CCS—due to its ability to generate negative emissions—can contribute to gaining public support (Babin et al., 2021; Vergragt et al., 2011).

In general, studies show that public opinion still has limited access to information on BECCS and public policies supporting BECCS. However, there is strong evidence that structured communication can change the perception of the technology, differentiating it from CCS and grounding it in good environmental practices (Babin et al., 2021).

3.3.4. Regulatory Challenges

The implementation of CCS technologies, including BECCS, requires a regulatory environment that ensures legal security for the agents involved and enables the commercial expansion of these solutions. In this context, the regulatory framework must establish conditions that promote the organization of the sector, with governance structures aimed at mitigating the technical and economic risks faced by companies (IBP, 2024a).

Studies indicate that BECCS technology is unlikely to grow without a supportive regulatory framework and political attention (Fridahl & Lehtveer, 2018).

The application of carbon capture and storage (CCS) in the ethanol sector in Brazil faces significant challenges due to the dispersed and small-scale nature of distilleries. Unlike oil refineries, which have greater concentration and operational capacity, ethanol distilleries are widely dispersed, especially in the Southeast region. This requires a complex infrastructure, including extensive pipeline networks to collect CO_2 from multiple sources, which increases costs and complicates the technical and logistical implementation of CCS. Thus, the development of effective transport hubs becomes an essential component to make carbon capture economically viable in this sector (Rochedo et al., 2016).

In addition to logistical barriers, the absence of a consolidated regulatory framework for CCS in Brazil represents another important obstacle. The viability of carbon capture projects, even in sectors with relatively low costs, such as ethanol fermentation, depends on clear climate policies and long-term guidelines. These policies must ensure adequate regulation for the transport, storage, and monitoring of captured CO_2. Without a robust institutional framework, the investments needed to develop and operate carbon transport networks face significant risks, hindering the consolidation of CCS as an effective emissions mitigation strategy in the country (Rochedo et al., 2016).

The implementation of a CO_2 transport infrastructure requires coordinated efforts among various actors and sectors. This includes defining property rights, establishing fair tariffs, planning hubs, and ensuring social acceptance of the use of pipelines for carbon transport. The creation of an integrated and regulated system is crucial to overcome the technical and financial challenges associated with CCS, ensuring its viability and alignment with Brazil's emission reduction targets. With adequate planning and the support of consistent public policies, CCS in ethanol distilleries can become a strategic alternative to mitigate emissions in the national energy and agricultural sectors (Rochedo et al., 2016).

It is important to recognize that RenovaBio establishes a carbon pricing mechanism for biofuels in Brazil. The policy also provides an additional 20% incentive for producers who prove negative emissions in their processes. Despite this, the values currently practiced are still considered low to make BECCS projects economically viable (Araújo et al., 2021).

The article "Costs and benefits of Brazil's climate policies on CCUS business: governmental cases of how institutional changes can shape the agent's behavior" analyzes the costs and benefits of Brazil's climate policies for the Carbon Capture, Utilization, and Storage (CCUS) sector. It discusses how institutional changes can shape the behavior of market agents and influence the implementation of large-scale carbon capture and storage (CCS) projects. The research examines three institutional incentives for large-scale CCS projects within the regulatory frameworks of renewable energy and the oil industry. The first incentive involves the incorporation of Bioenergy with Carbon Capture and Storage (BECCS) into the RenovaBio policy. The second discusses the use of Enhanced Oil Recovery (EOR) as a means of carbon storage in mature oil fields. The third explores the inclusion of CCS in the legal framework of the oil sector to mitigate uncertainties regarding long-term liability. The results show that Brazil has institutional incentives that favor the implementation of CCS, but still faces regulatory gaps and legal uncertainties that may discourage private sector investment. The article suggests that integrating CCS with existing energy policies, such as RenovaBio and tax incentives for the oil sector, can boost carbon capture and storage. However, for long-term viability, clearer regulatory reforms and more robust incentive mechanisms are needed (Araújo et al., 2021).

Finally, the need for adequate regulatory frameworks and public policies is highlighted. Creating normative structures that ensure the sustainable production of biomass and, at the same time, encourage investment in BECCS is a complex task, especially in countries with limited institutional capacities (Tiwari et al., 2024).

3.4. The Role of BECCS in the Brazilian Energy Transition

According to the Brazilian Institute of Petroleum and Gas (IBP, 2024b), CCUS technologies are presented as important options for achieving emission-reduction targets by 2050, particularly in hard-to-abate sectors. Within this broader category, only pathways that achieve durable removal can contribute to removing CO_2 already present in the atmosphere. For BECCS, this requires sustainable biomass, favorable lifecycle emissions, adequate capture performance, low-emission transport, and permanent geological storage.

According to the Brazilian Energy Research Company (2023), carbon capture and storage from biomass (Bio-CCS) is a technology that has the potential to generate negative emissions and combines the storage of CO_2, previously absorbed from the atmosphere by photosynthesis, with the generation of energy or biofuels, being a promising tool to achieve the goals of the Paris Agreement and contain global warming below 2˚C in relation to pre-industrial levels.

Moreira et al. (2016) address the potential of BECCS (Bioenergy with Carbon Capture and Storage) in Brazil, focusing on the production of negative emissions from the production of ethanol and electricity with sugarcane bagasse and other residues. He discusses the economic viability and environmental impact of this technology in the Brazilian context, considering that BECCS can capture the CO_2 released during sugar fermentation in ethanol production and during electricity generation with biomass. Furthermore, the article assesses the impact of BECCS implementation on ethanol and electricity costs and explores the policies needed to make this technology viable in Brazil.

According to Moreira et al. (2016), the mitigation potential that this technology offers to Brazil is significant, especially for regions of the country that face difficulties in achieving their emission reduction targets solely through deforestation reduction, and for the future national climate strategy, which will need to consider the growing contribution of greenhouse gas (GHG) emissions from the energy generation sector.

Rochedo et al. (2016) assess the potential and costs of carbon capture (CCS) in Brazil, considering sectors such as energy production, industry, and biofuels. The potential of ethanol distilleries, pre-salt oil platforms, and industrial plants stands out. Costs vary widely depending on the technology and application, with more economical capture in oil platforms and ethanol distilleries. According to the authors, the application of CCS can help Brazil achieve emission reduction targets, such as those established in the Paris Agreement, but there are significant technical and economic challenges.

Furthermore, according to Rochedo et al. (2016), given the relatively affordable cost of BioCCS in sugarcane-related processes, carbon capture in ethanol distilleries may have particular relevance for Brazil, representing an alternative with reduced capture costs. However, its viability will depend on the implementation of a comprehensive infrastructure of pipelines and carbon hubs capable of transporting CO_2 from both distilleries and other emitting sources. In addition, the possibility of generating additional revenue through EOR (enhanced oil recovery) in mature fields in the country makes this approach potentially even more attractive from an economic standpoint than suggested in the study.

Lap et al. (2023) examine the use of BECCS (Bioenergy with Carbon Capture and Storage) as an option for climate mitigation within a low-carbon Brazilian energy system. The authors assess the potential and impacts of this technology on a large scale for CO_2 removal from the atmosphere, considering the use of biomass and geological carbon storage. Using an energy system model, the study explores different scenarios of biomass availability and CO_2 storage capacities, as well as costs and injection rates. The study suggests that BECCS could play a significant role in Brazil's decarbonization, especially to serve sectors where the replacement of fossil fuels is more complex, such as freight transport and some industrial processes.

According to the scenarios outlined by Lap et al. (2023), biomass and BECCS play a prominent role in the final energy matrix in 2050, especially in terms of generating negative emissions that allow for the offsetting of other sectors, such as the reduced use of fossil fuels. This would be mainly related to the decarbonization of freight transport and industrial processes that are difficult to decarbonize.

At this point, it is worth mentioning that the prospects for the oil and natural gas (O&G) sector in Brazil continue to point towards large-scale production, with emphasis on the exploitation of pre-salt resources and the exploration of new frontiers, such as the Equatorial Margin (Hirose, 2024). Despite the country's commitment to ambitious climate goals, such as achieving carbon neutrality by 2050, official documents, including the National Energy Plan 2050 (PNE 2050), emphasize that Brazil should consolidate itself as one of the main oil exporters. It is estimated that national production will reach 5.5 million barrels per day by 2030, with exports reaching up to 3 million barrels per day (Hirose, 2024).

According to the study developed by Hirose (2024), the Pre-Salt, especially in the Campos and Santos basins, will continue to be one of the main pillars of national production. The high productivity of these reservoirs and technological advances reinforce their competitiveness. At the same time, the PNE 2050 encourages exploration in onshore and offshore areas, with special attention to new frontier basins and the Extended Continental Shelf.

Despite the gradual diversification of the energy matrix with the increase in renewable sources, such as solar and wind energy, dependence on fossil fuels is still evident. Primary energy production from fossil sources has increased in recent years, driven by the growth of P&G exports, reinforcing Brazil's position as an important player in the international market (Hirose, 2024).

The challenges include harmonizing energy and climate policies to reduce the socio-environmental impacts of P&G exploration in sensitive areas, such as the Amazon, and aligning exploration with the commitments made in the Paris Agreement. Additionally, the development of a competitive natural gas market and the expansion of transportation infrastructure are crucial points for maximizing the use of the resource and fostering the energy transition (Hirose, 2024).

Lap et al. (2023) provide direct scenario evidence for an offsetting role. In scenarios where CCS is available, negative emissions from BECCS create additional emissions space for sectors that are more difficult or costly to decarbonize, allowing some continued fossil-fuel dependence. This is a modeled system outcome rather than evidence that BECCS deployment necessarily causes fossil-fuel expansion.

Coutinho et al. (2024), using the BLUES Integrated Assessment Model, likewise examine climate strategies for Brazil's oil and gas sector under mitigation constraints. Their scenarios retain significant oil and gas production through 2050 and use negative emissions, including BECCS and reforestation, to offset residual emissions. The study therefore provides explicit evidence that BECCS can function as an offset within pathways that still contain fossil-fuel production; it does not establish that BECCS itself drives or legitimizes that production.

Coutinho et al. (2024) further identify Brazil's BECCS potential as an opportunity for actors in the oil and gas sector to participate in biofuel production and CO_2 storage. In this article, the governance concern arises from how such an offsetting function could be used in policy discourse: if negative emissions are treated as a substitute for feasible direct reductions, they may weaken incentives for fossil-fuel phase-down. This possibility is interpreted here as a governance and greenwashing risk, not as an empirically established consequence of BECCS deployment.

According to Poggio et al. (2024), who developed scenarios for achieving net-zero emissions for Brazil, it is expected that, given Brazil's potential in the biofuel sector, BECCS will play a relevant role in achieving net-zero CO_2 emission targets by 2050.

According to Moe and Røttereng (2018), countries that support CCS tend to be those with interests in fossil fuel exploration, using this technology as a strategy to balance, in the long term, their national interests linked to oil with internationally assumed commitments regarding climate action.

Thus, Netto et al. (2020) indicate that CCS may be a possible solution for controlling CO_2 emissions without compromising Brazilian development, meeting Sustainable Development Goals numbers 8 (sustainable economic growth) and 13 (urgent action to combat climate change).

4. Conclusion

Climate change has increased the importance of both rapid emissions reductions and carbon dioxide removal. In this context, BECCS is one of several potential CDR approaches rather than an intrinsically essential technology. This narrative review examined how the selected scientific literature frames BECCS within Brazil's energy transition and found that its prospective role is closely linked to the country's bioenergy base, especially ethanol, and to the availability of geological storage.

The reviewed literature indicates that BECCS may contribute to climate mitigation in Brazil by generating durable carbon removal and by compensating for residual emissions in hard-to-abate sectors. That contribution, however, is conditional rather than automatic. Net-negative emissions require sustainable feedstocks, control of land-use change, favorable lifecycle emissions, manageable capture-energy demand and transport emissions, and long-term storage permanence. BECCU and other utilization pathways should therefore not be treated as equivalent to BECCS unless they demonstrate comparably durable atmospheric removal.

The relationship between BECCS and continued fossil-fuel production requires particular care. Lap et al. (2023) explicitly model negative emissions from BECCS as creating emissions space for sectors that remain partially dependent on fossil fuels, while Coutinho et al. (2024) model residual-emissions offsets in scenarios where Brazilian oil and gas production remains significant. These studies support the conclusion that BECCS can perform an offsetting function in some transition pathways. The further concern that this function could be used to justify avoidable fossil-fuel expansion is an interpretation about governance incentives, not an established technological outcome.

Although individual elements of BECCS have been demonstrated and ethanol fermentation offers comparatively favorable capture conditions, large-scale feasibility in Brazil cannot yet be regarded as consolidated. Deployment depends on integrated CO_2 transport and storage infrastructure, economic incentives, regulatory certainty, monitoring and liability rules, social acceptance, and verification of lifecycle carbon removal. These conditions reinforce the need to evaluate BECCS project by project rather than infer climate benefit from capture alone.

The literature therefore supports treating BECCS as a complementary instrument rather than a substitute for direct mitigation, ecosystem protection, energy efficiency, and the replacement of unabated fossil fuels where feasible. A governance risk arises if projected negative emissions are used to delay or weaken direct reductions. Avoiding that risk requires transparent accounting, conservative lifecycle assessment, durable-storage requirements, and climate policies that distinguish residual emissions from emissions that can reasonably be eliminated.

Brazil's challenge is consequently not limited to technological adoption. The role of BECCS will depend on how carbon removal is integrated into a coherent transition strategy and on whether governance frameworks preserve the priority of direct emissions reductions. Under robust sustainability, accounting, and storage-permanence safeguards, BECCS can contribute to national climate objectives; without such safeguards, reliance on future removals may create incentives inconsistent with a credible long-term decarbonization pathway.

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Author Contributions

All authors contributed to the conception, development, analysis, and writing of the manuscript. All authors reviewed and approved the final version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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