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ENERGY
PROGRAM

INTEGRATING CCUS INTO BRAZIL'S DECARBONIZATION STRATEGY: INSIGHTS FROM NORWEGIAN EXPERTISE

REPORT

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HIGHLIGHTS

1. The state-of-the-art of this technology globally
2. Challenges to mainstream adoption
3. Potential business models: the case of Norway and the CCUS hubs as a compelling business model
4. Brazil: current status and potential partnerships to speed up the Brazilian energy transition

SUMMARY

The global urgency to address climate change has placed Carbon Capture, Utilization, and Storage (CCUS) at the forefront of technological solutions for decarbonizing some of the most challenging industrial sectors. As nations around the world strive to meet their ambitious climate goals, culminating in the global objective of Net Zero by 2050, CCUS emerges as a critical tool to balance greenhouse gas (GHG) emissions, particularly in sectors where alternative decarbonization options are limited (technically and/or economically).

The energy matrices of Brazil and Norway, despite differing in scale and economic context, show notable diversity and renewability. Both countries heavily rely on hydropower and renewables account for 49% of Brazil's energy mix and 56% in Norway (EPE, 2024; IEA, 2023). Besides Brazil's current energy matrix, there is a huge potential for further efficient integration, inspired by Norway's growing experience in CCUS for a more sustainable energy profile.

CCUS is not only an attractive technology but a necessary one. In a world where hydrocarbons will continue to play a role even in a Net Zero context, CCUS offers a pathway to mitigate the environmental impact while allowing for continued industrial growth. The energy matrix transformation represents one of society's most significant innovation challenges today.

Brazil stands at a pivotal juncture with the potential to generate USD 14 to USD 20 billion annually from the carbon credits market alone (EPE, 2024a). The country's extensive geological resources and diverse energy matrix position it uniquely to lead in Carbon Capture, Utilization, and Storage (CCUS) technologies. Annual investments in carbon capture and storage (CCS) projects are estimated to range from BRL 2 to 4.5 billion until 2050 (EPE, 2024a). The development of integrated CCUS hubs, particularly near major carbon dioxide (CO_2) emission zones, underscores the urgent need for a robust regulatory framework to support this growth.

Since 2008, Petrobras has been a pioneer in carbon capture, having injected over 40 million tons of CO_2 into reservoirs by 2022. The company aims to double this figure by 2025, emphasizing its commitment to this essential technology (Petrobras, 2024). Although in this case the injection is for the purpose of Enhanced Oil Recovery (EOR), it is combined with the CO_2 removal strategy and improves the technique and use of CCS, helping to mitigate the emissions from an activity that is essential for the

socioeconomic development of a country like Brazil, which has had almost 20% of its industrial gross domestic product in the oil and gas sector over the last decade (BNDES, 2023).

KEY FINDINGS

- The increasing pressures for decarbonization are driving a global green transformation, making CCUS a cornerstone for emission reduction across various industries. To be effective, CCUS must be deployed globally, integrated into both existing and emerging energy systems.
- Geological carbon storage techniques are also very important for removing excess CO_2 released into the atmosphere by centuries of anthropogenic impact.
- Offshore geological CO_2 storage offers a long-term strategy with vast potential, especially for large-scale emitters (Ringrose, 2020). In Brazil, it will be crucial for sectors like steel, cement, mining, chemicals, and energy.
- The growth of CCUS projects is accelerating, with a global pipeline that has expanded at an annual compound rate exceeding 35% since 2017. This momentum indicates a strong market appetite and room for further growth (GLOBAL CCS INSTITUTE, 2023).
- Norway's Longship project, led by Equinor, Shell, and TotalEnergies, serves as a model for successful carbon capture and storage (CCS) initiatives. This hub effectively combines government support with private sector innovation to develop scalable and replicable CCS infrastructure. The project demonstrates a significant capture capacity, capable of handling between 1 to 5 million tons of CO_2 annually.
- In Brazil, a recent study published by the Energy Research Office (EPE in its Portuguese acronym for *Empresa de Pesquisa Energética*) (EPE, 2024a) identified the South-Central and Central-West regions as having significant potential for implementing new projects and expanding existing ones. The study by S&P GLOBAL (2024) goes even further, highlighting eight areas capable of storing a substantial amount of carbon dioxide, including two areas off the southeast coast that could account for approximately 95% of the country's total storage capacity.
- Brazil's regulatory framework for CCUS is still under development, but presented an important advance at the end of 2024, with the approval of Law 14.993/24, known as the Fuel of the Future Law, which establishes the legal framework for geological carbon storage. With this legislation, the National Agency of Petroleum, Natural Gas, and Biofuels will be responsible for regulating CCS activities in Brazil. Drawing from international models, particularly those from Norway, could help Brazil build a robust regulatory environment that fosters both public and private investment in CCUS.

OPPORTUNITIES AND CHALLENGES

- The implementation of CCUS hubs in Brazil represents a strategic opportunity to address climate change while driving economic growth and sustainability. Brazil's unique geological resources and diverse energy matrix make it an ideal candidate for such initiatives.

- Economic viability remains a challenge, with the need for significant investments in infrastructure, especially in the capture and transport axes, and a clear regulatory framework that encourages public and private participation. Government support through financial incentives and appropriate policies is crucial to mobilizing the necessary resources.
- Social and environmental acceptance of CCUS projects is vital for their success. Building public awareness and trust through transparent and safe project development will be key.
- Continuous innovation in technologies is necessary to reduce costs and improve efficiency - particularly in the development of capture techniques suitable for the tropical climate which characterizes much of Brazil’s territory.
- International collaboration will be essential to accelerate the adoption of CCUS in Brazil, allowing the country to benefit from global best practices.
- Norway's longship project exemplifies the power of strategic collaboration in achieving large-scale carbon reduction. By leveraging Norway's expertise in carbon capture and storage (CCS) and Brazil's extensive resources, the two countries can cooperate to accelerate global decarbonization efforts and set a strong example for international climate action.

INTRODUCTION:
The Global Imperative for Carbon Capture, Utilization, and Storage

As the world faces the pressing challenge of climate change, reducing GHG emissions has become a paramount objective for governments, industries, and societies alike. The transition to a low-carbon economy is essential to meet the global targets set by the Paris Agreement, which calls for limiting global warming to well below 2°C, preferably to 1.5°C, compared to pre-industrial levels. However, achieving these ambitious goals is particularly challenging for carbon-intensive industries such as steel, cement, chemicals, and energy, where decarbonization options are limited.

Brazil, as a global frontline country in storage potential, embraces CCS initiatives nationwide since the disclosure of its National Climate Change Plan (Brazil, 2008). Pioneer surveys concerning CCS and the theoretical CO_2 storage capacity of Brazilian hydrocarbon fields, aquifers, and coalbeds underscored that its sedimentary basins could potentially accommodate more than 2,035 Gt of carbon dioxide (CO_2) (MACHADO; HAWKES; RIBEIRO, 2021).

Beyond the precise mapping of CCUS opportunities, the definitive approval of a regulatory framework and investments in lower-cost technologies are open issues.

The consolidated energy mix of Norway, according to the International Energy Agency (IEA), is predominantly renewable, with hydropower accounting for the vast majority of electricity generation, making Norway one of the countries with the highest share of renewables in the world. The energy mix is composed of approximately 56% renewable energy, mainly hydropower, and a small percentage of fossil fuels, primarily used in oil and gas production. Key industries include oil and gas extraction, which is still a significant part of the economy, alongside energy-intensive industries supported by abundant renewable energy.

Both Brazil and Norway have energy matrices that are predominantly renewable, with hydropower being the leading source of electricity generation. This similarity offers a foundation for decarbonization strategies, especially for hard-to-abate sectors such as steel, cement, and petrochemicals in Brazil. Norwegian success in maintaining a renewable-based energy system while continuing its oil and gas extraction shows how Brazil could leverage its renewable resources to reduce emissions in these sectors through CCUS technologies, while driving innovation and economic growth.

In this context, Carbon Capture, Utilization, and Storage (CCUS) emerges as a critical technology that can bridge the gap between current industrial practices and a sustainable future (AGATON, 2021). CCUS offers a viable solution for capturing CO_2 emissions from industrial sources or directly from the atmosphere, preventing them from contributing to global warming. By either storing CO_2 in geological formations or repurposing it for industrial applications, CCUS mitigates emissions and creates new opportunities for innovation and economic growth.

The global acceleration of CCUS is driven by supportive policies, technological advancements, and growing investments, with leading nations like those in North America and Europe making significant strides. Notably, Norway's Longship project exemplifies a successful CCUS hub model, which centralizes emissions from various sources to achieve economies of scale. By pooling resources and infrastructure, these hubs reduce costs, enhance efficiency, and foster technological innovation, while also promoting collaboration between governments, private sector, and research institutions. This integrated approach not only optimizes performance but also minimizes environmental impact and social disruption.

While the global CCUS landscape is evolving rapidly, Brazil faces a unique set of opportunities and challenges in this field, particularly if lessons are learned from existing business models like those in Norway. Despite being one of the world's top greenhouse gas emitters, Brazil's energy matrix is notably cleaner than many global counterparts, with a significant share of renewables - almost 49% of the Internal Energy Supply in 2023 according to EPE (2024b). However, the country’s industrial sectors - particularly cement, steel, and chemicals - still contribute substantially to national emissions, pointing out the urgent need for effective mitigation strategies.

Brazil's vast geological resources, including its pre-salt reservoirs, offer significant potential for CO_2 storage. Coupled with a diverse and growing industrial base could position the country as a key player in the global CCUS market. However, to fully realize this potential, Brazil must overcome several barriers, including the development of capture techniques suitable for the more humid tropical climate and a robust infrastructure, the establishment of a clear regulatory framework, and the need for increased public and private investment.

This report explores the current state of CCUS technology, the challenges to its widespread adoption, and the lessons Brazil can learn from international experiences, particularly from Norway's Longship project. By examining these factors, this document aims to provide a comprehensive overview of the opportunities and obstacles that lie ahead for CCUS in Brazil and to outline a pathway for the country to become a leader in the global fight against climate change.

GLOBAL OVERVIEW OF CARBON CAPTURE, UTILIZATION, AND STORAGE (CCUS)

The capture process typically involves methods such as chemical solvent capture, solid absorption, or membrane separation, which isolate CO_2 from combustion gases or industrial processes, resulting in high-purity CO_2 streams. After capture, the CO_2 is transported via pipelines, trucks or ships to storage or utilization sites. Geological storage involves injecting CO_2 into deep geological formations like saline reservoirs (also known as saline aquifers) or depleted oil fields, where it is securely and permanently contained (EPE, 2024c). Alternatively, CO_2 can be utilized in processes that convert it into valuable products, such as synthetic fuels, chemicals, or construction materials, fostering a circular economy.

Effective CCUS implementation requires careful integration between capture technologies, transport infrastructure, and storage or utilization options, along with a robust regulatory and economic framework that incentivizes investments and innovations.

The CCUS market is currently experiencing moderate expansion, driven by government policies, corporate sustainability goals, and increasing investments in technological innovation. CCUS projects are emerging worldwide, particularly in North America and Europe, where infrastructure, financial, and regulatory support are more advanced. In Brazil, Petrobras leads significant efforts in implementing this technology, leveraging its extensive experience in oil and gas operations to develop CCUS solutions, especially in offshore fields. Notably, the use of CCS in Enhanced Oil Recovery (EOR) operations not only captures carbon but also enhances oil recovery, creating a synergy between energy transition and the maximization of existing assets.

In 2022, Petrobras, using this technology, reinjected 10.6 million tons of CO_2 into pre-salt reservoirs, which accounted for 25% of the total CO_2 reinjected globally in the same year, according to the Global CCS Institute. This project has been crucial for Petrobras in enabling oil production with lower emissions per barrel - about 40% fewer emissions in production compared to the global average. Currently, the 22 platforms operating in the pre-salt Santos basin are equipped with CCUS-EOR technology (Petrobras, 2023).

Additionally, Petrobras is also developing a CCUS hub pilot project in northeastern Rio de Janeiro, scheduled for completion by 2027. It will capture, use, and store CO_2 from gas processing at the Cabiúnas facility in Macaé. The pilot is part of Petrobras' broader strategy to establish a CCUS hub in the state, designed to serve not only the company's operations but also other hard-to-abate industries like cement and steel manufacturing (Argus, 2023).

In Norway, the Northern Lights project stands out as a global milestone in CCUS development, establishing the first CO_2 transport and storage network of its kind in Europe. This initiative, part of Equinor's energy transition portfolio, aims to provide carbon transport and storage services for various industrial sectors across Europe, creating an infrastructure that can be replicated in other regions worldwide (MCKINSEY *et al.,* 2023). The Northern Lights project is remarkable not only for its scale but also for its integrated approach, combining CO_2 capture from industrial sources with an efficient transport system and safe geological storage in deep saline formations in the North Sea.

The project uses a submarine pipeline infrastructure to transport captured CO_2 from onshore industrial facilities to storage sites, demonstrating a viable technical solution to the challenge of transporting large volumes of CO_2. The selection of suitable geological formations for storage is based on rigorous geological and engineering studies, ensuring that the CO_2 is stored safely and permanently, minimizing the risk of leaks. Moreover, Northern Lights is designed to be scalable, allowing new emitters to join the network as demand for CCUS services grows (DE LUNA *et al.,* 2023; MCKINSEY & COMPANY, 2023).

For Brazil, this project serves as a valuable example of how a collaborative and integrated approach can facilitate large-scale CCUS implementation. Brazil has significant potential for carbon capture and storage, particularly in sectors such as cement, petrochemicals, and power generation. Learning from a model like Northern Lights could involve identifying suitable geological formations for CO_2 storage and developing a transport network that connects emitters to these storage sites. Additionally, collaboration between the public and private sectors, along with regulatory and financial incentives, will be crucial for fostering investments in CCUS infrastructure in Brazil. By drawing lessons from the Northern Lights project, Brazil can not only advance its emission reduction goals but also position itself as a leader in CCUS adoption in Latin America.

State of the Art of CCUS Projects Worldwide

1

Currently, the global landscape for Carbon Capture, Utilization, and Storage (CCUS) includes a limited number of projects that have reached Final Investment Decision (FID). Despite growing interest and initiatives to develop these technologies, few projects have proceeded to FID stage. Table 1 presents operational CCUS projects, those in the pipeline, their respective capacities in million tons per year, the number of injection wells and pipelines. According to McKinsey & Company (2023) in their article "Global Energy Perspective 2023: CCUS Outlook," achieving Paris Agreement-aligned nationally determined contributions will require a 100-fold increase in CCUS capacity, reaching approximately 4 to 6 gigatons by 2050 to effectively manage emissions from fossil sectors and other hard-to-abate industries.

A CCUS hub is a centralized infrastructure that connects multiple industrial CO_2 sources to efficiently capture, transport, and store carbon. It allows several companies to share the necessary infrastructure, reducing costs and increasing the effectiveness of emissions reduction.

Table 1 – Overview of CCUS Market Activity by Key Performance Indicators

Performance Indicator	Description	Count
CCUS projects in operation	Number of projects in operation	113
CCUS projects in pipeline	Number of projects in pipeline	785
Capacity in operation	Annual operational capacity	> 56 mtpa
Capacity in pipeline	Planned annual capacity	> 770 mtpa
Injection wells	Well demand (2000-2030)	1593
Wells in operation	2015 - 2024	572
Wells	2025 - 2030	1021
Transportation - Pipeline count	Number of transportation pipelines	492
Injection well drilling	2023/2024 (~57% growth)	458 kilometers

Source: CEBRI – Brazilian Center for International Relations

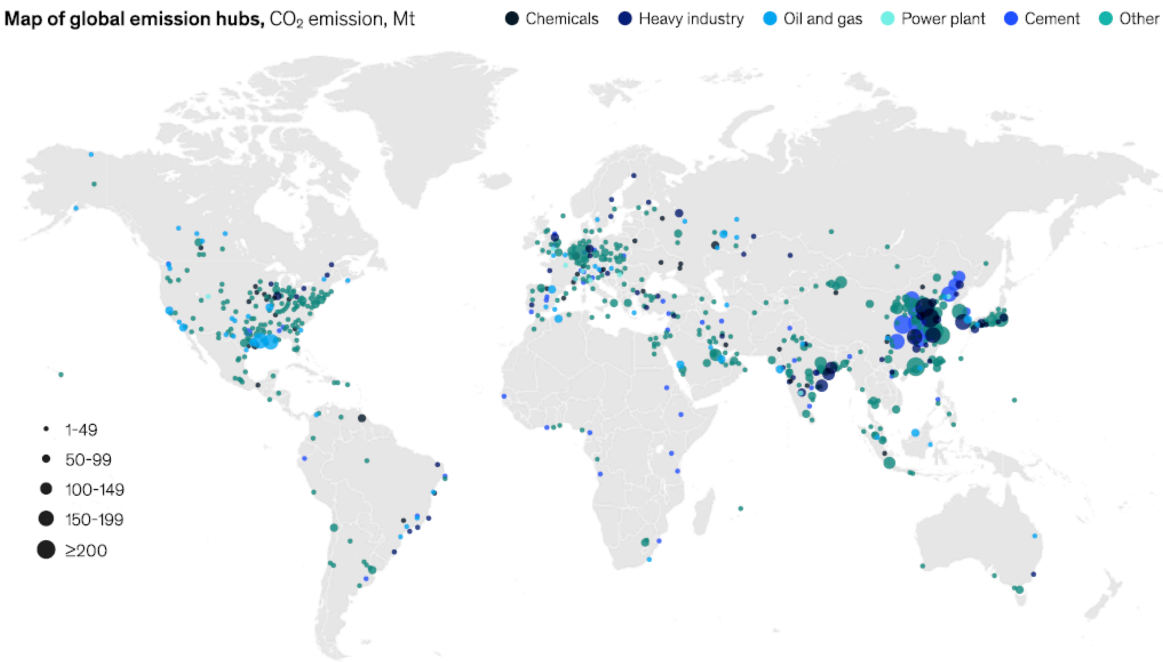
PROJECTS

During the consolidation of energy markets, several subsidy formats were implemented to meet different objectives. However, recently, with the purpose of minimizing the impacts of global warming and, consequently, meeting the goals established in the Paris Agreement, the energy sector, and especially the power sector, assumed an important role in the energy transition and raised discussions about efforts to meet established environmental goals. Thus, for some time now, subsidies for energy (and power) generation from renewable sources have been gaining ground in the countries involved. Several CCUS projects are either in operation or under development globally, spanning various industries and geographic regions. These projects differ in scale, employed technologies, and objectives, whether for storage or utilization of captured CO_2.

1. Sleipner (Norway): Operated by Equinor, Sleipner has been capturing and storing about 1 million tons of CO_2 annually in a saline aquifer in the North Sea since 1996, making it the oldest CCUS project in operation.
2. Quest (Canada): Managed by Shell, captures and stores approximately 1 million tons of CO_2 per year from an oil refinery in Alberta, storing it in deep geological formations.
3. Boundary Dam (Canada): Run by SaskPower, this was the first project to integrate CO_2 capture at a coal-fired power plant. It captures about 1 million tons of CO_2 annually, with some used for Enhanced Oil Recovery (EOR) and the rest stored geologically.
4. Gorgon (Australia): Operated by Chevron, the Gorgon project captures CO_2 from natural gas processing and stores it in a saline aquifer, with a capture capacity of up to 4 million tons of CO_2 per year.
5. Petra Nova (USA): Located in Texas, this project captures CO_2 from a coal-fired power plant and uses it for EOR.
6. Snøhvit (Norway): Another Equinor project, Snøhvit stores CO_2 from the Snøhvit gas field in the Barents Sea.
7. Illinois Industrial (USA): This project captures CO_2 from ethanol production and stores it in deep geological formations.
8. Al Reyadah (United Arab Emirates): The first CCUS project in the Middle East, it captures CO_2 from a steel plant and uses it for EOR.
9. Jafurah CCUS Hub (Saudi Arabia): Developed by Saudi Aramco, the Jafurah CCUS hub aims to capture and store up to 9 million tons of CO_2 annually by 2027.

These projects exemplify successful initiatives that have progressed through the FID stage and are either operational or in advanced implementation phases. There has been an increase in government funding requests aimed at developing CCUS hubs in Canada, Europe, and the United States to address industrial emissions and expedite the development of carbon removal technologies and infrastructure. Currently, around 15 CCUS hubs are in various stages of development worldwide, with many more in the planning phase. Image 1 illustrates a macromodel for assessing the viability of future CCUS hubs. It evaluates factors such as source industries, the purity of emission streams (which determines their potential for utilization, storage, or both), how close the emitters are from potential storage sites, and the potential for shared infrastructure and operational costs and other commercial synergies within a cluster. (MCKINSEY *et al.,* 2023)

Image 1 – Map with potentialities to develop around 700 CCUS hubs worldwide, with most situated near or at potential storage sites



Source: (MCKINSEY *et al.*, 2023)

Analysis by McKinsey & Company (2023) suggests that approximately 700 CCUS hubs could be established globally. Most of these hubs are strategically located near potential storage sites and areas for Enhanced Oil Recovery (EOR) and Enhanced Gas Recovery (EGR), with over 60% situated within 80 kilometers of these locations.

2

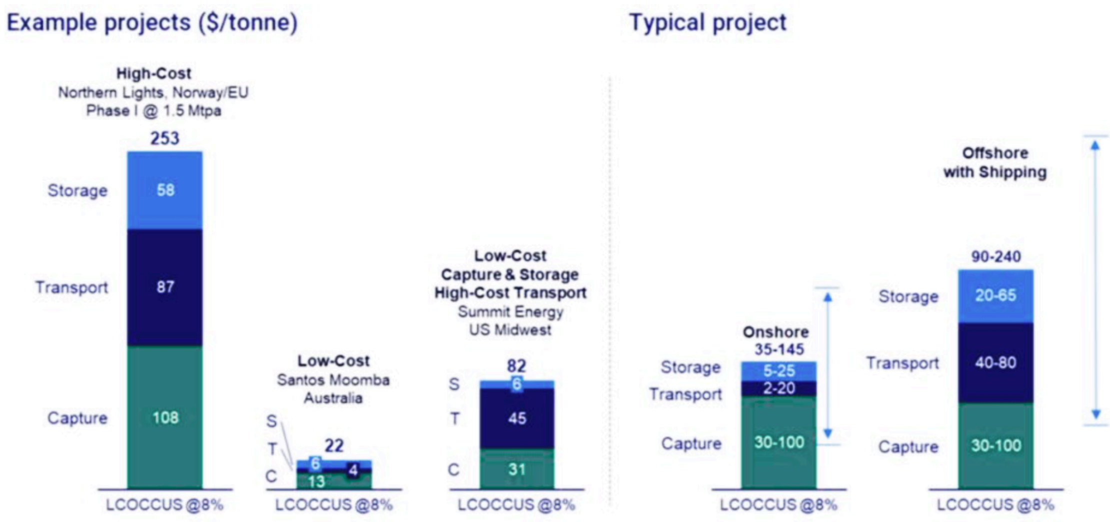
Challenges to Mainstream Adoption

The expansion of CCUS hubs faces significant challenges. Regulatory and legislative disparities across countries create uncertainties that hinder the implementation of new projects. Moreover, financial incentives and tax benefits are often insufficient to make CCUS projects economically viable. The lack of clear, long-term demand for captured CO_2 complicates planning and investment efforts.

Additionally, the economic feasibility of these projects is influenced by the costs of capture technologies, CO_2 transportation, and the availability of suitable storage sites. Among them, the capture is usually the most costly step considering the CCUS value chain (Mackenzie, 2023). According to literature on estimated costs for CCUS across different industries, it can also vary based on the CO_2 concentration in the emissions stream. Specifically, whether there is a low CO_2 concentration in the gas, more energy will be required to separate the CO_2, which in turn leads to higher costs (IISD, 2023).

Regarding capture costs, they are projected to range from approximately USD 30–100/tCO_2 (Wood Mackenzie, 2023). Capital Expenditure (CAPEX) estimates for a typical CCUS hub can range from USD 35 million/Mt to USD 145 million/Mt for onshore projects, and from USD 90 million/Mt to USD 240 million/Mt for offshore projects, depending on its scope and complexity (Wood Mackenzie, 2023). However, some general estimates can be provided based on similar projects and market studies, as represented in the image below:

Image 2 – CCUS Project Costs: Comparison Between Example and Typical Projects ($/tonne).



Source: Wood Mackenzie, 2023

The main factors influencing CAPEX in CCUS hub projects are:

I. Project Scale: Larger-scale projects (5 to 10 million tons of CO_2 captured per year), with the capacity to capture millions of tons of CO_2 per year, will have higher CAPEX but may benefit from economies of scale.

II. Capture Technology: The choice of capture technology (e.g., post-combustion, pre-combustion, oxycombustion) significantly influences costs. More mature capture technologies tend to be less expensive but still represent a significant portion of the CAPEX. Post-combustion is one of the most mature and widely used technologies. The cost estimates may include installation of capture systems, modification of existing infrastructure (in power plants or industries), and process integration. In countries with hot and humid climates, such as Brazil, there is an additional challenge of adapting capture methods and techniques developed in dry and cold climates, as is the case for the vast majority of projects in advanced stages of development. This difficulty is especially noticeable in direct air capture routes.

III. Transportation Infrastructure: It is necessary to assess the requirements needed to build new facilities or the option of using existing ones. The cost to build pipelines or other forms of transportation for the captured CO_2 to the storage site can represent a large part of the CAPEX, especially in projects involving long distances. In the case of pipeline transportation, very used for long distances, building an efficient pipeline network is crucial, as it provides a safe, reliable, and cost-effective connection between emission sources and storage facilities. Nevertheless, CO_2 pipeline transportation involves several challenges, including concerns about pipeline design, integrity, flow assurance, assessment of the remaining useful life (in the case of reuse of existing pipelines), operational difficulties (especially when infrastructures are shared), as well as environmental risks - this last one particularly with regard to the authorization of construction or reuse and the impacts of extreme weather events (IEA, 2020; Rui *et al.,* 2025). In the case of Brazil, a country of continental dimensions, the expansion of the pipeline network - and other transport modes - to the most inland parts of the territory is vital (EPE, 2024).

IV. Storage: The development of storage sites, such as geological reservoirs, injection wells, and long-term monitoring, also impacts costs. Projects in locations with existing storage infrastructure may have reduced CAPEX. Cost estimates may vary from USD 5 to USD 65 million. Overall, projecting storage costs is challenging and it may include well drilling, sealing, and long-term monitoring to ensure the safety and effectiveness of storage.

V. Geographical Location: Projects located in regions with existing industrial infrastructure may have lower costs than those in remote or less developed areas. Moreover, approving a clear legal and regulatory basis that enables the effective transport of CO_2 is one of the challenges for planned projects, particularly for cross-border cooperation. Agreements between countries could allow and facilitate this transport legally, as is being developed in Europe (ZEP, 2020).

VI. Geological challenges: This includes precise site characterization to delineate subsurface structures, understand CO_2 interactions with the geological framework, quantify storage capacity, and evaluate the technical and economic feasibility of proposed sites (Rui *et al.,* 2025). The need to increase the database specific to geological carbon storage at great depths is recognized worldwide. Although the oil and gas industry provides essential data for pre-selection of areas, interpretations focused on understanding the conditions for permanent storage should be encouraged, with emphasis on the recognition of reservoirs and layers of sealing rocks. In Brazil, in particular, it is necessary to further expand the mapping of the maximum limits of water aquifers for human use in order to ensure that CO_2 storage sites are located at safe distances from these aquifers (EPE, 2024c).

VII. Regulation and Licensing: Inconsistent regulatory frameworks, the length of permitting processes, as well as the lack of standardized storage and transport regulations discourage long-term investments, underscoring the need for stable and long-term policy commitments (Rui *et al.,* 2024). Moreover, costs related to compliance with environmental regulations and obtaining licenses can vary depending on the country or region. Since CCUS activities depend on public incentive policies, and recognizing the difficulty of direct funding by the Brazilian government, given that the country still has serious problems of social inequality that concentrate direct public resources, carbon pricing - possible from the regulation, until 2026, of the recently approved carbon credit market (Law No. 15,042/2024) -, the creation of financing lines, tax exemptions and facilitation of cooperation (national, international, public and private) are paths that can be explored by Brazil to leverage CCUS and its different routes.

Table 2 – Estimated Costs and Capacities of CCUS Projects by Scale

Size	Capacity	Cost	Example
Small CCUS Pilot Projects	Less than 1 million tons of CO_2 per year	$100 to $500 million	
Medium-sized Commercial Projects	Capture capacity of 1 to 5 million tons of CO_2 per year	$500 million to $1.5 billion	Northern Lights Project (Norway): The CAPEX is estimated to be around $650 million for the first phase, which aims to capture and store 1.5 million tons of CO_2 per year
Large-scale Projects	More than 5 million tons of CO_2 per year	$2 billion to $5 billion or more	

Source: Authors' compilation, based on data from the International Energy Agency (IEA) and S&P Global

MARKET UPDATE

Despite these obstacles, CCUS is well-positioned to play a crucial role in climate change mitigation, driven by increased focus on carbon reduction policies and clean technology investments. In 2023, the global CCUS market experienced a moderate growth of 23%, contrasting with the impressive 100% increase seen over the previous two years. According to the Visiongain report (2024), the global CCUS market is expected to grow at a compound annual rate of 20.6% until 2034. Established markets in Europe and North America have faced challenges in announced projects, while the Asia-Pacific region has made rapid progress.

The FID progress has been slow, with few projects reaching significant milestones in 2023. Earlier predictions suggested that at least one-third of ongoing projects would face delays. This slow development can be attributed to internal issues, such as prolonged FID studies, and external obstacles, like licensing and financing difficulties. 2023 was marked by a series of policy announcements and regulations worldwide. The European Union completed the reform of the EU ETS, and countries like Japan, South Korea, Singapore, and Malaysia set CCUS targets as part of their climate strategies. COP 28 also emphasized the need to accelerate low-emission technologies, such as CCS.

According to Rystad Energy (2024), in their latest "Energy Transition Report - CCUS Market Update", demand for CO_2 removal technologies, including Bioenergy with Carbon Capture and Storage (BECCS) and Direct Air Capture (DAC), had a significant growth in 2023. The EU's proposed Industrial Carbon Management Strategy outlines that approximately 40% of captured CO_2 should come from biogenic emissions and DAC by 2040, reinforcing the role of these technologies in long-term carbon reduction efforts.

In North America, the CCUS market expanded rapidly but faced regulatory challenges, particularly in obtaining permits for CO_2 injection wells. The number of applications for Class VI CO_2 injection wells in the US more than doubled, rising from 54 in 2022 to 128 in 2023. Despite this increase, delays in the approval process remain a major obstacle. Due to long wait times for Class VI permits, some operators have opted to use Class II wells as an alternative for CO_2 injection.

CO_2 utilization has received less attention, but rising demand for synthetic fuels and industrial applications is driving market expansion. 2025 will be crucial for building confidence in the CCUS market and setting the stage for rapid growth. To meet the expected capture of over 150 million tons of CO_2 annually by 2027, it is essential that many projects reach FID this year.

GROWTH IN 2023

At the end of 2023, the global Carbon Capture, Utilization, and Storage (CCUS) market had 101 commercial projects in operation, responsible for capturing more than 54 million tons of CO_2 per year. According to the CCUS Policies and Business Models report by the International Energy Agency (IEA, 2023a), this number reflects an almost 27% increase in the total number of projects compared to 2022, although growth has been more modest after two consecutive years of 100% expansion.

Currently, there are 663 projects in the planning phase, expected to start operation by 2032. Once fully operational, these projects have the potential to capture more than 678 million tons of CO_2 annually, demonstrating the growing global commitment to mitigate climate change. This expansion is crucial for achieving net zero emissions targets by 2050 but far beyond the necessary capacity of circa 1 Gt CO_2 per year estimated by the IEA's Net Zero Emissions (NZE) Scenario (IEA, 2023; RYSTAD ENERGY, 2024).

North America and Europe continue to be key regions for developing new projects, but the highlight of 2023 was the Asia-Pacific (APAC) region. With countries such as Australia, Japan, and South Korea leading the new announcements, APAC was responsible for almost half of the new projects announced globally. North America and Europe followed with 24% and 22%, respectively. The accelerated growth in Asia-Pacific is driven by the adoption of policies and regulations that encourage the development of CCUS technologies, such as carbon capture targets announced in Japan and South Korea and the amendment to the safeguard mechanism in Australia (RYSTAD ENERGY, 2024).

The IEA also highlights that Europe and North America showed a slower pace in expanding new projects, with operators focusing on advancing existing projects, and the Middle East, Africa, and South America lagged, representing only 7% of new project announcements in 2023. However, there are signs of progress in these markets, particularly with pilot projects focused on carbon removal, especially in the Middle East and Africa.

ADVANCES AND CHALLENGES IN PERMANENT STORAGE

In 2023, the focus of the global CCUS market continued to concentrate on permanent CO_2 storage projects - a crucial segment for achieving decarbonization goals. According to the IEA (2023), permanent storage projects have been largely led by geological reservoirs such as depleted oil and gas fields and deep saline aquifers, which offer the greatest storage capacity and long-term security. Additionally, there has been growing interest in emerging mineralization technologies in volcanic basalt, which capture and store CO_2 in stable mineral formations.

Geological storage capacity is essential for the long-term success of CCUS technologies. Therefore, in response to the need for greater CO_2 storage capacity, operators have announced more dedicated storage projects.

The market has also seen significant growth in CO_2 utilization projects, although on a smaller scale compared to permanent storage. The demand for synthetic fuels, such as e-methane, has driven these projects, especially in Europe and some East Asian countries like China. These synthetic fuels are viewed as a promising solution for decarbonizing sectors that are difficult to electrify, such as heavy transport and aviation (RYSTAD ENERGY, 2024).

The Global CCS Institute's report (VISIONGAIN, 2024) highlights that while CO_2 utilization projects are on the rise, they still represent a fraction of the total CCUS projects, with geological storage remaining the primary climate mitigation strategy. In terms of sectors, the energy and manufacturing industries continue to lead the implementation of CCUS projects, with a strong emphasis on blue hydrogen, ammonia, iron and steel, cement, and power generation. Utilities and non-energy industries also play important roles, with a growing number of projects being announced in 2023.

The trend for 2024 reflects an increase from 2023, regarding the focus on permanent CO_2 storage, albeit with a higher number of projects. As the CCUS market evolves, the development of new technologies and the expansion of geological storage infrastructure will remain crucial to ensuring that CCUS fulfills its role in the energy transition.

CARBON REMOVAL PROJECTS EMPHASIZE DIRECT AIR CAPTURE (DAC)

Carbon removal projects are increasingly concentrating on Direct Air Capture (DAC). In 2023, approximately 18% of announced CCS projects focused on carbon removal (Bioenergy with carbon capture and storage - BECCS and Direct Air Carbon Capture and Storage - DACCS), marking an almost 100% increase in new DAC projects compared to 2022. This growth has been primarily driven by the United States, as a consequence of the Inflation Reduction Act (IRA) and the Bipartisan Infrastructure Law, which offer tax credits of up to USD 130 per ton for Enhanced Oil Recovery (EOR) and up to USD 180 per ton for permanent storage, along with billions in funding for DAC hubs. While the U.S. leads with 50% of DAC announcements in 2023, significant projects have also emerged outside the U.S., such as Kenya's first large-scale DAC project with a capacity of 100,000 tons per year, estimated to commence by 2028, and Occidental Petroleum's project with ADNOC in the United Arab Emirates, planned to capture one million tons. Other countries, including Canada, Switzerland, and Iceland, have also announced new DAC projects. This growth is noteworthy, given that DAC projects were predominantly pilot or research-focused in the past.

AMID VARIOUS CHALLENGES, SEVERAL PROJECTS LIKELY TO FACE DELAYS

Despite significant momentum in the development of Carbon Capture, Utilization, and Storage (CCUS) technologies, the reality presents considerable challenges, resulting in probable delays for many ongoing projects. Approximately 34% of commercial CCUS projects scheduled for the coming years are expected to encounter delays relative to their original timelines. This figure reflects a continuation of the trend observed in 2022, when about 32% of future projects were delayed (RYSTAD ENERGY, 2024).

Rystad Energy, which monitors and evaluates CCUS projects at various stages of development, has identified that delays are frequently caused by factors related to project development. In 2023, these factors accounted for approximately 50% of the delays. Notably, prolonged completion of feasibility studies or Front-End Engineering Design (FEED) stands out as the primary reason for delays, reflecting a pattern similar to that observed in 2022. This issue is particularly prevalent as most commercial CCUS projects remain in the early stages of deployment.

Furthermore, regulatory issues have emerged as a growing challenge in 2023, especially concerning permits for pipeline routes and storage sites. About 26% of future projects face delays due to problems in obtaining these permits, whether due to delays in granting them or rejections requiring new submissions. A notable example is the cancellation of the Heartland Greenway pipeline project led by Navigator CO_2 Ventures, which was halted due to regulatory concerns regarding the pipeline's permit. Another significant example is the Class VI permitting process in the United States, overseen by the Environmental Protection Agency (EPA). This process, which involves five structured stages and an estimated timeline of 2 to 3 years, has been a major reason for delays in CCS projects seeking permanent storage.

In addition to regulatory challenges in the US, countries like the United Kingdom and Australia, which have licensing rounds for CO_2 storage, continue to face a deficit in the necessary permits compared to the growing demand for new CCS projects. This imbalance represents another subcategory of regulatory challenges that may lead to project delays.

Other factors contributing to delays include financial issues, responsible for 12% of the delays, as well as socioeconomic factors such as environmental protests, regional conflicts, and strategic changes within companies, including shifts in ownership of facilities where CCS was planned.

Although the benefits of CCUS projects, which are developed safely and sustainably, social and environmental acceptance remains a critical factor. Another challenge is the need for continuous innovation to reduce the costs of capture and storage technologies. Finally, international collaboration and knowledge exchange will be crucial to accelerating the global implementation of CCUS.

3

Potential business models: the case of Norway

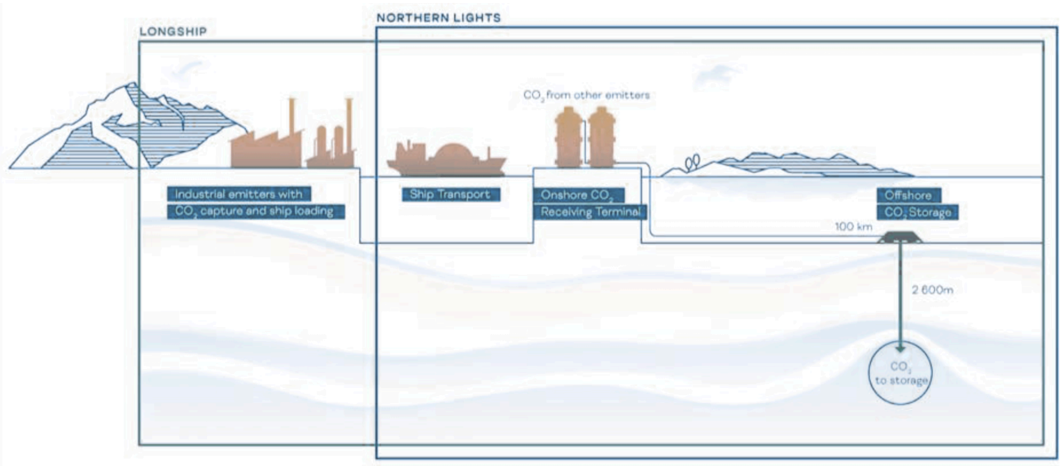
The Longship project, led by the Norwegian government, is one of the most ambitious and comprehensive carbon capture and storage (CCS) initiatives globally. The project is a significant milestone in the fight against climate change, demonstrating how Norway is at the forefront of carbon capture and storage technology. The primary goal of Longship is to reduce CO_2 emissions on a large scale and establish a robust infrastructure that can be replicated in other parts of the world (RIIS, 2018).

Within this context, Northern Lights is a critical component of the Longship project. It is a pioneering project that implements a full CCUS chain. The process involves capturing CO_2 from various industrial sources, transporting it via specialized ships to a receiving terminal on the western coast of Norway, and finally injecting the CO_2 into secure geological formations beneath the North Sea. The geological formations selected for storage are located at a depth of approximately 2,600 meters, ensuring the safety and integrity of the process (RIIS, 2018).

CAPACITY AND OPERATIONAL FLEXIBILITY

Initially, **Northern Lights** has the capacity to store up to 1.5 million tons of CO_2 per year. However, this capacity has the potential to be expanded to up to 5 million tons annually, depending on the increase in industrial demand (RINGROSE, 2020). This scalability is a key feature of the project, allowing it to adapt to the growing needs for carbon capture and storage both in Norway and other European countries, as demonstrated in the image below:

Image 3 – Industrial decarbonization and CO_2 Storage for Europe: Northern Lights Project



Source: IEA, 2021

Northern Lights adopts a flexible infrastructure, which enables the receipt of CO_2 from multiple industrial emitters. This operational flexibility allows different companies across Europe to safely and permanently store their CO_2 deep under the seabed in Norway. For instance, a cement factory in Brevik will capture CO_2, and through the construction of two dedicated CO_2 carriers, it will transport the captured CO_2 to an onshore terminal on the Norwegian west coast. From there, the CO_2 will be transported by pipeline to an offshore subsurface storage location in the North Sea (IEA, 2021). The cross-border aspect is one of the factors that make the project a model for global CCUS initiatives.

TECHNOLOGICAL INNOVATION AND MONITORING

One of the most significant innovations of the project is the use of advanced technologies to monitor and verify CO_2 storage. The use of 4D seismic monitoring and pressure sensors, which provide real-time data on the behavior of the injected CO_2, ensures that the storage integrity is maintained and that leakage risks are minimized (RINGROSE, 2020). These technologies are vital to ensuring that storage is safe in the long term and complies with strict environmental regulations.

THE NORTHERN LIGHTS HUB: PIONEERING BUSINESS MODELS AND FUTURE PROSPECTS FOR GLOBAL CCUS

The Northern Lights business model revolves around the development of an open CO_2 storage infrastructure that is accessible to a wide range of industrial sectors. This infrastructure provides a viable solution for companies with significant CO_2 emissions to meet their reduction targets. Moreover, the project's adaptable design allows for the future integration of new carbon capture technologies and methods, enhancing both storage capacity and operational efficiency as the demand for CCS grows.

The Northern Lights hub is a joint venture between **Equinor**, **Shell**, and **TotalEnergies**, designed to establish a financially sustainable model for CCS. In this collaboration, the costs associated with capturing and transporting CO_2 are offset by the fees paid by industrial emitters who utilize the storage services.

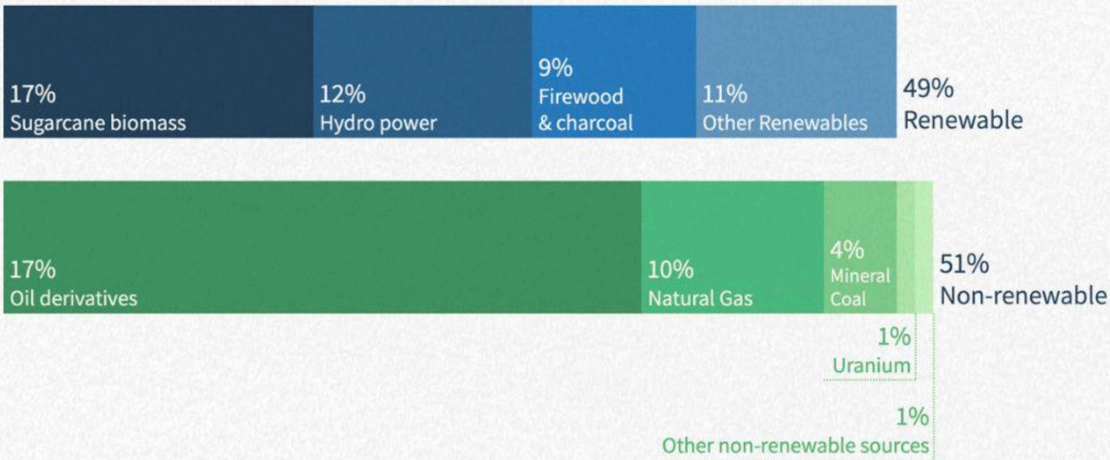
4

Brazil: current status and lessons from the Norwegian experience

In opposition to global trends, Brazil's energy matrix is characterized by a significant and growing share of renewable sources, accounting for 49% of the total energy supply (EPE, 2024b). In 2023, the main renewable sources include hydropower, accounting for 12,1% of the matrix, and sugarcane biomass, which represents 16.9%. Non-renewable sources are primarily dominated by fossil fuels, with oil constituting 35.1% of the energy consumed, followed by natural gas at 9.6%, and coal at 4.4% (EPE, 2024).

Key sources (image 4) in this energy matrix include electricity generation from hydropower, the use of biomass in thermal power stations, and sectors heavily reliant on oil, natural gas, and coal, such as transportation and manufacturing.

Image 4 – Brazilian Energy Matrix



Source: IEA, 2021

This detailed breakdown highlights the significant role of both types of sources in Brazil's energy landscape, reflecting the country's diverse energy profile.

This unique situation is reflected in the country's GHG emissions profile. While the energy sector is the largest emitter globally, in Brazil, it ranks third, following Land Use, Land-Use Change, and Forestry (LULUCF) and the agricultural and livestock sectors (EPE, 2024a; SIRENE, 2023).

Brazil could play a crucial role in the global context of CCUS. Studies highlight the importance of this technology in achieving Brazil's emission neutrality goals. Recently, several projects have been announced, showcasing the country's growing interest and commitment to addressing the energy trilemma[1].

The Brazilian Pre-Salt region, with geological formations like those in the North Sea, offers ideal conditions for safe CO_2 capture storage from the country's most emission-intensive industries, such as cement, steel, and chemicals, located close to the most populated regions of the country.

Furthermore, Norway's experience in creating a market for CO_2 transport and storage services can be adapted to the Brazilian context, particularly regarding the integration of CCUS projects with public climate change mitigation policies. International cooperation, as demonstrated by the Northern Lights project, can also be leveraged by Brazil, fostering partnerships with countries that have carbon-intensive industries and require storage solutions.

Currently, Brazil has at least two significant CCUS projects. One is a pilot project by Petrobras in Rio de Janeiro, aiming to store up to 100,000 tons of CO_2 per year from a natural gas processing facility. This project seeks to test injection, pressure management, monitoring, and plume migration in an onshore hypersaline aquifer, which shares characteristics with the offshore storage site planned for a future commercial hub. Another high-potential initiative is the FS CCS project, which involves a BRL 350 million investment to capture CO_2 generated in corn ethanol production in Lucas do Rio Verde, Mato Grosso. The carbon will be compressed and transported for underground storage in the Parecis Basin. The project, which is the first of its kind in South America, employs safe injection techniques in deep geological formations, ensuring permanent carbon containment and aligning with the bioenergy with carbon capture and storage (BECCS) strategy which can lead to so-called negative emissions and play an important role in removing CO_2 from the atmosphere.

The ArcelorMittal CCS project in Espírito Santo, involves a collaboration between ArcelorMittal Brasil and Petrobras to develop a CCS hub in the region, focusing on capturing CO_2 emissions from various industrial sources, including steel, thermoelectric plants, cement, and natural gas processing units. The captured CO_2 will be transported through a pipeline network and stored in geological reservoirs. This initiative is part of a broader effort to explore low-carbon business models, including renewable energy, hydrogen, and low-carbon fuels. The project aligns with both companies' decarbonization and diversification strategies, aiming to make CCS economically viable and contribute to a sustainable future.

Brazil stands out as a country with operational and pilot projects that have high potential for carbon dioxide removal. Some of these pilot projects are organized in the tables below, segregated by capture, storage, and transportation.

[1] The "Energy Trilemma" is the challenge of balancing three goals in the energy transition: ensuring energy security, maintaining economic accessibility, and promoting environmental sustainability. The shift to cleaner energy sources can complicate this balance, requiring solutions that simultaneously uphold reliable supply, affordable pricing, and reduced environmental impact.

Table 3 – CO_2 Capture pilot projects in Brazil (planned/ feasibility studies)

Project Name	Capture Capacity (Mtpa, max)	Startup year	Main Developer	Partners
Cabiunas natural gas processing facility	1.000	2028	Petrobras	
DACMA DAC	50	2027	DACMa	Repsol Sinopec Senai Cimatec
DACMA demonstrator	3	2026	Repsol Sinopec	PUC-Rio

Source: CEBRI – Brazilian Center for International Relations

Table 4 – CO_2 Storage pilot projects in Brazil (planned/ feasibility studies)

Project Name	Storage Site	Startup year	Purpose	Storage Type
DACMA demonstratator	Paraná Basin, BR	2026	permanent storage	Volcanics
Cabiunas natural gas processing facility	Santos Basin, BR	2028	permanent storage	Saline Aquifers
Cabiunas natural gas processing facility	Campos basin, BR	2028	permanent storage	Saline Aquifers

Source: CEBRI – Brazilian Center for International Relations

Table 5 – CO_2 Transportation pilot projects in Brazil (under construction/planned)

Transport Project	Carbon source	Transport mode	Construction type
Campos basin offshore pipeline	Gas processing	Offshore pipeline	Repurpose
Campos basin onshore pipeline	Gas processing	Onshore pipeline	Repurpose
DACMA pipeline	Direct Air Capture	Onshore pipeline	Newbuild
Repsol Sinopec CO_2 pipeline	Direct Air Capture	Onshore pipeline	Newbuild
Santos basin offshore pipeline	Gas processing	Offshore pipeline	Repurpose
Santos basin onshore pipeline	Gas processing	Onshore pipeline	Repurpose

Source: CEBRI – Brazilian Center for International Relations

Table 6 – CCUS Hubs and operational projects in Brazil

Project Name	Capture Capacity ($MtCO_2/y$)	Startup year	Main Developer	Initial CO_2 source	Potential CO_2 sources for commercial hub	Transport
Rio de Janeiro CCUS Hub	0,1 (demo pilot)	2027	Petrobras	natural gas processing	cement, power, refinery, metallurgy, gas processing	Pipeline
Espírito Santo	10	2033	Petrobras, ArcelorMittal			Pipeline

Hubs will play a prominent role in scaling CCUS in the near-term, providing a potential pathway to transition CCUS from a cost to a business opportunity.

Integrating BECCS into CCUS Hubs

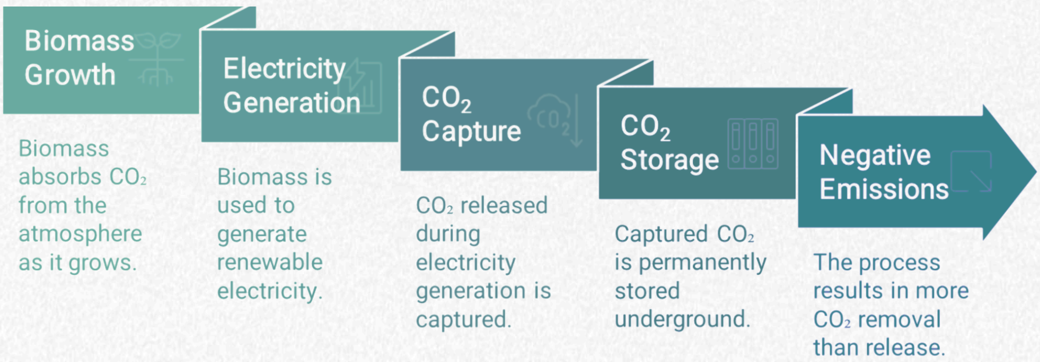
5

Bioenergy with Carbon Capture and Storage (BECCS) is a critical technology for climate change mitigation, combining bioenergy production with the capture and permanent storage of carbon dioxide (CO_2). By utilizing biomass as a feedstock, BECCS delivers net-negative emissions, actively removing CO_2 from the atmosphere while producing energy.

While conventional CCS technologies are effective for achieving short-term emission reductions, BECCS and Direct Air Capture (DAC) are expected to play pivotal roles in reaching long-term decarbonization goals. According to Rystad Energy's projections, BECCS and DAC are anticipated to account for up to 40% of the total CCS demand by 2050, with exponential growth starting in 2035.

The process leverages the ability of plants to absorb atmospheric CO_2 during their growth. This CO_2 is then captured during the conversion of biomass into energy. The captured carbon is compressed and stored in geological formations such as saline aquifers or depleted oil and gas reservoirs. Integrating BECCS into CCUS hubs maximizes economic and technical efficiencies by creating shared infrastructure, which reduces costs and accelerates decarbonization.

Image 5 – Bioenergy carbon capture with storage (BECCS) process



TECHNOLOGY STATUS AND COSTS

The Intergovernmental Panel on Climate Change (IPCC) highlights BECCS as a vital complement to renewable energy sources, particularly in sectors where electrification is challenging. Technology is mature, and certain applications, like bioethanol production, demonstrate cost-effective carbon capture solutions. For instance, capturing CO_2 during bioethanol fermentation can cost as little as USD 20 per ton of CO_2 due to the high purity of emissions produced in the process. This eliminates the need for energy-intensive absorption and separation technologies typical of traditional CCS.

A proven example of BECCS viability at a commercial scale is the Illinois Basin-Decatur Project in the United States. This pilot project successfully captured and stored 1 million tons of CO_2 between 2011 and 2014 at a total cost of USD 208 million, with 68% funding from the U.S. Department of Energy (DOE).

BECCS IN BRAZIL AND CASE STUDIES

CCUS hubs, which link multiple emission sources to shared infrastructure for carbon capture, transport, and storage, offer economic and technical synergies that can accelerate BECCS adoption. Such hubs enable bioenergy plants to benefit from economies of scale by sharing costs with other industrial emitters.

Brazil holds significant natural and industrial advantages for integrating BECCS, leveraging abundant biomass resources and the geological storage potential not only in the pre-salt reservoirs but also in onshore reservoirs.

GLOBAL CASE STUDIES AND BEST PRACTICES

1. Drax Project (United Kingdom): The largest biomass power plant in Europe aims to achieve negative emissions by 2030 through the integration of BECCS. This project showcases the feasibility of combining large-scale bioenergy with carbon capture technologies.

2. Illinois Basin-Decatur (United States): Operated by ADM, this pioneering initiative integrates bioenergy and CCS, with a 1 Mtpa (million tons per annum) capture capacity.

3. Mendota Biomass (United States): Focused on agricultural residues, this project is expected to capture 0.3 Mtpa of CO_2, with operations starting in 2025.

STRATEGIC OPPORTUNITIES

The integration of BECCS with CCUS hubs represents a strategic pathway for achieving cost-effective and sustainable emission reductions. Projects like FS Bioenergia and other global initiatives highlight the potential of this technology to complement the energy transition, leveraging renewable resources and carbon capture infrastructure to create a cleaner, more sustainable future.

By aligning policy incentives, enhancing collaboration, and developing robust infrastructure, BECCS can become a cornerstone of global efforts to achieve net-zero emissions and mitigate the impacts of climate change.

Table 7 – Comparison between different types of carbon capture technology

	Traditional CCS	Bioenergy with CCS (BECCS)
CO_2 source	Flue gas from point source	Flue gas from bioenergy generation
Application	Power plant, industry production, gas processing	Biomass and biofuels production
USD per tonne CO_2 range	\$20 - \$100	\$20 - \$250
Capture project capacity (million tpa)	0.1 - 15	0.06 - 10
Main capture technology	- Liquid solvent - Membrane - Solid absorbent	- No separation needed for CO_2 from bioethanol - Same as traditional CCS
Technology maturity comparison (TRL)	Mature, ready for commercial operation (TRL 9)	Mature, ready for commercial operation (TRL 9)
Main advantages	- Relatively cheap	- Existing technology - Negative emission
Main disadvantages	- Energy intensive - High CO_2 concentration needed	- Required land availability.

Source: CEBRI – Brazilian Center for International Relations

CONCLUSION

As the world confronts the escalating challenge of climate change, CCUS stands out as a pivotal technology for mitigating GHG emissions across some of the most challenging industrial sectors. This report has explored the global state of CCUS, examined the key challenges to its widespread adoption, and analyzed the potential for Brazil to become a leader in this critical field.

The global momentum behind CCUS is undeniable, with numerous projects indicating its viability and effectiveness. However, the path to mainstream adoption is fraught with challenges, including high costs, regulatory uncertainty, and the need for extensive infrastructure development. Despite these obstacles, the continuous innovation in capture and storage technologies, coupled with strong government policies and international collaboration, offers a promising path forward.

Despite differences in scale and economic context, Brazil and Norway share significant potential to leverage expertise from oil and gas reservoir development for carbon storage. Supportive policies and carbon market dynamics are expected to drive a recovery in CCUS project deployments by 2030, especially for hard-to-abate sectors. As the energy transition gathers pace, global CCUS projects are on track to remove significantly more CO_2 from the atmosphere each year by 2030.

Brazil's experience with large-scale industrial projects, particularly in the oil and gas sector, provides a strong foundation for developing integrated CCUS hubs that can significantly reduce emissions from multiple sources. Therefore, expertise from the oil and gas sector can be applied to the CCUS value chains, facilitating the transition by utilizing existing skills, which can help to address the challenges such as training workers for new decarbonization technologies — avoiding job losses (S&P Global, 2024).

Furthermore, since industrial development relies on hard-to-abate industries, CCUS has the potential to represent a significant economic opportunity, especially for industries that face obstacles in replacing fossil fuels. These industries can continue their operations without losing productivity or product quality. It is also relevant for Brazil, which has competitive oil reserves that support its domestic economy and generate foreign exchange.

Considering that oil and gas will remain in the national energy matrix in the long term, CCUS may be key for countries like Brazil and Norway, which have a renewable energy matrix and whose emissions do not primarily derive from the energy sector. It allows these countries to invest in alternative technologies that ensure the sustainability of the fossil sector, as the carbon intensity of Brazilian and Norwegian oil is lower than the global average.

To realize this potential, Brazil must address critical challenges, including the development of a robust regulatory framework capable of integrating different actors, securing investments, and building public trust and social acceptance.

Enhancing social and environmental acceptance of CCUS projects is vital. Raising awareness about the benefits of CCUS and ensuring that projects are developed safely and sustainably will help build public trust and support.

Fostering international collaboration and knowledge exchange will accelerate the implementation of CCUS in Brazil. The lessons from international experiences, particularly from projects like Norway's Longship, offer valuable insights for Brazil. By adopting best practices in governance, financing, and technological innovation, Brazil can not only contribute to global emission reduction efforts but also position itself as a leader in the CCUS landscape in Latin America and beyond.

As the world moves toward a more sustainable future, embracing CCUS will be a critical step in achieving Brazil's climate goals and strengthening its role in the global fight against climate change.

REFERENCES

Agaton, C. B. (2021). Application of real options in carbon capture and storage literature: Valuation techniques and research hotspots. Science of the Total Environment, 795, 148683. https://doi.org/10.1016/j.scitotenv.2021.148683

ARGUS. (2023). Petrobras construirá projeto de CCUS no Rio. https://www.argusmedia.com/pt/news-and-insights/latest-market-news/2515973-petrobras-construira-projeto-de-ccus-no-rio

BNDES. (2023). A transição energética e o setor de petróleo e gás brasileiro.

Brazil. (2008). Plano Nacional sobre Mudança do Clima. PNMC. Governo Federal, 28. http://www.mma.gov.br/estruturas/smcq_climaticas/_arquivos/sumrio_executivo_pnmc.pdf

EPE — Energy Research Office. (2024). Brazilian Energy Balance Summary Report 2024. https://www.epe.gov.br/sites-en/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-231/BEN_Síntese_2020_EN.pdf

EPE. (2024a). CAPTURA, ARMAZENAMENTO E UTILIZACÃO DE CARBONO NO BRASIL: Contribuições para a seleção de áreas de interesse. https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/captura-armazenamento-e-utilizacao-de-carbono-no-brasil-contribuicoes-para-a-selecao-de-areas-de-interesse

EPE. (2024b). Saline Reservoirs: What's behind one of the top targets for carbon storage sites? 2–5. https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-820/FS-EPE-DPG-SPG-001_2024-CCS_SalineReservoir_EN.pdf

IEA. (n.d.). Carbon Capture, Utilisation and Storage. https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage

IEA. (2020). Energy Technology Perspectives 2020. Energy Technology Perspectives 2020. https://doi.org/10.1787/ab43a9a5-en

IEA. (2021). CCUS around the world in 2021: Northern Lights. https://www.iea.org/reports/ccus-around-the-world-in-2021/northern-lights

IEA. (2023a). CCUS Policies and Business Models. CCUS Policies and Business Models. https://doi.org/10.1787/6ef05538-en

IEA. (2023b). Energy system of Norway. https://www.iea.org/countries/norway

IISD. (2023). Why the Cost of Carbon Capture and Storage Remains Persistently High. https://www.iisd.org/articles/deep-dive/why-carbon-capture-storage-cost-remains-high

Machado, P. G., Hawkes, A., & Ribeiro, C. de O. (2021). What is the future potential of CCS in Brazil? An expert elicitation study on the role of CCS in the country. International Journal of Greenhouse Gas Control, 112, 103503. https://doi.org/10.1016/j.ijggc.2021.103503

McKinsey&Company. (2023). The world needs to capture, use, and store gigatons of CO_2: Where and how? https://www.mckinsey.com/industries/oil-and-gas/our-insights/the-world-needs-to-capture-use-and-store-gigatons-of-co2-where-and-how

McKinsey&Company. (2024). Global Energy Perspective 2023: CCUS outlook. https://www.mckinsey.com/industries/oil-and-gas/our-insights/global-energy-perspective-2023-ccus-outlook

Petrobras. (2023). Petrobras obtém reconhecimento internacional por pioneirismo em captura e armazenamento de CO_2 (CCUS). https://agencia.petrobras.com.br/w/petrobras-obtem-reconhecimento-internacional-por-pioneirismo-em-captura-e-armazenamento-de-co2-ccus-

Petrobras. (2024). Caderno do Clima. https://petrobras.com.br/sustentabilidade/mudancas-climaticas#caderno-do-clima

Riis, F. (2018). Norway CCS demonstration project: Evaluation of Jurassic reservoirs for safe CO_2 injection and storage. 5th CO_2 Geological Storage Workshop, 2018-November(July 2018). https://doi.org/10.3997/2214-4609.201802954

Ringrose, P. (2020). Ensuring safe storage operations : learning from Sleipner and Snohvit Summary CCS in Norway. Baltic Carbon Forum (BCF 2020) 14th October 2020, October.

Rui, Z., Zeng, L., & Dindoruk, B. (2025). Challenges in the Large-Scale Deployment of CCUS. Engineering, 44, 17–20. https://doi.org/10.1016/j.eng.2024.11.031

RYSTAD ENERGY. (2024). Energy Transition Report CCUS Market Update Energy Transition Analytics Time to deliver on announced CCUS projects. https://www.rystadenergy.com/insights/energy-transition-ccus-market-update-whitepaper

S&P Global. (2024). CCUS Hubs in Brazil: Making the Case, Breaking the Barriers. 1–39.

SISTEMA DE REGISTRO NACIONAL DE EMISSÕES (SIRENE). (2023). Emissões de GEE por Setor. https://www.gov.br/mcti/pt-br/acompanhe-o-mcti/sirene/emissoes/emissoes-de-gee-por-setor-1

VISIONGAIN. (2024). Carbon Capture Utilisation and Storage (CCUS) Market Report 2024-2034. https://www.visiongain.com/report/ccus-market-2024/#download_sampe_div

Wood Mackenzie. (2023). What's shaping CCUS project costs? https://www.woodmac.com/news/opinion/ccus-project-costs/

ZEP — Zero Emissions Pathway. (2020). A Trans-European CO_2 Transportation Infrastructure for CCUS : Opportunities & Challenges. June, 1–81.

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