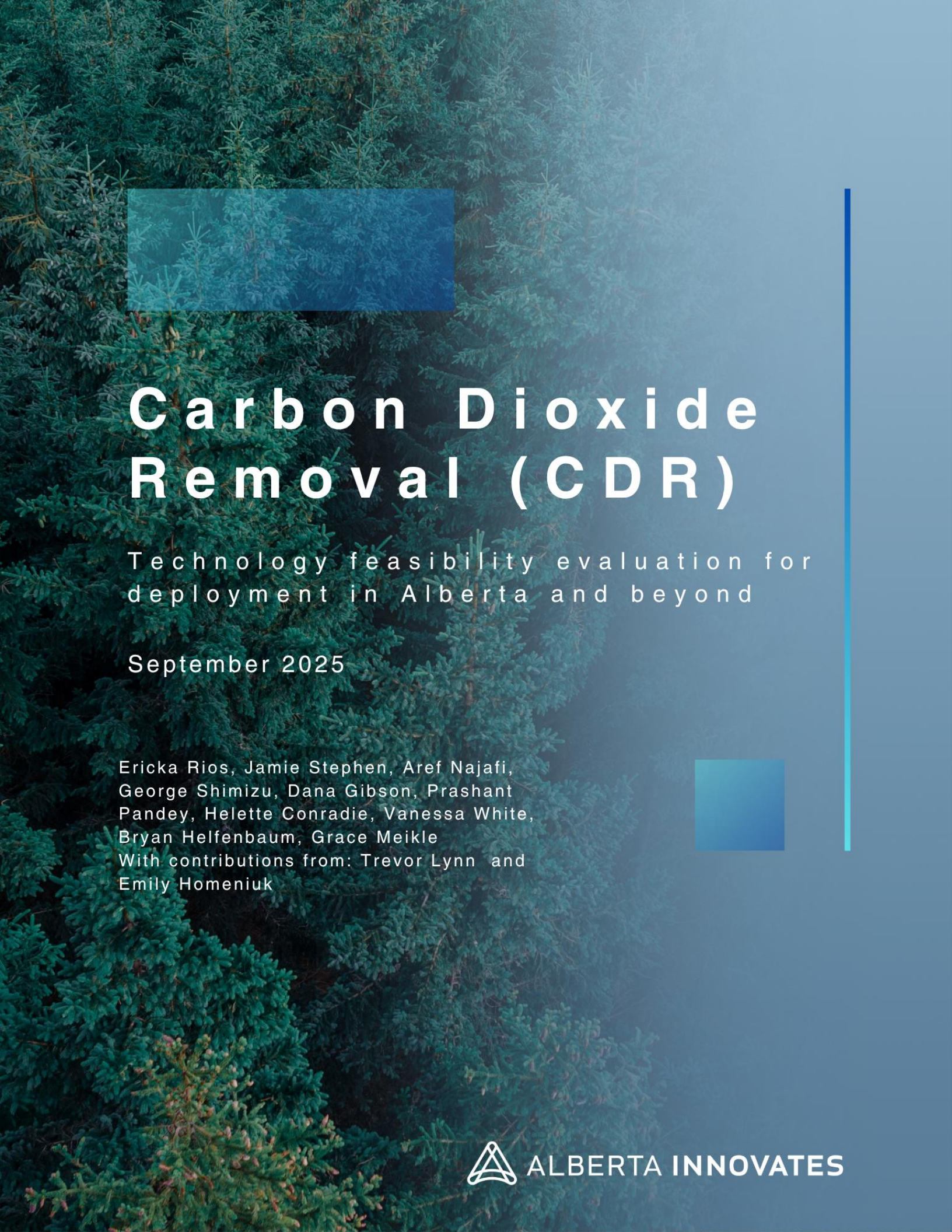




Carbon Dioxide Removal (CDR)

Technology feasibility evaluation for
deployment in Alberta and beyond

September 2025

Ericka Rios, Jamie Stephen, Aref Najafi,
George Shimizu, Dana Gibson, Prashant
Pandey, Helette Conradie, Vanessa White,
Bryan Helfenbaum, Grace Meikle
With contributions from: Trevor Lynn and
Emily Homeniuk



ALBERTA INNOVATES

Executive Summary

Alberta is poised to become a leader in the Carbon Dioxide Removal (CDR) market, presenting significant opportunities for growth and innovation. With its abundant natural resources and existing infrastructure, Alberta can harness its strengths to develop effective CDR technologies. The provincial government's supportive policies, along with investment in research and development, set the stage for advancements in carbon capture and sequestration techniques that can help drive CDR investment.

Alberta Innovates and Emissions Reduction Alberta (ERA) play pivotal roles in this transformation. Alberta Innovates drives innovation in CDR through research funding and collaboration initiatives, while ERA invests in new technologies to accelerate the deployment of carbon capture, utilization, and storage (CCUS) solutions. These organizations facilitate partnerships among academia, industry, and government, fostering a vibrant ecosystem for CDR initiatives.

Background and Importance of CDR

CDR technologies are essential for achieving global net-zero targets by 2050. They provide a means to remove CO₂ from the atmosphere, complementing efforts to reduce emissions. Alberta's energy sector, with its significant greenhouse gas emissions, stands to benefit greatly from integrating CDR solutions. The International Energy Agency (IEA) and Natural Resources Canada (NRCan) emphasize the importance of CDR in mitigating climate change and achieving sustainability goals.

Why CDR in Alberta?

Diversification of Alberta's economy is needed to mitigate economic risks due to fluctuating global energy prices and climate change policies. The province's oil sands are a significant source of greenhouse gas emissions. However, Alberta has several competitive advantages for CDR, including:

- **Geology:** The Western Canada Sedimentary Basin offers excellent conditions for large-scale, low-cost CO₂ storage.
- **Biomass Resources:** Alberta is the largest producer of biomass in Canada, providing ample feedstock for Bioenergy with Carbon Capture and Storage (BECCS) projects.
- **Regulations and Rule-of-Law:** Alberta has world-leading regulations for CO₂ storage and a robust industrial carbon pricing system.

Carbon Removal Methods

CDR encompasses various technologies aimed at reducing atmospheric CO₂ levels. Key methods include:

- Bioenergy with Carbon Capture and Storage (BECCS): Combines biomass energy production with CO₂ capture and storage.
- Direct Air Capture with Carbon Storage (DACCS): Captures CO₂ directly from the air.
- Nature Based Solutions (NBS): Utilizes natural processes like afforestation, soil carbon sequestration, and enhanced rock weathering.
- Permanence and Technology Readiness: Ensuring the permanence of captured CO₂ is critical.

Alberta's guidelines align with international best practices, emphasizing long-term storage with rigorous monitoring and verification. The technology readiness levels (TRL) of various CDR technologies in Alberta are comparable to those in other jurisdictions, with BECCS and DACCS being more advanced.

BECCS Technology Pathways

Alberta has significant opportunities for BECCS development, including:

- Post-Combustion Capture: Purifies CO₂ from biomass combustion flue gas.
- Oxy-Combustion: Uses pure oxygen for combustion, resulting in high-purity CO₂.
- Gasification for Hydrogen Production: Converts biomass into syngas for hydrogen production, capturing CO₂ in the process.
- Biomethane PCC (Post-combustion Capture) and ATR (Auto-Thermal Reforming): Uses biomethane as a substitute for natural gas in existing facilities.
- Ethanol Fermentation: Captures high-purity CO₂ from ethanol production.

Direct Air Capture with Carbon Storage (DACCS)

Canada is home to global leaders in DAC technology, such as Carbon Engineering and Svante. While there are no full-scale DAC projects in Canada yet, several pilot projects are underway. Alberta's cool and dry climate offers advantages for DAC operations, although the province's cold winters present challenges.

Nature Based Solutions (NBS)

NBS leverage ecosystems to combat climate change. Key methods include:

- Soil Carbon Sequestration: Enhances soil health and carbon storage through practices like no-till farming and cover cropping.
- Afforestation and Reforestation: Increases carbon sequestration by planting new forests and restoring existing ones.
- Peatland and Wetland Restoration: Restores degraded ecosystems to enhance carbon storage.
- Biochar: Stabilizes carbon in soil through the pyrolysis of organic matter.
- Enhanced Rock Weathering (ERW): Accelerates natural weathering processes to capture CO₂.

CDR Industry and Market Opportunities

The global CDR market is in the early growth stage, driven by net-zero commitments, regulatory mandates, and technological advancements. Alberta has the potential to establish a robust CDR market, attracting investments and creating jobs. Key industry trends include the expansion of CCUS projects, diversification of technologies, and significant investment growth.

Government Incentive Programs

Government incentives are vital for advancing CCUS technologies. In Canada, federal and provincial programs provide substantial funding and tax credits to support CCUS projects. Alberta's Carbon Capture Incentive Program (ACCIP) and other initiatives aim to accelerate the development of carbon capture and storage technologies.

CDR Opportunities in Alberta

1. Alberta's BECCS project development opportunities are numerous and can be grouped into five main categories:
 - Adding Capture to Existing Facilities: Capturing CO₂ from existing forest products and renewable fuel facilities.
 - Fuel Switching Existing Infrastructure: Converting former coal plants to biomass and adding carbon capture.
 - Developing New Biomass Heat and Power Facilities: Supplying existing consumers with biomass energy.

- Developing BECCS Biopower Facilities: Decarbonizing Alberta's electricity grid.
- Developing New Biomass-based Negative Carbon Products: Producing hydrogen, fuels, and chemicals with negative carbon intensity.

2. DACCS Opportunities:

- Carbon Sequestration Access: Alberta has significant underground storage capacity in the form of deep saline aquifers, with an estimated capacity to store 360 gigatonnes (Gt) of CO₂.
- Mineralization capacity is also promising, with studies suggesting enough glauconite sandstone to mineralize over 500 Gt of CO₂.
- Existing Infrastructure: Alberta's existing infrastructure, such as the Alberta Carbon Trunkline, can facilitate the transport and storage of captured CO₂, supporting DACCS projects.
- Cold and Dry Climate: The relatively dry climate in Alberta offers advantages for DAC operations, as it reduces the impact of humidity on the performance of solid or liquid absorbents.
- DAC Value Chain and Ecosystem: Alberta has a conducive business ecosystem for DAC technology development, with support from government policies and regulations, and a strong presence of private sector companies that can support the DAC value chain.

3. NBS Opportunities:

- Soil Carbon Sequestration: Alberta's agricultural sector can play a crucial role in implementing soil carbon sequestration techniques, enhancing soil health and carbon storage through practices like no-till farming and cover cropping.
- Afforestation and Reforestation: Alberta has significant potential for afforestation and reforestation projects, leveraging its vast land resources to sequester carbon naturally.
- Peatland and Wetland Restoration: Restoration initiatives focus on re-establishing degraded peatlands and wetlands, which are vital carbon sinks and provide essential ecological services.
- Biochar: Biochar production and application can enhance soil fertility, improve soil structure, and sequester carbon long-term, contributing to sustainable agriculture and climate change mitigation.

Conclusions and Recommendations

CDR is crucial for achieving net-zero emissions by 2050. Alberta's unique context, expertise in CCUS, and economic considerations make it an ideal candidate for exploring CDR solutions.

Integrating CDR into climate action frameworks enhances the effectiveness of existing emission reduction strategies, especially when paired with the following 10 recommendations: 1. Conduct comprehensive assessments, 2. Enhance regulatory frameworks, 3. Increase funding and incentives, 4. Foster collaboration, 5. Invest in research and development, 6. Engage stakeholders, 7. Develop a skilled workforce, 8. Monitor and evaluate progress, 9. Promote public awareness, 10. Align with climate goals.

Continued government support, investment in innovative technologies and collaboration among industry leaders and researchers will be pivotal in advancing CDR solutions that align with net-zero objectives.

Alberta's commitment to reducing greenhouse gas emissions, combined with its natural resources and regulatory framework, positions the province as a leader in the global transition to a low-carbon economy. By fostering an environment conducive to innovation and collaboration, Alberta can significantly contribute to global net-zero ambitions and drive economic prosperity.

Table of Contents

Executive Summary	2
<i>Background and Importance of CDR</i>	2
<i>Why CDR in Alberta?</i>	2
<i>Carbon Removal Methods</i>	3
<i>BECCS Technology Pathways</i>	3
<i>Direct Air Capture with Carbon Storage (DACCS)</i>	3
<i>Nature Based Solutions (NBS)</i>	4
<i>CDR Industry and Market Opportunities</i>	4
<i>Government Incentive Programs</i>	4
<i>CDR Opportunities in Alberta</i>	4
<i>Conclusions and Recommendations</i>	6
Table of Contents	7
Introduction	9
<i>The Role of CCUS in CDR</i>	10
<i>Why CDR in Alberta?</i>	10
<i>Alberta's Role in Permanent, Engineered CDRs</i>	12
Carbon Removal Methods	15
<i>Permanence</i>	15
Carbon Capture: Chemical vs. Physical	18
<i>Solid Sorbents</i>	20
<i>Membranes</i>	20
BECCS Technology Pathways	22
<i>Post Combustion Capture</i>	23
Oxy-combustion	24
<i>Gasification and Hydrogen Production</i>	25
<i>Biomethane PCC and ATR</i>	25
<i>Ethanol Fermentation</i>	26
Direct Air Capture with Carbon Storage (DACCS)	26
<i>Technology Description</i>	27
<i>Advantages of Direct Air Capture</i>	29

<i>Current Challenges of Direct Air Capture</i>	30
NBS (Nature Based Solutions).....	32
<i>Soil Carbon Sequestration</i>	32
<i>Importance of Forests in Carbon Sequestration</i>	33
<i>Peatland and Wetland Restoration</i>	35
<i>Biochar</i>	36
<i>Enhanced Rock Weathering (ERW)</i>	36
CDR Industry	38
<i>Overview of the CDR Market</i>	38
<i>Compliance vs. Voluntary Markets</i>	40
<i>Challenges</i>	42
<i>Notable Investment Activity</i>	43
<i>BECCS Industry Participants</i>	44
CDR Opportunities in Alberta	48
Bioenergy with Carbon Capture and Storage.....	48
<i>Nature Based Solutions</i>	56
<i>Direct Air Capture with Carbon Storage</i>	57
CDR Markets in Alberta - Exports or Other Compliance Markets	60
Conclusions	62
Recommendations	65
Appendix	66
<i>Carbon Capture Developers</i>	66
<i>NBS and BECCS Developers</i>	66
<i>DAC Developers</i>	67
<i>CDR Recent Activity</i>	68
Canadian Government and Global Incentive Programs	69
<i>Canadian Federal Incentives</i>	69
<i>Canadian Provincial Incentives</i>	71
<i>American Federal Incentives</i>	72
<i>Global Incentives</i>	73

Introduction

Carbon dioxide removal (CDR) refers to the process of capturing CO₂ from the atmosphere and storing it durably. CDRs are broadly categorized into nature-based solutions (NBS) and engineered removals, including both direct air carbon capture and storage (DACCS) and bioenergy with CCS (BECCS). While reducing emissions remains crucial, CDR provides an additional tool to combat climate change, particularly for sectors that aren't reducing emissions quickly enough to meet climate targets. Alberta's energy sector is both a major driver of Canada's economy as well as its largest source of emissions, and it is in this context that we understand the potential of CDR and how it fits within the broader carbon management framework.

The purpose of this document is to inform the public, policymakers, potential investors, and academics about the definition of Carbon Dioxide Removal (CDR), the technologies involved, and to evaluate the potential opportunities this emerging CDR market could present in Alberta, Canada.

Recognized in Canada and globally, the need for CDR is urgent. The International Energy Agency (IEA) highlights that without CDR, it will be challenging to offset legacy emissions¹. Natural Resources Canada (NRCan) supports this view, noting that CDR technologies are vital for reducing the carbon footprint of energy-intensive sectors². Reports from the World Resources Institute (WRI) suggest that up to 10 billion metric tons of CO₂ need to be removed annually by mid-century to meet climate goals³.

In Alberta, the adoption of CDR technologies can significantly contribute to the province's economic and environmental objectives. The energy sector stands to benefit from the integration of CDR solutions, which can enhance sustainability and create new economic opportunities.

¹ International Energy Agency (IEA). (2021). [“Net Zero by 2050: A Roadmap for the Global Energy Sector.”](#)

² Natural Resources Canada (NRCan). (2022). [“The Role of Carbon Capture, Utilization, and Storage in Canada's Climate Plan.”](#)

³ World Resources Institute (WRI). (2020). “Carbon Removal: How Much is Needed to Limit Global Warming?”

The Role of CCUS in CDR

CCUS is an important component of CDR, as it is the foundation for engineered removals, including BECCS and DACCS. Canada is developing a world-class, multibillion-dollar carbon management sector that supports inclusive employment and a sustainable economy. The Government of Canada is actively investing in and promoting CCUS, with programs such as an Investment Tax Credit (Bill C-59, 2023). By fostering innovation and collaboration among industry leaders, researchers, and policymakers, Canada is positioning itself as a global leader in carbon management⁴.

Within this broader context, CCUS is recognized as an important pathway to achieving a net-zero future, especially in Alberta, which already has operating commercial CCUS infrastructure. This document complements the [Carbon Capture, Utilization and Storage \(CCUS\)](#) (2022) white paper previously produced by Alberta Innovates, which provides a comprehensive overview of the potential economic impacts and strategic importance of CDR technologies in Alberta and beyond.

Why CDR in Alberta?

Alberta is an export-driven economy, with the highest export-import ratio in Canada. In 2022, Alberta exported \$1.16 in goods and services for every \$1.00 of imports. Every other province is a net importer, ranging from \$0.54 of exports for every \$1.00 of imports in Nova Scotia to \$0.98 of exports per \$1.00 of imports in Ontario⁵. This shows the importance of Alberta to Canada's overall international trade balance.

Energy exports accounted for 96% of Alberta's net exports in 2023. Crude oil is Canada's largest export, accounting for 17% of all exports but almost 50% of net exports by category⁶. While the export of Alberta's significant fossil fuel resources is essential to Canada's economy, this export dependency on fossil fuels and derivatives also presents an economic risk. Beyond swings in global commodity energy prices, the largest risk to Alberta's ability to continue growing fossil fuel exports is climate change policy – both domestically and internationally. This is particularly true for oil sands, which are Alberta's largest export industry but also, the largest GHG emitting industrial

⁴ Emissions estimates grouped into the activity sectors defined by the IPCC. CO₂ emissions calculations for the oil and gas sector in the energy category are based on resource recovery and combustion processes.

⁵ Statistics Canada, 2024. Gross domestic product, expenditure-based, provincial and territorial, annual. Table 36-10-0222-01.

⁶ Statistics Canada, 2024. International merchandise trade by commodity, monthly. Table 12-10-0163-01.

sector in Canada at 87 Mt CO₂e in 2022⁷. In total, oil and gas industries in Canada emitted 217 Mt CO₂e^{8,9}.

Oil extracted from oil sands is also among the highest-GHG intensity barrels in the world. There has been a significant reduction in the upstream carbon intensity of Alberta's oil sands over the past two decades; the intensity of oil sands operations has declined steadily from 126 kg CO₂e per barrel in 1990 to 77 kg CO₂e per barrel in 2022³. Currently, about 80% of life cycle emissions from petroleum products are associated with their end-use rather than extraction and processing. Despite this, the upstream carbon intensity of bitumen production continues to attract attention. This was a significant factor in the decision by several European oil majors and investors to divest oil sands assets.

Importantly, Alberta and Canada have a competitive advantage for social and governance performance of fossil fuel energy products compared to most international competitors, many of which lack the human rights record or institutional protections of the Canadian policy environment. This advantage has been emphasized in marketing campaigns emphasizing 'ethical oil' or sustainable and environmentally responsible produced oil from Alberta. Alberta has made significant strides using technology, operational improvements, and implementation of climate conscious policies to improve the environmental performance of its exports. The existing and proposed growth in CCUS is likely to be a large part of the upstream GHG improvement effort.

However, even widespread deployment of CCUS will not result in a net-zero operation for the industry but will only bring oil sands upstream carbon intensity in line with the current emissions of crude from Saudi Arabia, Kuwait, or the UAE¹⁰. This CCUS deployment will add costs to oil sands and natural gas recovery and processing, reducing the economic competitiveness of Alberta's exports, and does not address the largest life cycle emissions component of Alberta's fossil fuels – their use. It is estimated that the use of Canada's 2022 exported oil and gas, with most of this sourced from Alberta, generated 939 Mt CO₂e¹¹. This is 33% more than Canada's national GHG emissions and 233% more than domestic oil and gas industry emissions.

The health of Alberta's, and more broadly Canada's, economy currently depends on the continued export of fossil fuels. Applying CCUS to existing fossil fuel emitters and continued efforts to curtail

⁷ Environment and Climate Change Canada, 2024. National inventory report 1990-2022: greenhouse gas sources and sinks in Canada.

⁸ Crippa et al., 2024. GHG emissions of all world countries. European Commission.

⁹ https://publications.gc.ca/collections/collection_2024/ecccc/En81-4-2022-1-eng.pdf

¹⁰ Masnadi et al., 2018. Global carbon intensity of crude oil production. Science 361: 851-853.

¹¹ Bernstein J, 2024. Canada's uncounted emissions. CBC News. June 20, 2024.

methane emissions will eliminate much of the upstream, non-use emissions associated with its exports. CDR can offer a new export product to grow Alberta's economy and help further drive down some of the emissions intensity of energy related exports and use by counterbalancing some of the hard-to-abate emissions.

Alberta's Role in Permanent, Engineered CDRs

Many jurisdictions have opportunities in low durability, nature-based solutions or CDRs from biochar or enhanced rock weathering. However, Alberta has a competitive advantage in technology, relying upon the most durable, long-lasting form of CDR: engineered removals that rely on subsurface storage of CO₂. The two primary approaches for this are DACCS and BECCS.

While Alberta has an opportunity to develop DACCS projects for CDR, the province is challenged by a cold winter climate that makes deployment of liquid-based DACCS technologies difficult. In addition, Alberta is a large consumer of thermal energy, with almost 80% of the province's energy consumption being heat. Globally, biomass dominates renewable heat supply. For example, almost 90% of the renewable heat supply in the EU is from biomass¹². While DACCS consumes energy, BECCS is a generator of heat that can be used to reduce domestic fossil fuel consumption. Between DACCS and BECCS, it is BECCS where Alberta has a competitive advantage compared to any other jurisdiction in the world, for three main reasons:

- 1 Geology: Alberta has excellent geology in the Western Canada Sedimentary Basin (WCSB) for onshore, low-cost, large-scale permanent CO₂ storage.
- 2 Biomass Resources: Alberta is the largest producer of biomass in Canada, in the form of timber and crops, and has the potential to significantly increase production.
- 3 Regulations and Rule-of-Law: Alberta has world-leading regulations for CO₂ storage, Crown ownership of CO₂ pore space, and a long-lived industrial carbon pricing system that has been accepted by industry.

CDRs can become a major export product for Alberta, with the opportunity to offer a net-zero energy product with the oil and gas industry, or net-negative on its own. International sales and future purchase agreements are already occurring in other jurisdictions. For example, US-based Microsoft has committed to buying BECCS CDRs from Ørsted in Denmark and Stockholm Exergi in Sweden. The cost for BECCS CDRs in Alberta is anticipated to be significantly less than these purchases¹³.

¹² Eurostat, 2024. Complete energy balances. European Commission.

¹³ [New Study: Experts' views on future costs and deployment of DACCS and BECCS in Europe | Negem Project](#)

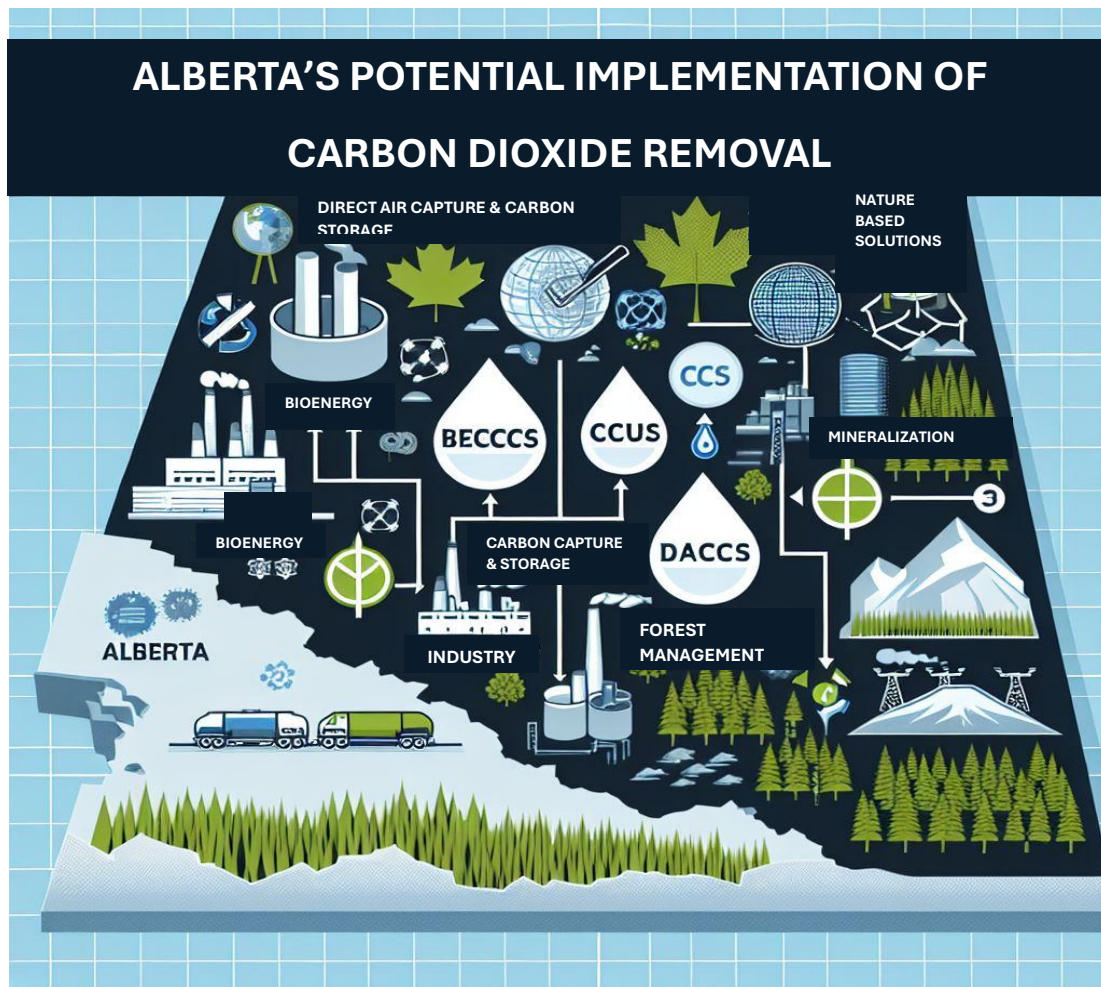
Alberta has an additional incentive to develop BECCS; one that is counterfactual to passively managing Crown (Provincially)-owned timberlands: wildfires. Wildfires are Canada's largest source of GHG emissions and are also the largest source of air pollution--more than all other sources combined for both types of emissions¹⁴. For context, according to a study done by NASA in 2023, wildfires in Canada released approximately 640 Mt CO₂e between May and September the same year, fueled by the warmest and driest conditions in decades, representing 5% of Canada's forests.¹⁵ The province has been particularly hard hit by wildfires over the past fifteen years, with major losses of property in Fort McMurray, Slave Lake, and Jasper. BECCS can serve as a market that not only reduces fossil fuel consumption but also removes CO₂ from the atmosphere.

In summary, Alberta's unique context, expertise in CCUS, and economic considerations make it an ideal candidate for exploring CDR solutions. As we move toward a net-zero future, CDR will play a pivotal role in mitigating climate change and ensuring a sustainable planet. To accomplish this, new technologies and integration solutions will require derisking at progressive scales prior to commercial implementation. The historical energy innovation landscape in Alberta and wealth of existing and emerging industry creates ample opportunities for meaningful demonstrations and risk-mitigating collaboration.

¹⁴ MacCarthy et al, 2024. Extreme wildfires in Canada and their contribution to global loss in tree cover and carbon emissions in 2023. *Global Change Biology* 30: e17392.

¹⁵ [New NASA Study Tallies Carbon Emissions From Massive Canadian Fires - NASA](#)

The image below highlights Alberta's strengths and opportunities in the CDR market, showcasing its abundant natural resources, existing infrastructure, supportive policies, and various CDR technologies.



Carbon Removal Methods

Carbon removal methods encompass a range of technologies aimed at reducing atmospheric CO₂ levels. They can be categorized in different ways, but a common categorization is BECCS, DACCS, and nature-based solutions (NBS). BECCS combines biomass energy production with CO₂ capture, DACCS directly captures CO₂ from the air, and NBS refers to strategies that utilize natural processes and ecosystems to address environmental challenges. These technologies vary in their readiness levels, with some still in experimental stages and others nearing commercial viability. A critical aspect of these methods is CO₂ permanence, ensuring that captured carbon remains sequestered long-term, thus effectively mitigating climate change. Understanding and advancing these technologies is crucial for achieving global climate goals. These solutions are essential for reducing atmospheric carbon dioxide levels and mitigating climate change impacts. Alberta, with its rich resources, sequestration potential and innovative spirit, is well-positioned to lead in the deployment of these technologies.

Permanence

A critical element to ensure carbon removal is determining the permanence of CO₂. Carbon dioxide (CO₂) permanence refers to the duration that captured CO₂ remains stored without being released back into the atmosphere. In Canada, CO₂ permanence is defined by the federal government as the ability to securely store CO₂ for at least 100 years, ensuring that it does not contribute to atmospheric greenhouse gas levels¹⁶. Alberta, having significant CCUS initiatives, aligns with this definition but also emphasizes rigorous monitoring and verification processes to ensure the integrity of storage sites¹⁷. Globally, the definition of CO₂ permanence varies, with some countries adopting a 100-year benchmark similar to Canada, while others may have shorter or longer timeframes depending on their regulatory frameworks and technological capabilities¹⁸. Comparing CO₂ permanence definitions and methods, Canada and Alberta focus on long-term storage with stringent monitoring and verification to ensure the CO₂ remains sequestered. This approach is consistent with best international practices, which often include geological storage, mineralization, and other methods to enhance permanence. However, some regions may prioritize different technologies or have varying levels of regulatory oversight, leading to differences in how permanence is achieved and verified. Ensuring permanence is critical to the effectiveness of CDR technologies. For the purpose of this study, the following guidelines followed according to the Government of Alberta: ensuring the ability to securely store CO₂ for at least 100 years, resulting in no contribution to atmospheric greenhouse gas levels.

¹⁶ [Greenhouse gas emissions - Canada.ca](#)

¹⁷ [2025 National Inventory Report supports Canada's climate plan is working: emissions have dropped to their lowest level in 27 years \(excluding pandemic years\) - Canada.ca](#)

¹⁸ [Chapter 2: Emissions trends and drivers](#)

Difference Between Capture and Removal:

Carbon Capture involves capturing CO₂ emissions at their source, such as power plants or industrial facilities, before they enter the atmosphere (a more in-depth description of the process is provided in the “*Carbon Capture: Chemical vs. Physical section*”). The captured CO₂ is then stored or utilized in various ways. Carbon Removal refers to extracting CO₂ directly from the atmosphere. This can be achieved through natural processes like afforestation (establishing a new forest), or technological methods like direct air capture (DAC). Once the carbon is captured, the CO₂ is either sequestered or converted into value-add products. This process prevents CO₂ from entering the atmosphere, thus contributing to climate change mitigation.

Definitions and Examples of Carbon Capture and Removal Technologies:

- 1 **Direct Air Capture (DAC):** Direct Air Capture (DAC) is a technology that captures CO₂ directly from the ambient air. This process involves using chemical solutions to bind with CO₂ molecules, which are separated from the binding solutions later in the process and stored. Companies like Carbon Engineering, based in British Columbia, are pioneering DAC technologies that can be adapted for use in Alberta¹⁹.
- 2 **Bioenergy with Carbon Capture and Storage (BECCS):** BECCS combines biomass energy production with carbon capture and storage. Biomass, such as agricultural waste, low-grade wood or wood pellets, is burned to produce energy, and the resulting CO₂ emissions are captured and stored underground (or permanently converted to carbon-based materials). This method not only generates renewable energy but also removes CO₂ from the atmosphere. Bioenergy can be a net-zero process, and the inclusion of CCUS makes it a negative emission approach. **Error! Hyperlink reference not valid.Error! Hyperlink reference not valid..**
- 3 **Biomass Carbon Removal and Storage (BiCRS):** BiCRS involves using organic materials (such as agricultural residues or sustainably managed forests) to remove CO₂ from the atmosphere and store it in soil or biomass.
- 4 **Nature Based Solutions – Broad Category:**
 - **Mineralization:** Mineralization involves converting CO₂ into stable minerals through chemical reactions. This process can occur naturally or be accelerated through industrial processes. Companies like Carbfix in Iceland are leading the way in

¹⁹ [Carbon Capture | MIT Climate Portal](#)

mineralization by injecting CO₂ into basaltic rock formations, where it reacts to form stable carbonate minerals²⁰.

- **Afforestation and Reforestation:** Afforestation (planting new forests) and reforestation (restoring existing forests) are natural methods of carbon removal. Trees absorb CO₂ as they grow, storing carbon in their biomass. Alberta has significant potential for afforestation and reforestation projects, leveraging its vast land resources to sequester carbon naturally⁵.
- **Soil Carbon Sequestration:** Soil carbon sequestration involves enhancing the carbon content of soils through practices like no-till farming, cover cropping, and agroforestry. These practices increase the amount of organic matter in the soil, which in turn sequesters CO₂. Alberta's agricultural sector can play a crucial role in implementing soil carbon sequestration techniques²¹.

Comparison of Technology Readiness Levels (TRL):

The table below compares the Technology Readiness Levels (TRL) of various carbon dioxide removal (CDR) technologies in Alberta with those in other jurisdictions. Direct Air Capture (DAC) and Bioenergy with Carbon Capture and Storage (BECCS) are more advanced, at TRL 6-7 and 5-6, respectively. Mineralization and Ocean Alkalinity Enhancement show similar development stages globally, with TRLs ranging from 3-5. Overall, Alberta's CDR technologies are aligned with international advancements.

Technology	TRL in Alberta	TRL in Other Jurisdictions
Direct Air Capture (DAC)	6-7 (Pilot to Demonstration)	6-9*
Bioenergy with Carbon Capture and Storage (BECCS)	5-6 (Development to Pilot)	5-9*
Mineralization	4-5 (Development)	4-5*
Afforestation	8-9	8-9*
Soil Carbon Sequestration	6-7	7-8*
Biomass Carbon Removal and Storage (BiCRS)	5-6 (Development to Pilot)	6-7*

* Similar stages globally

²⁰ [What is Carbon Capture and Storage \(CCS\)? | World Resources Institute \(wri.org\)](https://www.wri.org/what-is-carbon-capture-and-storage-ccs/)

²¹ <https://albertawater.com/virtualwaterflows/agriculture-in-alberta/#:~:text=There%20are%20over%2041%2C500%20farms,of%20Canada's%20total%20farm%20land.>

Carbon Capture: Chemical vs. Physical

The assessment of carbon capture technologies is hampered with many challenges spanning a combination of technical hurdles, risk tolerance of new technologies, and broad understanding of a multidisciplinary and multiscale problem^{22,23}. Carbon capture is not a one-size-fits-all solution, but one that is different for each CO₂-containing gas stream, that could have^{24,25}. Rather than seeking a single form of capture technology, it is increasingly evident that the “best” capture system for a specific process is a bespoke one that factors in²⁶ low-cost options for waste, and/or renewable energy for regeneration^{27,28}.

For both solvent and solid-based capture systems, a synergy will be present between the molecular features of the *capture material* and the engineering features of the *capture system*²⁹. This optimal coupling relates the synchronization of capture and regeneration stages of an engineering process with the saturation and desaturation of the molecules achieving the capture. Assessment of carbon capture materials at an early stage is often done through easily acquired metrics. This is typically carbon dioxide capacity at a given pressure and temperature and the selectivity for carbon dioxide over a competing gas, typically nitrogen. The extrapolation of the performance and cost of an industrial-scale capture system can be informed from bench-scale projects. For all capture systems, necessary derisking at progressive scales is ideal though not necessarily practical. The following image summarizes different carbon capture methods.

²² Dziejarski, B.; Krzyżyńska, R.; Andersson, K. Current Status of Carbon Capture, Utilization, and Storage Technologies in the Global Economy: A Survey of Technical Assessment. *Fuel* 2023, 342, 127776, DOI: 10.1016/j.fuel.2023.127776

²³ Hekmatmehr, H.; Esmaeili, A.; Pourmahdi, M.; Atashrouz, S.; Abedi, A.; Ali Abuswer, M.; Nedeljkovic, D.; Latifi, M.; Farag, S.; Mohaddespour, A. Carbon Capture Technologies: A Review on Technology Readiness Level. *Fuel* 2024, 363, 130898, DOI: 10.1016/j.fuel.2024.130898

²⁴ A. K. Rajagopalan, A. M. Avila, A. Rajendran, *Int. J. Greenhouse Gas Control*, 2016, 46, 76.

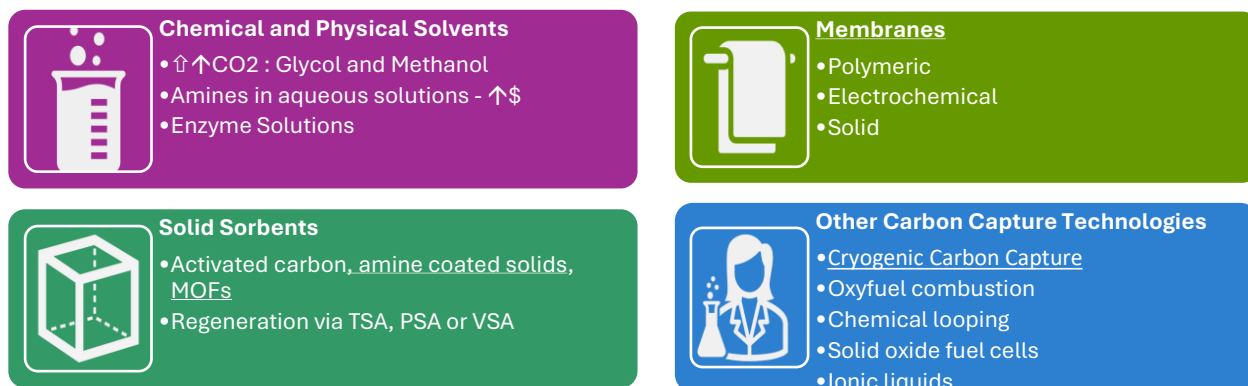
²⁵ J. Park, H. O. Rubiera Landa, Y. Kawajiri, M. J. Realff, R. P. Lively, D. S. Sholl, *Ind. Eng. Chem. Res.* 2020, 59, 7097.

²⁶ M. Khurana, S. Farooq, *Ind. Eng. Chem. Res.* 2016, 55, 2447.

²⁷ A. H. Farmahini, S. Krishnamurthy, D. Friedrich, S. Brandani, L. Sarkisov, *Chem. Rev.* 2021, 121, 10666.

²⁸ M. Taddei, C. Petit, *Molecular Systems Design & Engineering* 2021, 6, 841

²⁹ Z. Hu, Y. Wang, B. B. Shah, D. Zhao, *Adv. Sustainable Syst.* 2018, 1800080.



Solvent-based Capture Systems

Solvents are historically the most industrially demonstrated type of carbon capture technology having evolved from technologies to scrub carbon dioxide from natural gas³⁰. Their main advantages are high capture capacity and selectivity for carbon dioxide and the availability of existing infrastructure to implement better and more advanced solvent systems at sizeable scales. Advanced solvent systems have lower heat capacities (energy needed to raise the temperature of a given mass of the material) to reduce regeneration costs. They can also incorporate specific orientations of the amine groups to facilitate carbon dioxide binding.

Solvents function by both physical and chemical sorption. Physical solvents lack a reactive chemical component and are more stable. Their capture mechanism relates simply to higher dissolution of CO₂ at higher pressures and lower temperatures of CO₂. Thus, lower concentration carbon dioxide streams are a challenge. Widely used solvents are alcohol, glycol, or alkyl carbonate, or ionic liquid based. Examples of commercial processes based on physical solvent separation are Selexol, Rectisol, Fluor and Purisol³¹.

For chemical sorptive solvents, mainly amines, their main advantages are high capture capacity and selectivity for carbon dioxide. Monoethanolamine (MEA) is the benchmark material^{32,33}. Advanced chemical solvents can incorporate crowding of the amine groups to make regeneration less energy intensive. Also, designing blends of different solvents can incorporate and optimize

³⁰ Feron, P. H.; Cousins, A.; Jiang, K.; Zhai, R.; Garcia, M. An update of the benchmark post-combustion CO₂-capture technology. *Fuel* 2020, 273, 117776

³¹ F. Raganati, P. Ammendola, *Energy Fuels* 2024, 38, 15, 13858–13905.

³² I. M. Bernhardsen, H. K. Knuutila, *Int. J. Greenhouse Gas Control*, 2017, 61, 27.

³³ Aghel, B.; Janati, S.; Wongwises, S.; Shadloo, M. S. Review on CO₂ Capture by Blended Amine Solutions. *International Journal of Greenhouse Gas Control* 2022, 119, 103715,

desired features of different solvents³⁴. For chemisorptive solvents, degradation of the chemicals from repeated exposure to flue gases, oxidizing environments, and high temperatures can challenge process sustainability³⁵. When citing key performance indicators for a technology, consideration must be given to operational costs over time, factoring in chemical degradation, solvent replacement, and waste disposal.

Solid Sorbents

The performance of a physisorbent carbon capture system is much more sensitive to the pressures and temperatures of the process as the carbon dioxide is not being chemically bound. In that regard, finding the optimal pairing of material and process is even more significant²⁸. In recent years, it has been demonstrated that selection based simply on capacity and selectivity is flawed. Most CO₂ capacity data is based on pure carbon dioxide alone. The impact of even a small amount of water in the flue gas with CO₂ can have a pronounced effect on capacity and selectivity and greatly influence the choice of sorbent²². Progressively larger demonstration of these meaningful, competitive experiments for carbon capture requires the powdered sorbent to be placed into a stable, macroscopic form that enables efficient mass and heat transfer. A key takeaway is that the potential performance of a solid sorbent cannot, and should not, be concluded from the simpler metrics of capacity and selectivity for carbon dioxide: they face a challenge concerning degradation, and sorbents can't be replaced during operation.

Progressive derisking is demonstrated by the Calgary Framework (CALF)-20³⁶ metal-organic framework. The unique element of CALF-20 is that a physisorbent was shown to not just be able to sorb carbon dioxide in wet gas but to suppress water sorption in the presence of carbon dioxide. With BASF, Svante have scaled the sorbent synthesis to multi-tonne batches and pilot plant at 1 and 25 tonnes per day have been operating for 1-3 years for capture from a cement plant (Lafarge) and a steam generator (Chevron), respectively.

Membranes

Membranes are widely used for gas and liquid separations. The two most important intrinsic properties of polymeric membranes are permeability and selectivity^{26,27,37,38}. These properties

³⁴ A. Samanta, A. Zhao, G. K. H. Shimizu, P. Sarkar, R. Gupta, Ind. Chem. Eng. Res. 2011, 51, 1438.

³⁵ M. Kumari, F. Vega, L. M. Gallego Fernández, K. P Shadangi, N. Kumar, J. Mol. Liquids, 2023, 384, 122288.

³⁶ Reaction Chemistry & Engineering. (2021). "[Understanding the opportunities of metal-organic frameworks \(MOFs\) for CO₂ capture and gas-phase CO₂ conversion processes.](#)"

³⁷ L. M. Robeson, J. Membrane Sci. 1991, 62, 165.

³⁸ R. Hou, C. Fong, B. D. Freeman, M. R. Hill, Z. Xie, Separ. Purif. Tech. 2022, 300, 121863.

typically have a contrary relationship (i.e., membrane features that permit high flux often reduce the potential for selection). In the previous CCUS white paper, polymeric membranes, electrochemical membranes, and solid membranes were discussed. An emerging class of membranes are so-called mixed-matrix membranes^{28, 29,39,40}.

Mixed-matrix membranes are composite structures composed of a solid sorbent dispersed in a polymeric matrix. Ideally, this marriage of different materials gives a product better carbon capture properties than either component. Components can be selected not only for their carbon dioxide-specific features but for their complimentary properties. There are a myriad of combinations of polymer matrix and solid dopant that can be made. Even with a single combination of solid sorbent and polymer, performance would vary greatly with the specific ratio of solid/polymer, the dispersion and domain sizes of the solid, and the processing methods of manufacturing the composite. Hollow fibre structures represent an interesting form to merge separation with high process feeds^{30,41}.

As with the solvents and sorbents, durability is a critical element and assessing performance based on initial results can be misleading. Beyond the degradation, membranes can foul and have their pore structures blocked²⁷⁻²⁹. Regarding durability, a significant consideration is the adhesion between the chemically different components. An advantage that membrane technologies have is that scaling is often modular, meaning a more linear translation between different scales of demonstration.

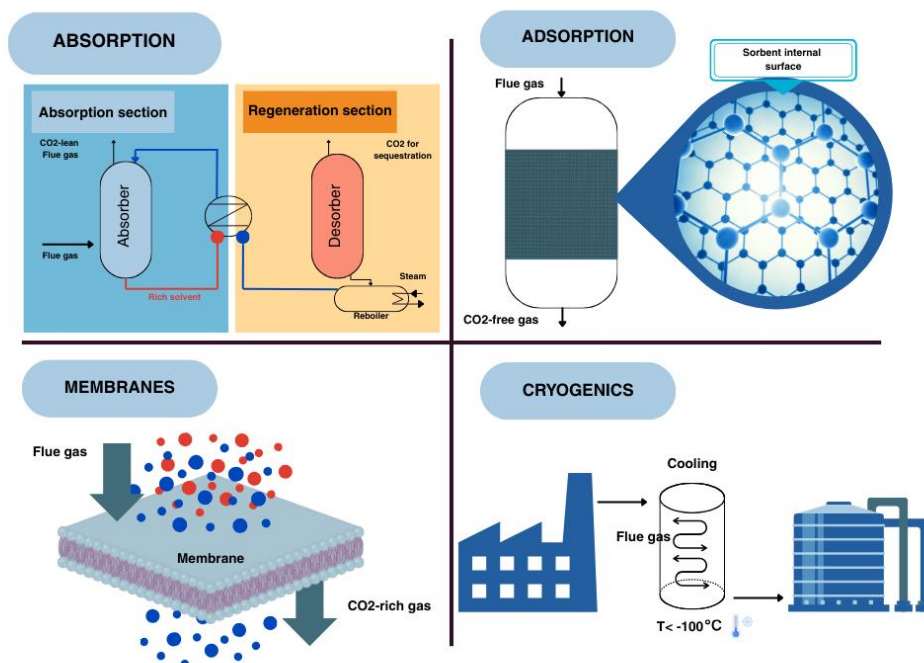
In a comparative evaluation done in 2021, researchers found that, at smaller scales, adsorbents and membranes can be competitive in their techno-economic assessment results (i.e., below sizes of 100 tonnes of flue gas processed per day and 40% CO₂ recovery rate). However, for larger scale and higher recovery rates, the absorption-based processes remain more competitive⁴². However, in 2024, researchers updated the findings from the technologies mentioned above with the addition of cryogenics. Cryogenics was added to the study due to leverage low temperature to attain high purity CO₂. His study concluded that it is necessary to continue investigating and de-risking new solutions that leverage a multi-disciplinary methodology: including new materials, chemical processes and addressing operation challenges.

³⁹ Kanehashi, C. A. Scholes, *Front. Chem. Sci. Eng.* 2020, 14, 460-469.

⁴⁰ A. Katare, S. Kumar, S. Kundu, S. Sharma, L. M. Kundu, B. Mandal, *ACS Omega* 2023, 8, 17511-17522.

⁴¹ A. Shiravi, M. S. Maleh, A. Raisi, M Sillanpää, *Carbon Capture Sci. Tech.* 2024, 10, 100160.

⁴² <https://doi.org/10.1021/acsengineeringau.1c00002>

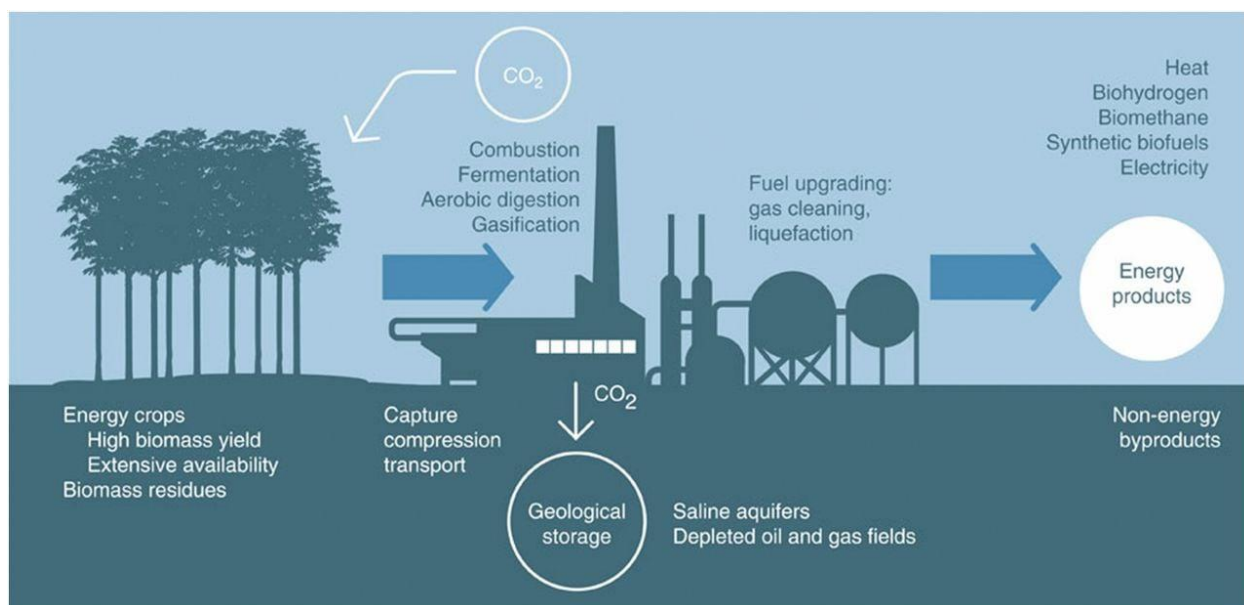


Large emitters require large-scale solutions, and with an urgency to address emissions, next generation capture technologies can face a challenge of scale if they are not “drop-in” solutions for existing or easily retrofitted infrastructure. New technologies require derisking at progressive scales and smaller demonstrations offer smaller economic input, and the required infrastructure for progressive derisking is common for different carbon capture technologies. Items such as standard upstream gas mixtures, chemical analysis and monitoring instrumentation, waste management are common needs. If these facilities are shared, it would expedite technological development in the carbon capture space by enabling meaningful assessment of new technologies at a lower cost. An example of such facilities is Alberta Carbon and Conversion Technology Centre (ACCTC), located adjacent to the Shepard Energy Centre in Calgary, providing innovators with the ability to test and refine their technologies using flue gas emissions from the natural gas-fired power plant. Users of the ACCTC test and advance carbon dioxide capture and conversion technologies that assist in greenhouse gas emission reductions by enabling the conversion of CO₂ into commercially viable, value-added products.

BECCS Technology Pathways

Biomass is a carbon-containing material and its combustion results in the oxidation of the carbon which creates a form of carbon dioxide known as biogenic CO₂. In general, the technologies that are used for carbon capture and storage of CO₂ generated from the combustion of fossil fuels

(anthropogenic CO₂) can also be used for biogenic CO₂. Five primary BECCS technology pathways are described here, although there are large number of variations specific to fuel type and energy pathway. The following image⁴³ summarizes, at a high level, the BECCS technological pathways identified to date.



Post Combustion Capture

Post combustion capture (PCC) involves the purification of CO₂ from a biomass combustion flue gas stream. In many cases, the combustion will be of solid biomass – wood, solid waste, and/or straw. The concentration of CO₂ in the flue gas from solid biomass combustion typically ranges between 10% and 18%. There are a variety of PCC technologies under development, but amine-based technology is commercial and already deployed at non-biogenic PCC projects in Canada such as Boundary Dam and Quest. Other PCC technologies being operated at the demonstration or pilot scale include hot potassium carbonate (HPC) and solid sorbent.

PCC can be applied to existing biogenic CO₂ emitters, with the forest products industry by far the largest source. In Canada, there are over 40 Mt CO₂/yr of biogenic CO₂ stack emissions at forest products facilities, with approximately 8 Mt CO₂/yr from facilities in Alberta⁴⁴. The largest of these facilities emit almost 2 Mt CO₂/yr. The largest sources of emissions include solid biomass boilers at pulp mills (power boilers), sawmills, board mills, and chemical recovery boilers at kraft-type pulp

⁴³ [Can bioenergy with carbon capture and storage make an impact? | PNAS](#)

⁴⁴ TorchLight Bioresources, 2024. Canadian forest bioenergy database. Prepared for Natural Resources Canada.

mills. In addition, some existing fossil fuel infrastructure can be retrofitted and converted to bioenergy production, thereby serving as a basis for BECCS. For example, electricity generating stations formerly operating on coal could be fuel switched to solid biomass and have CCUS added – converting the generating stations from large GHG emitters to large removers of CO₂ from the atmosphere.

Additionally, BECCS with PCC (or oxy-combustion, as described below) can be used to supply heat and/or electricity to existing consumers of fossil fuels in a ‘behind-the-meter’ contract arrangement. Solid biomass combustion-based BECCS can also be used to supply negative carbon intensity electricity to Alberta’s provincial power grid, thus reducing the average grid intensity. Negative CI electricity from BECCS facilities can be used to remove the GHG emissions from unabated natural gas-fired peaking plants, enabling attainment of a net-zero grid.

Oxy-combustion

Oxygen (O₂) is required for combustion of carbon containing fuels, including biomass. The O₂ for combustion typically comes from the air, which is 21% O₂. However, this means the resulting flue gas is largely composed of the primary component of air, nitrogen (78% content in air). Separation is required for pure CO₂. In contrast, oxy-combustion uses pure oxygen as the source of O₂ for combustion, with recirculated CO₂ in the flue gas used in place of the 79% of gases in air that are not O₂. The resulting flue gas is 90%-95% CO₂, with only flue gas ‘polishing’ required to remove moisture and other contaminants prior to compression and storage. In general, the chemistry of oxy-combustion is simpler than PCC but requires pure O₂.

The dominant technology for supplying pure O₂ sourcing is air separation in an air separation unit (ASU), although O₂ could also be co-produced with hydrogen (H₂) via electrolysis of water. Both ASUs and electrolyzers require electricity, which impacts the energy balance for BECCS. ASUs are substantially more energy efficient, in kWh per kg O₂, than electrolyzers. There are opportunities for ASUs to serve as interruptible loads on electricity grids seeking to balance intermittent electricity supply from renewables with variable demand.

There are only a few biomass boiler companies that offer oxy-combustion, including the necessary CO₂ recirculation and air ingress prevention. These boilers operate only on solid biomass fuel and there is a substantial capital cost increase compared to conventional air combustion. In general, oxy-combustion can only be considered for new biomass boiler installations. Although not deployed extensively due to the lack of valuation of GHG emissions, oxy-combustion technology is straightforward. Avoidance of air ingress is critical to achieving CO₂ purity performance targets.

Gasification and Hydrogen Production

Biomass is composed of carbon, oxygen, and hydrogen. Like coal or natural gas, biomass can be gasified into syngas, composed of H_2 and carbon monoxide (CO), by partially oxidizing biomass in an oxygen-limited environment. This is the first step of combustion, which is the full oxidation of carbon to CO_2 and co-production of H_2O . Prior to full oxidation occurring, the H_2 component syngas can be recovered, with the H_2 used for fuel or production of chemicals, fertilizer, or steel. The co-produced CO_2 is relatively pure and can be upgraded prior to compression and storage. The resulting H_2 product is negative carbon intensity, meaning its use removes carbon from the atmosphere.

While biomass gasification for production of H_2 and other chemicals, such as methanol, ethanol, or hydrocarbons via reforming reactions, is well understood, commercialization success has been limited. This is despite the success of very large fossil fuel gasification-based projects. Many of the difficulties surrounding biomass gasification can be attributed to technical challenges of gasifying an oxygen-containing, relatively inconsistent (e.g., moisture content, particle size) feedstock, side reactions and ‘tar’ (multi-carbon molecules) formation, and challenges attaining the required scale to be economically competitive.

Biomethane PCC and ATR

Biomethane is chemically identical to fossil methane, CH_4 , and is produced using anaerobic processes from biomass feedstocks such as manure, biosolids (sewage), crop residues, and landfill (solid waste) gas. This chemical composition permits the use of the same CCUS technologies deployed commercially for natural gas to be used for biomethane-based BECCS. These options include PCC on natural gas-fired power plants, PCC on steam-methane reforming (SMR) facilities as is used in the Shell Quest project, or methane autothermal reforming (ATR) for H_2 production which is being implemented by Linde in Alberta at its planned H_2 production facility to supply the future Dow ethylene plant.

ATR is also planned for ATCO’s proposed Hydrogen Hub in Fort Saskatchewan. ATR differs from SMR in that steam and O_2 are mixed with methane instead of just steam, as is the case for SMR. While SMR is the dominant H_2 production technology at present, ATR has higher CO_2 capture rates. However, ATR also requires pure O_2 , likely sourced from an ASU, which increases electricity consumption.

As noted, biomethane can be substituted for natural gas in existing thermal and electricity generation facilities. In this manner, an existing CCS project, such as Quest or the

Nutrien Redwater Fertilizer plant, can be converted into a full or partial BECCS project without any change in fuel use or capture infrastructure.

Ethanol Fermentation

Ethanol is the largest volume liquid biofuel globally. Conventional ethanol is produced by fermenting six-carbon sugars, such as glucose, into a two-carbon alcohol. Sugars can be sourced from disaccharide (sugar) feedstocks, such as sugarcane or sugar beet, or polysaccharide feedstocks, such as starch. In Canada and the United States, the dominant feedstock for ethanol production is starch from corn, although there is some wheat-based production. One of these wheat-based plants, Permox, is based in Alberta. Alberta is also Canada's largest producer of sugar beets, with production centered around Taber.

During fermentation of sugars to ethanol by yeast, CO₂ is generated as a metabolic product. In general, two molecules of ethanol and two molecules of CO₂ are produced for every molecule of glucose. The concentration of CO₂ from fermentation is almost 99%, meaning very little to no polishing of the gas is required prior to compression and storage. This provides a major cost advantage compared to PCC of flue gas from biomass combustion, with CO₂ concentration of 10%-15%, because capture is the largest capital component for onshore CCS projects⁴⁵. In contrast, the costs for BECCS from ethanol-based CO₂ are largely associated with transportation and storage because of the lack of any major costs for the capture. This economic advantage is why CO₂ sourced from ethanol plants is the largest source of BECCS CDRs, with most of them bundled with ethanol.

Direct Air Capture with Carbon Storage (DACCS)

Canada is home to global leaders in the direct air capture (DAC) space. Carbon Engineering, founded in Alberta and now headquartered in Squamish, B.C., is a leading DAC technology developer. They supplied the technology for the Stratos DAC plant in Texas, which is expected to come online in 2025. When complete, it will have an annual removal capacity of 500,000 tonnes of CO₂. Carbon Engineering was acquired by Occidental in 2023⁴⁶. Svante is another technology developer based in B.C. that provides contactor equipment – the technology that extracts the CO₂

⁴⁵ IEAGHG, 2016. Techno-economic evaluation of retrofitting CCUS in a market pulp mill and an integrated pulp and board mill.

⁴⁶ <https://www.oxy.com/news/news-releases/occidental-enters-into-agreement-to-acquire-direct-air-capture-technology-innovator-carbon-engineering/>

from the air – for both CCS and DAC applications. They are involved in the development of several DAC hubs selected by the U.S. Department of Energy⁴⁷.

Even though several DAC technology developers are based in Canada, there are currently no full-scale DAC projects deployed in the country. However, several pilot scale projects and testing facilities are active or in development. Work is underway to understand what DAC technologies are best suited for the Canadian climate, as well as what policy structures can best help spur development. The technology has similarities to carbon capture and storage (CCS), an industry with established expertise in Canada which extracts CO₂ from industrial point sources. However, the concentration of CO₂ in the gas from industrial point sources is generally much higher than that in the atmosphere, leading to significant differences in system optimization.

Technology Description

Direct air capture (DAC) describes technologies used to extract CO₂ from ambient air. There are four classes of technological approaches to achieve this: chemical separation, cryogenic separation, membrane separation, and electrochemical separation.

Chemical Separation has been extensively defined in the previous section.

Cryogenic Separation: CO₂ gas is frozen out of the air. As part of cryogenic oxygen production, CO₂ is recovered from the air by freezing as a byproduct of the process. This method is widely used to produce food-grade CO₂ and dry ice⁴⁸.

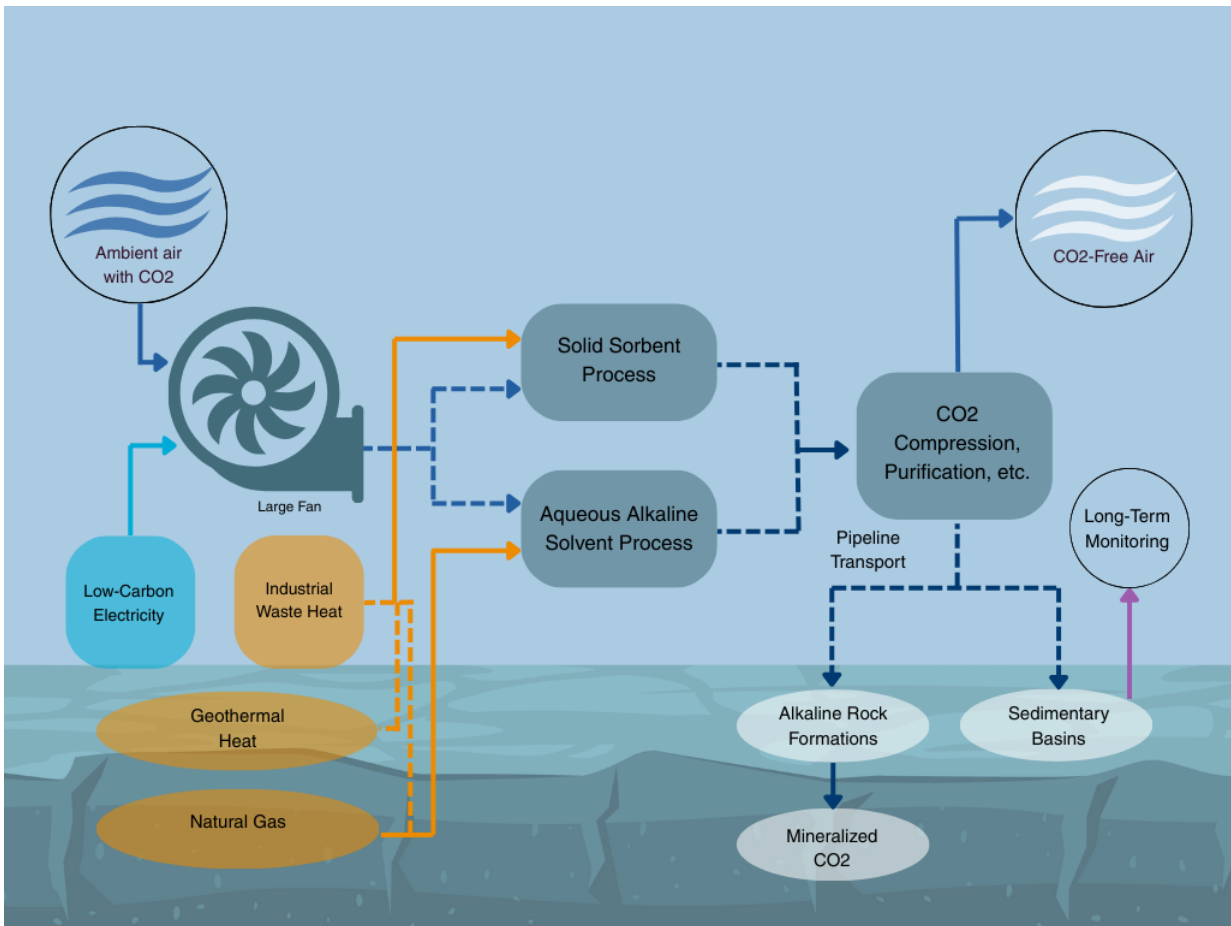
Membrane Separation: CO₂ is separated from air using membranes that selectively capture CO₂, including ionic exchange and reverse osmosis membranes.

Electrochemical Separation: Air is introduced into a molten medium which is equipped with electrodes used for separating CO₂ from the air and releasing the remaining air components.

⁴⁷ <https://www.svanteinc.com/press-releases/climeworks-and-svante-collaborate-in-development-and-supply-for-direct-air-capture/>

⁴⁸ <https://www.sciencedirect.com/science/article/pii/S1383586622012904>

The following image⁴⁹ provides a simple representation of different technology avenues for DACCS.



Many companies developing DAC technology primarily use chemical methods, such as liquid solvents or solid sorbents. While effective, these methods require heat and power to regenerate the key chemical agents resulting in high energy needs when deployed at large scale. Companies and researchers at universities are actively working to:

- Increase how much CO₂ is caught by air contactors.
- Reduce required energy input.
- Reduce capital and operational costs.
- Enhance concentrations of CO₂ in the produced gas mixture.

⁴⁹ Sovacool, Benjamin & Baum, Chad M. & Low, Sean & Roberts, Cameron & Steinhauser, Jan. (2022). Climate policy for a net-zero future: ten recommendations for Direct Air Capture. Environmental Research Letters. 17. 10.1088/1748-9326/ac77a4.

Potential Innovation Areas

In general, there are two critical aspects of the DAC process that can be influenced by research and development, Chemical performance and Equipment performance.

Chemical performance: Critical aspects of a DAC system design are the selection of the right material to trap CO₂ and its reuse. Reusing sorbent materials eventually leads to material degradation, reducing its ability to trap CO₂ and requiring routine replenishment. Chemical stability is an important factor in technological selection to minimize chemical degradation. Releasing the trapped CO₂ from the material is called regeneration, which is commonly done by heating the material. Other methods used to regenerate sorbents include adjusting moisture or pressure or applying electrochemical processes. Innovation in the regeneration process can help significantly reduce the energy required for a DAC process.

In summary, a single best design or material has not been established. Ambient geographic characteristics and jurisdiction-specific factors, like access to abundance zero-emission energy, will determine the innovation pathways for this technology. This highlights the need for Alberta-specific research and development efforts to formulate optimal DAC designs and strategies within the province.

Equipment performance: In the first phase of CO₂ extraction, the air contactor pulls large volumes of air across the liquid sorbent, solid sorbent or, in some cases, a fluidized bed system. To maximize the collection of CO₂ the design of the air contactor is critical, and the following factors need to be considered:

- 1 Materials
- 2 Geometry
- 3 Pressure Drops
- 4 Fluid Flow Behavior

This contactor must be accompanied by auxiliary processing units, such as air handling and circulating systems and other utility operations, to provide the required supportive process inputs such as steam, heat, vacuums, or water.

Advantages of Direct Air Capture

DAC applications paired with permanent storage can offer high-quality carbon removal along the dimensions of additionality, measurability, and durability, compared to other pathways. Depending

on the application, this duo may have unique advantages regarding site selection and land use that enable their potential to be a valuable, additional tool for addressing CO₂ emissions.

Additionality and measurability: Understanding how DACCS works is straightforward, as the path of the CO₂ molecules can easily be traced from the atmosphere to the capture unit and to the storage site.

Measuring the amount of carbon dioxide removed by a DAC process is also straightforward, compared to other pathways, because the system is closed, meaning it does not allow mass transfer across the system boundary. Also, the amount of CO₂ removed can be directly measured. This creates confidence in the effectiveness of this CDR pathway, which is important for driving measurable climate impact and for the organizations and governments that will potentially be paying for this removal to occur. In this way, the additionality of direct air capture – or how much CO₂ is removed that would not have otherwise been removed naturally – is clear and able to be measured directly.

The potential of high additionality is only realized if the carbon dioxide is stored permanently. In scenarios where the extracted carbon dioxide is used in a way that results in its subsequent release back into the atmosphere, the life cycle analysis is likely to result in positive carbon intensity. The use of carbon dioxide from DAC for synthetic fuel production, for example, would be considered an emissions reduction pathway rather than a removal pathway.

Land and environmental impact: Direct air capture with carbon storage can be deployed anywhere, provided there is access to energy and physical capacity for CO₂ storage. This allows it to potentially avoid land use issues that are common in other industrial sectors and other CDR approaches. The amount of land required for DAC is also small relative to other CDR approaches that leverage biomass for capturing atmospheric CO₂. However, the footprint for DAC per tonne of CO₂ captured is higher.

The long-term continuous deployment of DACCS, while limited by CO₂ storage capacity, will not be constrained by the availability of biomass. This results in DAC having a relatively large cumulative removal potential.

Current Challenges of Direct Air Capture

To maximize the effectiveness of the CO₂ removal process, the emissions from the energy used need to be as low as possible. Using emissions intensive energy sources limits the net carbon removal achieved by a DAC process, and in some cases would even push the process into being a net emitter. Using renewable energy or waste heat sources will be critical for DAC projects in

Alberta where the grid carbon emissions intensity is the third highest amongst Canadian provinces as of 2022⁵⁰. Powering DAC with wind and solar energy is being pursued in Alberta, as potential offtake buyers of credits and international certification bodies have established requirements around the use of additional renewable energy as key to ensuring high-quality carbon removals. In summary, there are two most important challenges for DAC implementation:

High costs: All these benefits come at a significant cost. According to market data aggregator cdr.fyi, the spot price for advanced commitments for DAC credits is \$710 USD per tonne removed⁵¹. Climeworks suggests that current costs for their first project, Orca, are around \$1,000 USD per tonne of CO₂ removed, and estimates they can reach \$400-600 USD/tCO₂ by the end of the decade^{52,53}. Capital and energy costs make up the bulk of these costs. The expectation is that research, innovation, learning-by-doing, and economies of scale will drive down these costs over time.

High energy requirements: Current DAC processes have high energy requirements, with estimates of 6 to 10 gigajoules (GJ) per tonne of CO₂ removed in the form of electricity and low or high-grade heat depending on the technology⁵⁴. In addition to high costs, this high energy usage has other implications.

The growing prospects of DAC are prompting a discussion of whether new renewable energy capacity is best used to power new DAC operations or to decarbonize the grid. Alberta's electricity market offers a unique opportunity for developers to directly procure the clean electricity they need to deploy effective DAC projects. Research and innovation efforts towards lowering energy requirements for the process, as well as designing deployments that integrate with other operations, can help mitigate tradeoffs. For example, sharing CO₂ compression and storage infrastructure amongst several DAC operations could help reduce capital costs and energy consumption.

⁵⁰ Environment and Climate Change Canada, "Canada's official greenhouse gas inventory." <https://www.canada.ca/en/environment-climate-change/services/climate-change/greenhouse-gas-emissions/inventory.html>

⁵¹ <https://www.cdr.fyi/> as of June 7, 2024

⁵² <https://climeworks.com/press-release/next-gen-tech-powers-climeworks-megaton-leap>

⁵³ <https://carbonplan.org/research/dac-calculator-explainer>

⁵⁴ <https://www.iea.org/reports/direct-air-capture-2022> (22)

NBS (Nature Based Solutions)

Nature based solutions (NBS) leverage the power of ecosystems to combat climate change. This section explores various methods such as enhanced rock weathering, peatland and wetland restoration, and soil carbon sequestration. These approaches not only capture and store carbon but also offer additional environmental benefits like improved biodiversity and water regulation. Enhanced rock weathering accelerates natural processes to absorb CO₂, while peatlands and wetlands act as significant carbon sinks. Soil carbon sequestration enhances soil health and productivity. Each method varies in carbon intensity and environmental impact, highlighting the need for a balanced and integrated approach to maximize climate benefits.



Soil Carbon Sequestration

Soil carbon sequestration is the process of capturing and storing atmospheric carbon dioxide (CO₂) in the soil through natural processes such as plant growth, photosynthesis, and microbial activity. This method helps to mitigate climate change by reducing the amount of CO₂ in the atmosphere. As implied earlier, achieving permanence implies ensuring that the carbon remains stored for extended periods (typically 100 years). Factors influencing permanence include the form of carbon

input, soil type, climate conditions, land-use, land management practices, and the potential for carbon loss due to erosion, land-use change, or extreme weather events⁵⁵.

Soil carbon sequestration can be integrated into agricultural systems through various practices that enhance soil health, improve crop yields, and contribute to climate change mitigation. By increasing organic matter in the soil, these practices can boost water retention, nutrient availability, and microbial activity, leading to healthier soils and more resilient agricultural ecosystems. Additionally, implementing carbon farming practices enables farmers to participate in carbon credit markets, adding an economic incentive to sustainable agriculture. It has been estimated that soils, particularly agricultural ones, could sequester over a billion tonnes of carbon annually. This makes soil-based carbon sequestration a key “negative emissions” technology, removing CO₂ from the atmosphere and storing it in a stable form⁵⁶.

The Marin Carbon Project⁵⁷ and the “4 per 1000 Initiative”⁵⁸ demonstrate soil carbon sequestration’s benefits, including increased soil carbon, enhanced productivity, reduced emissions, and contributions to climate mitigation through sustainable practices.

Importance of Forests in Carbon Sequestration

Forests act as critical carbon sinks, absorbing carbon dioxide (CO₂) from the atmosphere through photosynthesis and storing it in biomass (trees, soil, and vegetation). Alberta’s boreal forests face challenges from wildfires and pests, limiting carbon sequestration⁵⁹. Eastern Canada’s mixed forests, with higher biodiversity, offer better carbon storage⁶⁰. Internationally, tropical forests sequester more carbon due to rapid growth rates and dense biomass⁶¹. Each region’s unique conditions affect their carbon sequestration potential.

⁵⁵ Smith P. An overview of the permanence of soil organic carbon stocks: Influence of direct human-induced, indirect and natural effects. *European Journal of Soil Science*. 2005 Oct;56(5):673-80.

⁵⁶ National Academies of Sciences, Division on Earth, Life Studies, Ocean Studies Board, Board on Chemical Sciences, Board on Earth Sciences, Board on Energy, Environmental Systems, Board on Atmospheric Sciences, Committee on Developing a Research Agenda for Carbon Dioxide Removal, Reliable Sequestration. Negative emissions technologies and reliable sequestration: a research agenda.

⁵⁷ <https://marincarbonproject.org/>

⁵⁸ <https://4p1000.org/?lang=en>

⁵⁹ <https://www.osler.com/en/insights/blogs/energy/generating-and-selling-emission-offsets-from-forest-activities-in-canada/>

⁶⁰ <https://www.frontiersin.org/journals/ecology-and-evolution/articles/10.3389/fevo.2020.547696/full>

⁶¹ <https://link.springer.com/article/10.1023/A:1011396115488>

Afforestation (planting new forests) and reforestation (restoring lost forests) increase carbon sequestration by enhancing forest cover. Improved forest management can sustain these processes by reducing deforestation and maintaining ecosystem health. A recent study estimates the total ecosystem carbon storage potential of natural woody ecosystems is 328 GtCO₂e lower than the natural potential⁶², i.e., forests today store much less carbon than they could if they were fully healthy. This means there's a big opportunity to help the climate by protecting and restoring forests.

This presents significant opportunities for carbon capture through restoration of existing degraded forests, conservation and sustainable management of converted lands, and integration of local communities into restoration efforts. Overall, these steps can help mitigate emissions, enhance carbon sequestration, and improve climate resilience.

Improved forest management includes:

- 1 Management of logging intensity to ensure that forests remain healthy and continue optimal carbon sequestration.
- 2 Forest growth management, which involves the strategic use of management practices to maintain ecosystem balance while optimizing tree growth. Pre-planting site preparation is essential to ensure the land is suitable for planting by addressing limiting factors such as soil compaction, competition, and moisture levels. By improving soil conditions, both practices support healthy forest regeneration and long-term sustainability. The density of forest cover is also important for optimal carbon sequestration. For example, following a burn, naturally recovered lodgepole pine forests are often overly dense, and would need to be thinned for optimal growth and carbon sequestration capacity.
- 3 Biodiversity management to reduce the long-term risk that a forest ecosystem and its carbon cycle becomes impaired (for example, due to a pest) resulting in both direct loss of carbon and the ability to sequester effectively in future. Additionally, genetics of individual species could also be explored to improve production and resilience to future climate conditions.

⁶² Mo L, Zohner CM, Reich PB, Liang J, De Miguel S, Nabuurs GJ, Renner SS, van den Hoogen J, Araza A, Herold M, Mirzaghali L. Integrated global assessment of the natural forest carbon potential. *Nature*. 2023 Dec 7;624(7990):92-101.

Old-growth forests store vast amounts of carbon, including significant amounts of dead biomass, which increase the risk of catastrophic wildfires and the release of carbon into the atmosphere. Systematic deforestation of old forests could prevent uncontrolled wildfires while protecting the capacity of these forests to sequester carbon from the atmosphere. The Pacific Northwest⁶³ study and Darkwoods Forest Carbon Project⁶⁴ highlight the potential of forest management to increase carbon storage through extended rotation lengths, conservation, and sustainable practices.

Peatland and Wetland Restoration

Peatlands are a type of wetland characterized by waterlogged conditions, leading to the accumulation of partially decayed organic material, known as peat. They are crucial carbon sinks, storing more carbon per hectare than any other terrestrial ecosystem, and insulating permafrost from warming temperatures, effectively keeping frozen organic material from decomposing and releasing methane and CO₂. Wetlands are areas where water covers the soil or is present near the surface, supporting diverse ecosystems. They include swamps, marshes, and bogs, playing vital roles in water filtration, flood control, and habitat provision. Peatlands and wetlands are vital carbon sinks, holding significant amounts of carbon in their soils. Beyond their role in carbon storage, they provide essential ecological services, such as flood regulation, water purification, and wildlife habitats, making them crucial for both climate mitigation and biodiversity conservation. Peatlands are the largest natural terrestrial carbon reservoirs, storing more carbon than all other vegetation types combined. Conserving, protecting, and restoring peatlands globally can reduce emissions and revive ecosystems that offer numerous benefits, including their essential function as natural carbon sinks. Currently, land-use changes and drainage of peatlands contribute to 5%-10% of global annual anthropogenic carbon dioxide emissions, making the restoration of these degraded ecosystems an important focus in climate change mitigation efforts^{65,66,67}. A great example is Canadian peat bog restoration⁶⁸ using the Moss Layer Transfer Technique has restored carbon sequestration, improved water tables, and enhanced wildfire resilience within four growing seasons.

⁶³ Chisholm PJ, Gray AN. Forest carbon sequestration on the west coast, USA: Role of species, productivity, and stockability. PLOS ONE. 2024 May 31;19(5): e0302823.

⁶⁴ <https://www.natureconservancy.ca/en/what-we-do/nature-and-climate/dw-carbon.html>

⁶⁵ <https://www.nature.com/collections/ggbefcbbgj>

⁶⁶ <https://iucn.org/resources/issues-brief/peatlands-and-climate-change>

⁶⁷ <https://www.unep.org/news-and-stories/story/peatlands-store-twice-much-carbon-all-worlds-forests>

⁶⁸ <https://www.nature.com/articles/s43247-022-00547-x#Sec10>

Biochar

Biochar is a stable, carbon-rich material created through the pyrolysis of organic matter under low-oxygen conditions. It can remain in soil for hundreds to thousands of years, making it a promising tool for long-term carbon sequestration and climate change mitigation. By stabilizing carbon in a durable form, biochar reduces atmospheric CO₂ levels while also improving soil health. Recent studies highlight its potential for carbon dioxide removal (CDR), with crop residues (CRs) contributing up to 2.4 Gt of carbon annually and offering a theoretical biochar production potential of 1.0 Gt of carbon per year, potentially sequestering 10% of total carbon emissions^{69,70}. Biochar is produced through pyrolysis, where organic materials are heated in the absence of oxygen. Feedstocks for biochar production can include agricultural residues (e.g., crop waste), woody biomass, forestry residues, and organic waste such as manure or municipal green waste. Production methods range from small-scale traditional kilns to industrial-scale pyrolysis units. The specific feedstock and pyrolysis conditions can influence the properties of the resulting biochar, including its carbon content, porosity, and nutrient profile⁷¹.

Biochar enhances soil fertility, improves soil structure, increases crop production, and can be used to produce biofuels. When applied to soil through methods like topsoil incorporation or top dressing, biochar improves water retention, nutrient availability, and soil permeability. It also helps in soil remediation by adsorbing heavy metals and organic pollutants, enhancing soil health and microbial activity. Additionally, biochar can mitigate climate change by sequestering carbon and reducing greenhouse gas emissions, with potential to significantly increase crop yields and contribute to sustainable agriculture⁷². Despite its benefits, biochar production and application face several challenges: Scalability remains a significant issue, as large-scale production requires substantial investments in technology and feedstock supply.

Enhanced Rock Weathering (ERW)

Enhanced rock weathering (ERW) is a CDR technique that accelerates the natural process of silicate rock weathering to capture atmospheric CO₂. By finely grinding specific minerals like olivine and basalt and spreading them over land or oceans, ERW enhances the rate of carbon sequestration through chemical reactions that convert CO₂ into stable carbonate minerals. This approach is part of broader climate mitigation efforts, aiming to reduce atmospheric carbon levels

⁶⁹ <https://biochar-international.org/about-biochar/>

⁷⁰ Potential for biochar carbon sequestration from crop residues: A global spatially explicit assessment. Shivesh Kishore Karan, Dominic Woolf, Elias Sebastian Azzi, Cecilia Sundberg, Stephen A. Wood. 13 October 2023 <https://doi.org/10.1111/gcbb.13102>

⁷¹ <https://www.sciencedirect.com/science/article/pii/S2215017X20300023>

⁷² <https://www.sciencedirect.com/science/article/pii/S2666154323000054#sec4>

and contribute to long-term climate solutions. The cost of ERW per tonne of CO₂ removed is estimated to be higher in developed nations like the U.S. and Canada (\$160-190 USD per tonne) compared to developing countries like China, India, and Brazil (\$55-120 USD per tonne). These costs fall within projected carbon pricing ranges for 2050, making ERW a viable option for countries transitioning to low-carbon economies⁷³.

The primary types of rocks suitable for Enhanced Rock Weathering (ERW) include olivine, basalt, and serpentine. These rocks are rich in silicate minerals that can capture CO₂ through chemical weathering. Serpentine, a magnesium-rich rock with high levels of nickel, weathers slowly but releases significant amounts of magnesium and nickel, acting as natural fertilizers that enhance plant growth. It also sequesters carbon dioxide by converting it into stable mineral forms, with studies suggesting it can capture up to 0.5 tonnes of CO₂ per hectare annually. Olivine, a magnesium and iron-rich mineral, is one of the most abundant rocks in Earth's crust and weathers rapidly, making it effective for quick carbon sequestration. When olivine reacts with atmospheric CO₂, it forms carbonate minerals that remain stable for thousands of years. Research indicates that applying olivine to fields could potentially reduce atmospheric CO₂ levels by up to 90% by the century's end, capturing up to 5 tonnes of CO₂ per hectare annually. Basalt, a volcanic rock, is widely used in ERW for its availability and carbon capture potential. Although it weathers slowly, it can sequester up to 2 tonnes of CO₂ per hectare annually. Additionally, the minerals in basalt, such as calcium, magnesium, and iron, improve soil fertility and crop yields while reducing the need for chemical fertilizers that contribute to greenhouse gas emissions.

⁷³ <https://www.nature.com/articles/s41586-020-2448-9>

CDR Industry

In this section, we discuss the industry around CDRs, including an overview of the CDR market, differences between compliance and voluntary markets, challenges to market growth, and recent investment activities.

Overview of the CDR Market

CDR technologies are part of all modeled scenarios that limit global warming to 2°C or lower by 2100⁷⁴. The IPCC estimates between 5 and 10 billion tonnes of CDR will be required by 2050 to meet these targets. The current CDR market, while growing rapidly, is still nowhere near that size.

The global market for CDR technologies is in the early growth stage, characterized by increased R&D investment, government support, and early commercialization of technologies. The market is driven by global net-zero commitments, regulatory mandates (such as carbon pricing and emissions reduction targets), corporate sustainability pledges, technological advancements, and the need to decarbonize existing facilities for hard-to-abate sectors like heavy industry, power generation, and aviation, that don't have a clear or expedient pathway to emissions reduction.

In 2022, the global CDR market was valued at \$370,000,000 USD. This included approximately 600,000 tCO₂e of CDRs purchased and 37,000 tCO₂e CDRs delivered⁷⁵. As a result of substantial investment by carbon credit buyers, the market experienced sharp growth between 2022 and 2023, and the global market for carbon dioxide removal is expected to experience a Compound Annual Growth Rate (CAGR) of 31.0% from 2023 to 2028. North America contributes 45.1% of the market share in terms of value, most of which is from the U.S.⁷⁶

⁷⁴ Carbon Dioxide Removal (CDR) Market, BCC Publishing, BCC Research Short Report: ENV069A Carbon Dioxide (February 2024)

⁷⁵ [CDR.fyi 2022 Year in Review: Understanding the key trends in carbon removal | CDR.fyi](#)

⁷⁶ Carbon Dioxide Removal (CDR) Market, BCC Publishing, BCC Research Short Report: ENV069A Carbon Dioxide (February 2024)

Global Market for Carbon Dioxide Removal, by Technology Type, Through 2028 (\$ Millions)

Technology Type	2022	2023	2028	CAGR% 2023–2028
Biochar	212.2	1,204.2	4,529.7	30.3
Direct Air Capture	55.5	332.9	1,665.6	38.0
Enhanced/Carbon Mineralization	74.0	410.1	1,381.3	27.5
BECCS	14.8	83.6	268.1	26.3
Ocean Alkalinization	8.9	49.4	170.6	28.1
Others	4.6	26.8	109.7	32.6
Total	370.0	2,107.0	8,125.0	31.0

Source: BCC Research

7

Geographic trends in the CDR market

Geographic trends in CDR reflect regional priorities, resources, and climate policies. North America and Europe lead in engineered solutions driven by strong policy support and technological capabilities. The North American region currently dominates the global market.

In 2022, total revenue from the North American market reached \$166,900,000 US, which comprises 45.1% of the market overall. Together, Europe and North America account for the largest share of planned projects, at more than 80% of announced capacity, largely driven by policy incentives⁷⁷.

Global Market for Carbon Dioxide Removal, by Region, Through 2028 (\$ Millions)

Region	2022	2023	2028	CAGR% 2023–2028
North America	166.9	934.5	3,297.1	28.7
EMEA	95.5	554.3	2,437.5	34.5
APAC	77.3	444.1	1,868.8	33.3
South America	30.3	174.1	521.6	24.5
Total*	370.0	2,107.0	8,125.0	31.0

*Note: Totals in this report's tables and figures might not match precisely because of rounding.

In Canada, the CDR market is still emergent. In terms of potential buyers of CDRs, currently, 74% of Canada's emissions come from the following economic sectors: oil and gas (26%), transport

⁷⁷ <https://www.mckinsey.com/industries/oil-and-gas/our-insights/global-energy-perspective-2023-ccus-outlook>

(25%), buildings (12%) and heavy industry (11%).⁷⁸ CCUS and CDR technologies with applications to these economic sectors therefore represent the largest opportunities to reducing emissions.

Compliance vs. Voluntary Markets

There are two main types of carbon markets impacting CDRs. Compliance markets are supported by governments, whereas the voluntary carbon market (VCM) operates independently of government.

The **voluntary carbon market (VCM)** involves companies and organizations participating in voluntary carbon markets purchasing carbon credits generated from CDR projects to offset their emissions and enhance their sustainability credentials. This includes investors, brokers, and platforms that aggregate and sell credits from various carbon removal projects. Examples of participants include voluntary buyers, carbon offset brokers, and platforms like Puro.earth and Climate Trade.

The **compliance carbon market** involves entities that are required to comply with carbon regulations under cap-and-trade systems or carbon pricing schemes, while purchasing carbon credits from CDR projects to meet their mandated emissions reduction targets. Examples include the EU Emissions Trading System (EU ETS) and California Air Resources Board (CARB).

Recent Trends in the VCM

Unlike markets backed by governments, VCM must earn credibility with buyers through establishment of rigorous standards and protocols that define the sustainability, permanence, and other aspects of carbon offset projects. These standards and protocols are typically developed by third-party organizations that are ultimately responsible for certifying voluntary carbon offsets. It is also possible for the VCM to rely on compliance-based protocols and standards, which can increase credibility.

In the past, the VCM has faced reputational issues – with buyers facing media backlash for misrepresenting the impact of certain carbon offset projects. The VCM is currently transitioning into “VCM 2.0”, a more sophisticated framework with participants who are much more informed

⁷⁸ <https://www.canada.ca/en/environment-climate-change/news/2022/03/2030-emissions-reduction-plan--canadas-next-steps-for-clean-air-and-a-strong-economy.html>

about opportunities and risks. This transition is expected to stimulate and increase demand and credibility around transactions on the voluntary market.

Participants in the voluntary market are just that – voluntary. They typically engage as part of their own corporate sustainability goals. Partly for this reason, most of the voluntary transactions that have occurred to date are much smaller than what will ultimately be required to meet climate targets.

Most CDR transactions currently occur on the voluntary market, since CDRs are typically not a requirement set by governments and are only recently gaining traction as a necessary tool to mitigate the impacts of climate change. That makes voluntary markets – their credibility, and the standards they develop – essential in the development of CDR projects.

Recent Trends in Compliance Markets

In a compliance market, entities are required to meet an emissions reduction target set by a regulatory body. The TIER framework in Alberta is an example of a compliance market. Other examples include the EU ETS and the CARB. Compliance markets have inherent credibility compared to the VCM by virtue of being part of the rule of law.

In most compliance markets, including TIER, biogenic CO₂ is tracked, but is not considered part of the overall emissions inventory. Therefore, unlike an emissions reduction project, there is often no imperative to pursue a CDR project under a compliance market. However, this is not the case everywhere worldwide.

There are also other challenges with enabling CDR transactions in compliance markets. CDR credits are typically considered higher value than emissions reduction credits, meaning they can seek a higher price on a VCM. Additionally, compliance markets are typically local, whereas CDRs can be traded globally. For CDR transactions to occur within compliance markets on a global scale, there must be ways to reconcile credit generation between different compliance markets.

It is possible for compliance and VCM to complement one another. For example, a CO₂ credit could be retired in a compliance market and then traded in a VCM, thus leveraging the credibility of the standards and protocols established under rule of law in the compliance market. In the long term, for CDR transactions to occur at the scale required, it is anticipated that the industry will increasingly move towards compliance markets.

Challenges

Several challenges to CDR market growth are noted below, including alignment on definitions, high costs, policy uncertainty, and competition. This list is not comprehensive.

Alignment on CDR Definitions, Standards, and Protocols

The CDR market is emerging, and there is no common understanding and awareness of what CDRs are. Ultimately, buyer confidence requires a common understanding of CDRs and accounting practices. For example, biogenic emissions are generally considered carbon neutral, but this is not universally the case. Furthermore, lack of alignment between standards and protocols can create uncertainty and confusion to buyers and can impact the bankability of projects.

Costs

High capital costs remain an issue, especially for engineered removals reliant on CCUS. Many CCUS projects have failed to reach their intended capture capacities or timelines due to technical setbacks, cost overruns, and logistical challenges. Several high-profile projects have been scaled back or suspended due to escalating costs and technical difficulties in achieving consistent CO₂ capture rates. These challenges highlight the need for continued research, innovation, and policy support to address the uncertainties and technical barriers that currently hinder the widespread deployment of CCUS and thus engineered CDR technologies.

Policy Uncertainty

Carbon markets are driven by policy. Changes in political parties and their associated policies create investment uncertainty, especially for large-scale, capital-intensive emissions reduction projects.

Competition

There is significant competition from alternative decarbonization technologies (e.g., electrification, renewable energy), and in many cases, limited investment dollars to make major projects go forward.

Notable Investment Activity

In May 2023, JPMorgan Chase, an American multinational financial services firm, announced an investment of \$200,000,000 US to support the development of CDR technologies⁷⁹. The partner companies include Climeworks, CO280 Solutions Inc., Charm Industrial, and Frontier.

In November 2023, Microsoft Corp., an American technology company, announced an investment in numerous large-scale projects to support carbon dioxide removal as part of its targets to be carbon negative by 2030 and to remove the equivalent of all its cumulative GHG emissions by 2050. The partner companies include Heirloom, Ørsted A/S, Carbon Capture, and Running Tide. Other large-scale CDR deals include Charm Industrial's \$53,000,000 US long-term contract with Frontier and a CDR purchase contract between Mitsubishi Corp. and NextGen, among others. Since August 2024, several new projects and investments have been announced for CDR credits worldwide. Notable examples include Terraset's purchase of carbon removal credits from Climeworks, Isometric's issuance of 107.21 carbon removal credits from Charm Industrial to JPMorgan Chase, Shopify, and Stripe, and the SLB and Aker Carbon Capture joint venture's contract with CO₂80 for the front-end engineering and design of a carbon capture plant at a U.S. Gulf Coast pulp and paper mill⁸⁰. Additionally, Deep Sky launched Deep Sky Labs, the world's first DACCS innovation center in Innisfail, Alberta, Canada, and Spiritus filed a Class VI permit application for its Orchard One project, aiming to be the world's largest DACCS facility 1. Between August 2024 and May 2025, Microsoft and Stockholm Exergi extended their existing BECCS relationship by 1.75 million tonnes to a total of 5.08 million tonnes, making it one of the largest durable CDR deals ever recorded 1. Exomad Green signed an offtake agreement with Microsoft for 1.24 million tonnes of CDR, making it the largest biochar carbon removal deal to date. JPMorgan Chase signed an offtake agreement with CO₂80 for 450,000 tonnes of carbon removal using BECCS. Mitsui O.S.K. Lines became the first Japanese shipping company to retire technology-based CDR credits, having purchased 2,000 tonnes of biochar carbon removal from Exomad Green through NextGen CDR. Capgemini signed two long-term offtake agreements with Charm Industrial and Climeworks for 29,500 tonnes of CDR 1. Charm Industrial will remove 16,500 tonnes of CO₂ via Biomass Geologic Sequestration of CO₂, while Climeworks will remove 13,000 tonnes through Direct Air Capture under the agreements. Occidental and investment company XRG agreed to evaluate a joint venture to develop a facility in the South Texas DAC hub that can capture 500,000 tonnes of CO₂ a year, with XRG considering a \$500,000,000 US investment. Project developer Residual Carbon partnered with Isometric to work with industrial and agricultural partners to turn waste biomass into high-quality CDR projects that meet Isometric's standards for scientific integrity and transparency 1⁸¹.

⁷⁹ Carbon Dioxide Removals (CDR) Industry Research Report 2024 - Yahoo Finance

⁸⁰ [CDR Monthly Recap - May 2025](#)

⁸¹ Carbon Dioxide Removal (CDR) Market, BCC Publishing, BCC Research Short Report: ENV069A Carbon Dioxide (February 2024)

BECCS Industry Participants

The primary customers of CCUS and related technologies span across various sectors and industries that have direct interests in reducing their carbon footprints, complying with regulatory requirements, or achieving sustainability and net-zero targets.

Category	Sector / Entity Type	Carbon Management Strategies	Example Organizations
High Carbon Footprint Industries	Oil & Gas Companies	CCUS, BECCS, Enhanced Oil Recovery (EOR), Net-zero commitments	Shell, BP, ExxonMobil, Chevron, Occidental Petroleum
High Carbon Footprint Industries	Heavy Industry & Manufacturing	Carbon capture for industrial processes, compliance with carbon pricing	Cement: LafargeHolcim, HeidelbergCement; Steel: ArcelorMittal, Tata Steel; Chemicals: BASF, Dow Chemical
High Carbon Footprint Industries	Power Generation Companies	BECCS, CCUS for fossil fuel plants, transition to cleaner energy	Drax Group, Orsted, Equinor, Southern Company
Net-Zero Committed Corporations	Tech & Consumer Goods Companies	Purchase carbon removal credits (Climeworks, Charm Industrial, CarbonCure)	Microsoft, Google, Amazon, Shopify, Unilever, Nestlé, Coca-Cola
Public Sector Entities	National/Regional Governments	Invest in CCUS/BECCS, fund climate tech, meet Paris Agreement goals	U.S. DOE, Natural Resources Canada, European Commission
Public Sector Entities	Municipal Governments	Local climate action plans, urban emissions reduction	City of San Francisco, City of Copenhagen
Agriculture & Forestry Sector	Agribusinesses	Soil carbon sequestration, biochar, carbon credits	Cargill, Bayer Crop Science, Yara International
Agriculture & Forestry Sector	Forestry Companies & Landowners	Afforestation, reforestation, forest management	Weyerhaeuser, The Nature Conservancy, Forest Carbon Partners
Sustainable Manufacturing	Green Construction Firms	CO ₂ utilization in low-carbon building materials	CarbonCure Technologies, Solidia Technologies, LafargeHolcim
Sustainable Manufacturing	Chemical & Plastics Manufacturers	CO ₂ as feedstock for sustainable fuels and materials	Twelve (Opus 12), LanzaTech, Covestro
Financial Sector	Impact Investors & Climate Funds	Invest in CDR, BECCS, CCUS for financial and environmental returns	Breakthrough Energy Ventures, Lowercarbon Capital, Prime Impact Fund
Financial Sector	Banks & Asset Managers	Green bonds, ESG-aligned funding for carbon tech	HSBC, BlackRock, Goldman Sachs
Research & Academia	Universities & Research Institutions	R&D in carbon capture and removal, partnerships with industry	MIT, Imperial College London, Stanford University, University of Alberta
Technology Developers	CDR Technology Companies	Focus on energy demand, cost, commercialization, partnerships	Snapshot available in appendix

Corporations and Industries with High Carbon Footprints

Oil and Gas Companies: These companies face significant pressure to reduce their greenhouse gas emissions due to regulatory mandates, investor demand for sustainable practices, and market shifts toward cleaner energy. They use CCUS and BECCS technologies to decarbonize their

operations, enhance oil recovery (EOR) while storing CO₂, and meet net-zero commitments. Examples: Shell, BP, ExxonMobil, Chevron, and Occidental Petroleum.

Heavy Industry and Manufacturing: These industries are among the most challenging to decarbonize due to their reliance on carbon-intensive processes. Carbon capture technologies are essential to help them reduce direct emissions from industrial processes and comply with carbon pricing regulations and emissions reduction targets. Examples: Cement (LafargeHolcim, HeidelbergCement), Steel (ArcelorMittal, Tata Steel), and Chemicals (BASF, Dow Chemical).

Power Generation Companies: Power generation companies that rely on fossil fuels (coal, natural gas) are turning to BECCS and CCUS technologies to capture CO₂ emissions from power plants. This allows them to continue operating while reducing their carbon footprint, meeting regulatory requirements, and transitioning to greener energy sources. Examples: Drax Group, Orsted, Equinor, and Southern Company.

Corporations Committed to Net-Zero Goals

These companies have pledged to achieve net-zero emissions, often committing to substantial carbon removal purchases to offset their unavoidable emissions. They purchase carbon removal credits from firms like Climeworks, Charm Industrial, and CarbonCure to fulfill their climate commitments. Examples: Microsoft, Google, Amazon, Shopify, Unilever, Nestlé, and Coca-Cola.

Governments and Public Sector Entities

National and Regional Governments: Governments purchase carbon removal services and invest in CCUS and BECCS technologies to meet national and international climate commitments, such as those under the Paris Agreement. They provide funding, grants, and incentives to scale these technologies, often partnering with private companies to develop projects that help achieve their net-zero goals. Examples: United States (DOE), Canada (Natural Resources Canada), and the European Union (European Commission).

Municipalities and Local Governments: Local governments use carbon capture and removal technologies to meet local climate action plans, reduce urban emissions, and support sustainable development goals. Examples: City of San Francisco and the City of Copenhagen.

Agriculture and Forestry Sector

Agribusinesses and Food Producers: Companies in the agriculture sector invest in soil carbon sequestration, biochar, and other carbon removal technologies to reduce emissions from farming

practices, enhance soil health, and generate carbon credits. Examples: Cargill, Bayer Crop Science, and Yara International.

Forestry Companies and Landowners: These entities invest in afforestation, reforestation, and forest management practices to capture CO₂, sell carbon credits, and promote sustainable land management. Examples: Weyerhaeuser, The Nature Conservancy, and Forest Carbon Partners.

Sustainable Product and Material Manufacturers

Green Construction and Building Materials Firms: These firms use CO₂ utilization technologies to produce low-carbon building materials, like concrete, which helps meet the growing demand for sustainable construction materials and reduce the carbon footprint of buildings. Examples: CarbonCure Technologies, Solidia Technologies, and LafargeHolcim.

Chemical and Plastics Manufacturers: Companies in the chemical and plastics sectors use captured CO₂ as a feedstock to produce sustainable fuels, chemicals, and materials, aligning with circular economy principles and reducing reliance on fossil fuels. Examples: Twelve (formerly Opus 12), LanzaTech, and Covestro.

Investors and Financial Institutions

Impact Investors and Climate Funds: Investors focused on sustainability and climate impact invest in CDR, BECCS, and CCUS technologies to generate financial returns while achieving positive environmental outcomes. They provide capital to companies developing innovative carbon management solutions. Examples: Breakthrough Energy Ventures, Lowercarbon Capital, and Prime Impact Fund.

Banks and Asset Managers: Financial institutions provide funding and financial products (e.g., green bonds) to support the growth of carbon capture and removal technologies, aligning with their ESG investment strategies and helping clients meet sustainability goals. Examples: HSBC, BlackRock, and Goldman Sachs.

Research Institutions and Universities

These institutions engage in research, development, and deployment of carbon capture and removal technologies, often partnering with private companies to advance scientific knowledge and accelerate commercialization. Examples: Massachusetts Institute of Technology (MIT), Imperial College London, Stanford University, and University of Alberta.

Technology Developers

The CDR sector is an emerging one with a recent influx of technology developers. Many of these organizations are immersed in research and development. The core technology processes are expected to be similar across most of these companies, and so the key differentiators will be energy demand, capital cost requirement, effectiveness of the company's commercialization strategy, brand recognition and strategic partnerships. A snapshot of CDR companies currently in the space can be found in the appendix.

CDR Opportunities in Alberta

Bioenergy with Carbon Capture and Storage

Alberta has the necessary prerequisites to be a world leader in BECCS. It has excellent geology for CO₂ storage, the largest biomass production of any province in Canada, and has the most robust industrial carbon pricing and CO₂ storage regulatory regimes globally. Alberta's BECCS project development opportunities are numerous, and can be grouped into five main categories:

- 1 Adding capture to existing forest products (and renewable fuel) facilities.
- 2 Fuel switching existing energy infrastructure to biomass fuels and adding capture.
- 3 Developing new biomass heat and/power facilities to supply existing consumers.
- 4 Developing BECCS biopower facilities to decarbonize Alberta's electricity grid.
- 5 Developing new biomass-based negative carbon hydrogen, fuel, and chemical facilities.

Existing Biogenic CO₂ Emitters

Alberta is home to a strong and growing forest products industry, including four kraft (chemical) pulp mills, two mechanical pulp mills, a newsprint mill, twenty-one sawmills, and six board mills. Three wood pellet plants are also located in Alberta, including Canada's largest in Entwistle⁸². Bioenergy generation for heat and power is an integral and necessary part of forest products production. Chemical pulp mills require steam (process heat) for the pulping process while mechanical pulp and newsprint mills are amongst the largest consumers of electricity in the province. Sawmills and board mills usually consume grid electricity but often rely upon biomass to supply thermal (heat) energy to drying kilns. A large percentage of the fuel used for bioenergy production is the bark and residues generated from processing. However, at kraft pulp mills, the largest source of biogenic CO₂ emissions is typically the recovery boiler, which burns black liquor, a lignin-dominated mixture, to recover pulping chemicals. Lignin is the 'glue' that holds wood cellulose fibers together and must be removed to produce chemical pulp.

⁸² TorchLight Bioresources, 2024. Canadian forest bioenergy database. Prepared for Natural Resources Canada.

Based upon industry averages of biogenic CO₂ emissions per unit of product, it is estimated that Alberta's forest products industry currently generates approximately 8 million tonnes (Mt) of biogenic CO₂ per year.⁸² Capturing these existing emissions is the logical starting point for launching a BECCS industry, with PCC being the most likely technology approach for existing facilities. The best candidates for biogenic CO₂ sources are Alberta's four kraft pulp mills, which emit 1-2 Mt CO₂ per year each and account for over 75% of the existing biogenic CO₂ CDR potential in Alberta. These large sources enable the economies-of-scale essential to economically viable capture projects. In comparison, sawmills and board mills generally range between 20,000 and 200,000 tonnes of biogenic CO₂ per year. This smaller volume is more applicable to modular PCC units than custom-engineered, large PCC facilities.

In most cases, the capacities of the existing boilers at forest products facilities are maximized for existing energy demand. This means that to implement carbon capture, which mostly has a high energy demand, additional energy supply is required. Unless using a grid electricity-based capture process, this necessitates the development of new biomass heat and/or power plants to supply the required capture process energy. The advantage of BECCS over fossil fuel capture projects is that the capture process energy supply, when coming from biomass, increases the climate positive impact by removing more carbon from atmosphere via increased biomass consumption and increased CDR volume. Since CDRs are a saleable, exportable product, the energy demands for PCC and associated increased CDR volume thus improve the economies-of-scale and economics of a capture project. In comparison, using fossil fuels for capture creates a GHG liability, necessitating additional capture capacity, that limits the net GHG reductions and is also a major net project cost. Considering the additional energy and biomass required for capture projects at existing forest products facilities, it is estimated the total PCC BECCS volume potential at these facilities would be approximately 12 Mt CO₂ removal/yr. This is more than all of Alberta's light duty vehicle GHG emissions, thus eliminating these emissions on a net basis, or approximately the total emissions for Canada's largest emitter, the Syncrude upgrader.

Alberta is home to one ethanol plant and two renewable diesel plants. Biogenic CO₂ emissions from ethanol production are high purity, making ethanol-based BECCS projects very low cost. Capturing and storing biogenic CO₂ emissions from renewable diesel production lowers the net carbon intensity of the resulting product, increasing its value under policies such as low carbon fuel standards (LCFS).

Fuel Switching Existing Facilities

Biomass is a carbon-containing fuel and can substitute fossil fuels in some existing facilities. Modifications, such as handling systems, storage, and equipment controls, are typically needed for solid biomass fuel switching. In other cases, such as biomethane substituting for natural gas, no changes are required. Replacement of boilers, a more substantial undertaking that goes beyond simple fuel switching, is addressed in the next section.

The largest opportunity for fuel switching in Alberta is at the province's existing electricity generating stations that were previously fueled by coal. Alberta no longer uses coal for electricity generation, with all stations converted to natural gas or closed. There have been numerous pulverized coal power plants converted to wood pellets, with a lesser number converted to biomass-based syngas. The latter requires the addition of a biomass gasifier, with the resulting syngas injected into the existing boiler. Both approaches result in the CO₂ in the flue gas from the generating stations becoming biogenic and an opportunity for BECCS project development. Alberta has six units, formerly operating on coal, with a combined capacity of approximately 2,600 MW_e scheduled to operate on natural gas post 2030⁸³.

While fuel switching all this capacity would be large undertaking, it is the same as the generating capacity UK company Drax converted from coal to biomass at a single plant. Drax' primary generating station relies 100% on imported fuel, from North America, which makes conversion in biomass-rich Alberta a more technically approachable proposition than what Drax has already accomplished. Drax is proposing to add PCC to half of its 2,600 MW biomass capacity, which would result in 8 Mt of CDRs per year⁸⁴.

Biomethane can be substituted for natural gas in any application where the latter is used. The easiest way to generate BECCS CDRs would be to fuel switch to biomethane at a facility already fitted with carbon capture and storage, such as Quest or the Nutrien Redwater Nitrogen Fertilizer Plant, which relies on the Alberta Carbon Trunk Line for CO₂ transport.

New Bioheat, CHP, and Behind-the-Meter Power

Approximately 80% of Alberta's energy consumption is for heat: industrial process heat and heating buildings⁸⁵. Almost all industrial heat demand in Alberta outside the forest products industry is met with fossil fuels, including natural gas, still gas/producer gases (gases generated

⁸³ [Alberta's coal phase-out: Pros and cons - Canadian Mining Journal](#)

⁸⁴ Drax, 2022. Drax submits plans to build world's largest carbon capture and storage project.

⁸⁵ Canada Energy Regulator, 2024. Canada's energy future.

from fossil fuel processing), and coal (for lime/cement production). A substantial proportion of this heat demand is in applications that require steam temperatures of less than 575°C. Steam temperatures less than 575°C can be generated using unprocessed solid biomass fuel, such as wood chips. Examples include steam for bitumen in situ extraction, such as steam-assisted gravity drainage (SAGD), or hot water processing of bitumen from mining operations. Use of biomass in applications that require temperatures higher than 575°C generally necessitates significant additional biomass processing, such as conversion of wood to biochar, to produce fuels with sufficiently high flame temperatures. Very high temperatures are typically required for refining and chemicals production. For example, ethane cracking for ethylene production requires temperatures exceeding 800°C⁸⁶.

Substitution of natural gas-fired steam with biomass-fired steam, combined with CCUS (i.e., BECCS), results in negative carbon intensity steam supply. Steam can be used in a heat-only application, used to generate electricity in a behind-the-meter, electricity-only application, or used to supply both heat and power to industrial facilities. Supply of negative carbon intensity energy to an industrial processing facility results in the decrease of the life cycle carbon intensity of the resulting products from that facility.

Alberta is in a unique position to offer zero or negative carbon intensity crude to customers because of the significant energy demands for oil sands bitumen recovery and processing. CDRs from BECCS steam supply could be bundled with synthetic crude oil (SCO) or heavier crudes to make the products zero carbon on a life cycle basis. This means the carbon intensity of the resulting products, such as jet fuel or gasoline, will be the decision of the customer. This decision would likely be based on a cost-carbon intensity tradeoff.

The second large thermal energy demand in Alberta is building heat for both space and domestic hot water. Substantially more energy is used for building heat than the total electricity consumption, for all purposes, in the province. To address the large building heat market in Alberta with negative carbon intensity heat from BECCS, centralization of heat generation is required. This is because large-scale energy generation facilities are required to enable carbon capture projects and biomass cannot be delivered to every building. When heat generation is centralized, a means of distributing heat from a centralized energy facility to thousands, tens of thousands, or even hundreds of thousands of individual building heat consumers is required. In most northern countries, the dominant form of building heat system is district energy – networks of underground hot water pipes connecting one or more central energy facilities to thousands of buildings. In the Nordic countries of Denmark, Sweden, and Finland, the most common source of heat for district energy systems is central biomass heat and combined heat and power plants⁸⁷. The most

⁸⁶ Fisher Controls International, 2010. Ethylene production. Chemical Sourcebook.

⁸⁷ Swedish Energy Agency, 2024. Statistics.

advanced BECCS projects in Europe are at large biomass CHP plants, providing heat to district energy networks and electricity to the national grid, in major cities of Copenhagen and Stockholm. These cities consider BECCS a necessity to meet their 2030 net-zero climate goals. The dominance of district energy in cold climates has been recognized by the cities of Edmonton and Calgary, with both including large district energy infrastructure build-out in their energy transition strategies. With BECCS, the networks could supply negative carbon heat, eliminating the emissions from harder-to-abate sources in the cities, such as transportation.

Greenfield BECCS Biopower

The Government of Canada has stated that reaching a net-zero electricity grid is a policy priority. However, there are significant challenges, both economic and technical, to reaching this goal. Alberta lacks the significant hydropower resources of provinces such as Quebec, British Columbia, and Manitoba, and relies heavily on natural gas-fired electricity generation.

BECCS is the essential technology to economically achieve a net-zero electricity grid because it is the only technology that generates energy and CDRs at the same time. The most economical way to reach net-zero is to consider both positive and negative emissions. As noted above, fuel switching Alberta's existing (former) coal generating stations to biomass and CCUS would result in a negative carbon electricity grid in Alberta. An alternative approach is to add CCUS to natural gas-fired generating stations that operate as baseload supply, but to leave low-capacity natural gas-fired plants unabated. New greenfield BECCS plants, with either PCC or oxy-combustion designs, would operate as baseload plants and generate the CDRs required to make the grid negative emissions. A 60 MW_e baseload BECCS plant can remove all the emissions from 1,000 MW_e of natural gas-fired plants operating with a 15% capacity factor.

Oxy-combustion offers electricity grid management opportunities beyond carbon. Pure oxygen (O₂), a required input for oxy-combustion, is typically generated using an Air Separation Unit (ASU). An ASU is a large consumer of electricity, which reduces the net energy balance of an oxy-combustion BECCS unit. However, pure oxygen can be stored and used when required. Therefore, an ASU can function as a dispatchable or interruptible load to assist electricity grid management, particularly as the penetration of intermittent renewables (wind, solar) increases on the grid. When electricity supply is high, relative to demand, the ASU can operate at full capacity (high price of electricity significantly increasing operating costs). When electricity supply is low, relative to demand, the ASU can be curtailed. For the ASU to function in this manner but still operate the BECCS project at full capacity baseload, the ASU must be oversized relative to hourly O₂ demand and substantial oxygen storage capacity must be included in the BECCS project design.

Greenfield Negative Carbon Products

Biomass, composed of carbon, oxygen, and hydrogen, can be converted via various conversion processes into a variety of products, fuels, and chemicals. Examples include gasification + reformation into methanol and diesel, hydrolysis of cellulose followed by fermentation into ethanol or other chemicals, and fast pyrolysis into 'bio-oil' (pyrolysis liquids) and subsequent upgrading. These processes require energy, and it is typically the biomass itself that provides the conversion process energy, resulting in the release of biogenic CO₂.

Capture and storage of the CO₂ generated from processing will typically result in the end bioproduct, biochemical, or biofuel being negative carbon intensity. The specific figure is highly dependent upon product yield, fossil fuel inputs to the conversion process (e.g., heat, hydrogen), upstream emissions, including biomass production (e.g., fertilizer), and harvest operations. In general, the greater the percentage of biogenic carbon from input biomass that is captured and stored instead of being incorporated into a product, the lower the carbon intensity of that product. There can be a tradeoff between carbon valuation, as CDRs, and the value of the carbon included within the bioproduct, biochemical, or biofuel.

At the extreme end of the spectrum is bio-based hydrogen (H₂). In this case, all carbon and oxygen in the biomass input is targeted for capture and storage as CO₂, resulting in a very negative carbon intensity H₂. The H₂ can be used in any application considered for conventional fossil fuel-based H₂ or electricity-based hydrogen produced using electrolysis of water. Due to the very negative carbon intensity of H₂ produced from biomass, with CCUS included in the process, use of this H₂ in upgrading and refining can have a meaningful impact on the life cycle carbon intensity of end products, such as gasoline, diesel, and jet fuel. Therefore, it can be considered an alternative pathway to behind-the-meter, negative carbon heat and/or power for decarbonizing Alberta's largest exports.

Economic and Carbon Efficiency

Any product produced from oil and gas can technically be produced from biomass, though performance specifications and longevity will vary. In addition, biomass has additional markets for food (agriculture) and structural materials/buildings (largely wood). With this broad variety of options for biomass use, it begs the question: Is BECCS the best use of biomass? To answer this question, it is essential to consider that both forestry and agriculture are systems with multiple products produced from different types of biomass within each system.

The forest products industry has four main categories of products: 1) lumber; 2) board products, such as OSB, plywood, and MDF; 3) pulp and paper; and 4) bioenergy. The first three categories all require energy for production and if this energy is not supplied by bioenergy, the likely alternative is fossil fuels. Hence, biogenic CO₂ emissions will be generated in addition to these products if using

bioenergy. High quality sawlogs will always have a best use as lumber for construction. As for board products and pulp and paper, the question of whether to use wood for these products or bioenergy is largely determined by quality of material, markets, and industrial capacity.

Alberta is the only province in Canada with a higher timber harvest at present (2024) than twenty years ago⁸⁸. Nationally, the timber harvest has dropped by approximately 40% over this time, largely driven by the closure of pulp and paper mills⁸⁹. Newsprint and mechanical pulp have taken a particularly hard hit. The strength of the provincial industry means that bioenergy from Alberta-sourced wood will be limited to low-value mill residues, harvest residues (tops, branches), and very low-value timber including salvage logs harvested following wildfires. This may not be the case for other provinces, where a market for residues is acute because of the ongoing operation of sawmills. The Canada Energy Regulator, in its global net-zero scenario, modelled that millions of tonnes per year of woody biomass would be transported from other provinces to Alberta for BECCS project operation due to the superior geological CO₂⁹⁰ capacity in Alberta⁹¹. In all cases, BECCS facilities, including those capturing existing biogenic CO₂ emissions from forest products operations, would only be developed if they add value to the existing industry.

For agriculture, the largest volume products in Alberta are grains and meat. The primary bioenergy opportunity for the latter is use of ‘waste’ products, such as beef tallow, for renewable transportation fuel (renewable diesel) production. Waste also includes solid waste (‘garbage’), which is approximately 50% biogenic by carbon content. Approximately a dozen countries have eliminated landfilling, and all have used thermal energy generation, in the form of waste-to-energy (WtE), to do so. Due to the heterogeneous nature of this material, conversion of solid waste into products other than heat and power is technically difficult. In addition, since half the carbon in the fuel is non-biogenic and processing requires substantial inputs, fuels produced from solid waste are generally not low carbon unless avoided landfill methane emissions (i.e., avoidance credit added to the life cycle carbon intensity) are considered. Even WtE for power and CHP does not have a substantial carbon advantage over natural gas due to the non-biogenic component of solid waste – largely plastic. However, when CCUS is added to WtE, the process becomes negative carbon due to the biogenic component of waste, making WtE with CCUS the only pathway for eliminating GHG emissions from solid waste. While Alberta has a relatively modest population, several EU countries import solid waste for use as a fuel and Alberta may want to consider this opportunity, given the negative price for the fuel and the opportunity for BECCS.

⁸⁸ National Forestry Database, 2022. Harvest statistics. Canadian Council of Forest Ministers.

⁸⁹ Natural Resources Canada, 2023. The state of Canada’s forests – annual report 2023.

⁹⁰ Canada Energy Regulator, 2024. Canada’s energy future.

⁹¹ Doluweera et al, 2022. The path towards net-zero greenhouse gas emissions in Canada’s electricity sector. IAEE Energy Forum.

Many net-zero and energy-climate models assume use of biomass for ‘hard-to-abate’ sources of GHG emissions, such as aviation, rail, and long distance trucking, to complement widespread electrification of heat and light duty transportation. However, these are typically goal seeking models designed to substitute renewable energy for fossil fuels and do not consider the potential of BECCS to avoid fossil fuel emissions (bioenergy replacing fossil fuels) and remove fossil fuel emissions from the atmosphere. They also do not generally include fuel conversion efficiencies, carbon efficiency, nor economic optimization for specific biomass types, leaving the decision on ‘best’ biomass use up to the modeler. Unfortunately, goal-seeking modelling, with an assumption of electrification of all applications that are technically possible, does not reflect economic reality and results in erroneous conclusions on likely use of biomass and cost of decarbonization.

When considering the use of woody biomass for decarbonization, energy/fuel yield and carbon efficiency must be considered. Producing liquid and gaseous fuels from woody biomass is generally 30%-40% energy efficient. These fuels are then used in engines with 20%-24% efficiency, resulting in an overall energy efficiency of less than 10%. In contrast, it is more efficient, per km, to generate electricity and use the bio-based electricity in an electric vehicle, even before considering the heat co-product. When heat is considered, biomass CHP is five to eight times more efficient for energy use (when the electricity is used for transportation) than conversion to liquid fuels. Looking at carbon efficiency, a biomass CHP plant with CCUS (i.e., BECCS) in Alberta reduces GHG emissions, per tonne of wood, by six times that of conversion to liquid fuels⁹². If GHG emissions are valued at \$170/t CO₂e, this represents a difference of approximately \$425 per bone dry tonne of wood in avoided carbon costs and CDR revenue. This difference is also an indicator of the relative value a tonne of wood would have for the Government of Alberta, which owns most of the province’s forests, forest managers, forestry operators, and the forest products industry.

In many cases, the lowest cost approach to reduce GHG emissions is to continue using fossil fuels and remove the GHG emissions using BECCS. For these GHG sources, the cost of fuel substitution and emissions avoidance is higher cost, per tonne of CO₂e, than an Alberta-based BECCS CDR. Globally, there are approximately 54 Gt CO₂e of GHG emissions annually. For these emissions, Goldman Sachs publishes a GHG Emission Cost Abatement Curve, which estimates the cost of avoiding GHG emissions via fuel switching and substitution – but critically not removal. Based upon TorchLight Bioresources’ estimates for the cost of BECCS CDRs in Alberta, projections indicate that it is a lower cost to continue using fossil fuels and remove the GHG emission using BECCS, than to avoid the emission, for approximately half of global emissions. When set against other economic, social, and environmental priorities, economic efficiency is essential to achieve meaningful progress towards global climate goals. Therefore, when planning the use of biomass, and more broadly forests and agriculture, and the approaches to reduce GHG emissions, BECCS and associated CDRs must be considered a valuable tool.

⁹² Stephen J, 2024. Going negative: how Canada can help decarbonize the world. Policy – Canadian Politics and Public Policy.

Nature Based Solutions

In Alberta, *soil carbon sequestration* is gaining recognition as a vital component of sustainable agriculture and climate change mitigation. Soil carbon sequestration projects in Alberta are diverse and involve various approaches. The Conservation Cropping Protocol supports farmers in adopting no-till farming, helping to increase carbon storage in soils. The Olds College Smart Farm uses advanced technology to enhance soil health and carbon sequestration. Additionally, the University of Alberta is leading research on improving grassland carbon storage through better grazing management⁹³. A recent study found that moderate livestock grazing in northern temperate grasslands enhances soil organic carbon (SOC) concentrations, particularly in the top 15 cm of soil⁹⁴. Alberta offers several agricultural carbon offset protocols, including Conservation Cropping, Nitrous Oxide Emissions Reduction (NERP), and protocols for Beef Feedlot and Genetics. These protocols help reduce greenhouse gas emissions, generate carbon credits, and offer financial incentives for sustainable farming practices. Other related protocols, like Biogas and Micro-Generation, provide opportunities for renewable energy projects within agriculture. Alberta's Emission Offset System lists all protocols and suggests that agricultural participation can contribute to both environmental benefits and economic gains⁹⁵.

Alberta supports forest conservation and carbon sequestration through various afforestation and reforestation initiatives, such as partnerships with Indigenous communities to restore degraded forest lands and government policies promoting sustainable forestry practices. The Government of Alberta has initiated several programs aimed at enhancing forest carbon sequestration. These efforts include the Forest Resource Improvement Association of Alberta (FRIAA), which supports reforestation projects; the Enhanced Forest Management Program (EFM), which promotes sustainable forestry to maximize carbon storage; and Alberta's Timber Management Regulation that requires companies to replant harvested areas accounting for most trees planted in the province. Additionally, Alberta's Carbon Offset System provides protocols for forestry projects that reduce emissions and increase carbon capture. These initiatives are part of the province's broader climate strategy to manage carbon emissions effectively.

Wetlands cover approximately 21.7% of Alberta's total area. The most prevalent type is fen (muskeg), accounting for 12.0% of the province's area, followed by open water (3.5%), swamps (2.7%), bogs (1.8%), and marshes (1.6%). A significant portion of these wetlands (23.4%, or 33,656 km²) falls within protected areas, primarily located in northern Alberta and the Rocky Mountain Natural Region. These wetlands are ecologically important and include sites recognized for their

⁹³ <https://www.ualberta.ca/en/folio/2023/09/researchers-to-explore-how-canadas-grasslands-could-store-more-carbon.html>

⁹⁴ Mo L, Zohner CM, Reich PB, Liang J, De Miguel S, Nabuurs GJ, Renner SS, van den Hoogen J, Araza A, Herold M, Mirzaghali L. Integrated global assessment of the natural forest carbon potential. *Nature*. 2023 Dec 7;624(7990):92-101.

⁹⁵ <https://www.alberta.ca/agricultural-carbon-offsets-all-protocols-update>

conservation value, such as Ramsar wetlands and important bird areas⁹⁶. Alberta's peatlands and wetlands are vital carbon sinks, but many have been degraded by industrial activities and agriculture. Restoration initiatives, such as those supported by the Alberta Wetland Policy, focus on re-establishing these ecosystems. Partnerships between government, conservation organizations, and local communities are driving efforts to protect and restore these critical landscapes. Ducks Unlimited Canada, for example, leads several wetland conservation projects in the province⁹⁷.

In Alberta, *biochar* has gained attention as a potential tool for enhancing soil carbon storage and improving agricultural sustainability. The Alberta Biochar Initiative (ABI) was launched in 2011, led by Alberta Innovates, Technology Futures (AITF) now Alberta Innovates, with support from Lakeland College and funding from Western Economic Diversification Canada (now Prairies Economic Development). Over a 3.5 year period, ABI operated two demonstration pyrolysis units, meeting all project goals and growing to over 60 members. AITF supported Air Terra in obtaining Canadian Food Inspection Agency (CFIA) approval for biochar products in 2015. ABI continues developing biochars and activated carbons in Vegreville, Alberta, and plays a role in forming the North American Biochar Working Group to enhance market potential and collaboration opportunities in North America⁹⁸.

Alberta's geology offers potential opportunities for *ERW*, especially considering the province's rich deposits of basalt and serpentine. With 25.3 million acres of cropland, the existing mining and energy infrastructure in Alberta could support the scaling of *ERW*. However, there is very little information available regarding ongoing and future projects related to *ERW* in Alberta.

Direct Air Capture with Carbon Storage

Alberta possesses several core characteristics that make the province favorable for DACCS deployment; however, these characteristics also create some barriers that will need to be overcome.

Carbon Sequestration Access

Direct air capture produces a pure, isolated stream of carbon dioxide (CO₂) that can be stored in highly permanent forms, including sequestration in deep saline aquifers or mineralized in mafic or ultramafic rock.

⁹⁶ <https://wetland-report.abmi.ca/atlas-home/2.0-Alberta-Wetlands/2.1-Alberta-Wetland-Inventory.html>

⁹⁷ <https://www.alberta.ca/alberta-wetland-policy-implementation>

⁹⁸ <https://biochar-us.org/presentation/alberta-biochar-initiative-and-introduction-north-american-biochar-working-group>

Alberta has access to significant underground storage capacity in the form of deep saline aquifers. In Western Canada, there is an estimated capacity to store 360 gigatonnes (Gt) of CO₂⁹⁹. Mineralization capacity is less understood, but some studies have looked at glauconite, a sandstone that could offer mineralization potential, and have estimated enough in Alberta to mineralize over 500 Gt of CO₂¹⁰⁰.

Existing infrastructure that can move CO₂ can help unlock a lot of this storage capacity. One example is the Alberta Carbon Trunkline, a 240 kilometer pipeline transporting captured CO₂ from the Alberta Industrial Heartland to aging oil fields/storage sites near Lacombe. This CO₂ is used in enhanced oil recovery (EOR), boosting oil extraction while storing CO₂ underground. This process supports low carbon oil production by reducing greenhouse gas emissions and promoting sustainable energy practices.

Existing Expertise

The skills and experience required to deploy DACCS projects are similar to those needed in oil and gas and other industries prevalent in Alberta. Rotary equipment, fluid systems, fluid compression, pipelines, and downhole drilling are all required components of a DACCS system. Expertise will be needed in engineering, construction, manufacturing, project management in industrial settings, and geology. Alberta has all this expertise and a workforce with the relevant skills.

Cold and Dry Climate

The relatively dry climate in Alberta offers advantages for DAC operations because there is less of an impact of humidity on the performance of solid absorbents or liquid absorbents. However, the ever-changing weather conditions present a challenge for DAC operation in the region, compared to other jurisdictions. Throughout the year, DAC technology can be exposed to fluctuations in humidity and temperature – ranging from 35°C in the peak of summer to -51°C in winter. Overcoming this challenge requires robust chemistry and strong utility operation support to ensure reliable and year-round operational DAC technology. Some companies offer approaches for operating DAC in conditioned air spaces, providing a potential solution for deployment in Alberta or other cold climates.

⁹⁹ Richard Hares, Sean McCoy and David B. Layzell, *Review of Carbon-Dioxide Storage Potential in Western Canada: Blue Hydrogen Roadmap to 2050* (The Transition Accelerator, 2022), 11. <https://transitionaccelerator.ca/reports/review-of-carbon-dioxide-storage-potential-in-western-canada-blue-hydrogen-roadmap-to-2050/>

¹⁰⁰ Qin Zhang, Benjamin M. Tutolo, “Evaluation of the potential of glauconite in the Western Canadian Sedimentary Basin for large-scale carbon dioxide mineralization,” *International Journal of Greenhouse Gas Control* 117 (2022), 103663. <https://doi.org/10.1016/j.ijggc.2022.103663>

DAC Value Chain and Ecosystem

DAC is a brand-new industry which will require the establishment of a full value chain to succeed. Continued government support through policies and regulations can help facilitate the development and adoption of this technology. This could involve offering incentives and financial support to foster a favorable business environment. In Alberta, there is already the Technology Innovation and Emission Reductions (TIER) regulation, which requires industrial emitters to compensate for emissions above a certain threshold. Agencies like Emissions Reductions Alberta and Alberta Innovates are actively involved in advancing the TIER program's objectives. Currently, there is not a protocol for DAC within the TIER program, meaning CO₂ removed through DAC cannot be purchased to count towards an industrial emitter's obligations.

DAC technology providers are small to medium enterprises that supply DAC technology to a variety of end users, including those in industries like oil and gas, power, cement, iron and steel, chemicals, aviation, transport, and technology. Alberta has been the birthplace of many companies involved in CO₂ capture technology development including DAC – notably, Carbon Engineering. This has created a conducive environment for realizing the potential of DAC technology and encouraging the emergence of more startups in this field. An example is The Deep Sky DAC plant in Innisfail, Alberta. This plant tests various direct air capture (DAC) technologies to remove CO₂ from the atmosphere. Powered by renewable energy, it aims to capture and store CO₂ underground¹⁰¹.

The private sector, including end users such as oil and gas companies, can support startups through venture funding. Other private companies in hard-to-abate sectors, such as aviation, can also play a significant role in developing the DAC value chain by purchasing DAC credits to offset their emissions. These purchases can kickstart the industry by providing capital and access to financing for project developers. Alberta is a hub for many private sector companies that have the potential to support the DAC value chain.

In summary, Alberta already has a suitable business ecosystem to foster the development of DAC technologies. The continued growth of the DAC value chain in Alberta is expected to cultivate more technological development in the province and even attract DAC technologies from other places to be deployed here.

¹⁰¹ <https://www.deepskyclimate.com/blog/deep-sky-to-build-worlds-first-carbon-removal-innovation-commercialization-centre-deep-sky-labs-in-innisfail-alberta>

Areas of Investment and Development

To enable the deployment of DAC technology in Alberta, there are six key focus areas for further investment and development:

- 1 Development of novel chemistry that can be effective for operation in a cold climate.
- 2 Improvement of processing equipment to lower energy demand and capital and operational costs.
- 3 Establishment of DAC hubs situated near industrial operations or CO₂ storage sites with access to zero-emissions electricity or heat, to reduce overhead costs and integrate with industrial operations to reduce energy demands.
- 4 Investment in automation for developing autonomous DAC operation capabilities in remote areas to minimize the cost.
- 5 Development of more cost-effective CO₂ utilization technology to improve the business case for DAC, and reduce the need for compression, transportation, and storage in the case of DACCS.
- 6 Determination of optimal energy production for DAC within Alberta, and integration of renewable energy and DAC.

CDR Markets in Alberta - Exports or Other Compliance Markets

Currently, there is limited recognition for CDR projects in Alberta within compliance markets. The Alberta Emission Offset System, which provides facilities regulated under the Technology Innovation and Emissions Reduction (TIER) System with flexible options to meet emissions requirements, does not have protocols that recognize CDR pathways. In September 2024, the CO₂ Capture and Permanent Storage in Deep Saline Aquifers protocol was flagged. A new version of the protocol was indeed published in January 2025¹⁰², and it allows for a flexible for project developers to source CO₂ from direct air capture (DAC) facilities in Alberta.

¹⁰² [Quantification Protocol for Carbon Dioxide Capture and Permanent Geologic Sequestration v2](#)

Within the federal Greenhouse Gas Offset Credit System, there is recognition of nature-based carbon removal through the Improved Forest Management on Private Land. Additionally, a Direct Air Carbon Dioxide Capture and Sequestration protocol is currently under development. A Bioenergy Carbon Dioxide Capture and Sequestration (BECCS) protocol is also being considered for future development.

That said, CDR projects in Alberta have opportunities to access select international compliance markets. Direct air capture projects in Alberta can earn Low Carbon Fuel Standard credits through the California Air Resources Board, which currently does not have project location stipulations¹⁰³. This enables DACCS projects located in Alberta to access demand from emitters in California. The Japan Green Transformation emissions trading system (GX-ETS), which is currently a voluntary program until 2026 when it transitions to a mandatory compliance program, recognizes carbon removal credits from pathways including DACCS, bio-energy carbon capture and storage (BECCS) and coastal blue carbon. The program will recognize CDR projects outside of Japan if they are at least 20% owned by an organization within the GX-League program.

¹⁰³ <https://ww2.arb.ca.gov/resources/fact-sheets/carbon-capture-and-sequestration-project-eligibility-faq>

Conclusions

Carbon Dioxide Removal (CDR) is a crucial element in the global strategy to achieve net-zero emissions by 2050. As countries and organizations commit to reducing their carbon footprints, CDR technologies offer viable solutions to not only mitigate emissions, but also to actively remove carbon from the atmosphere. In Alberta, this potential is amplified by the province's rich geological formations and established energy sector, which can support large-scale carbon capture and storage initiatives.

Integrating CDR into climate action frameworks enhances the effectiveness of existing emission reduction strategies. By systematically incorporating CDR into their plans, stakeholders can offset hard-to-abate emissions from various sectors, thereby facilitating a more comprehensive approach to achieving climate goals. Continued government support, investment in innovative technologies, and collaboration among industry leaders and researchers will be pivotal in advancing CDR solutions that align with net-zero objectives.

In Alberta, nature-based carbon capture and storage solutions have immense potential. More than 14% of Alberta's total land is covered by grasslands, which globally capture one-third of the world's terrestrial carbon stocks and can serve as a significant soil carbon sink. Alberta's grasslands have great potential for carbon capture and storage if biodiversity is maintained for long-term sustainability. Similarly, the boreal ecosystems of forests and wetlands in northern Alberta also have the potential to become a carbon sink. Unfortunately, due to recent wildfires, the region has become a source of carbon emissions. More research and conservation efforts are required to restore the boreal ecosystem and reestablish it as a net carbon sink.

Alberta is exceptionally well-positioned to lead in Bioenergy with Carbon Capture and Storage (BECCS) due to its unique combination of geological, biomass, and regulatory advantages. The province's Western Canada Sedimentary Basin offers ideal conditions for large-scale, low-cost CO₂ storage. Alberta's significant biomass resources, including timber and crops, provide ample feedstock for BECCS projects. Additionally, Alberta's regulatory framework, featuring world-leading CO₂ storage regulations and a robust industrial carbon pricing system, supports the development and deployment of BECCS technologies. The province's existing forest products industry, which includes pulp mills and sawmills, generates substantial biogenic CO₂ emissions that can be captured and stored. Converting former coal plants to biomass and adding carbon capture can further enhance Alberta's BECCS potential, creating negative carbon intensity energy and contributing to a net-zero electricity grid. BECCS projects can also support Alberta's economic

growth by creating jobs, attracting investments, and positioning the province as a leader in sustainable energy solutions.

Alberta's commitment to reducing greenhouse gas emissions aligns with global sustainability goals, attracting international partnerships and funding opportunities. The province's strategic investment in BECCS can drive innovation, stimulate economic growth, and enhance Alberta's competitiveness in the global market. Overall, Alberta's combination of natural resources, industrial capacity, and regulatory support makes the province an ideal location for developing and scaling BECCS technologies, positioning the province as a leader in carbon removal and sustainable energy solutions.

The next frontier for biological carbon capture and storage in Alberta lies in its vast agricultural lands. A recent long-term study found that compost plays a critical role in storing carbon in semi-arid cropland soils, offering a strategy to offset CO₂ emissions. Over 19 years, the study compared soil carbon levels in conventional, cover-cropped, and compost-added plots. Results showed that conventional soils neither store nor release much carbon; however, cover cropping increases topsoil carbon but may lead to deeper carbon loss. In systems combining both compost and cover crops, soil carbon increased by 12.6% over the study period, exceeding global carbon storage targets. In addition to composting and cover cropping, biochar can be incorporated as a soil additive to enhance soil quality and long-term carbon storage. However, more research is needed to understand the long-term impacts of biochar on soil health and its effectiveness in soil management.

Improved forest management and the adoption of regenerative agricultural practices on conventionally managed fields have gained traction as climate mitigation strategies due to their potential to sequester carbon and reduce greenhouse gas emissions. However, their success relies on the implementation of a unified, province-wide measurement, reporting, and verification (MRV) system.

Photosynthesis is nature's most efficient carbon capture system, powered entirely by solar energy. Each year, it removes approximately 250 billion tonnes of carbon dioxide from the atmosphere. Nature-based carbon capture and storage solutions are essential for mitigating climate change and harnessing the power of ecosystems to reduce global carbon levels.

While Alberta stands at the forefront of the CDR movement, its success will depend on the collective efforts of government, industry, and the public, to address these challenges proactively. By fostering an environment conducive to innovation and collaboration, Alberta can not only contribute significantly to global net-zero ambitions but also position itself as a leader in the burgeoning CDR market. In this pivotal moment, Alberta has the chance to turn captured carbon

into an asset, creating a market that not only mitigates climate change but also drives economic prosperity. Now, let us seize this momentum and build a thriving CDR market – one that transforms liabilities into opportunities and accelerates our journey toward a sustainable, carbon-neutral future.

Recommendations

From this assessment, there are ten critical recommendations for assessing gaps and successfully implementing Carbon Dioxide Removal (CDR) projects within Alberta:

- 1 **Conduct Comprehensive Assessments:** Evaluate existing infrastructure, resources, and technologies to identify gaps in current CDR capabilities and potential areas for improvement.
- 2 **Enhance Regulatory Frameworks:** Develop clear and supportive regulations that facilitate the deployment of CDR technologies, ensuring compliance while promoting innovation.
- 3 **Increase Funding and Incentives:** Establish financial incentives, such as grants and tax credits, to encourage investment in CDR projects and support research and development.
- 4 **Foster Collaboration:** Create partnerships among government, industry, and academia to share knowledge, resources, and best practices for CDR implementation.
- 5 **Invest in Research and Development:** Prioritize funding for R&D in CDR technologies, focusing on Alberta-specific solutions that leverage local resources and conditions.
- 6 **Engage Stakeholders:** Involve local communities, Indigenous groups, and other stakeholders in the planning and implementation of CDR projects to ensure social acceptance and support.
- 7 **Develop a Skilled Workforce:** Invest in training programs to equip workers with the necessary skills for emerging CDR technologies and practices.
- 8 **Monitor and Evaluate Progress:** Implement robust monitoring and evaluation frameworks to assess the effectiveness of CDR projects and make data-driven adjustments as needed.
- 9 **Promote Public Awareness:** Increase awareness of CDR benefits and technologies through outreach and education campaigns to garner public support and understanding.
- 10 **Align with Climate Goals:** Ensure that CDR initiatives are integrated into Alberta's broader climate action plans and sustainability goals, reinforcing their importance in achieving net-zero emissions.

These recommendations aim to create a supportive environment for CDR projects, addressing gaps and maximizing Alberta's potential in carbon management.

Appendix

Carbon Capture Developers

Segment	Firm	Established	Description	Location
CCUS	Carbon Clean	2019	Carbon Clean provides modular and scalable carbon capture technology for industries such as cement, steel, and waste management. Their technology captures CO ₂ and repurposes it for use in various industries or stores it underground.	London, United Kingdom
CCUS	Climeworks	2009	Climeworks specializes in direct air capture and storage solutions, capturing CO ₂ from the air and storing it permanently underground or using it in various industries.	Zurich, Switzerland
CCUS	Occidental Petroleum (Oxy Low Carbon Ventures)	2018	Oxy Low Carbon Ventures is a subsidiary of Occidental Petroleum, focusing on carbon capture and storage technologies to remove and store CO ₂ in depleted oil and gas reservoirs.	Houston, Texas, USA

NBS and BECCS Developers

Segment	Firm	Established	Description	Location
Biochar	Biochar Now	2011	Biochar Now produces biochar from wood waste, providing a solution for carbon sequestration by converting organic material into a stable form of carbon. Their biochar is used in agriculture, environmental remediation, and water filtration.	Berthoud, Colorado, USA
Biochar	Carbon Gold	2007	Carbon Gold manufactures biochar products to improve soil health and sequester carbon. Their biochar is used in horticulture, agriculture, and forestry.	Bristol, United Kingdom
Biochar	Pacific Biochar	2015	Pacific Biochar focuses on the production and supply of biochar for soil enhancement, carbon sequestration, and water filtration in agricultural applications.	Santa Rosa, California, USA
Enhanced Carbon/Mineralization	CarbonCure Technologies	2012	CarbonCure injects CO ₂ into concrete during production, where it is mineralized, permanently trapping the carbon within the material. The process strengthens the concrete while sequestering carbon.	Dartmouth, Nova Scotia, Canada
Enhanced Carbon/Mineralization	44.01	2020	44.01 uses carbon mineralization to permanently remove CO ₂ by turning it into rock formations through natural reactions between CO ₂ and peridotite.	Muscat, Oman
Enhanced Carbon/Mineralization	Project Vesta	2019	Project Vesta accelerates the natural process of weathering to capture CO ₂ by enhancing the reaction between olivine sand and seawater, which stores the CO ₂ as bicarbonate in the ocean.	San Francisco, California, USA
BECCS	Drax Group	2003	Drax operates the largest BECCS project in the world. The company uses biomass for energy generation and captures the resulting carbon emissions, storing them underground.	Selby, North Yorkshire, United Kingdom
BECCS	Equinor	1972	Equinor operates various BECCS and CCUS projects globally, focusing on carbon capture from biomass energy plants and using carbon storage solutions in deep geological formations.	Stavanger, Norway
BECCS	Vattenfall	1909	Vattenfall is involved in the BECCS field, capturing carbon from its bioenergy plants and developing carbon capture and storage projects.	Stockholm, Sweden

Ocean Alkalinization	Planetary Technologies	2019	Planetary Technologies uses ocean alkalinization to enhance the ocean's natural ability to absorb CO ₂ by adding alkalinity to seawater, promoting permanent carbon removal.	Halifax, Nova Scotia, Canada
Ocean Alkalinization	Running Tide	2017	Running Tide focuses on ocean-based carbon sequestration by enhancing alkalinity and utilizing natural marine ecosystems to capture and store CO ₂ .	Portland, Maine, USA
Ocean Alkalinization	Seafields Solutions	2021	Seafields is developing large-scale ocean alkalinization projects to remove CO ₂ by enhancing natural marine processes that sequester carbon in seawater.	London, United Kingdom
Other	Charm Industrial	2018	Charm Industrial converts waste biomass into bio-oil and injects it underground for permanent carbon storage, offering an alternative carbon sequestration solution.	San Francisco, California, USA
Other	Removr	2021	Removr focuses on modular direct air capture technologies to remove CO ₂ from the atmosphere and store it underground or reuse it in industrial processes.	Oslo, Norway
Other	Lithos Carbon	2021	Lithos Carbon uses enhanced weathering of minerals in agricultural soils to capture and store atmospheric CO ₂ while improving soil health and crop yields.	Chicago, Illinois, USA

DAC Developers

DAC Companies	Technology Description	Operational Summary	Website	Sequestration Mode
Air Capture	Solid adsorbent	- Modular - Designed for integration within existing operations for on-site CO₂ production - Flexible feed stream	https://www.aircapture.com	On-site utilization
Aircela	Solid adsorbent	Modular	https://www.aircela.com	E-fuel
Airhive	Solid adsorbent	- Modular - Fluidized bed contactor	https://www.airhive.earth	E-fuel, food-grade CO ₂
Avnos	Solid adsorbent	- Modular - Hybrid water and CO₂ production - Moisture swing process - No water required	https://www.avnos.com	CO ₂ as product
Carbon Capture Inc	Solid adsorbent	- Modular - Replaceable solid adsorbent - Stackable modules	https://www.carboncapture.com	Storage
Carbon Corp	Molten medium	- Modular design - High temperature	https://carboncorp.org	Carbon nano Tube
Carbon Engineering	Liquid absorbent	- Centralized large-scale operation - Three-stage process - Include liquid and solid handling	https://carbonengineering.com	Storage, e-fuel
Climate Cure Corp.	Solid adsorbent	- Modular deployment - Micro and macro scale - Temperature swing	https://www.climatecure.ca	E-fuel, sustainable aviation fuel (SAF)
Climeworks	Solid adsorbent	- Temperature swing - Centralized large-scale operation	https://climeworks.com	Storage, CO ₂ as product
Global Thermostat	Solid adsorbent	- Modular deployment - Temperature swing	https://www.globalthermostat.com	CO ₂ as product
Greenlyte	Liquid absorbent	Hydrogen by-product via alkaline water electrolysis	https://www.greenlyte.tech	CO ₂ as product

Heirloom	Solid adsorbent	• Modular deployment • Limestone as CO₂ adsorbent	https://www.heirloomcarbon.com	Geological storage
Mission Zero	Liquid absorbent	• Modular • Electrodialysis	https://www.missionzero.tech	CO ₂ as product
NEG8 Carbon	Solid adsorbent	• Modular deployment • Temperature swing	https://neg8carbon.com	CO ₂ as product
Noya	Solid adsorbent	• Modular design • Readily available material • Temperature swing	https://www.noya.co	CO ₂ storage
Octavia Carbon	Solid adsorbent	• Low-grade heat temperature swing	https://www.octaviacarbon.com	Geological storage via mineralization
Phlair	Liquid absorbent	• Compatible with intermittent energy • Hydrolyzer	https://phlair.com	CO ₂ as product
Skyrenue	Solid adsorbent	• Amine polymer	https://skyrenue.com/en	CO ₂ as product
Skytree	Solid adsorbent	• Modular deployment • Micro and macro scale • Temperature swing	https://www.skytree.eu	CO ₂ as product
Sustaera	Solid adsorbent	• Modular deployment • Temperature swing	https://www.sustaera.com	CO ₂ as product
TerraFixing	Solid adsorbent	• Zeolite adsorbent	https://www.terrafixing.com	Geological storage
Verdorex	Electro cell	• Electrochemical process • Purely electrified • Modular deployment	https://verdorex.com	CO ₂ as product

CDR Recent Activity

Firm	Sector	Technology	Details	Location
Carbon Clean	Carbon Capture	Modular Carbon Capture Systems	Carbon Clean develops compact and modular carbon capture systems that can be retrofitted to existing industrial facilities, such as cement plants, steel mills, and refineries. Their technology utilizes a proprietary solvent-based capture process that efficiently captures CO ₂ emissions at smaller scales. The systems are designed to be flexible and easy to deploy, reducing the cost and complexity of implementing carbon capture solutions. Chevron recently invested in Carbon Clean as part of a \$75M US funding round to help scale up its technology and expand deployment in global industrial applications.	London, UK
Svante	Carbon Capture	Solid Sorbent-Based Carbon Capture	Svante has developed a proprietary solid sorbent-based technology that captures CO ₂ directly from industrial flue gas emissions, such as those from cement, steel, and natural gas plants. Their technology uses structured adsorbent beds that rapidly capture CO ₂ at low temperatures and then release it for storage or utilization. Svante's systems are designed to be cost-effective and compact, suitable for retrofitting into existing plants. They have recently raised \$75M US in funding to scale up production and deploy their technology at multiple industrial sites globally.	Burnaby, British Columbia, Canada
Carbfix	Carbon Capture and Storage (CCS)	Mineralization for Carbon Storage	Carbfix has developed a technology to capture CO ₂ and inject it into basalt rock formations, where it undergoes rapid mineralization and is permanently stored as carbonate minerals. This method leverages Iceland's abundant basalt geology to provide a cost-effective and secure form of carbon storage. The company collaborates closely with Climeworks and operates the storage component of the Orca DAC plant.	Reykjavik, Iceland

			Carbfix has received funding from the European Union and other investors to expand its operations and explore new storage sites across Europe.	
Carbon Engineering	Carbon Capture	Direct Air Capture (DAC) with Air to Fuels™	Carbon Engineering's Direct Air Capture (DAC) technology captures CO ₂ directly from the atmosphere using a liquid solvent in a contactor design. The captured CO ₂ can then be utilized in their Air to Fuels™ process, which produces synthetic, low-carbon fuels by combining the captured CO ₂ with hydrogen generated from water electrolysis using renewable energy. This process effectively recycles atmospheric CO ₂ , creating a closed-loop system. The company has received substantial funding from investors like Bill Gates and Occidental Petroleum to build large-scale DAC facilities, including a major plant in the Permian Basin, USA.	Squamish, British Columbia, Canada
Global Thermostat	Carbon Capture	Direct Air Capture (DAC)	Global Thermostat uses a patented Direct Air Capture (DAC) technology that employs amine-based sorbents on porous, high-surface-area filters to capture CO ₂ from ambient air. The captured CO ₂ can be released for utilization or permanent storage through low-temperature steam or hot air, making the process energy-efficient. They are focusing on developing partnerships to scale their technology globally and have received funding from multiple investors, including ExxonMobil , to further commercialize their DAC systems.	New York, USA
CarbonCapture Inc.	Carbon Capture	Modular Direct Air Capture (DAC) Units	CarbonCapture Inc. is developing modular Direct Air Capture (DAC) units designed for scalability and mass deployment. The company uses proprietary metal-organic framework (MOF) materials that selectively capture CO ₂ from ambient air. The modular nature of their units allows for flexible deployment across various locations, from remote areas to industrial sites. Recently, they raised over \$35M US in venture capital funding to advance the development of their technology and deploy their first commercial units in the U.S.	Los Angeles, California, USA
12 (Twelve, formerly Opus 12)	Carbon Capture and Utilization (CCU)	Electrochemical CO ₂ Conversion	Twelve is developing an electrochemical process to convert captured CO ₂ into chemicals, materials, and fuels, effectively replacing the fossil carbon in products. The company's proprietary technology utilizes renewable energy to power the conversion, offering a sustainable alternative to traditional chemical production methods. Twelve raised \$57,000,000 US in Series A funding to expand its technology's commercial applications and accelerate its market deployment.	Berkeley, California, USA
Remora	Carbon Capture	Mobile Carbon Capture for Vehicles	Remora is developing a mobile carbon capture device that attaches to semi-trucks to capture CO ₂ emissions from their exhaust. This innovative solution targets the transportation sector, which is traditionally challenging to decarbonize. The company received part of a \$5,500,000 US Seed Round to advance its technology and prepare for commercial deployment.	Ann Arbor, Michigan, USA

Canadian Government and Global Incentive Programs

Canadian Federal Incentives

Canada centers its efforts on reducing emissions in the oil and gas sector through tax incentives, direct funding, and credit systems to foster innovation and large-scale project deployment.

A February 2024 report published by Wood Mackenzie (a global provider of data and analytics for the energy transition) found that CCUS incentives in Canada are “in fact already much higher than in the U.S. [...] Few post-combustion projects are moving forward in the U.S. because the 12-year IRA-enhanced 45Q is simply insufficient to incentivize long-term capture.” According to Wood Mackenzie, [“The real challenge for Canadian CCUS \[...\] is not insufficient incentives – they are some of the most attractive in the world – but the uncertainty of their existence throughout project life.”](#)

Investment Tax Credit (ITC) for CCUS (Bill C-59, 2023): This program provides refundable tax credits to companies investing in CCUS projects, covering eligible expenses like equipment for carbon capture, transportation, and storage. The goal is to reduce the financial burden and encourage the development and deployment of CCUS technology in Canada.

- **Total Funding Available:** Up to \$2.6B CAD over five years.
- **Example Project:** *Shell Quest Carbon Capture and Storage Project* (Funded in 2015, \$865M CAD). The Quest project captures and stores up to 1.2 million tonnes of CO₂ per year from the Shell-operated Scotford Upgrader in Alberta. It aims to demonstrate the commercial viability of CCUS technology in the oil sands sector.

Emissions Reduction Fund: A federal fund that provides grants, loans, and repayable contributions to support projects that reduce greenhouse gas emissions, including those that deploy CCUS technology in the oil and gas sector.

- **Total Funding Available:** \$750M CAD.
- **Example Project:** *Enhance Energy’s Alberta Carbon Trunk Line (ACTL)* (Funded in 2020, \$45M CAD). This project transports captured CO₂ from industrial sources to aging oil fields in central Alberta for enhanced oil recovery and long-term storage, with a goal of sequestering 14.6 million tonnes of CO₂ annually.

Strategic Innovation Fund – Net-Zero Accelerator: A federal initiative to provide funding for large-scale projects that reduce greenhouse gas emissions and drive the transition to a net-zero economy, including projects involving CCUS technologies.

- **Total Funding Available:** \$8B CAD over seven years.
- **Example Project:** *Suncor’s Base Plant CCUS Project* (Funded in 2022, \$300M CAD). This project involves retrofitting Suncor’s Base Plant in Alberta with CCUS technology to capture up to 4 million tonnes of CO₂ annually by 2026.

Clean Fuel Regulations (2022): Regulations that introduce a market-based credit system where CCUS projects that reduce emissions can generate credits to be sold or traded, incentivizing investments in carbon capture and utilization.

- **Total Funding Available:** No direct funding; incentives are through a market-based credit system.

- **Example Project:** *Svante and Carbon Clean Solutions Partnership* (Recognized in 2023, value through market credits). This partnership is developing a modular carbon capture system to be installed at several industrial sites across Canada, aiming to capture 30 million tonnes of CO₂ by 2035.

Canadian Provincial Incentives

Alberta Carbon Capture Incentive Program (ACCIP): Grants to help accelerate the development of carbon capture, utilization and storage in Alberta.

- In total, the ACCIP program is expected to provide between \$3.2B to \$5.3B CAD of support between 2024 and 2035. [Over the next decade, the government estimates that these incentives will support \\$35B CAD in new investment and create up to 21,000 jobs.](#)

Alberta Carbon Trunk Line (ACTL): A major CCUS infrastructure project supported by the Alberta government to transport CO₂ from industrial facilities to oil fields for enhanced oil recovery and permanent storage.

- **Total Funding Available:** \$1.24B CAD (including federal and provincial support).
- **Example Project:** *Wolf Midstream ACTL System* (Funded in 2019, \$300M CAD). The project captures and stores CO₂ from industrial facilities for use in enhanced oil recovery and storage, with a target of 14.6 million tonnes of CO₂ per year.

Saskatchewan's Oil and Gas Processing Investment Incentive: A program providing royalty credits to companies investing in CCUS technologies and infrastructure to manage carbon emissions in the province's oil and gas sector.

- **Total Funding Available:** Estimated \$60M CAD in royalty credits.
- **Example Project:** *Boundary Dam Carbon Capture Project* (Funded in 2014, \$1.5B CAD). This project retrofitted a coal-fired power plant with CCUS technology to capture 1 million tonnes of CO₂ annually, making it the first large-scale CCUS project on a power plant in the world.

Quebec's Green Fund: A provincial fund that supports projects and initiatives aimed at reducing greenhouse gas emissions, including CCUS and other clean technologies, as part of Quebec's broader environmental strategy.

- **Total Funding Available:** \$6B CAD over 10 years.
- **Example Project:** *CO₂ Solutions' Valorisation Carbone Québec (VCQ) Project* (Funded in 2017, \$15M CAD). This project aims to develop and demonstrate technologies for capturing and using CO₂ from industrial emissions in various products, such as biofuels and construction materials.

American Federal Incentives

The United States takes a broader, multi-sector approach, combining diverse incentives like tax credits, substantial federal funding, and state-level initiatives to support innovation and infrastructure development.

45Q Carbon Capture Tax Credit: A federal tax credit available to companies that capture and sequester CO₂ from industrial facilities or directly from the atmosphere, providing financial incentives based on the amount of CO₂ captured and stored or utilized.

- **Total Funding Available:** Unlimited; structured as a tax credit rather than a set fund.
- **Example Project:** *Petra Nova Carbon Capture Project* (Tax credit recognized in 2017, approximately \$100M USD in credits). This project was designed to capture 1.4 million tonnes of CO₂ annually from a coal-fired power plant in Texas, transporting the captured CO₂ for enhanced oil recovery.

Department of Energy (DOE) CarbonSAFE Initiative: A DOE program providing funding to develop geological storage sites for large-scale carbon capture, with a focus on projects that demonstrate safe, long-term storage of CO₂.

- **Total Funding Available:** \$190M USD.
- **Example Project:** *Illinois Basin Decatur Project* (Funded in 2018, \$67M USD). The project aims to store 1 million tonnes of CO₂ per year in a deep saline reservoir, demonstrating large-scale carbon storage potential.

Infrastructure Investment and Jobs Act (2021): A major federal infrastructure bill that includes substantial funding for CCUS projects and related infrastructure to support emissions reductions and clean energy transition.

- **Total Funding Available:** \$12B USD for CCUS and related infrastructure.
- **Example Project:** *Project Tundra* (Funded in 2022, \$100M USD). This project aims to retrofit the Milton R. Young coal-fired power plant in North Dakota to capture 4 million tonnes of CO₂ annually, storing it in nearby geological formations.

Advanced Research Projects Agency-Energy (ARPA-E): A U.S. Department of Energy agency that funds high-risk, high-reward research into innovative energy technologies, including CCUS and CDR technologies.

- **Total Funding Available:** Variable, approximately \$70M USD allocated for specific CCUS-related projects.
- **Example Project:** *Carbon Capture Inc.* (Funded in 2021, \$5M USD). This company is developing modular direct air capture units that can be deployed in various locations to remove CO₂ directly from the atmosphere.

Global Incentives

Globally, programs in regions such as the EU, UK, Norway, and Australia are driven by international climate commitments and focus on large-scale demonstration projects, innovation, and cross-border collaboration, using direct funding, grants, and market-based mechanisms to align with global climate strategies.

European Union, Innovation Fund: A funding program aimed at supporting the development and scaling of innovative low-carbon technologies, including CCUS, to help the EU achieve its climate targets.

- **Total Funding Available:** €10B EUR (2020-2030).
- **Example Project:** *Northern Lights Project* (Funded in 2020, €1B EUR). This joint venture by Equinor, Shell, and Total aims to develop an open-source CO₂ transport and storage network in the North Sea, initially storing up to 1.5 million tonnes of CO₂ per year from industrial sources.

Horizon Europe – Green Deal Call: A research and innovation program that provides funding for projects aimed at addressing climate change, including CCUS, as part of the EU's broader European Green Deal strategy.

- **Total Funding Available:** €1B EUR.
- **Example Project:** *Porthos CCUS Project* (Funded in 2021, €102M EUR). This project will capture CO₂ from industries in the Port of Rotterdam and store it in depleted North Sea gas fields, aiming to reduce emissions by 2.5 million tonnes per year.

UK CCUS Infrastructure Fund: A government fund to support the development of CCUS clusters and infrastructure, aiming to capture and store millions of tonnes of CO₂ annually by 2030.

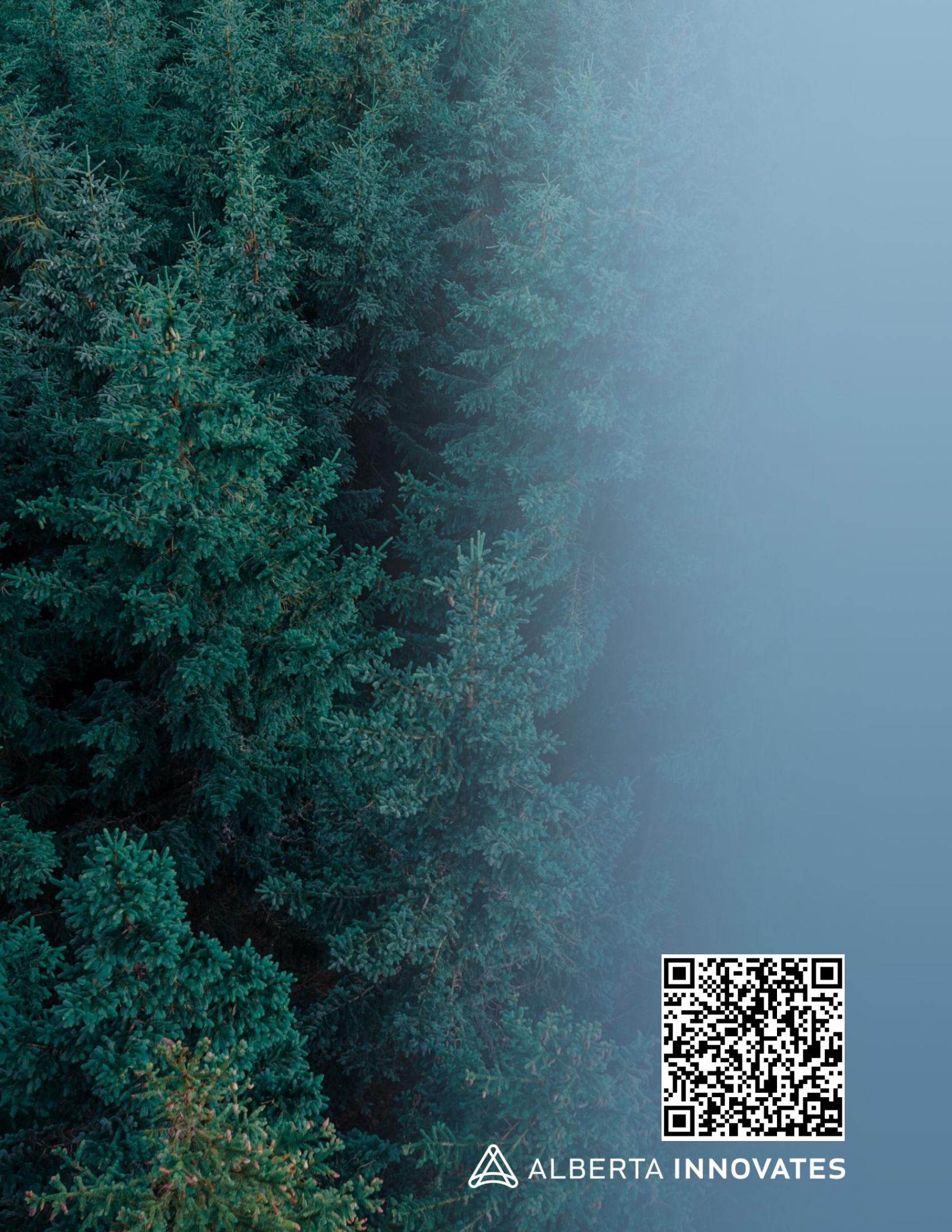
- **Total Funding Available:** £1B GBP.
- **Example Project:** *Acorn CCUS Project* (Funded in 2021, £100M GBP). Located in Scotland, this project aims to capture and store CO₂ from various industrial facilities, including hydrogen production, targeting 5-10 million tonnes of CO₂ per year by 2030.

Australia, Carbon Capture Use and Storage Development Fund: A fund established by the Australian government to support the development of CCUS technologies and projects to reduce emissions from heavy industries.

- **Total Funding Available:** \$50M AUD.
- **Example Project:** *Moomba CCUS Project* (Funded in 2021, \$15M AUD). This project, led by Santos Ltd., aims to capture and store up to 1.7 million tonnes of CO₂ per year from the Moomba gas processing plant in South Australia.

Norwegian CCUS Fund (CLIMIT Programme): A government-funded program that supports the development and demonstration of CCUS technologies in Norway to help meet national and international climate targets.

- **Total Funding Available:** NOK 3.5 billion (approximately \$350M USD).
- **Example Project:** *Sleipner CO₂ Storage Project* (Ongoing since 1996, various funding rounds). This project captures and stores approximately 1 million tonnes of CO₂ annually from offshore natural gas production, demonstrating the feasibility of long-term CO₂ storage in saline aquifers.



ALBERTA INNOVATES