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Engineered Carbon Dioxide Removal in a Net-Zero Canada

Opportunities and challenges for non-biological CDR deployment

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Carson Fong and Scott MacDougall

April 2023

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Executive summary

Canada is one of many nations committed to keeping the global temperature rise below 1.5°C relative to pre-industrial levels. To contribute to this, Canada's goal is to reduce emissions by 40-45% from 2005 levels by 2030, and then achieve net-zero in 2050. A state of net-zero emissions means the amount of greenhouse gases going into the atmosphere must be balanced by removal out of the atmosphere. Net-zero can be achieved with early, deep and sustained reductions of direct emissions, and then tackling the remaining hard-to-reduce emissions with additional tools like carbon dioxide removal (CDR). No less an authority than the United Nations Intergovernmental Panel on Climate Change (IPCC) has noted the need for CDR, saying: "The deployment of CDR to counterbalance hard-to-abate residual emissions is unavoidable if net-zero CO_2 or GHG emissions are to be achieved."

CDR processes extract CO_2 from the atmosphere and durably store it so that it does not re-enter the atmosphere. It can be an indirect solution for hard-to-reduce emissions by removing the equivalent amount of CO_2 emitted. CDR can also counteract emissions if Canada overshoots its carbon budget and can even help achieve negative net emissions after net-zero is reached. In this way, it can extract some of the legacy carbon that humanity has released into the atmosphere over the last few centuries.

Some studies estimate CDR could reduce the cost of tackling these remaining emissions by 40% compared to alternatives. The cost of not doing enough to prevent climate change, meanwhile, could cause economic damage in Canada totaling $391 billion to $865 billion annually by 2100, not to mention the human toll of climate-related disasters.

Many biological CDR approaches (afforestation, reforestation, soil sequestration) are well known, heavily discussed and available for deployment now. They make up the majority of currently implemented CDR and are expected to continue to play a significant role in carbon removal in the following decades.

By contrast, engineered non-biological CDR solutions, such as direct air capture (DAC) with geologic storage, carbon dioxide mineralization, and many types of carbon use, are technologically immature and more expensive, but they have the potential to offer verifiable and durable CDR in the medium-to-long term. It takes time to develop new technologies into commercial options. Investing in development and testing now will ensure technological readiness and economic feasibility when CDR is needed at full-scale around mid-century, when cheaper emissions reduction opportunities have been fully implemented. This means a ‘yes and’ policy approach, where the potential of CDR should not be a rationale for delaying short-term emissions reductions, and vice versa.

This report provides an overview of some of the key technology and policy considerations that enable or constrain the development of non-biological CDR in Canada. While there is potential across the country that requires further investigation, several areas hold promise for DAC with geologic storage development particularly, due to underground storage potential with nearby access to renewable energy: B.C., Alberta, Saskatchewan, Manitoba, the Northwest Territories and the Yukon.

To promote the development of non-biological CDR in Canada, further policy development must take place in the following areas:

- Regulations relevant to CDR are inconsistent and ambiguous across Canada. Pore space ownership — a key issue for CO_2 storage — is unclear in some jurisdictions, and there is no clear path to license new offshore projects, particularly involving sub-oceanic storage. Addressing these regulatory gaps can help remove a barrier to development while promoting safe deployment.
- Early, rapid deployment and testing can quickly generate learning that improves operational efficiency and technological advancement. This research and development, as well as first-, second-, and third-of-a-kind pilot and demonstration projects, will require capital support. These projects should have knowledge-sharing requirements to better enable a learning curve to significantly reduce the high capital and operating costs and environmental risks associated with many non-biological CDR solutions.
- Non-biological CDR methods are currently excluded from federal and provincial carbon pricing and offset programs, resulting in a lack of predictable operational revenue making project financing difficult. Including non-biological CDR as an eligible pathway in decarbonization policies can create a business case for deployment and remove a significant barrier to CDR growth in Canada.

Indigenous communities need to be involved as decision-makers where there are potential impacts to their Aboriginal and Treaty rights, cultural and spiritual practices, and traditional lands. These decisions range from broader CDR development strategies to project-specific siting.

Taking these steps could help Canada become a leader in non-biological CDR, generating knowledge and technologies the world needs to prevent catastrophic climate change.

1. Canada's path to net-zero

1.1 Emissions reductions alone will not get Canada to net-zero

In 2021, Canada updated its nationally determined contribution under the Paris Agreement to reduce emissions by 40-45% below 2005 levels by 2030 and achieve net-zero emissions by 2050, to contribute to keeping global temperature rise below 1.5°C relative to pre-industrial levels.[1]

There is a clear path to achieving the 2030 target through conventional direct emissions reduction strategies.[2] However, reaching the 2050 net-zero target will prove more difficult, as it will require addressing all the remaining emissions.

Some of these emissions have few viable paths to reduction with current and expected technology and economic conditions.[3] For example, aviation would be considered a difficult-to-decarbonize sector, as there are no commercial-scale solutions ready to entirely eliminate carbon emissions associated with jet fuel use.

By mid-century, it is expected that all the remaining emissions will fall within this difficult-to-decarbonize category, estimated at 10-15% of today's emissions, if reduction efforts proceed according to plan.[4] With limited ability to avoid these emissions, another option is to remove them from the atmosphere after they are emitted.

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[1] Government of Canada, *Canada's 2021 Nationally Determined Contribution Under the Paris Agreement*, 1. https://unfccc.int/sites/default/files/NDC/2022-06/Canada%27s%20Enhanced%20NDC%20Submission1_FINAL%20EN.pdf

[2] Government of Canada, "2030 Emissions Reduction Plan: Clean Air, Strong Economy." https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/climate-plan-overview/emissions-reduction-2030.html

[3] Deloitte, "Getting from hard-to-abate to a low-carbon future." https://www.deloitte.com/global/en/our-thinking/insights/topics/business-strategy-growth/industrial-decarbonization-hard-to-abate-sectors.html

[4] Michael Bernstein, "Canada can't achieve climate goals without supercharging carbon removal," *Policy Options*, August 31, 2020. https://policyoptions.irpp.org/magazines/august-2020/canada-cant-achieve-climate-goals-without-supercharging-carbon-removal/

1.2 A necessary part of the solution

Carbon dioxide removal (CDR) is the process of extracting CO_2 from the atmosphere and storing it in a way that prevents it from being re-emitted, thereby reducing the concentration of atmospheric CO_2.[5] This can address the leftover, difficult-to-avoid emissions indirectly, by removing an equivalent amount of CO_2 from the atmosphere.

In their Climate Change 2022 report, the Intergovernmental Panel on Climate Change (IPCC) states, "The deployment of carbon dioxide removal (CDR) to counterbalance hard-to-abate residual emissions is unavoidable if net-zero CO_2 or GHG emissions are to be achieved."[6]

Canada's latest long-term climate change strategy recognizes engineered carbon dioxide removal technologies as a key enabler to achieving net-zero in 2050.[7]

CO_2 remains in the atmosphere for hundreds of years after it is emitted, causing a long-lasting, continued warming effect.[8] Once net-zero is reached, CDR can help address these legacy CO_2 emissions and achieve negative net emissions.

1.3 What is carbon dioxide removal?

Vast amounts of CO_2 are removed from the atmosphere naturally all the time. Forests and oceans are examples of naturally-occurring carbon sinks, which absorb more CO_2 from the atmosphere than they release. Oceans absorb 25% of all CO_2 emissions annually[9] and plants and soils absorb an estimated 30%.[10] All this is part of the natural carbon cycle. However, human-caused activities have overwhelmed these natural carbon sinks by emitting more CO_2 than they can absorb. As a result, these natural

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[5] World Resources Institute, "Carbon Removal." https://www.wri.org/initiatives/carbon-removal

[6] Intergovernmental Panel on Climate Change, *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (2022), "Summary for Policymakers," 36. https://www.ipcc.ch/report/ar6/wg3/

[7] Environment and Climate Change Canada, *Exploring Approaches for Canada's Transition to Net-Zero Emissions* (2022), 41. https://unfccc.int/process/the-paris-agreement/long-term-strategies

[8] Alan Buis, "The Atmosphere: Getting a Handle on Carbon Dioxide," *NASA Global Climate Change*, October 9, 2019. https://climate.nasa.gov/news/2915/the-atmosphere-getting-a-handle-on-carbon-dioxide/

[9] UN Climate Action, "The ocean – the world's greatest ally against climate change." https://www.un.org/en/climatechange/science/climate-issues/ocean

[10] Josie Garthwaite, "Soils or plants will absorb more CO_2 as carbon levels rise – but not both, Stanford study finds," *Stanford News Service*, March 24, 2021. https://news.stanford.edu/press/view/38728

carbon sinks are no longer enough to prevent the atmospheric concentration of CO_2 from increasing.[11]

To mitigate this problem, reducing human emissions is the priority. However, a necessary complement will be to permanently remove CO_2 from the atmosphere. For a process to be considered CDR, it needs to:

- remove CO_2 from the atmosphere, either directly or indirectly,
- store the CO_2 durably so that it does not re-enter the atmosphere,
- remove more CO_2 than it emits, with the entire process life cycle considered in the calculation, and
- be additional to any naturally-occurring processes.[12]

The last point is the key distinguishing characteristic between naturally-occurring carbon sinks and biological CDR solutions like afforestation. Afforestation is the planting of new forests on land that did not previously have trees. This means that the CO_2 removed by this new forest is additional to what would have happened naturally.

These biological methods are already available at scale, are cost competitive and are expected to continue to be the majority of carbon dioxide removal efforts until at least the mid-century mark.

Considering the maturity of many biological CDR options, this report will instead focus on engineered non-biological solutions that have the potential to play a larger role in the future but need additional attention to get there.

One process that is similar and related to CDR is carbon capture, utilization and storage (CCUS). Both are methods of capturing CO_2 which then either use it as an input to another process or store it in a way where it cannot enter the atmosphere.

As shown in Figure 1, the key difference is that CCUS reduces CO_2 emissions from industrial processes by capturing it from a point source, like the flue of an industrial facility, before it enters the atmosphere. With CDR, the CO_2 is removed from the atmosphere after it has been emitted from a source. CDR is referred to as a negative emissions technology because it removes more CO_2 from the atmosphere than it emits.

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[11] Carol Konyn, "What Are Carbon Sinks?" *Earth.org*, August 24, 2021. https://earth.org/carbon-sinks/

[12] Stephen M Smith, Oliver Geden, Gregory F Nemet, et al. *State of Carbon Dioxide Removal* (University of Oxford: Smith School of Enterprise and the Environment, 2023), 11. https://www.stateofcdr.org/resources

Thus, theoretically it could be used in the future to go beyond removing current emissions and begin removing historic emissions as well.[13]

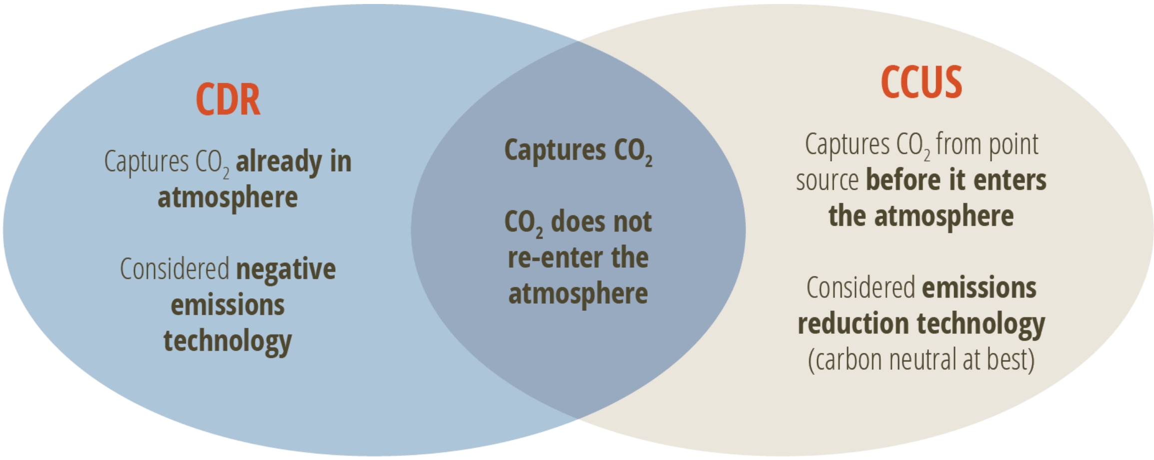

Figure 1. Diagram comparing CDR and CCUS

CCUS is considered an emissions reduction technology because it is always tied to an emitting source.

1.4 Remove what cannot be reduced

Most of the progress towards net-zero can and should be made by reducing CO_2 emissions. The International Energy Agency (IEA) Net Zero by 2050 scenario describes a cost-effective path to net-zero by 2050 that ensures stable, affordable and accessible energy supplies. In it, direct emissions reductions account for eliminating 32 of the 34 billion tonnes of CO_2 in 2020 annual emissions. Specifically, fossil fuel use decreases from 80% of total energy supply in 2020 to just 20% in 2050. Much of that is replaced by renewable energy sources, which grow to account for two-thirds of total energy supply.[14]

Strategically, the cheapest and easiest solutions should be implemented first to maximize climate change mitigation impact, leaving the emissions that are most difficult and expensive to eliminate for later. Towards mid-century in the IPCC scenario, CDR becomes important as a solution to counter these remaining emissions, at the scale of billions of tonnes of CO_2 removed each year. Figure 2 depicts this timeline. To

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[13] American University, “Explainer: Carbon Removal,” March 10, 2020. https://www.american.edu/sis/centers/carbon-removal/explaining-carbon-removal.cfm

[14] International Energy Agency, *Net Zero by 2050: A Roadmap for the Global Energy Sector* (2021). https://www.iea.org/reports/net-zero-by-2050

feasibly achieve this capacity, the groundwork needs to happen now.

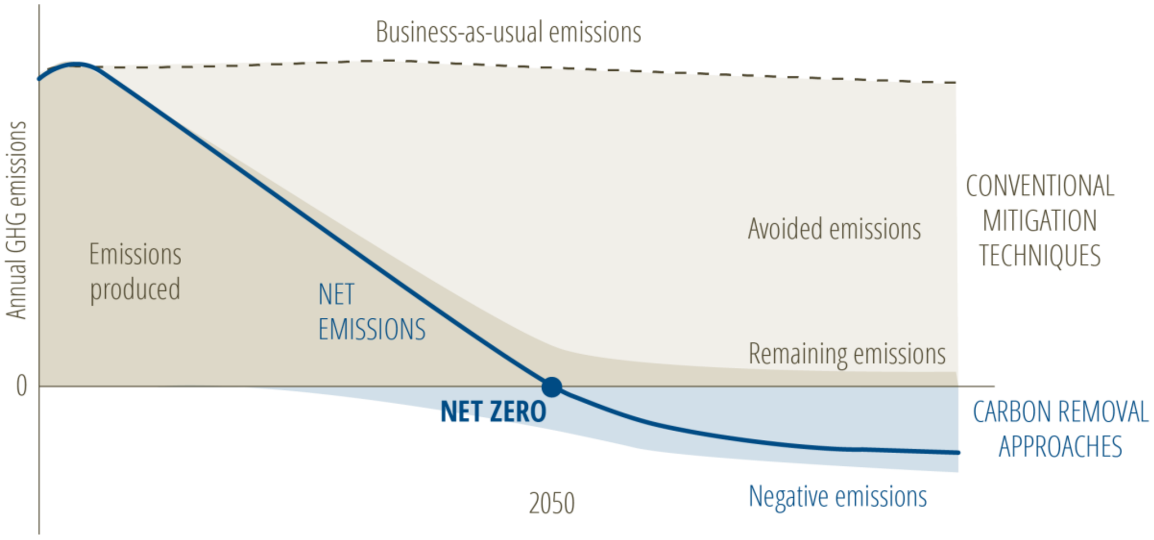

Figure 2. Stylized timeline of net carbon dioxide emissions

Source: Adapted from IPCC[15]

CDR is only a complement to emissions reductions and cannot be considered a solution on its own, for several reasons.

First, CDR is much more expensive than many reduction methods right now, with levelized costs for non-biological CDR currently estimated around $300-800 per tonne of CO_2 removed (/tCO_2).[16] By comparison, the estimated cost to reduce Canada's annual emissions by 75% is $60 billion per year, working out to a cost of $109/t$CO_2$.[17]

Second, the magnitude of CDR required to achieve net-zero even with sharp emissions reductions is enormous. Scenarios aligned with limiting warming to 1.5°C estimate CDR deployment in the range of 5 to 15 billion tonnes (gigatonne; Gt) CO_2 per year globally by 2050,[18] which is already expected to be a difficult scale to achieve.[19] In the IEA Net Zero by 2050 scenario, an estimated 980 million tonnes (megatonne; Mt) CO_2 per year is

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[15] IPCC, *Climate Change 2022: Mitigation of Climate Change*, 1263.

[16] Katie Lebling, Haley Leslie-Bole, Zach Byrum, Liz Bridgwater, "6 Things to Know About Direct Air Capture," *World Resources Institute*, May 2, 2022. https://www.wri.org/insights/direct-air-capture-resource-considerations-and-costs-carbon-removal

[17] RBC, *The $2 Trillion Transition: Canada's Road to Net Zero* (2021). https://thoughtleadership.rbc.com/the-2-trillion-transition/

[18] Andrew Bergman, Anatoly Rinberg, "The scale of hard-to-avoid emissions and the CDR needed to offset them," in *CDR Primer* (2021). https://cdrprimer.org/read/chapter-1#sec-1-4

[19] IPCC, *Climate Change 2022: Mitigation of Climate Change*, 1264.

removed from the atmosphere via direct air capture by 2050.[20] Currently, it removes a mere 0.01 $MtCO_2$/year.[21] It is unrealistic to consider CDR as a viable solution to address all of the 37 Gt emitted each year,[22] hence why reductions are required first.

Third, the longer a greenhouse gas is in the atmosphere, the more impact it has on climate change. Any delay to emissions reductions will have a compounding effect on the climate and require even more investment to counteract in the future.

Early investment in CDR technologies now is important so they are ready to rapidly scale into widespread use in the mid-century, when only hard-to-abate emissions remain. The price of solar electricity has decreased by 85% from 2007 to 2020 due to technology performance and manufacturing cost reductions as installed capacity increased.[23] This underscores the importance of continuous "learning by doing" CDR. Executing pilot and commercial scale demonstrations can advance the learning curve for CDR, yielding major technology performance improvements and cost reductions. Photovoltaic solar energy is a shining example of learning curves in practice.

And despite CDR's high costs, some studies estimate CDR could reduce the cost of tackling difficult-to-avoid emissions by 40% compared to alternatives.[24] The cost of some of these alternatives for the most difficult-to-avoid CO_2 emissions far exceed \$1,000/tCO_2.[25] Also, inaction on climate is expensive. The estimated economic damage of climate change on Canada is estimated to potentially reach \$391 billion to \$865 billion annually by 2100 if not mitigated, not to mention the human toll of climate-related disasters.[26]

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[20] Sara Budinis et al., *Direct Air Capture: a key technology for net zero* (International Energy Agency, 2022), 16. https://www.iea.org/reports/direct-air-capture-2022

[21] Budinis et al., *Direct Air Capture: a key technology for net zero*, 19.

[22] Hannah Ritchie, Max Roser and Pablo Rosado, "CO_2 and Greenhouse Gas Emissions," *Our World in Data*, 2020. https://ourworldindata.org/co2-emissions

[23] Mark Bolinger, Ryan Wiser, Eric O'Shaughnessy, "Levelized cost-based learning analysis of utility-scale wind and solar in the United States," *iScience* 25, 6 (2022), 104378. https://doi.org/10.1016/j.isci.2022.104378

[24] International Energy Agency, *Exploring Clean Energy Pathways* (2019), 3. https://iea.blob.core.windows.net/assets/fc698d6d-1f9d-4c46-9293-e67a600d01c6/Exploring_Clean_Energy_Pathways.pdf

[25] Michele Della Vigna, Zoe Clarke, Bepul Shahab, Derek R. Bingham, *Carbonomics* (Goldman Sachs, 2022), 3. https://www.goldmansachs.com/insights/pages/gs-research/carbonomics-affordability/report.pdf

[26] Canadian Climate Institute, *Damage Control: Reducing the costs of climate impacts* (2022), 6. https://climateinstitute.ca/wp-content/uploads/2022/09/Damage-Control_-EN_0927.pdf

2. Overview of non-biological CDR technologies

There are a wide range of CDR methods, all at varying levels of technological readiness. While this report focuses on non-biological, engineered CDR solutions, it is important to note that the majority of CDR deployed currently are biological, primarily afforestation and reforestation.[27] These biological methods are expected to continue to contribute a significant portion of CDR efforts.[28]

Biological engineered approaches are also predicted to play a large role in carbon removal. Biomass carbon removal and storage is a hybrid approach that involves removing carbon via photosynthesis, and then converting the organic matter into CO_2 that can be stored. Another method involves biochar, a carbon-rich material created from biomass that can be mixed into soil to store CO_2. These CDR types leverage biological carbon removal mechanisms and combine them with technology.

Technology readiness levels (TRL) measure how mature a technology is on a scale from level 1 to 9, with level 9 indicating readiness for full-scale commercial deployment in real life conditions (see text box below). Non-biological CDR methods are much newer in comparison to biological ones. No full-scale, non-biological CDR system has reached level 9 on the technology readiness level scale.

Technology readiness level (TRL)

Technology readiness levels (TRLs) provide a system for measuring the maturity of a technology by rating them from 1 to 9, with 9 being the most mature. Developed by NASA in the 1970s, TRLs help provide consistent language for describing new technologies.

TRL 1-2 represent the fundamental research stage, when basic principles are identified and published. TRL 3-5 indicate the research and development phase when proof of concepts are developed, and processes are validated in ideal environments. TRL 6-8 include pilot tests and successful full-scale prototypes in operational environments. TRL

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[27] Smith et al., *State of Carbon Dioxide Removal*, 65.

[28] IPCC, *Climate Change 2022: Mitigation of Climate Change*, 1265.

9, the final level on the scale, indicates successful full-scale deployment through a full range of conditions.[29]

Being at lower TRLs is part of what makes CDR more expensive, and unready for commercial deployment today. There is uncertainty in what costs and scales these technologies will be able to achieve. Despite this, these technologies have the potential to provide high-quality carbon removal, possibly more durably than biological solutions can. This report will focus on a subset of non-biological technologies, summarized in Table 1, that could play a growing role in Canada in the decades to come. The challenges listed represent areas needing further work to understand and mitigate potential issues, rather than fundamental negatives or barriers to those technologies.

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[29] Government of Canada, "Technology Readiness Level (TRL) Assessment Tool," https://ised-isde.canada.ca/site/clean-growth-hub/en/technology-readiness-level-trl-assessment-tool

Table 1: Summary of economic and environmental considerations for engineered, non-biological CDR technologies in Canada

Technology	Type	Estimated costs at scale ($\$/tCO_2$)	Technology Readiness Level (TRL)	Potential environmental positives (likelihood)[30]	Potential environmental challenges (likelihood)[30]	Difficulty of measuring CO_2 removed/ stored
Direct air capture	Removal	130-390 [31]	6 [32]	Lower land-usage (high) Can be on non-arable land (high) Solid DAC produces water as byproduct (high)	High energy use (high)	Low
Ocean alkalinity enhancement	Removal and Storage	52-338 [33]	1-2 [34]	Slow-down of ocean acidification (high)	Increased mining activity (high) Eutrophication (unknown) Ecosystem damage (unknown)	High

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[30] In comparison to afforestation unless otherwise stated.

[31] David W. Keith, Geoffrey Holmes, David St. Angelo, Kenton Heidel, “A Process for Capturing CO_2 from the Atmosphere,” *Joule* 2, 8 (2018), 1573. https://doi.org/10.1016/j.joule.2018.05.006

[32] IPCC, *Climate Change 2022: Mitigation of Climate Change*, 1275.

[33] IPCC, *Climate Change 2022: Mitigation of Climate Change*, 1275.

[34] IPCC, *Climate Change 2022: Mitigation of Climate Change*, 1275.

Surficial mineralization	Can be removal and storage	65-260 [35]	1-5 [36, 37]	Improved plant growth on farmland (high)	Increased mining activity (high) Toxic metals contamination (unknown)	High
In situ mineralization	Storage	26-39 [38] Seafloor basalt: 260-520 [39]	2-6 [40]	Increased permanence (high) Lower risk of leakage than geologic storage (high)	Higher water usage (medium) Risks related to well bore connectivity (low) Drinking water contamination due to leakage (low) Induced geological or seismic activity (unknown)	Medium

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[35] IPCC, *Climate Change 2022: Mitigation of Climate Change*, 1275.

[36] Cara N. Maesano, James S. Campbell, Spyros Foteinis et al. "Geochemical Negative Emissions Technologies: Part II. Roadmap," *Frontiers in Climate* 4 (2022). https://doi.org/10.3389/fclim.2022.945332

[37] Mission Innovation, *Carbon Dioxide Removal Technology Roadmap: Innovation Gaps and Landscape Analysis* (2022), 2. https://explore.mission-innovation.net/wp-content/uploads/2022/09/Carbon-Dioxide-Removal-Mission-Roadmap-Sept-22.pdf

[38] Peter Kelemen, Sally M. Benson, Hélène Pilorgé, Peter Psarras, Jennifer Wilcox, "An Overview of the Status and Challenges of CO_2 Storage in Minerals and Geological Formations," *Frontiers in Climate* 1 (2019). https://doi.org/10.3389/fclim.2019.00009

[39] Kelemen et al., "An Overview of the Status and Challenges of CO_2 Storage in Minerals and Geological Formations."

[40] Maesano et al., "Geochemical Negative Emissions Technologies: Part II. Roadmap."

Ex situ mineralization	Storage	68-300[41]	Wide range, some as high as 9[42]		Increased mining activity (high)	Low
Geologic storage	Storage	9-23[43]	9[44]	Increased permanence (high)	Risks related to well bore connectivity (low) Drinking water contamination due to leakage (low) Induced geological or seismic activity (unknown)	Low
Carbon use	Storage	Net revenue generator	Wide range, some as high as 9[45,46]	Varies	Varies	Low

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[41] Fei Wang and David Dreisinger, “Status of CO_2 mineralization and its utilization prospects," *Minerals and Mineral Materials* 1, no. 1 (2022), 4. http://dx.doi.org/10.20517/mmm.2022.02

[42] Colin D. Hills, Nimisha Tripathi, Paula J. Carey, “Mineralization Technology for Carbon Capture, Utilization, and Storage,” *Frontiers in Energy Research* 8 (2020). https://doi.org/10.3389/fenrg.2020.00142

[43] Susan Hovorka and Peter Kelemen, “Geological Sequestration: Current costs and estimated costs” in *CDR Primer* (2021). https://cdrprimer.org/read/chapter-2#sec-2-9-5

[44] David Kearns, Harry Liu and Chris Consoli, *Technology Readiness and Costs of CCS* (Global CCS Institute, 2021), 23. https://www.globalccsinstitute.com/wp-content/uploads/2021/03/Technology-Readiness-and-Costs-for-CCS-2021-1.pdf

[45] John Zhou, David Van Den Assem, Rick Chalaturnyk, et al. *Carbon Capture, Utilization, and Storage (CCUS): Technology Innovation to Accelerate Broad Deployment in Alberta* (Alberta Innovates, 2022), 14. https://albertainnovates.ca/app/uploads/2022/06/AI-CCUS-WHITE-PAPER_2022_WEB.pdf

[46] Hills et al., “Mineralization Technology for Carbon Capture, Utilization, and Storage.”

2.1 Direct air capture

Imagine a big filter that catches CO_2 but nothing else. If air was blown through this filter, then CO_2 could be captured and the concentration of it in the air could be decreased.

That is what direct air capture (DAC) aims to do. Ambient air blows across a capture unit that binds CO_2 in the air to it, and then that CO_2 is processed and compressed into pipes that carry it to storage underground or to be used as a component in value-added products or processes.[47]

There are two main types of DAC, differentiated by what is used to separate the CO_2 from the air. Solid DAC (S-DAC) uses a solid filter called an adsorber, whereas liquid DAC (L-DAC) uses a liquid solution that reacts with CO_2 when they come into contact.

With solid DAC, fans are used to draw ambient air through the adsorber. The adsorber has special characteristics on its surface that attract and bind CO_2. The rest of the air passes through the filter and returns to the atmosphere.

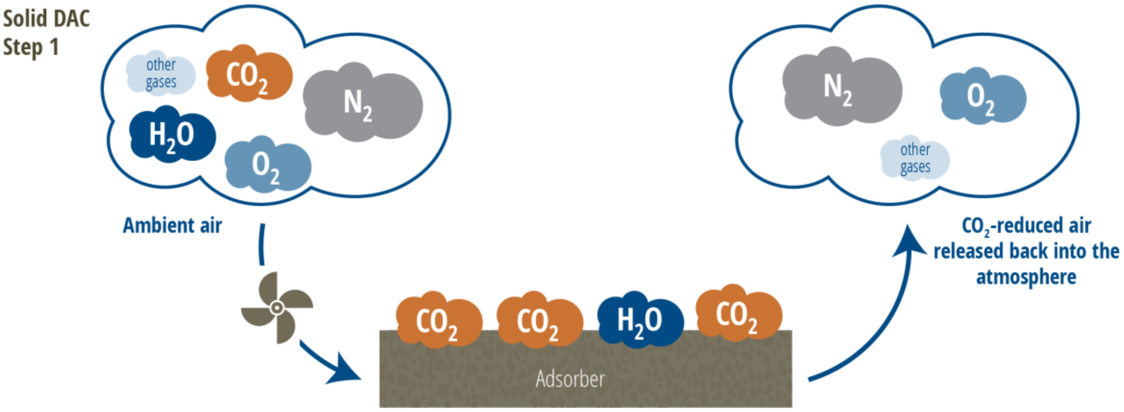

Figure 3. Step 1 of carbon capture in a solid DAC system

Carbon dioxide in the air binds to the solid adsorber, while the rest of the air is released back into the atmosphere.

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[47] IEA, "Direct Air Capture." https://www.iea.org/reports/direct-air-capture-2022

Once the filter is full of CO_2, the unit is closed and heated to approximately 100°C at low pressure to release CO_2 from the adsorber. This pure CO_2 is then collected, compressed and sent out to be used in a process or product, or to be stored underground.[48]

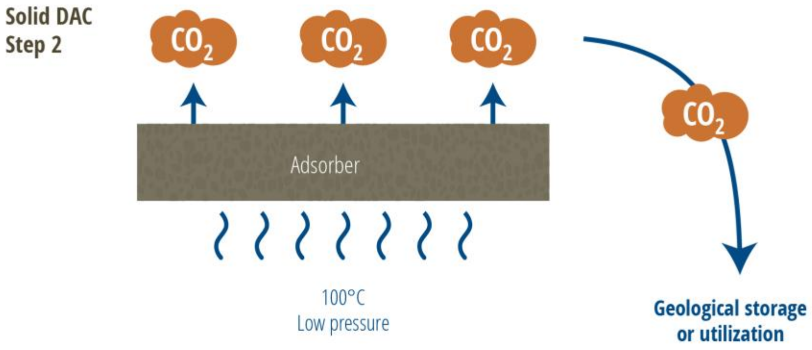

Figure 4. Step 2 of carbon capture in a solid DAC system

Heating the adsorber releases the CO_2 from the material, resetting it to start the process over again.

In liquid DAC (L-DAC), a liquid solution is used to trap CO_2, rather than a solid filter. A continuous process extracts the CO_2 from the liquid and recycles the liquid to be used again. Carbon Engineering, a DAC company based in Canada, is one of the earliest companies to deploy this technology.

The specific process varies, but in Carbon Engineering's case, the ambient air is blown across the surface of a basic (i.e., high pH) liquid solution in a contactor, causing the CO_2 molecules in the air to form carbonate salt in the liquid (Figure 5). The liquid then passes through a pellet reactor that converts the carbonate salt into solid pellets. The pellets then are heated to high temperatures over 900°C to turn the CO_2 back into a gas that can be separated, compressed, and transported to storage or use. The liquid solution is then re-hydrated and recycled back to the contactor to get used again.[49]

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[48] Noah McQueen and Jennifer Wilcox, "The Building Blocks of CDR Systems: Direct Air Capture" in *CDR Primer* (2021). https://cdrprimer.org/read/chapter-2#sec-2-8

[49] IEA, "Direct Air Capture."

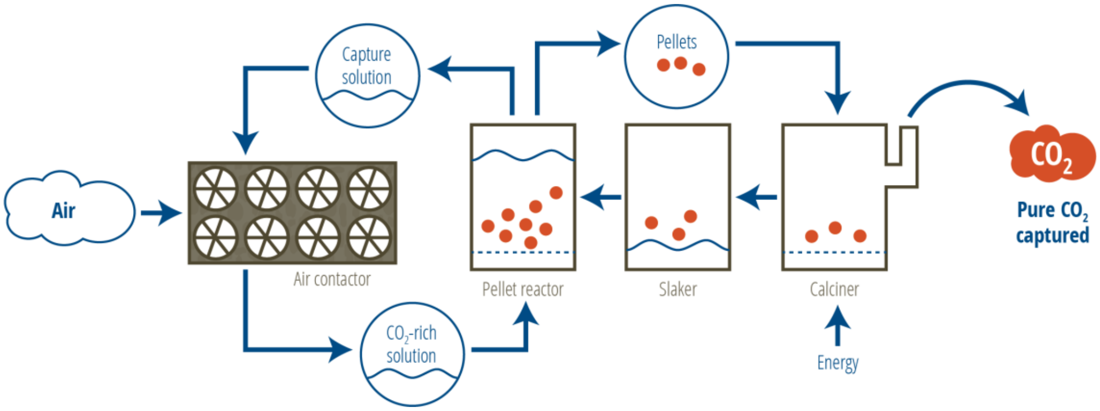

Figure 5. High-level overview of a liquid DAC system

Source: adapted from Carbon Engineering[50]

DAC by itself is not a complete CDR solution because it only removes the CO_2. It can be paired with geologic storage, *in situ* mineralization or carbon use to permanently remove CO_2 and form a CDR solution.

Carbon Engineering

Location: Headquarters and research facility are in Squamish, B.C. Their first commercial plant will be in Texas.

Description: Liquid direct air capture for underground storage or usage.

Status: Pilot plant operations since 2015. The Innovation Centre completed construction in 2021 and is the research & development centre for the company. Construction started in 2022 on their first large-scale commercial plant in partnership with Occidental subsidiary 1PointFive. This Texas facility is expected to start capturing 500,000 tonnes of CO_2 annually by 2025, with capacity to expand to 1 million tonnes per year.[51,52]

Why they are noteworthy: Founded in 2009, Carbon Engineering is one of the first direct air capture companies. They plan to combine their DAC expertise with 1PointFive's

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[50] Carbon Engineering, "Our Technology." https://carbonengineering.com/our-technology/

[51] Carbon Engineering, "Occidental, 1PointFive to Begin Construction of World's Largest Direct Air Capture Plant in the Texas Permian Basin," media release, August 25, 2022. https://carbonengineering.com/news-updates/construction-direct-air-capture-texas/

[52] Sabrina Valle, "Occidental raises spending budget, delays direct air capture launch," *Reuters*, February 27, 2023. https://www.reuters.com/business/energy/occidental-misses-fourth-quarter-profit-estimates-2023-02-27/

project engineering experience to deploy 70-135 DAC facilities by 2035, each removing one million tonnes of CO_2 per year.[53]

2.2 Ocean alkalinity modification

The ocean naturally absorbs CO_2 from the air as part of the natural carbon cycle. By artificially increasing the alkalinity of the ocean by adding finely ground rocks, the amount of carbon that the ocean absorbs can be increased.

A co-benefit of increasing the alkalinity of the ocean is that it can counter the acidification of the ocean, which is caused by increasing levels of atmospheric CO_2 and is harmful to marine ecosystems.[54]

There is a high theoretical potential for this CDR option, given the vastness of the ocean. However, there are questions around impacts to marine biota. Though the chemical process is well understood, this technology is in the early stages of research and development.

2.3 Mineralization

Carbon mineralization is the process of creating solid carbonate material by reacting CO_2 with alkaline, or basic, material. The reaction releases energy, making the resulting solid carbonate quite stable.[55]

The alkaline material can be naturally occurring material like basalts located underground near past volcanic activity, or anthropogenic like certain waste materials from industrial processes.[56]

Mineralization can be used in a number of ways in CDR. It can be a storage mechanism, where CO_2 removed by another process is mineralized for permanent storage. It can also form a complete removal and storage solution by itself, where the alkaline material

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[53] Carbon Engineering, "Occidental, 1PointFive to Begin Construction of World's Largest Direct Air Capture Plant in the Texas Permian Basin."

[54] American University, "What is Ocean Alkalinization?" https://www.american.edu/sis/centers/carbon-removal/fact-sheet-ocean-alkalinization.cfm

[55] Greeshma Gadikota, "Carbon mineralization pathways for carbon capture, storage and utilization," *Communications Chemistry* 4, 23 (2021). https://doi.org/10.1038/s42004-021-00461-x

[56] Greg Dipple, Peter Kelemen and Caleb M. Woodall, "The Building Blocks of CDR Systems: Mineralization" in *CDR Primer* (2021). https://cdrprimer.org/read/chapter-2#sec-2-1-1

reacts directly with natural concentrations of CO_2 in air or water, and is then permanently stored.

There are three types of mineralization, categorized by where the process takes place.

In situ mineralization

In situ mineralization involves injecting the CO_2 underground into naturally occurring formations of alkaline material. Mafic and ultramafic (i.e. high metals content) rocks are good candidates as they are rich in magnesium and calcium, which have the necessary alkalinity to react with CO_2. These would include basalt formations near past and present volcanos, as well as rock formations with magnesium located near past and present mountain ranges called peridotites and serpentinites.[57] The reaction converts the CO_2 into carbonate solids that remain in place underground.

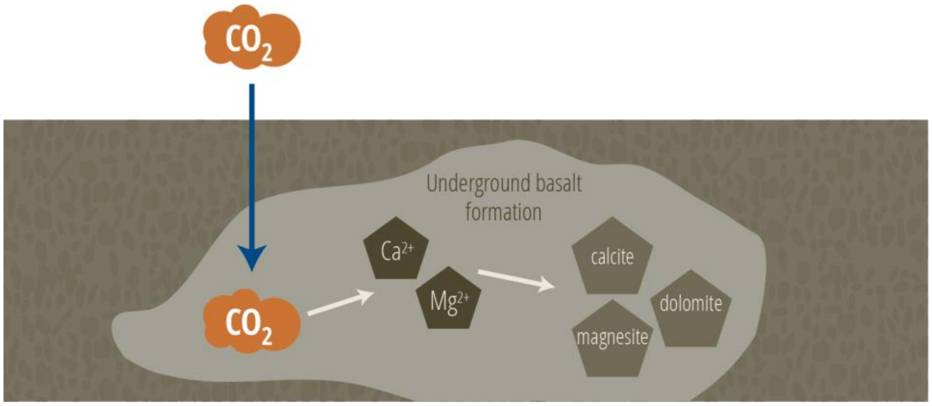

Figure 6. Overview of *in situ* mineralization

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[57] Dipple et al., “The Building Blocks of CDR Systems: Mineralization” in *CDR Primer*.

Solid Carbon

Location: Headquarters are in Victoria, B.C., and their operations are planned to be off the coast of B.C. in the Pacific Ocean.

Description: Their solution includes direct air capture on a floating platform in the ocean, powered by offshore wind energy, for *in situ* mineralization into basalt formations beneath the ocean. The current formation under study is estimated to be able to store 0.6 $MtCO_2$ per year.[58]

Status: They are in a feasibility study, with a site demonstration planned for 2024.

Why they are noteworthy: The approach is attractive because of the sediment layer cap below the ocean and above the basalt, the readily available water and renewable energy, and the high permanence achieved by mineralization. The Cascadia basin is a well-understood basalt formation. If successful, this offshore deployment could expand offshore CDR options globally, as there is an estimated potential to store 250,000 Gt of CO_2 in sub-ocean basalt formations worldwide.[59]

Ex situ mineralization

In *ex situ* mineralization, the alkaline material is collected and brought to an industrial site to be reacted with CO_2.[60] This would typically be at a site where the CO_2 was captured.[61] The carbonate solids are then available for use as a product, or for storage. This method requires the application of heat, pressure, or chemical reagents in order to speed up the mineralization process, which impacts the overall cost.[62]

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[58] Romany M. Webb and Michael B. Gerrard, *The Legal Framework for Offshore Carbon Capture and storage in Canada* (Sabin Center for Climate Change Law, Columbia Law School, 2021). https://scholarship.law.columbia.edu/faculty_scholarship/2744/

[59] Rochelle Baker, "An ocean of optimism to trap emissions," *National Observer*, January 10, 2022. https://www.nationalobserver.com/2022/01/10/news/ocean-optimism-trap-emissions

[60] National Academies of Sciences, Engineering, and Medicine, "Carbon Mineralization of CO_2" in *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda* (Washington (DC): National Academies Press (US); 2018), 6. https://www.ncbi.nlm.nih.gov/books/NBK541437

[61] Hills et al., "Mineralization Technology for Carbon Capture, Utilization, and Storage."

[62] Hills et al., "Mineralization Technology for Carbon Capture, Utilization, and Storage."

Surficial mineralization

Surficial mineralization describes reacting CO_2 with materials lying on the ground, like mine tailings, industrial waste or exposed sedimentary formations.[63] The key here is ensuring that the material has a high surface-area-to-volume ratio, which increases how much contact it makes with CO_2 in the air.

Enhanced weathering is a form of surficial mineralization where the natural breakdown of rocks and minerals over time is accelerated by crushing the rock and spreading it across a large area of land to increase the surface area of reaction.[64]

Though the chemistry is well understood, terrestrial enhanced weathering has not yet been demonstrated at a large scale, and thus any potential adverse reactions are unknown. Some possible impacts that require further investigation include: silicate mineral dissolution rates in soils, the fate of released products, risks of greater dust generation, direct habitat destruction, local water quality and expansion of mining industry to supply the rock.[65]

2.4 Geologic storage

Geologic storage refers to injecting CO_2 into deep saline aquifers located in underground sedimentary basins for long term storage. While some of this CO_2 will mineralize like in *in situ* mineralization, other trapping mechanisms are at play here, including capillary forces trapping CO_2 between rock pores and dissolution of CO_2 into brine.[66] High temperatures and pressures are found at these great depths, which keeps the CO_2 in a supercritical state, a state between a liquid and a gas, roughly 300 times denser than when in an atmospheric gas form. This helps increase storage capacity, as well as the permanence of the storage. Ideally, these formations also have an impermeable rock layer above, known as a cap rock. This helps prevent the CO_2 from rising back to the surface.[67]

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[63] National Academies of Sciences, Engineering, and Medicine, *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda* (Washington DC: National Academies Press, 2018), 249. https://www.ncbi.nlm.nih.gov/books/NBK541442/

[64] IPCC, *Climate Change 2022: Mitigation of Climate Change*, 1267.

[65] IPCC, *Climate Change 2022: Mitigation of Climate Change*, 1268.

[66] Susan Hovorka and Peter Kelemen, “Geological Sequestration: Introduction” in *CDR Primer* (2021). https://cdrprimer.org/read/chapter-2#sec-2-9-1

[67] Hovorka et al., “Geological Sequestration: Introduction” in *CDR Primer*.

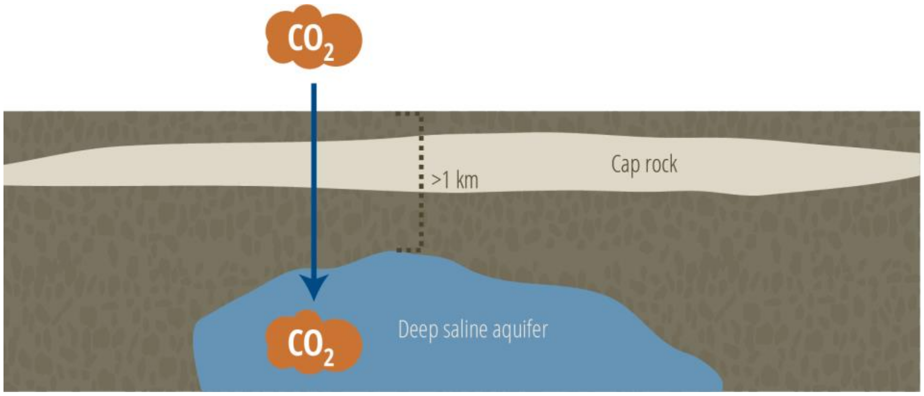

Figure 7. Geologic storage in aquifers or reservoirs over 1 km below the surface

2.5 Carbon use

Carbon use refers to taking the CO_2 that has been removed from the atmosphere and recycling it to create a product or good. There are a wide range of potential uses for captured CO_2, such as treating cement, making fertilizer, carbonating drinks and even decaffeinating coffee.[68]

On a larger scale, CO_2 can be injected into concrete to mineralize with calcium found in the cement. This makes it stronger, reducing the amount of cement required in concrete production. The carbon removal benefits come not only from storing carbon in the cement, but also because stronger concrete means you can use less of it. This cuts down on cement manufacturing emissions, by far the largest source of emissions in concrete production.[69]

Enhanced oil recovery (EOR) involves injecting CO_2 into oil wells to increase the amount of oil that can be recovered from them. Although this is a popular use case for captured CO_2, it should not be considered part of a viable CDR system because the CO_2 released when the end product is combusted and incremental oil production enabled by EOR make the whole process unlikely to be net negative emissions. The production of synthetic fuel using CO_2 as a feedstock also would not be considered CDR because of the CO_2 released upon combustion. However, these could both be considered as emissions reductions pathways.

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[68] Old City Coffee, “Decaffeination.” https://oldcitycoffee.com/about-our-products/coffee/decaffeination

[69] Pete Psarras, Caleb M. Woodall, and Jennifer Wilcox, “CO_2 utilization for concrete coupled with low-carbon cement” in *CDR Primer* (2021). https://cdrprimer.org/read/chapter-5#sec-5-2-3

Making urea, a component of fertilizer, is currently the largest use of CO_2, taking up 57% of the market share. However, the CO_2 is released back into the atmosphere when the fertilizer is applied in the field.[70] Thus, urea, too, is not considered an applicable carbon use in a CDR system.

CarbonCure

Location: Dartmouth, Nova Scotia

Description: Carbon dioxide is injected into concrete during mixing. It mineralizes within the concrete, improving its strength and securely locking in CO_2. Projects using concrete from CarbonCure have reduced CO_2 usage compared to conventional concrete production.[71]

Status: CarbonCure is operating at commercial scale and has supplied concrete to projects across Canada and the United States. Carbon removal offset credits are also offered.

Why they are noteworthy: Founded in 2012, CarbonCure has developed products that remove carbon permanently, while also reducing material costs for builders. They recently partnered with Heirloom to demonstrate the use of CO_2 captured via DAC to produce concrete at a Central Concrete plant in California.[72]

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[70] Pete Psarras, Caleb M. Woodall, and Jennifer Wilcox, "How CO_2 is sourced today" in *CDR Primer* (2021). https://cdrprimer.org/read/chapter-5#sec-5-1

[71] Carbon Cure, "CarbonCure Ready Mix." https://www.carboncure.com/ready-mix/

[72] Carbon Cure, "CarbonCure Technologies, Central Concrete and Heirloom Achieve First-Ever Concrete Storage of Atmospheric CO_2 Captured By Direct Air Capture," media release, February 3, 2023. https://www.carboncure.com/news/carboncure-technologies-central-concrete-and-heirloom-achieve-first-ever-concrete-storage-of-atmospheric-co2-captured-by-direct-air-capture/

3. Cost and environmental impacts

3.1 Economics of CDR

Engineered CDR technologies are currently expensive. The range of estimated costs of each technology, levelized per tonne of CO_2 removed, are shown in Figure 8. High costs are a barrier for market adoption.

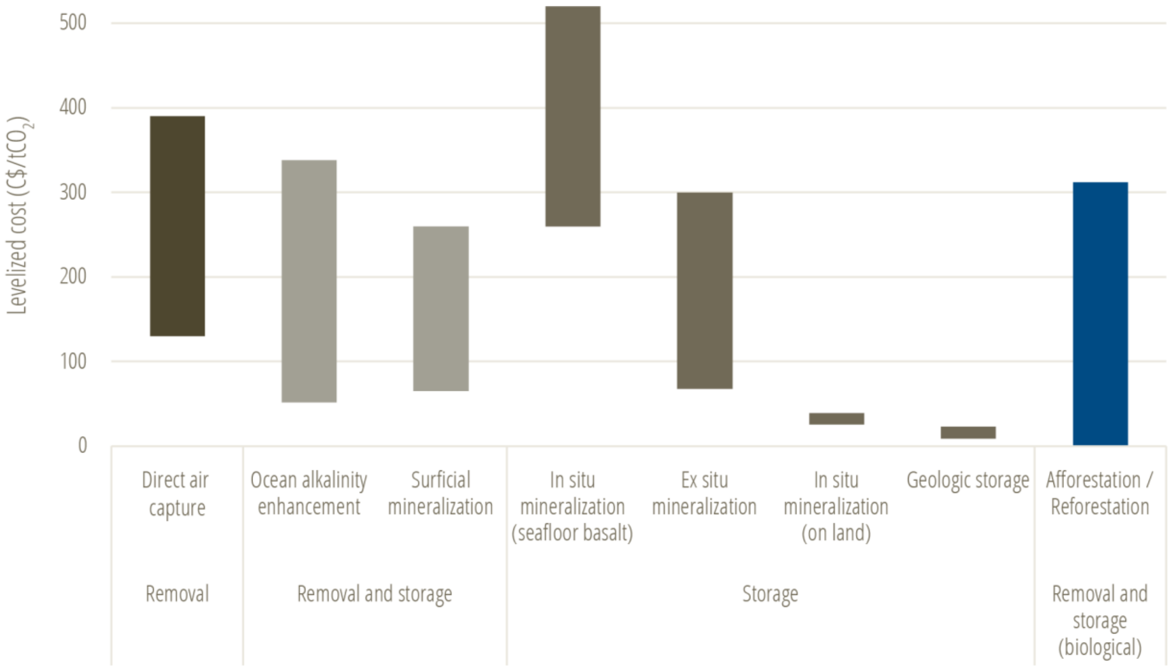

Figure 8. Range of estimated levelized costs of removal and storage for non-biological engineered CDR solutions, alongside afforestation/reforestation for comparison

Data sources: various, see Table 1; afforestation/reforestation data from IPCC[73]

A significant proportion of future cost reductions are expected to come from economies of scale as the deployment of CDR grows, learning from prior project experience to improve operational efficiency, and from research innovations.[74] A key approach to

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[73] IPCC, *Climate Change 2022: Mitigation of Climate Change*, 1276.

[74] Budinis et al., *Direct Air Capture: a key technology for net zero*, 31.

lowering costs is to iteratively deploy quickly, accelerating through learning curves and compounding improvements faster (see text box).

Learning curves: Learning by doing to reduce costs

The first version of any type of technology is usually quite expensive. All the problems encountered are new, requiring extra time to solve. Components are mostly off-the-shelf and not optimized for the task at hand. The primary goal is to just get things working. Afterward, better ways of doing things become apparent, and learnings can be applied to subsequent iterations.

This learning curve means it gets cheaper as the amount produced from a technology increases, due to economies of scale and learning by doing.[75] For example, the cost of solar energy has decreased by 24% every time the amount of solar energy capacity built doubled.[76] This has resulted in a levelized cost reduction of 85% from 2007 to 2020.[77] Wind energy has a lower learning rate of 15%, but even that resulted in a 93% cost reduction per megawatt-hour from 1982 to 2020.[78] Based on a conservatively estimated learning rate of 10% for DAC and assuming 1 $MtCO_2$/year deployed today, 90 $MtCO_2$/year in 2030 and 985 $MtCO_2$/year in 2050,[79] capital expenditures for DAC projects could reduce by 50% by 2030 and 65% by 2050.[80]

3.2 Environmental considerations

This section discusses key environmental challenges for the CDR technologies in Table 1. These represent areas where further work is likely needed to understand and mitigate potential issues, rather than fundamental negatives or barriers to certain CDR technologies. Discussion of relative impacts are in comparison to afforestation and

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[75] Johan Lilliestam, “Focusing on technological learning in learning rate assessments,” *Behaviour and Social Sciences at Nature Portfolio*, January 14, 2020. https://socialsciences.nature.com/posts/58259-focusing-on-technological-learning-in-learning-rate-assessments

[76] Wind Energy Technologies Office, "Learning a Better Way To Forecast Wind and Solar Energy Costs," *Office of Energy Efficiency & Renewable Energy*, October 17, 2022. https://www.energy.gov/eere/wind/articles/learning-better-way-forecast-wind-and-solar-energy-costs

[77] Bolinger et al, “Levelized cost-based learning analysis of utility-scale wind and solar in the United States.”

[78] Bolinger et al, “Levelized cost-based learning analysis of utility-scale wind and solar in the United States.”

[79] IEA, *Net Zero by 2050*, 80.

[80] Budinis et al., *Direct Air Capture: a key technology for net zero*, 32.

reforestation CDR methods, since they are currently the most common. Refer to Appendix B for additional information.

3.2.1 Land use advantages for DAC

A key advantage of DAC is its low land-use impact. It does not require as much land to build a DAC plant compared to other CDR options that remove atmospheric carbon using plant-growth-like afforestation. To remove one million tonnes of CO_2 each year, an estimated 0.4 to 66 square kilometres (km^2) of land would be required to build enough DAC capacity along with its associated energy sources, whereas 862 km^2 of forests would be required to remove the same amount.[81] And crucially, DAC systems can be placed on unproductive land, meaning it does not compete with agriculture or bioenergy.[82]

3.2.2 Underground risks for geological storage and *in situ* mineralization

Underground CO_2 storage offers the potential for highly permanent storage compared to storage in plant material; for example, in 2021, 0.5 $GtCO_2$ was released from boreal forest fires.[83] However, there are potential risks and impacts that need to be considered.

For both geologic storage and *in situ* mineralization, geological activity such as induced seismic activity is a potential risk. Though no seismic events have been reported from any carbon storage projects, underground fluid injection in general has been linked to seismic activity.[84] That said, recent insights have shown that injecting CO_2 does not generally critically stress sedimentary formations.[85] Additionally, best practices have been developed to mitigate much of the risk, including proper site selection to avoid

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[81] Lebling et al., “6 Things to Know About Direct Air Capture.”

[82] Sara Budinis et al. *Direct Air Capture: a key technology for net zero*, 22.

[83] Bo Zheng, Philippe Ciais, Frederic Chevallier et al. “Record-high CO_2 emissions from boreal fires in 2021,” *Science* 379, no. 6635 (2023), 912. https://doi.org/10.1126/science.ade0805

[84] Earthquake Hazards, “Myths and Misconceptions About Induced Earthquakes,” *USGS*. https://www.usgs.gov/programs/earthquake-hazards/myths-and-misconceptions-about-induced-earthquakes

[85] Victor Vilarrasa and Jesus Carrera, “Geologic carbon storage is unlikely to trigger large earthquakes and reactivate faults through which CO_2 could leak,” *Proceedings of the National Academy of Sciences* 112, no. 19 (2015), 5938. https://www.pnas.org/doi/10.1073/pnas.1413284112

brittle formations, diligent pressure management during injection, and microseismic monitoring.[86]

Leakage of CO_2 from geological storage sites is possible, but rare in the previous decades of injecting CO_2 underground. Some studies have found that 0.1% of CO_2 injection operations have a physical leakage incident.[87]

Leakage can happen vertically through faults or previously drilled wells in the caprock, as well as laterally through migration into other formations. These risks highlight the need for thorough analysis prior to selecting a location for underground storage, including understanding where CO_2 might migrate during and after injection. Continuous long-term monitoring to detect leakage or unwanted contamination can help identify issues down the road. Strong regulation on development can prevent situations where the integrity of a cap rock is compromised because of having too many open wells. Standards on well construction and historical well-closure techniques can significantly reduce leakage risks, as that is a major cause of physical leakage.[88]

Studies have found that long-term CO_2 leakage from geological storage sites is expected to be well under 0.01% per year and capable of securing CO_2 underground for thousands of years.[89] Compared to geologic storage, *in situ* mineralization can even further lower the risk of leakage. Complete mineralization of the injected CO_2 is expected to happen within several years, turning it into a solid carbonate that does not try to escape back to the surface.[90] However, if leakage does occur, one concern is that toxic metals may be released when basalt rock reacts with CO_2, causing issues if it reaches groundwater sources.[91] Proper site selection and monitoring can address this to ensure that the storage site and travel path of the CO_2 are far from groundwater sources. In addition,

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[86] Jonny Rutqvist, Antonio P. Rinaldi, Frederic Cappa, et al. "Fault activation and induced seismicity in geological carbon storage – Lessons learned from recent modeling studies," *Journal of Rock Mechanics and Geotechnical Engineering* 8, issue 6 (2016), 789. https://doi.org/10.1016/j.jrmge.2016.09.001

[87] Preston D. Jordan and Sally M. Benson, "Well blowout rates and consequences in California Oil and Gas District 4 from 1991 to 2005: implications for geological storage of carbon dioxide," *Environmental Geology* 57 (2009), 1103. https://doi.org/10.1007/s00254-008-1403-0

[88] Susan Hovorka and Peter Kelemen, "Geological Sequestration: Current challenges" in *CDR Primer* (2021). https://cdrprimer.org/read/chapter-2#sec-2-9-4

[89] Johannes M. Miocic, Stuart M. V. Gilfillan, Norbert Frank, et al. "420,000 year assessment of fault leakage rates shows geological carbon storage is secure," *Scientific Reports* 9, no. 769 (2019). https://doi.org/10.1038/s41598-018-36974-0

[90] Arshad Raza, Guenther Glatz and Raoof Gholami, "Carbon mineralization and geological storage of CO_2 in basalt: Mechanisms and technical challenges," *Earth-Science Reviews* 229, no. 104036 (2022). https://doi.org/10.1016/j.earscirev.2022.104036

[91] Raza et al., "Carbon mineralization and geological storage of CO_2 in basalt."

proper closure of adjacent historical wells can reduce the potential for leakage through these pathways.

As geologic storage increases, new risks may become apparent due to cumulative effects and increased magnitudes of injection. The mitigation approaches learned from operations so far may or may not carry over to solve the problems faced when operations increase by orders of magnitude.

3.2.3 Ecosystem impacts of enhanced weathering and ocean alkalinity modification

The possible impact of techniques like enhanced weathering and ocean alkalinity modification are not well understood and require thorough investigation, given that both solutions operate in open systems with high potential for adverse ecosystem impact.[92]

Eutrophication is a potential side effect that might be triggered by modifying ocean alkalinity.[93] Enriching a marine environment with nutrients can unbalance ecosystems, setting off a chain reaction that leads to algal blooms, fish kills and habitat destruction.[94] More research is required to better understand the impacts of this open system approach.

Run-off from terrestrial enhanced weathering can cause ocean alkalinity modification and subsequently poses the same concerns with ecosystem imbalance. The resultant accumulation of nickel and chromium in soils has the potential to be a risk.[95] The technique is already being used for accelerating acid rain recovery and increasing sugarcane production, but more research is required to understand environmental impacts at large deployment scales.[96]

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[92] Lennart T. Bach, Sophie J. Gill, Rosalind E.M. Rickaby, et al. "CO_2 Removal With Enhanced Weathering and Ocean Alkalinity Enhancement: Potential Risks and Co-benefits for Marine Pelagic Ecosystems," *Frontiers in Climate* 1 (2019). https://doi.org/10.3389/fclim.2019.00007

[93] Sara Budinis et al., *Direct Air Capture: a key technology for net zero*, 53.

[94] National Oceanic and Atmospheric Administration, "What is eutrophication?" *National Ocean Service*. https://oceanservice.noaa.gov/facts/eutrophication.html

[95] Arshad Raza et al., "Carbon mineralization and geological storage of CO_2 in basalt."

[96] Sara Budinis et al., *Direct Air Capture: a key technology for net zero*, 53.

4. Canada's CDR opportunities

Canada is home to several geographical features that can be excellent resources for certain types of non-biological CDR development. Paired with ample renewable electricity resources, a skilled workforce and existing infrastructure that can be utilized, some locations have all the right ingredients to kickstart this new industry.

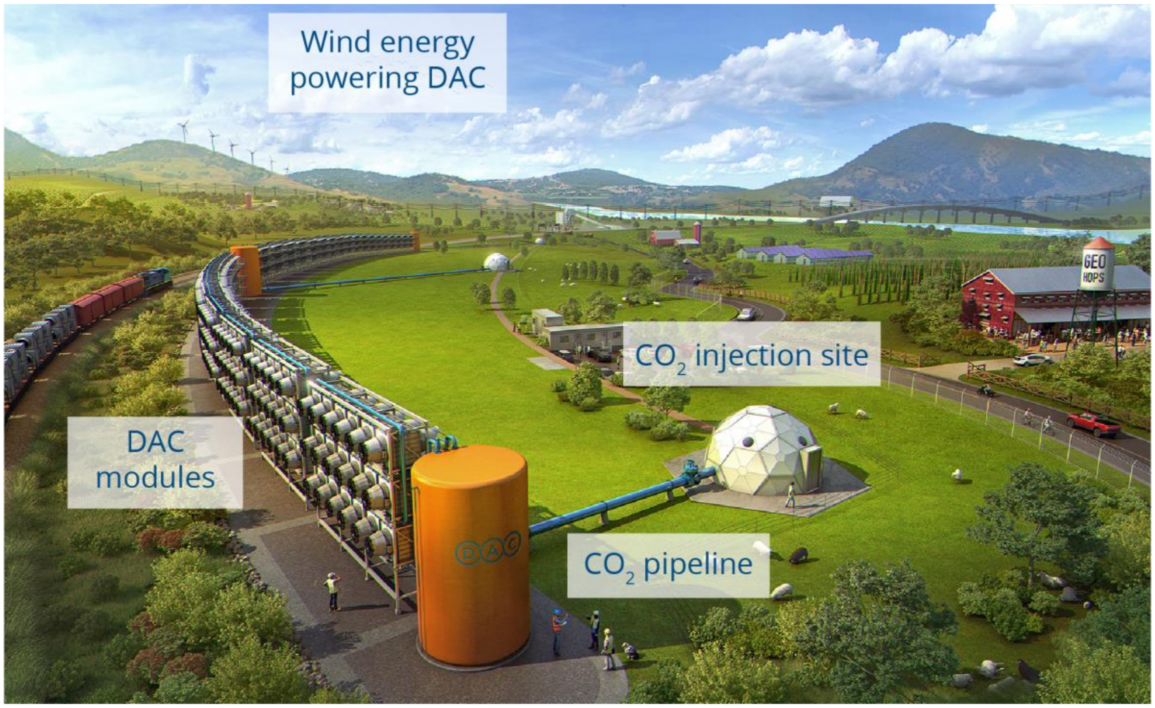

Figure 9. Depiction of a rural landscape with direct air capture integrated into the community

Carbon dioxide is removed by a row of DAC modules powered by wind energy, and then transported to an injection site where it is sent underground.

Source: Adapted from Third Way[97]

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[97] Simone Stewart and Rudra V. Kapila, "Rural Direct Air Capture," in *Picture It: Carbon Management Across America* (Third Way and National Wildlife Federation, 2022). https://www.thirdway.org/blog/picture-it-carbon-management-across-america

4.1 Storage potential

Canada has substantial geological and mineral storage options for CDR. Saline aquifers offer an estimated capacity to store 360 Gt of CO_2,[98] or 10 times more than all the CO_2 emitted from fossil fuels and industry in Canada to date.[99] However, there is still likely to be competition for prime locations with competing projects and technologies.

Storage potential via mineralization in mafic or ultramafic rock is not as well quantified. There is estimated to be enough accessible magnesium minerals in B.C. to store 56 Gt of CO_2 via *ex situ* mineralization.[100] One potential constraint for this technology is finding space to store the resulting carbonate rock if the mineralization is not turned into a useful product like building materials.

A high-level estimate indicates B.C. has the potential to store 5,000 $GtCO_2$ via *in situ* mineralization in underground ultramafic rock.[101] 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 CO_2.[102]

If mineralization in undersea basalt formations proves to be viable, then there is the chance to store 250,000 Gt of CO_2 in sub-oceanic basalt worldwide.[103] A potential limiting factor is that there is an ideal rate of injection. Injecting too fast can clog rock pores, reducing the available capacity in the rock that the CO_2 can reach.[104]

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[98] 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/wp-content/uploads/2022/07/Review-of-Carbon-Dioxide-Storage-Potential-in-Western-Canada-V-1.pdf

[99] Hannah Ritchie, Max Roser and Pablo Rosado, "Canada: Cumulative: how much CO_2 has it produced to date?" in *CO_2 and Greenhouse Gas Emissions* (OurWorldInData.org, 2020). https://ourworldindata.org/co2/country/canada#cumulative-how-much-co2-has-it-produced-to-date

[100] Dianne Mitchinson, Jamie Cutts, Dominique Fournier et al. *The Carbon Mineralization Potential of Ultramafic Rocks in British Columbia: A Preliminary Assessment* (Geoscience BC, 2020), 1. https://www.mdru.ubc.ca/wp-content/uploads/2020/11/MDRU-Pub452-CaMPBC-v2020Nov04red.pdf

[101] Mitchinson et al., *The Carbon Mineralization Potential of Ultramafic Rocks in British Columbia: A Preliminary Assessment*, 22.

[102] 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

[103] Rochelle Baker, "An ocean of optimism to trap emissions," *National Observer*, January 10, 2022. https://www.nationalobserver.com/2022/01/10/news/ocean-optimism-trap-emissions

[104] Raza et al., "Carbon mineralization and geological storage of CO_2 in basalt."

The scalability of carbon use is limited by the current uses for CO_2. Currently, only 230 Mt of CO_2 each year is used as a feedstock globally.[105] This is expected to grow significantly, with estimates ranging from 1 Gt to 7 Gt by 2030.[106] The concrete market alone could use more than 1 Gt of CO_2 annually by 2050.[107] While there is flexibility in where carbon use operations can be situated, siting will likely be dependent on existing industry and infrastructure.

4.2 Co-located geologic storage and renewable energy potential

CDR solutions like DAC paired with geologic storage (DACCS) are best situated in locations with nearby access to both a renewable energy supply and geologic storage potential. Alberta, Saskatchewan, northeast British Columbia, and southwest Manitoba offer that combination. Not only does this help reduce the cost of transporting the CO_2 from removal site to storage site, but using renewable energy is key to ensuring the whole process is removing more CO_2 than it emits.

The majority of Canada's known underground storage potential is in western Canada.[108] As depicted in Figure 10, the underground formations that house this storage spread from the Yukon to southwestern Manitoba, with the majority in Alberta and Saskatchewan.[109]

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[105] International Energy Agency, *Putting CO_2 to Use* (2019). https://www.iea.org/reports/putting-co2-to-use

[106] IEA, *Putting CO_2 to Use.*

[107] Volker Sick, Gerald Stokes and Fred C. Mason, "CO_2 Utilization and Market Size Projection for CO_2-treated Construction Materials," *Frontiers in Climate* 4 (2022). https://doi.org/10.3389/fclim.2022.878756

[108] International CCS Knowledge Centre, *Canada's CO_2 Landscape: A Guided Map for Sources & Sinks* (2021), 4. https://ccsknowledge.com/pub/Publications/CO2-Sources_&_Sinks_Map_Canada%20(2021-05-12).pdf

[109] *Canada's CO_2 Landscape: A Guided Map for Sources & Sinks*, 11.

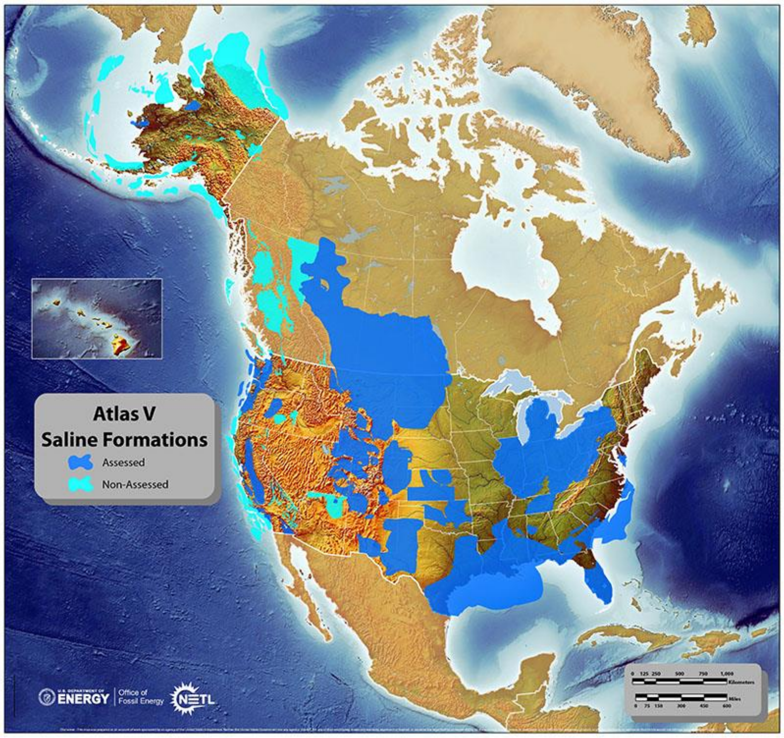

Figure 10. Map of saline aquifers in North America with carbon dioxide storage potential

Source: NETL[110]

Much of this storage potential overlaps with renewable energy potential. Southern Alberta and Saskatchewan have both strong solar and wind[111] energy potential, and B.C. and Manitoba have substantial hydroelectric generation. Figure 11 illustrates solar potential across Canada.

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[110] National Energy Technology Laboratory, "CO_2 Storage Resource Methodology." https://www.netl.doe.gov/node/5964

[111] Environment and Climate Change Canada, "Wind Atlas: Overall Map." http://www.windatlas.ca/maps-en.php

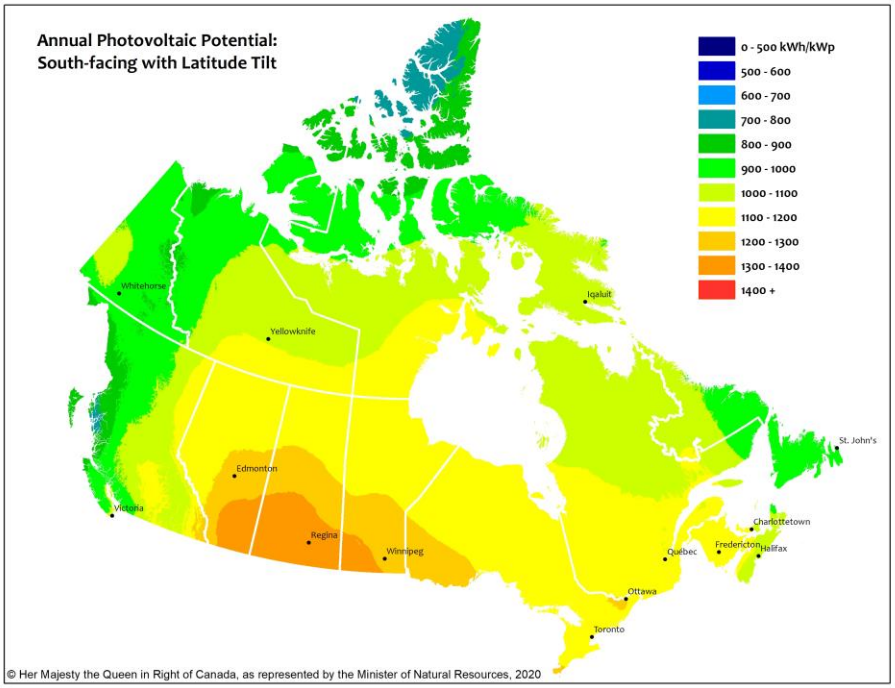

Figure 11. Solar energy potential in Canada

Source: Natural Resources Canada[112]

Geothermal energy could be a viable low-carbon heat source. Across B.C., Alberta and Saskatchewan, the geothermal potential overlaps with geologic storage potential. Figure 12 shows a map highlighting heat energy found at a depth of 6.5 km.

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[112] Natural Resources Canada, “Photovoltaic potential and solar resource maps of Canada.” https://www.nrcan.gc.ca/our-natural-resources/energy-sources-distribution/renewable-energy/solar-photovoltaic-energy/tools-solar-photovoltaic-energy/photovoltaic-potential-and-solar-resource-maps-canada/18366

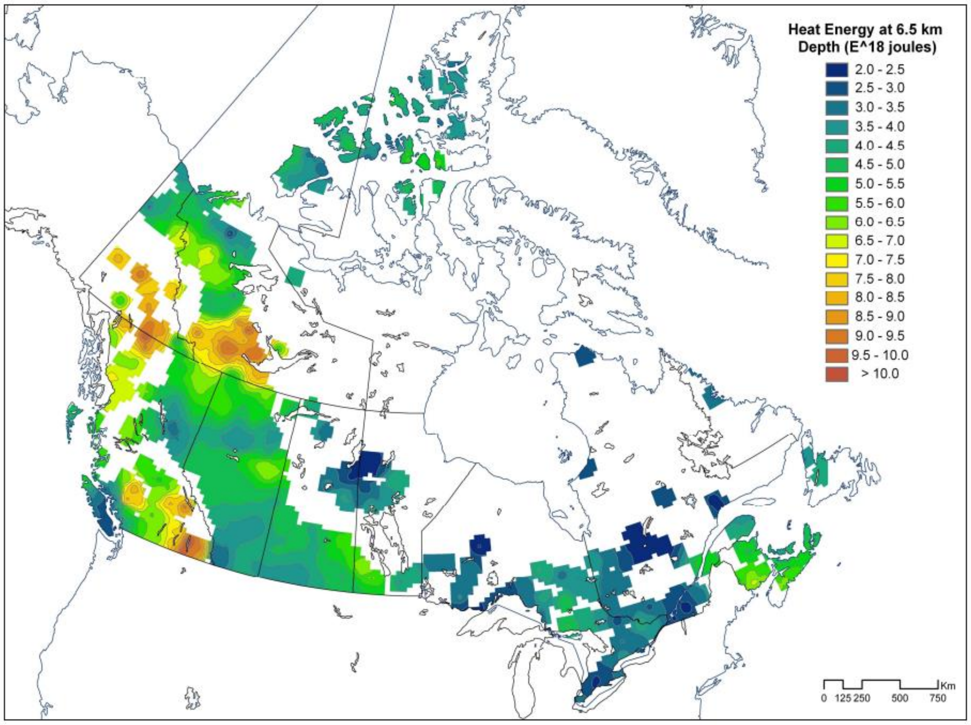

Figure 12. Geothermal energy at 6.5 km depth in Canada

Source: Grasby et al.[113]

There is potential in southwestern Ontario to tap into both the Appalachian and Michigan basins that extend south, but further exploration is required.[114] If storage in Ontario is not possible, carbon captured could be transported for storage in the United States via cross-border pipeline.[115]

4.3 Offshore opportunities

Carbon dioxide storage is not just limited to land; there are potential opportunities underneath the ocean as well. The Cascadia Basin, off the coast of British Columbia, features a basalt formation that could provide an *in situ* mineralization site. A benefit is that normally an additional water source is required in which to dissolve the CO_2 prior

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[113] Stephen Grasby, Diana Allen, Sebastian Bell, et al. *Geothermal Energy Resource Potential of Canada* (Geological Survey of Canada, 2012), VII. https://publications.gc.ca/collections/collection_2013/rncan-nrcan/M183-2-6914-eng.pdf

[114] Environmental Registry of Ontario, *Discussion Paper: Geologic Carbon Storage in Ontario* (2022), 2. https://prod-environmental-registry.s3.amazonaws.com/2022-01/Geologic%20Carbon%20Storage%20Discussion%20Paper%20-%20FinalENG%20-%202022-01-04.pdf

[115] *Canada’s CO_2 Landscape: A Guided Map for Sources & Sinks*, 11.

to injection, to improve the performance of mineralization. Operating in the ocean negates that need.[116]

There is also potential for geologic storage in Atlantic Canada, in the Gulf of St. Lawrence and Atlantic Basins, but further exploration is required. The potential for offshore wind energy here is high, with high average wind speeds, shallow water depths, and appropriate substrates for fixed-bottom turbines.[117]

4.4 Leveraging existing human capital

Large-scale CDR will need a large workforce — a single DAC plant that removes 1 $MtCO_2$ each year is estimated to create 3,428 jobs.[118] Regions with large existing industrial bases offer a skilled workforce to draw from, since CDR requires skillsets similar to other industrial sectors. This would include engineering, construction, manufacturing, and project management in industrial settings, oil and gas geology, process, operations, and reservoir engineering. Existing workforces in Alberta, Saskatchewan, B.C., Ontario, and Quebec would all be well suited to a growing CDR industry. Saskatchewan and Alberta are already world leaders with know-how in geologic storage.

4.5 Leveraging existing infrastructure

Existing capital infrastructure can also be leveraged to get CDR projects going. Alberta and Saskatchewan have hundreds of kilometres of CO_2 pipelines. Specifically, the Alberta Carbon Trunk Line is an existing 240-km-long CO_2 pipeline system that transports CO_2 captured from the Alberta Industrial Heartland to a storage site near Lacombe. It is an open access pipeline designed to accommodate multiple sources and end-use opportunities.[119] Organizing in a hub model, where multiple adjacent removal facilities can access the same storage site, is a way to distribute storage costs.

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[116] Raza et al., "Carbon mineralization and geological storage of CO_2 in basalt."

[117] Net Zero Atlantic, "Value mapping Nova Scotia's Offshore Wind Resources." https://netzeroatlantic.ca/research/value-mapping-nova-scotias-offshore-wind-resources

[118] John Larsen, Whitney Herndon, Galen Hiltbrand, *Capturing New Jobs: the employment opportunities associated with scale-up of Direct Air Capture (DAC) technology in the US* (Rhodium Group, 2020), 15. https://rhg.com/wp-content/uploads/2020/06/Capturing-New-Jobs-Employment-Opportunities-from-DAC-Scale-Up.pdf

[119] Wolf Midstream, "Carbon." https://wolfmidstream.com/carbon/

5. Policy current state and barriers

Supports from policies and standards can help accelerate the development of non-biological CDR. The following section provides a review of key policies and identifies several gaps in Canada.

5.1 Measurement standards

A key issue with CO_2 removal is knowing how much CO_2 is being removed and being able to verify that quantity. This is critical for proper crediting and measuring the impact to justify the investments into these technologies. Accounting transparency builds trust and social acceptance in CDR.

Measuring the CO_2 removed by methods like ocean alkalinity modification and terrestrial enhanced weathering is particularly difficult, given the open nature of the approach. To add to the difficulty, additionality needs to be measurable, meaning there needs to be a way of determining how much additional CO_2 is removed over natural processes.

For mineralization, *ex situ* methods are much easier to quantify CO_2 stored compared to *in situ* because the output of the reaction can be measured directly. More research is required to develop measurement and monitoring methods for *in situ* mineralization. Standard geophysics monitoring techniques like seismic surveys or vertical seismic profiling cannot be applied to water-saturated CO_2 media.[120]

Clear requirements for life cycle analysis of CDR solutions will ensure that all CO_2 emissions and removals are considered across a full process. The net balance of carbon emissions in CDR solutions depends on the emissions of the energy sources used, additional processes required like mining, and the release of any CO_2 from any uses of the CO_2.

If left up to market participants individually, CDR accounting will be inconsistent and easy to misinterpret. Lessons can be learned from the carbon offset market, which has seen discrepancies in CO_2 avoidance methodologies lead to a loss of market

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[120] Raza et al., “Carbon mineralization and geological storage of CO_2 in basalt.”

credibility.[121] Industry leaders have jointly called for improved standardization in measurement, reporting and verification (MRV) standards, suggesting a non-profit, unbiased, central authority be established.[122] Forthcoming quantification protocols from Environment and Climate Change Canada should help close this gap.[123] However, it will be important for these regulations to keep pace with new CDR methods that become viable at scale.

5.2 Regulatory gaps

The relative maturity of carbon capture and storage regulation provides a useful foundation for pipeline transport and geologic storage that can be leveraged for CDR purposes. Modifications to legislation may be required in some cases to account for new CDR technologies, but these likely will not differ much from CCUS.[124]

For geologic storage, the space between rocks where the carbon would be stored is called the pore space. Provinces handle licensing the pore space differently. In Alberta, the pore space is owned by the province, as stated in the Mines and Mineral Act, which was modified by the Carbon Capture and Storage Statutes Amendment Act.[125] This is also the case in British Columbia, as per the Petroleum and Natural Gas Act.[126] Pore space ownership is less clear in Saskatchewan, where the Crown owns pore spaces once occupied by Crown Minerals, as per The Crown Minerals Act.[127] However, pore space

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[121] Patrick Greenfield, "Revealed: more than 90% of rainforest carbon offsets by biggest certifier are worthless, analysis shows," *The Guardian*, January 18, 2023. https://www.theguardian.com/environment/2023/jan/18/revealed-forest-carbon-offsets-biggest-provider-worthless-verra-aoe

[122] Greg Dipple et al. "Industry Call for a Standards Body for Long-Duration Carbon Dioxide Removal," open letter, January 18, 2023. https://climeworkscom.cdn.prismic.io/climeworkscom/4c5e8ea8-c83f-4e68-9982-936d798d06cf_CDR-MRV-Standards-Letter-01-18-2023.pdf

[123] Environment and Climate Change Canada, "Canada's Greenhouse Gas Offset Credit System: Protocols." https://www.canada.ca/en/environment-climate-change/services/climate-change/pricing-pollution-how-it-will-work/output-based-pricing-system/federal-greenhouse-gas-offset-system/protocols.html

[124] Neil Craik, Anna-Maria Hubert, Chelsea Daku, "The Legal Framework for Carbon Dioxide Removal in Canada," *Alberta Law Review* 59, no. 4 (2022). https://albertalawreview.com/index.php/ALR/article/view/2699

[125] Government of Alberta, *Mines and Minerals Act*. https://open.alberta.ca/publications/m17

[126] Matrix Solutions Inc. and Osler, *Emerging technologies in energy: environmental and regulatory considerations for Western Canada* (2021), 43. https://www.osler.com/osler/media/Osler/infographics/Osler_Emerging-technologies-in-energy_full-publication.pdf

[127] Matrix, *Emerging technologies in energy*, 46.

ownership on freehold lands is not clearly stated. Pore space ownership is expected to be clarified as part of Saskatchewan's CCUS recent priorities.[128]

By contrast, underground CO_2 storage is prohibited in Ontario by the Oil, Gas and Salt Resources Act, as of this writing.[129] While the decision has been made to remove the prohibition and begin fostering development, Ontario is early in the process compared to other provinces.[130]

While no specific regulation for DAC exists in Canada, a DAC plant would fall under standard land use, industrial health and safety, and environmental considerations as would other industrial operations.

Offshore operations would involve its own set of requirements. Due to the lack of existing projects, there is not a clear path of licensing required to initiate an offshore project that involves sub-oceanic storage.[131]

One scenario that may have to be handled in the future is different applications competing for the same pore space, i.e., if a DAC and a carbon capture project both want to use the same deep saline aquifer for storage. How licensing is managed in these situations may shape the landscape of geologic storage. The associated potential impact of cumulative effects would also need to be considered. The potential risks associated with geological events or leakage may be amplified if multiple projects co-locate in the same or adjacent geological formations.

Clear regulations and processes are important to promote safe and sustainable development. Ambiguity and unpredictability are barriers to investment.

5.3 Investment support

There are announced and existing programs to support the upfront development of CDR in Canada. The federal government has proposed a CCUS investment tax credit that includes DAC. Until 2030, organizations can receive 60% of investments in DAC

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[128] Government of Saskatchewan, "Saskatchewan Announces Carbon Capture Utilization and Storage Priorities," media release, September 7, 2021. https://www.saskatchewan.ca/government/news-and-media/2021/september/07/saskatchewan-announces-carbon-capture-utilization-and-storage-priorities

[129] Environmental Registry of Ontario, "Proposed amendments to the Oil, Gas and Salt Resources Act, to remove the prohibition on carbon sequestration." https://ero.ontario.ca/notice/019-6296

[130] Government of Ontario, "Geologic carbon storage." https://www.ontario.ca/page/geologic-carbon-storage

[131] Webb et al., *The Legal Framework for Offshore Carbon Capture and Storage in Canada*, i.

equipment back in tax credits, and 37.5% of investments related to transportation, storage, and utilization back. These numbers reduce by 50% in 2031 to encourage early adoption.[132] This would be a helpful nudge to spur new investment into DAC, by offsetting a large portion of the initial capital investment.

In Saskatchewan, a tax credit of 20% is now expanded to include CO_2 pipeline projects, as part of the Oil Infrastructure Investment Program.[133] This credit can help with project siting, by making longer distances between removal and storage potentially feasible.

Other, more general, programs are available to help incentivize CDR development, and are likely needed for early deployments that offer important learning opportunities that will drive down this technology's future costs and uncertainties. The federal government has a basket of funding available for climate action research and development which could be leveraged. Both the Net Zero Accelerator Initiative[134] and the Climate Action and Awareness Fund[135] have funding available that CDR development could apply for. Sustainable Development Technologies Canada offers $750 million over five years to scale new clean technologies.[136] Natural Resources Canada operates an Energy Innovation Program that funds research towards transitioning Canada into a low-carbon economy.[137]

Continued investment in research and development will be key to improving CDR technologies and lowering their associated costs. Increasing the rate of testing means increasing the speed across learning curves, which is crucial for cost reduction.

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[132] Government of Canada, "Chapter 3: Clean Air and a Strong Economy," in *Budget 2022*. https://www.budget.canada.ca/2022/report-rapport/chap3-en.html

[133] Government of Saskatchewan, "Oil Infrastructure Investment Program (OIIP)." https://www.saskatchewan.ca/business/agriculture-natural-resources-and-industry/oil-and-gas/oil-and-gas-incentives-crown-royalties-and-taxes/oil-infrastructure-investment-program

[134] Innovation, Science and Economic Development Canada, "Net Zero Accelerator Initiative." https://ised-isde.canada.ca/site/strategic-innovation-fund/en/net-zero-accelerator-initiative

[135] Government of Canada, "Climate Action and Awareness Fund." https://www.canada.ca/en/services/environment/weather/climatechange/funding-programs/climate-action-awareness-fund.html

[136] Government of Canada, "Clean technology and climate innovation" in *Canada's 2030 Emissions Reduction Plan – Chapter 2*. https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/climate-plan-overview/emissions-reduction-2030/plan/chapter-2.html#toc13

[137] Natural Resources Canada, "Energy Innovation Program." https://www.nrcan.gc.ca/science-and-data/funding-partnerships/funding-opportunities/funding-grants-incentives/energy-innovation-program/18876

5.4 Integration into carbon pricing programs

Non-biological CDR is currently excluded from carbon pricing and offset programs. This results in a lack of predictable operating revenue, making it difficult to justify market entry. CDR projects are expected to be financed, built and operated under a standard project-finance model, which necessitates reliable revenue streams upon which to secure financing. Thoughtful inclusion into Canada's carbon pricing systems, in which CDR projects can monetize the act of permanently removing CO_2 from the atmosphere, will be key.

Currently, CO_2 removed using any of the non-biological CDR activities described in this paper cannot be credited in Canadian carbon pricing or offset programs. This means they lack predictable operating revenue, making it difficult to justify market entry, but policies are starting to advance.

The federal government has announced they are developing a protocol to include DAC with geological storage within the Greenhouse Gas Offset Credit System.[138] Additionally, steps have been taken to increase certainty of revenue from offset programs, including the requirement that provincial and territorial pricing systems follow the federal pricing schedule from 2023 to 2030 and the requirement that demand for credits must always be higher than supply, ensuring appropriate value for each credit.[139] Assuring long-term carbon price certainty through contracts for difference is integrated in the Canada Growth Fund, announced in 2022.[140] These are promising developments that, once finalized, will help support more CDR projects.

Recognition of CDR in provincial and territorial offset systems expands the number of potential market participants even further, given the federal system only applies in provinces and territories that do not have their own industrial carbon pricing system in force. The Alberta Emission Offset System has offsets and credits for carbon capture and geologic storage, but only if the CO_2 is captured directly from a regulated industrial

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[138] Environment and Climate Change Canada, "Canada's Greenhouse Gas Offset Credit System." https://www.canada.ca/en/environment-climate-change/services/climate-change/pricing-pollution-how-it-will-work/output-based-pricing-system/federal-greenhouse-gas-offset-system.html

[139] Environment and Climate Change Canada, "Update to the Pan-Canadian Approach to Carbon Pollution Pricing 2023-2030." https://www.canada.ca/en/environment-climate-change/services/climate-change/pricing-pollution-how-it-will-work/carbon-pollution-pricing-federal-benchmark-information/federal-benchmark-2023-2030.html

[140] Department of Finance Canada, *Canada Growth Fund: Technical Backgrounder* (2022), 7. https://www.budget.canada.ca/fes-eea/2022/doc/gf-fc-en.pdf

facility.[141] The BC GHG Offsets program is currently working on including afforestation, a form of biological CDR.[142] The Quebec Carbon Market – Offset Credits program does not have any inclusion for CDR.[143]

The one program that Canadian CDR efforts can obtain offset credits through is the Low Carbon Fuel Standard in California. This program offers credits for CO_2 captured by DAC and stored underground even outside of California.[144]

5.5 Integrating Indigenous perspectives

There has been limited discussion on the role Indigenous communities could play in CDR development, as well as the possible environmental impacts that large-scale CDR could have on their communities and traditional territories.[145] Environment and Climate Change Canada has invited Indigenous participation in developing protocols within the Federal GHG Offset System.[146] However, the extent of the proposed Indigenous engagement does not include Canada's larger strategy around CDR deployment. As per the United Nations Declaration on the Rights of Indigenous Peoples Act, any decisions affecting the rights and interests of Indigenous peoples would require "free, prior and informed consent."[147] Broader decisions around how CDR technologies are handled in Canada fall within this need for consent.

Certainly, Indigenous communities express long-standing, serious concerns about how climate change impacts their Aboriginal and Treaty rights, cultural and spiritual

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[141] Government of Alberta, "Quantification protocol for CO_2 capture and permanent storage in deep saline aquifers." https://open.alberta.ca/publications/9780778572213#summary

[142] Government of British Columbia, "Greenhouse gas emission offset projects." https://www2.gov.bc.ca/gov/content/environment/climate-change/industry/offset-projects

[143] Ministère de l'Environnement, de la Lutte contre les changements climatiques, de la Faune et des Parcs, "Carbon Market: Offset Credits." https://www.environnement.gouv.qc.ca/changements/carbone/credits-compensatoires/index-en.htm

[144] California Air Resources Board, "Carbon Capture and Sequestration Project Eligibility FAQ." https://ww2.arb.ca.gov/resources/fact-sheets/carbon-capture-and-sequestration-project-eligibility-faq

[145] Craik et al., "The Legal Framework for Carbon Dioxide Removal in Canada," 868.

[146] Environment and Climate Change Canada, "Carbon Pollution Pricing: Considerations for facilitating Indigenous participation in the Federal Greenhouse Gas Offset System." https://www.canada.ca/en/environment-climate-change/services/climate-change/pricing-pollution-how-it-will-work/output-based-pricing-system/federal-greenhouse-gas-offset-system/considerations-indigenous-participation.html

[147] Department of Justice Canada, "Backgrounder: United Nations Declaration on the Rights of Indigenous Peoples Act." https://www.justice.gc.ca/eng/declaration/about-apropos.html

practices, and traditional lands.[148] For instance, for the past few decades, the oilsands in Alberta have had an adverse effect on the Athabasca Chipewyan First Nation (ACFN), Beaver Lake Cree Nation (BLCN) and Mikisew Cree First Nation (MCFN). Negative health outcomes in communities near oilsands have been linked to worsened air quality and tailings pond leaks.[149] Nearby operations have caused low water levels in the Athabasca River, impacting local wildlife and constraining boat travel. Winter roads are available for less time due to climate change, restricting supply transport into Fort Chipewyan. Caribou populations are threatened due to oilsands development in their habitat.[150]

It is with this context that the ACFN, BLCN and MCFN proposed an amendment to the Canadian Net-Zero Emissions Accountability Act in 2021, in efforts to guard against continued fossil fuel production and consumption. The proposed amendment stipulates that the net-zero emissions target be achieved by reducing emissions by at least 90% below 2005 levels.[151] This would safeguard against using CDR to delay reduction efforts, while still recognizing the need for CDR to address the emissions that cannot be reduced. This highlights an important perspective that while CDR represents a viable option for difficult-to-eliminate emissions and for net negative emissions, it cannot delay the deployment of direct emissions reductions options.

5.6 Integrating community perspectives

Public awareness of CDR as a general topic has been found to be low, with most of the attention focused on biological methods. Within the existing awareness, there is overall support for more research into CDR, and a generally increasingly positive sentiment toward CDR over time.[152] That said, perception of CDR projects from nearby

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[148] National Collaborating Centre for Indigenous Health, “Climate Change and Indigenous Peoples’ Health in Canada” in *Health of Canadians in a Changing Climate: Advancing our Knowledge for Action* (2022). https://changingclimate.ca/health-in-a-changing-climate/chapter/2-0/

[149] Sarah Lawrynuik, “Downstream of oilsands, death by cancer comes too often,” *National Observer*, December 17, 2019. https://www.nationalobserver.com/2019/12/17/news/downstream-oilsands-death-cancer-comes-too-often

[150] Lisa Tssessaze, Crystal Lameman, and Melody Lepine, “Indigenous concerns with using carbon dioxide removal to achieve Canada’s net-zero target: a submission to the Standing Senate Committee on Energy, the Environment and Natural Resources regarding Bill C-12,” June 7, 2021. https://sencanada.ca/content/sen/committee/432/ENEV/Briefs/2021-06-07_Brief_ACFNBLCNMCFN_e.pdf

[151] Tssessaze et al., “Indigenous concerns with using carbon dioxide removal to achieve Canada’s net-zero target.”

[152] Smith et al., *State of Carbon Dioxide Removal*, 41.

communities may be different, similar to how general acceptance of renewable energy is high, but local acceptance can vary.[153]

Large-scale industrial projects will undoubtedly attract concern from nearby communities, particularly if new technology is involved. Proper consultation with communities is required to ensure that environmental impact concerns are addressed, including land use, noise and visual impact. Lessons learned from other industrial developments can be adapted for CDR. As an example, the Canadian Renewable Energy Association has published best practices for Indigenous and community engagement, many principles of which would be useful for CDR development.[154] Social acceptance and responsible development will be critical for the success of large-scale CDR, and so high standards for community engagement should be required for CDR projects.

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[153] Marco Segreto, Lucas Principe, Alexandra Desormeaux, et al. “Trends in Social Acceptance of Renewable Energy Across Europe—A Literature Review,” *International Journal of Environmental Research and Public Health* 17, no. 24 (2020), 9161. https://doi.org/10.3390/ijerph17249161

[154] Canadian Renewable Energy Association, *Best Practices for Indigenous & Public Engagement* (2017). https://renewablesassociation.ca/wp-content/uploads/2020/06/Wind-energy-development-best-practices_June-2020.pdf

6. Conclusion and next steps

Emerging engineered non-biological technologies show promise of durable and measurable CO_2 removal. Timely investment and rapid deployment can advance the technology and address questions and challenges around environmental impacts and high current costs of deployment, so it is a viable solution when needed in the coming decades. However, investing in advancing CDR should not be seen as an alternative to, or delay, investment in direct near-term emissions reduction efforts. If that were allowed to happen, it would likely negatively impact public acceptance of CDR and hinder progress.

B.C., Alberta, Saskatchewan, Manitoba, the Northwest Territories and the Yukon all feature underground storage potential near renewable energy sources, either through low-carbon grids or location-specific generation potential. This makes them prime locations for DAC with geologic storage development. Existing expertise and infrastructure in Alberta and Saskatchewan relevant for geologic storage can be leveraged.

Canada's strategy towards CDR development may impact the rights and interests of Indigenous communities, and thus needs to involve them as decision-makers and to provide consent for any actions. Education and engagement with other communities should continue in order to build public support.

Current areas requiring attention include:

- Measurement and verification standards for each type of CDR will ensure credible accounting and help scale procurement.
- Support is critical for research and development aimed at addressing risks, uncertainties and high costs of CDR.
- Investment in progressively larger implementations can advance CDR technologies down their learning curves, improving their costs and lowering their risks.
- Unambiguous regulation that keeps pace with CDR development can reduce investment uncertainty, while also ensuring safe deployment.
- Supporting the business case for CDR through credit market deployment, including recognizing CDR within offset protocols, can provide reliable revenue to justify investment.

As the CDR space in Canada evolves, the Pembina Institute plans to continue to provide thought leadership and collaboration with various stakeholders, participants and government in this space. This includes collaboration with the University of Calgary in a multi-year research project aimed at developing policy options for CDR in Canada, as well as engagement with other groups across many parts of Canada on ways to spur market deployment. For the latest insights and developments, visit www.pembina.org.

Appendix A. Additional cost information

A.1 DAC cost variables

Published current costs for DAC operations are stated to be around \$900/tCO_2.[155] This is estimated to reduce to \$130-400 by 2035.[156,157] Note that this is just the cost of removal and does not include the cost of storage, transport, or use, which are required for a complete CDR solution.

Direct air capture is an expensive technology, due mainly to the fact that CO_2 is so dilute in the air. For comparison, CCS capturing exhaust flue gas from natural gas power plants would see CO_2 concentrations around 100 times more than is typical in the atmosphere. This results in DAC having substantially higher annual energy operating costs than CCS — each tonne of CO_2 removed with DAC requires 6 to 10 GJ[158] of energy compared with 0.7 to 1.8 GJ for CCS.[159]

Climate is one factor that may influence the cost of operating a DAC plant. Some studies have suggested worse performance at colder temperatures,[160] though there may be energy savings[161] and design optimizations[162] that can improve how it runs. More

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[155] McQueen et al., "The Building Blocks of CDR Systems: Direct air capture."

[156] Catherine Clifford "From milligrams to gigatons: Startup that sucks carbon dioxide from the air is building a big plant in Iceland," *CNBC*, June 28, 2022. https://www.cnbc.com/2022/06/28/climeworks-carbon-dioxide-removal-company-building-iceland-plant.html

[157] Keith et al., "A Process for Capturing CO_2 from the Atmosphere," 1573.

[158] IEA, "Direct Air Capture."

[159] Xiaoxing Wang and Chunshan Song, "Carbon Capture From Flue Gas and the Atmosphere: A Perspective," *Frontiers in Energy Research* 8 (2020). https://www.frontiersin.org/articles/10.3389/fenrg.2020.560849/full

[160] Keju An, Azharuddin Farooqui, Sean T. McCoy, "The impact of climate on solvent-based direct air capture systems," *Applied Energy* 325, issue 1 (2022). https://doi.org/10.1016/j.apenergy.2022.119895

[161] Guanhe Rim, Fanhe Kong, Mingyu Song, et al. "Sub-Ambient Temperature Direct Air Capture of CO_2 using Amine-Impregnated MIL-101(Cr) Enables Ambient Temperature CO_2 Recovery," *Journal of the American Chemical Society* 2, no. 2 (2022), 380. https://doi.org/10.1021/jacsau.1c00414

[162] Sean M.W. Wilson, "The potential of direct air capture using adsorbents in cold climates," *iScience* 25, issue 12 (2022), 105564. https://doi.org/10.1016/j.isci.2022.105564

research is required to investigate these climate effects on DAC performance. Lower performance would increase the cost of removing each tonne of carbon.

Some opportunities for cost reduction include:

- Changes in the geometry and depth of air contactors for both S-DAC and L-DAC systems are expected to yield significant cost savings.
- Waste heat from other industrial processes could be used for solid DAC, which does not require as high heat as liquid DAC. Of the energy required for DAC plants, 80% is thermal energy and only 20% is electricity.[163]
- New methods to separate the CO_2 from the capturing unit could potentially reduce the high energy input required. Verdox is an organization looking to use an electrochemical swing instead of temperature.[164]
- Economies of scale and learning by doing offer the potential for significant cost savings. As the DAC industry grows, mass production will allow cost reductions through optimized supply chains and shared infrastructure. Better ways to design, build and operate DAC plants will be learned through deployment experience.

A.2 Mineralization

Storage via *ex situ* mineralization is much more expensive than *in situ*, and 10 times more expensive than geologic storage.[165] Associated costs including the mining of alkaline material, grinding of material to increase the surface area, transport of material to the site, and then dealing with the carbonate material afterwards.

Surficial mineralization methods have a wide range of estimated costs depending on the source of the alkaline material. Using waste mine tailings would be a lower cost option, whereas mining for mafic and ultramafic rocks for the purpose of CO_2 removal and storage is estimated to cost between \$75/tCO_2 to \$675/tCO_2, depending on various factors.[166]

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[163] Noah McQueen, Jennifer Wilcox, Joseph Hamman, Jeremy Freeman, "The cost of direct air capture," *CarbonPlan*, February 1, 2021. https://carbonplan.org/research/dac-calculator-explainer

[164] Verdox, "Video: Our Technology." https://verdox.com/video/technology

[165] Raza et al., "Carbon mineralization and geological storage of CO_2 in basalt."

[166] Kelemen et al., "An Overview of the Status and Challenges of CO_2 Storage in Minerals and Geological Formations."

A.3 Carbon use

Converting captured carbon into a sellable product can reduce the overall cost of CDR solutions. There are emerging pathways to use CO_2 as a source of carbon for chemical production.[167] Finding use cases where the inclusion of stored CO_2 is cheaper than the traditional alternative will be the key to finding market opportunities for carbon use. There is good potential for this in concrete production.[168]

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[167] IEA, *Putting CO_2 to Use*.

[168] Larry Stewart, "CarbiCrete makes cheaper, stronger concrete blocks carbon negative," *CONEXPO-CON/AGG*, October 19, 2022. https://news.conexpoconagg.com/news/carbicrete-makes-cheaper-stronger-concrete-blocks-carbon-negative/9961.article

Appendix B. Additional potential environmental impacts

B.1 Water usage with *in situ* mineralization

Water usage is a potential concern with *in situ* mineralization. When CO_2 is injected underground for mineralization, the reaction happens more quickly and smoothly if it is first dissolved in water. Dissolving in water also reduces chances for leakage, as the CO_2 is no longer buoyant.[169] This is unlike deep geologic storage, in which the CO_2 is in a buoyant supercritical phase. However, approximately 27 tonne of water is required per tonne of CO_2.[170] Ocean-based solutions can reduce the need for additional water.[171] S-DAC systems produce water as a byproduct, which can reduce the amount of additional water brought into a system using *in situ* mineralization.

B.2 Additional mining activity for alkaline material

Ex situ mineralization, some forms of surficial mineralization, and ocean alkalinity modification would require extracting minerals to react with CO_2, leading to an increase in mining activity. Measures have to be taken to ensure this activity is low carbon to keep the entire process net negative in emissions. The mining activity would also be accompanied by its associated environmental impacts.

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[169] Bergur Sigfusson, Sigurdur R. Gislason, Juerg M. Matter, et al. "Solving the carbon-dioxide buoyancy challenge: The design and field testing of a dissolved CO_2 injection system," *International Journal of Greenhouse Gas Control* 37 (2015), 213. https://doi.org/10.1016/j.ijggc.2015.02.022

[170] Raza et al., "Carbon mineralization and geological storage of CO_2 in basalt."

[171] Raza et al., "Carbon mineralization and geological storage of CO_2 in basalt."