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RESEARCH REPORT

Ready for Removal:
A Decisive Decade for Canadian Leadership in Carbon Dioxide Removal

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Acronyms and abbreviations

BECCS
Bioenergy with carbon capture and storage

BiCRS
Biomass carbon removal and storage

CCfDs
Carbon contracts for difference

CCUS
Carbon capture, utilization and storage

CDR
Carbon dioxide removal

CO_2
Carbon dioxide

CO_2e
Carbon dioxide equivalent

DAC
Direct air capture

DOE
U.S. Department of Energy

GDP
Gross domestic product

GHG
Greenhouse gas

Gt
Gigatonne

IPCC
Intergovernmental Panel on Climate Change

IRA
Inflation Reduction Act

ITC
Investment tax credit

LULUCF
Land use, land-use change and forestry

MMRV
Measurement, monitoring, reporting and verification

Mt
Megatonne

R&D
Research and development

RD&D
Research, development and demonstration

UNFCCC
United Nations Framework Convention on Climate Change

About Carbon Removal Canada

Carbon Removal Canada (CRC) is an independent policy initiative focused on the rapid and responsible scaleup of carbon removal solutions needed to meet Canada's climate goals. Based in Toronto, Ontario, CRC is a project of the Clean Prosperity Foundation and the first group in Canada dedicated to shaping policies and strengthening systems to build an innovative and inclusive carbon removal field.

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We acknowledge with respect that this report was produced on the traditional, ancestral, and unceded territories of many nations including the Mississaugas of the Credit, the Anishinaabeg, the Chippewa, the Haudenosaunee and the Wendat — whose deep connections with this land continue to this day.

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Image courtesy of: Carbon Engineering

Executive summary

Carbon dioxide removal (CDR) is the intentional, human-driven process of removing carbon dioxide (CO_2) that is already in the atmosphere and storing it away for centuries or longer. It is an indispensable complement to deep emissions cuts across the economy, because even after society reaches net-zero emissions, there will still be a need to pull billions of tonnes of CO_2 out of the atmosphere to meet global temperature targets.

Consistent with Canada's commitment to the goals of the Paris Agreement, this means building an industry ready to remove hundreds of millions of tonnes of CO_2 from the atmosphere per year by mid-century. An industry at this scale will play an important role in helping Canada achieve its national climate goals by compensating for residual emissions that are technically difficult or prohibitively expensive to mitigate directly or for sources of emissions that do not currently have mitigation options. Even more importantly, it will enable Canada to draw down its fair share of historical emissions and contribute to global CDR needs this century.

Canada has an abundance of land, extensive coastlines, and large geologic storage potential needed to achieve CDR at large scale. This is in addition to a clean energy supply, skilled workforce, traditional knowledge systems and a culture of innovation that is vital for the creation of a robust CDR sector.

If policymakers take targeted action to lead the creation of this critical industry now, they can mobilize Canada's innovation ecosystem to support the CDR sector and capture a major economic opportunity. An analysis commissioned by Carbon Removal Canada estimated that a CDR industry removing hundreds of millions of tonnes of CO_2 from the atmosphere by 2050 could **create over 300,000 jobs, add $143 billion in GDP**, and support other critical industrial sectors like construction, equipment manufacturing, steel and cement.

The Government of Canada, working closely with the provinces and territories, should implement policies that create a strong CDR demand signal, accelerate technology advancement, and enable rapid and responsible deployment of CDR projects. In this formative decade for CDR, policy decisions taken today will affect the trajectory of this industry for decades to come. If Canada is going to build out the CDR industry to help address climate change, considerable actions must be taken this decade to achieve the required scale by mid-century. **This is a critical moment for policymakers, in partnership with the broader community of CDR actors, to take bold action on this exciting and necessary climate solution.**

Section 1

Why carbon dioxide removal?

CDR — the process of removing CO_2 from the atmosphere and storing it away for centuries or longer — is an indispensable tool alongside aggressive emissions reduction strategies to achieve global climate goals.

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Since the Industrial Revolution, humanity has emitted an estimated 2.5 trillion tonnes of CO_2 which has led to a buildup of this heat-trapping greenhouse gas (GHG) in the atmosphere.[1]

The current concentration of atmospheric CO_2 is unprecedented in the last several million years[2] and is having a profoundly negative impact on the planet. At present, the global average surface temperature stands at approximately 1.3 °C above pre-industrial levels.[3] Taking into account the totality of national climate pledges established to date, warming by the end of the century is expected to range from 1.7 °C (fulfillment of all climate pledges) to 2.6 °C (fulfillment of only credible climate pledges).[4,5]

In response to rising temperatures, 196 nations committed to the goals of the Paris Agreement in 2015, which means limiting an increase in global average surface temperature to less than 2 °C above pre-industrial levels with the further ambition of keeping warming below 1.5 °C.[6] Regrettably, global annual CO_2 emissions continue to trend upwards (reaching nearly 41 billion tonnes of CO_2 [$GtCO_2$] in 2022[7]) and push the world further away from meeting the Paris climate targets. Society has been moving too slowly on mitigation, and while reducing emissions must remain the primary focus of the global effort to address climate change, we also need to cultivate additional solutions to manage the problem. CDR — the process of removing CO_2 from the atmosphere and storing it away for centuries or longer — is an indispensable tool alongside aggressive emissions reduction strategies to achieve global climate goals.

The purpose of this report is to help identify the role and potential scale of CDR needed in Canada; highlight the economic benefits that could be unlocked by leveraging national advantages to position Canada as a major player in this new industry; and recommend what policymakers should do to maximize this opportunity for global leadership.

Canada will require megatonne-scale CDR that quickly scales from tens to hundreds of millions of tonnes of CO_2 per year over the coming decades to help meet national and global climate goals.

Based on our findings, Canada will require megatonne-scale[8] (Mt) CDR that quickly scales from tens to hundreds of millions of tonnes of CO_2 per year over the coming decades to help meet national and global climate goals.

Canada's natural resources, clean energy assets, geologic storage potential, a culture of innovation and other strategic advantages position it to scale CDR for positive climate impact while also realizing economic gains.

Near-term actions matter; policy decisions made today will have a longstanding influence on the future of the CDR industry in Canada. Immediate actions are needed around target-setting, policy incentives, regulatory structures, programmatic implementation, and mobilizing adequate financial support (among other factors). This is the decisive decade to support CDR and climate solutions more broadly so society can prepare the most promising options for deployment at scale.

Role of CDR

Society is faced with the twin challenges of drastically reducing CO_2 emissions (and other GHGs) into the atmosphere while simultaneously removing legacy CO_2 from the atmosphere that has accumulated over time in excess of pre-industrial levels. Although reaching net-zero is expected to lead to a rapid cessation of warming within several years,[9] society will still be 'locked in' to the magnitude of negative climate impacts associated with the particular level of warming at that level. Every fraction of a degree matters and the difference in projected climate impacts between 1.5 °C and 2 °C of warming are stark.[10] This underscores the urgent need to stop emitting new GHGs into the atmosphere that add to the cumulative stock of emissions while also developing a set of technologies and strategies that can begin removing historical CO_2 from the atmosphere. CDR is a vital and necessary complement to, but not a substitute for, deep and rapid reductions in global GHG emissions and must not be used for mitigation deterrence.[11] Indeed, the more successful society is at reducing emissions, the less historical CO_2 will need to be removed from the atmosphere to achieve climate goals.

Image courtesy of: Carbon Engineering

CDR is a vital and necessary complement to, but not a substitute for, deep and rapid reductions in global GHG emissions.

CDR is the intentional, human-driven process of removing CO_2 from the atmosphere and storing it away for centuries or longer in a way that cannot be easily reversed. The Intergovernmental Panel on Climate Change (IPCC) has clearly articulated the need for CDR to help meet global climate goals and defined its role to include:

1. lowering net CO_2 or other GHG emissions into the atmosphere in the near term,
2. the "unavoidable" need to compensate for residual emissions[12] that are difficult to eliminate from the economy in fulfillment of net-zero emissions; and
3. achieving net-negative emissions in the longer term.[13]

CDR features in all scenarios that are compatible with the goals of the Paris Agreement[14] and provides the opportunity to reduce atmospheric CO_2 concentrations through sustained net-negative emissions and lower global average surface temperatures. Doing so will necessitate developing a new enterprise that is comparable in size to the oil and gas industry[15] but which works in reverse to remove historical CO_2 emissions from the atmosphere at the gigatonne[16] scale per year.

CDR is society's only means to address historical emissions, and thus can serve as a risk management tool that helps to limit temperature overshoot[17] above global climate targets and potentially reduce the amount of time that is spent in a period of overshoot. Importantly, CDR is distinct from carbon capture, utilization and storage (CCUS). Whereas CCUS seeks to prevent new CO_2 emissions from entering into the atmosphere from various emitting sources, CDR seeks to remove already emitted CO_2 from the atmosphere.[18]

CDR and CCUS are two distinct sets of technologies that exist to solve two different aspects of the climate problem:

Carbon Dioxide Removal (CDR)
Seeks to **remove already emitted CO_2** from the atmosphere

Carbon Capture, Utilization, and Storage (CCUS)
Seeks to **prevent new CO_2 emissions** from entering into the atmosphere

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Defining the CDR need in Canada

Bringing CDR to the requisite scale is a massive challenge (**Table 1**) and will require deploying a broad portfolio of solutions (**Figure 1**); conventional methods alone (such as planting trees) will likely not be enough.[19] Total anthropogenic CDR is estimated to be roughly 2,000 million tonnes of CO_2 ($MtCO_2$) per year globally, of which the vast majority occurs through land-based interventions such as forestry, with only 2 $MtCO_2$ per year being met through longer-duration CDR methods such as direct air capture (DAC).[20] In a future of worsening climate impacts and increasing strain on biological systems, higher-durability CDR solutions must be prioritized.[21] Financial flows will also need to increase dramatically to help realize the scale potential of CDR in Canada and globally. **It has been estimated that only USD$200 million was invested in new CDR capacity worldwide from 2020 – 2022,**[22] **— a paltry sum compared to the USD$1.7 trillion that is expected to be invested in clean energy in 2023.**[23]

TABLE 1: ESTIMATED CUMULATIVE NEED FOR CDR GLOBALLY IN ALIGNMENT WITH 1.5 °C TEMPERATURE TARGET, 2020 – 2100

Scenario Type	Total CDR Need (All removal options) ($GtCO_2$)
<1.5 °C (No or limited overshoot)	740 (420 – 1,100)
<1.5 °C (High overshoot)	850 (590 – 1,300)

Note: These estimates contain inherent uncertainties, and other literature estimates may vary depending on the methodology and assumptions. Data is presented as the median value and 5 per cent – 95 per cent range of values.

Source: Smith et al., 2023[24]

FIGURE 1: OVERVIEW OF VARIOUS CDR METHODS

1

CARBON MINERALIZATION

CO_2 absorbed into rocks above or below the surface for storage in solid mineral form

2

BIOCHAR

Plant biomass converted to a carbon-rich solid for various uses

3

DIRECT AIR CAPTURE

Use of special chemicals and materials that selectively bind CO_2 from ambient air

4

ENHANCED ROCK WEATHERING

Crushed rocks spread onto agricultural lands or other areas to capture atmospheric CO_2

5

DIRECT OCEAN CAPTURE

Directly processing seawater using electrochemistry to remove CO_2

6

OCEAN ALKALINITY ENHANCEMENT

Alkaline material added to the surface layer of the ocean to neutralize dissolved CO_2

7

MACROALGAE CULTIVATION

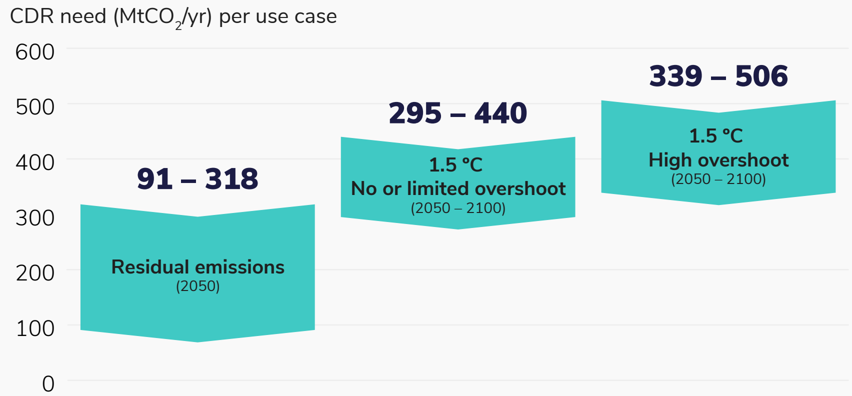
Growing seaweed in marine environments for the purposes of sinking it to the bottom of the ocean or harvesting it for various biomass-related applications

This section describes two critical needs for CDR (**Figure 2**):

1. to deploy CDR to compensate for residual emissions that may remain across the Canadian economy by mid-century to help fulfill the mandate of net-zero emissions by 2050; and
2. to deploy CDR to address historical emissions, enabling Canada to do its fair share of helping the world remain in alignment with global climate targets.[25]

Ideally, the amount of CDR needed to achieve net-zero emissions would be minimal, so the industry can deploy its capacity and efforts toward limiting temperature overshoot and cleaning up historical emissions.

FIGURE 2: POTENTIAL CDR NEED IN CANADA ACROSS DIFFERENT USE CASES



Note: The following bars pertain to the estimated amount of CDR that could be required for Canada to manage its residual emissions by mid-century, and also contribute to global CDR needs to meet Paris-aligned temperature targets based on its share of historical emissions. Excluding the bar for residual emissions, the lower bounds pertain to fossil fuel emissions only and the upper bounds pertain to economy-wide emissions (fossil fuel use and land-use change). A detailed methodology can be found in the appendix.

Source: Carbon Removal Canada, 2023

Residual emissions

Considerable uncertainty exists regarding the amount of residual emissions that will remain by mid-century and require the use of CDR to achieve net-zero emissions. An analysis of national long-term strategies submitted to the United Nations Framework Convention on Climate Change (UNFCCC)[26] found that residual emissions in Canada were anticipated to be approximately 20 per cent of its 2019 emissions level[27] or 149 $MtCO_2e$[28] by 2050.[29] Previous modelling studies have also sought to estimate the implicit demand for CDR in Canada to help meet its mid-century climate target and address residual emissions (**Table A-2**). Based on these studies, the estimated or implicit need for CDR in Canada by 2050 **ranged widely between 91 – 318 $MtCO_2$ per year.**[30] While residual emissions are likely to remain across the economy by

2050, further innovation and technology breakthroughs could provide viable alternatives to reduce the need for CDR to compensate for residual emissions beyond mid-century. Therefore, these estimates are likely to be a ceiling for the amount of residual emissions in Canada by 2050, rather than a floor.[31]

In the event that residual emissions do approach zero by mid-century, CDR capacity that is not used for residual emissions would instead contribute toward the urgent need to reduce historical emissions from the atmosphere.

If Canada continues to experience record-breaking wildfire activity similar to that experienced in 2023 — with resultant emissions that could be more than triple those from all other sectors of the economy combined[32,33] — the need for CDR to address residual emissions could be considerably higher.

It will therefore be imperative that Canada pursue an inclusive portfolio of CDR solutions that promotes durable carbon storage over long timescales.[34]

Historical emissions

If the world is to avoid the worst impacts of climate change, society will need to go beyond net-zero emissions and remove billions of tonnes of CO_2 from the atmosphere cumulatively by the end of this century.

Given the need for large-scale CDR to help avoid or limit temperature overshoot, Canada should also seek to pursue CDR in accordance with total global CDR needs to have a chance of meeting the 1.5°C target over the long term (**Table 1**). If the world is to avoid the worst impacts of climate change, society will need to go beyond net-zero emissions and remove billions of tonnes of CO_2 from the atmosphere cumulatively by the end of this century.[35] Functionally, society cannot begin to address its historical emissions until it surpasses net-zero emissions toward sustained net-negative emissions globally.[36]

Although assigning a proportion of this historical emissions burden at the national level is complicated, we believe an appropriate approach would be to contribute to global CDR needs over the course of this century based on the percentage of historical emissions that Canada is responsible for since the pre-industrial era. This could equitably position Canada as taking on its 'fair share' of CDR and contribute to climate change solutions commensurate with its contribution to the problem and could serve as a model for other countries to follow.

Canada is responsible for an estimated 73 $GtCO_2$ of cumulative historical emissions since the pre-industrial era.[37,38,39,40,41] These emissions levels correspond to roughly three per cent of global historical emissions across the economy or two per cent of global historical emissions from fossil fuel use only.

Given an estimated total global CDR need of 740 $GtCO_2$ to remain below 1.5 °C with no or limited overshoot, or 850 $GtCO_2$ to remain below 1.5 °C with high overshoot by 2100,[42,43,44] Canada would require an approximate annual CDR capacity of **295 – 440 $MtCO_2$ or 339 – 506 $MtCO_2$ from 2050 – 2100**, respectively, after net-zero emissions have been achieved.

The potential scale of CDR needed in Canada is substantial. While mid-century may still seem far off, reaching the low end of the scale ranges described in this section (approximately 300 $MtCO_2$ per year of CDR by 2050) will require developing CDR capacity right away.

For example, if CDR were to achieve the remarkable annual growth rates experienced by the solar industry of over 20%,[45] Canada would need to have at least 5 $MtCO_2$ per year of CDR under development by 2030 to give it a chance to reach 300 $MtCO_2$ per year by 2050.

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Section 2

Why Canada?

Scaling up CDR in Canada is not only a path to achieving net-zero goals and contributing to our fair share of meeting global temperature targets, but also presents **a major economic opportunity for Canada**.

Globally, the CDR industry is beginning to attract billions of dollars in funding across the public[46] and private[47] sectors. An analysis commissioned by Carbon Removal Canada[48] showed that scaling CDR using DAC within the range of estimated annual removal needs defined in Section 1 **could create over 300,000 jobs and $143 billion in gross domestic product (GDP) by 2050**. Critically, Canada has existing strategic advantages that position the country to immediately capitalize on this economic opportunity.

Economic impact

Removing 1 megatonne of CO_2 per year created over 1,000 jobs and contributed over $460 million to GDP.

Addressing climate change is widely considered the biggest economic opportunity of the current era.[49] **Globally, demand for durable[50] CDR could reach 80 – 900 MtCO_2 in 2040 at a market value of USD$20 – 135 billion.[51]** This massive market potential could greatly benefit Canadian companies, innovators, workers and investors.

Pursuing CDR could create an attractive new engine of economic growth for Canada that would create hundreds of thousands of high-quality jobs. The analysis commissioned by Carbon Removal Canada showed that removing 1 megatonne of CO_2 per year created over 1,000 jobs (almost 1,800 jobs per megatonne facility during periods of construction) and contributed over $460 million to GDP. The resulting jobs span a diverse array of industries and specializations from chemicals to construction to engineering and transportation.

A scenario analysis was used to model the Canadian energy system where total annual DAC capacity in Canada reached 312 MtCO_2 by 2050. Such a scenario falls in the range of estimated CDR needed for addressing historical emissions in Canada set out in Section 1 (though even more CDR might be

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FIGURE 3: JOBS CREATED BY INDUSTRY FROM 312 $MTCO_2$ DAC CAPACITY IN CANADA BY 2050

213,000 Construction

44,000 Operations

33,000 Engineering

17,000 Transportation

13,000 Equipment

11,000 Energy

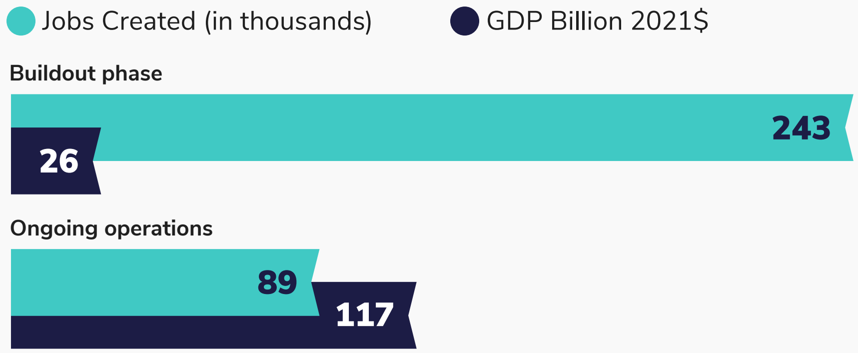
1,000 Other Manufacturing

332,000 potential jobs created

Source: Carbon Removal Canada, 2023

needed for residual emissions). The modelling showed that 312 $MtCO_2$ per year of CDR could lead to the creation of more than 330,000 jobs and $143 billion in GDP by 2050 (**Figure 3 and Figure 4**).[52] These economic gains are split between the extensive buildout and construction of DAC facilities, and the subsequent operation of these facilities. Even after the investment-heavy buildout phase, the economic benefits of the ongoing operation of DAC facilities in Canada were still significant — contributing $117 billion in GDP and creating 89,000 permanent jobs by 2050.

FIGURE 4: POTENTIAL DAC JOB CREATION AND GDP ACCRUED FROM 312 $MTCO_2$ DAC CAPACITY IN CANADA BY 2050



Source: Carbon Removal Canada, 2023

An expansion of CDR in this way could support many other critical industrial sectors in Canada, including construction, equipment manufacturing, cement production and steel manufacturing. The model estimated that DAC investment would create $23 billion in construction demand, and add over $1 billion in new demand for equipment manufacturing, $2.5 billion for steel and $170 million for cement (**Figure 5**).

Additionally, Alberta and Saskatchewan could be major recipients of much of Canada's CDR investment, given that they possess the vast majority of pore space for geologic storage of CO_2 in Canada and are home to many workers in the oil and gas sector with expertise that could be directly transferable to the CDR industry. The benefits of developing a domestic CDR industry could have positive economic impacts outside of DAC, too. For example, an analysis of **Charm Industrial**, a CDR company that converts biomass feedstocks into a bio-oil that is injected underground, found that the company's operations could create 200,000 jobs and contribute USD$20 billion to the GDP by 2040 across the agriculture, forestry, logistics and manufacturing sectors.[53]

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FIGURE 5: POTENTIAL NEW INVESTMENT IN INDUSTRIES FROM 312 $MTCO_2$ DAC CAPACITY IN CANADA BY 2050

New investment (2021$) in 2050

$23B
Construction

$1B
Equipment Manufacturing

$2.5B
Steel

$170M
Cement

Source: Carbon Removal Canada, 2023

Carbon Removal Canada intends to conduct additional research to estimate the economic impacts of scaling up a portfolio of CDR methods in Canada. Such studies could identify region-specific job creation opportunities across Canada by analyzing a diverse set of CDR methods such as biomass carbon removal and storage (BiCRS), ocean CDR and carbon mineralization. Additional research is also needed to inform equitable access to job opportunities created by a growing CDR industry and how best to partner with Indigenous communities in both the management and ownership of CDR projects to promote inclusive economic gains.

Leveraging Canada's strategic advantages

Canada has a number of strategic advantages that can be leveraged to capitalize on the economic opportunity of CDR and contribute to national and global climate goals.

Natural resources

Canada is the second largest country in the world by land area (including territorial waters) and boasts the longest coastline on Earth.[54,55] Canada is also home to the third largest forest area of any country[56] and contains agricultural lands that equate to more than six per cent of its total land area.[57] This extensive geographic area could serve as fertile ground for demonstration and commercial-scale projects across the spectrum of CDR methods, and position Canada as a global deployment hub in this new industry.

Clean energy

Canada has an abundance of clean energy resources that can be leveraged for CDR purposes. Roughly 82 per cent of the electricity generated in Canada in 2021 came from non-fossil energy sources,[58] and Canada is already a global leader in hydroelectric capacity.[59] By 2050, the proportion of Canada's clean electricity generation is projected to increase to 99 per cent if the country is to achieve its net-zero target while still meeting the challenge of future load growth on the grid.[60] Canada may therefore be better positioned than other countries to leverage existing clean energy in a non-competitive manner with mitigation efforts and generate new clean power needed for the rapid buildout of a large CDR sector.

Geologic storage

Canada has a large potential geologic CO_2 storage resource,[61] estimated to range between 198 – 678 $GtCO_2$ across several provinces and federal offshore areas that will need to balance mitigation and CDR use cases.[62] Most of this storage resource is located in saline formations across Saskatchewan and Alberta, with the Western Canadian Sedimentary Basin alone having a potential storage capacity of around 600 $GtCO_2$ (**Figure 6**).[63] If this resource were converted into practical capacity, Canada could store between 360 and over 1,000 years' worth of current annual economy-wide CO_2 emissions.[64,65] This potential storage resource is sizable compared to other countries at the national level.[66]

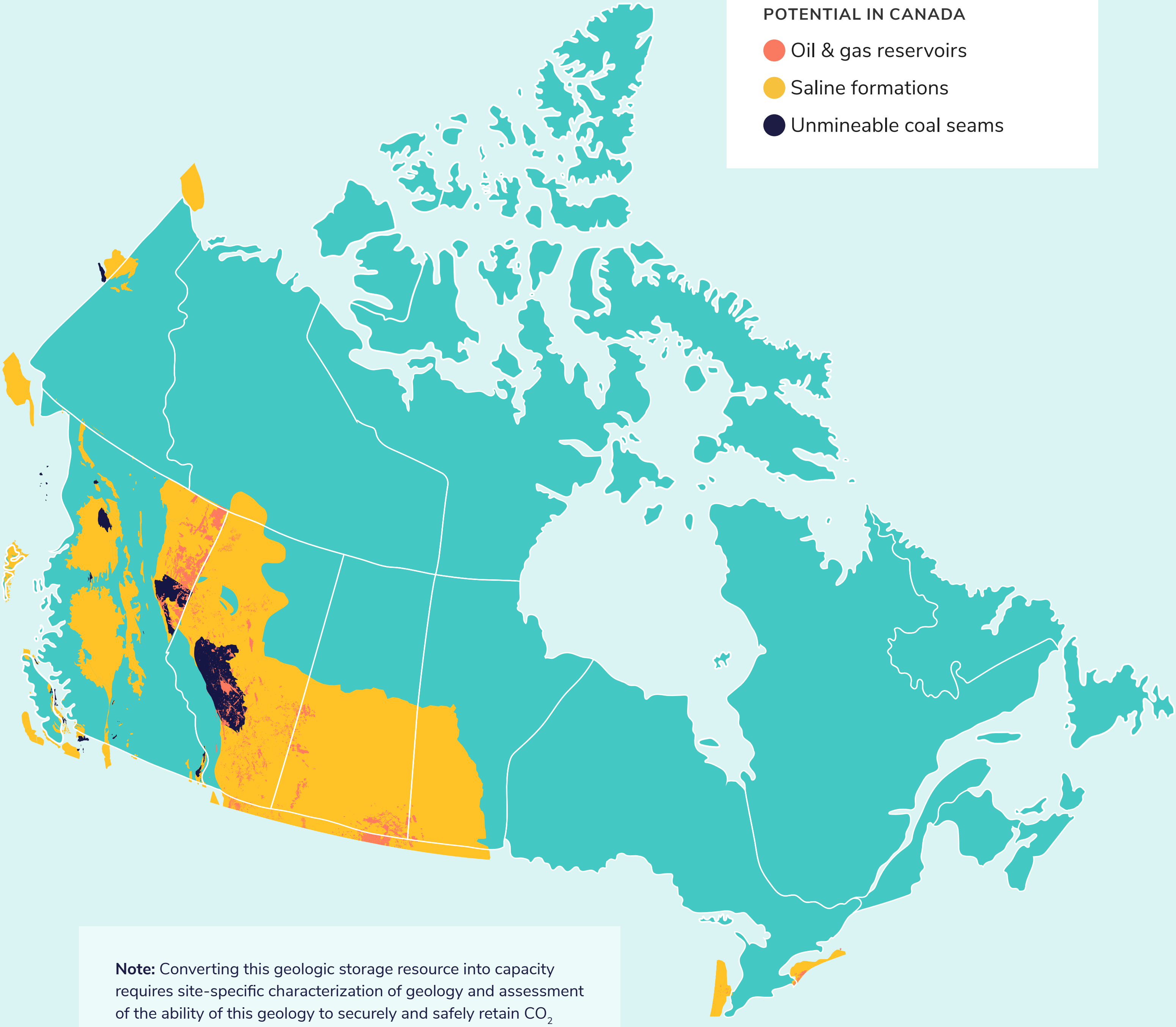
Skilled workforce

Canada has a highly-skilled workforce across a range of sectors that possess the technical know-how to build large infrastructure projects and scale industries. In particular, Canada has tens of thousands of workers with the type of subsurface expertise needed for the CDR sector. CDR companies can tap into translatable skills from oil and gas, mining, and other pertinent industries like forestry. Canada is also regarded as a global destination that can attract highly talented and educated workers who could assist with building a robust CDR industry.

Research and innovation

Canada is recognized as a global leader in science and technology, ranked among the top G7 countries for research and development (R&D) and its ability to attract venture capital.[67] This culture of innovation and entrepreneurial spirit must now be harnessed to seize upon the economic opportunity that CDR presents. Canadian universities are the heart of the R&D innovation ecosystem and can help advance science and maximize the opportunity of CDR, through programs such as the **CanCO2Re Initiative**.[68] Canada's incubators and cleantech accelerators are also central to success in this nascent industry, such as the **Mission from MaRS CDR Accelerator** and **Foresight's CarbonNEXT** program which can help translate lab-scale CDR innovations into commercial opportunities.

FIGURE 6: GEOLOGIC STORAGE POTENTIAL IN CANADA



Note: Converting this geologic storage resource into capacity requires site-specific characterization of geology and assessment of the ability of this geology to securely and safely retain CO_2 injected at practical rates. In offshore environments, real-world project factors such as distance from shore and water column depth could increase the cost of accessing storage resources.[69]

Source: Carbon Removal Canada, 2023. Compiled using data from the U.S. Department of Energy National Energy Technology Laboratory[70] and the Government of Canada.[71]

Section 3

Why now?

Federal, provincial, and territorial governments must act swiftly to create a supportive policy and regulatory environment for CDR or risk Canadian innovators establishing operations and deploying projects outside of Canada.

Canada is uniquely positioned to usher in a new era of industrial opportunity and play a major role in scaling CDR. However, Canada must act quickly as the CDR industry is moving fast in technology, policy and business model innovation in countries around the world.

Developing a CDR industry could help Canada assume a global climate leadership position, promote economic competitiveness, unlock new export markets and create new jobs across the economy in both urban and rural areas. The U.S., EU and China are all seeking to carve out a leadership position in this space.

For Canada, the opportunity cost of advancing CDR is relinquishing the potential economic, social and environmental benefits of leading in this new sector. Given the current policy development landscape in other jurisdictions (such as the United States and EU), Canada must take additional actions now to catalyse a domestic CDR industry and provide a much-needed boost to its nascent CDR innovation system to remain competitive on the global stage.

Therefore, federal, provincial and territorial governments must act swiftly to create a supportive policy and regulatory environment for CDR or risk Canadian innovators establishing operations and deploying projects outside of Canada, which is already beginning to occur in the clean energy sector more broadly.[72,73] There is a real need to remain economically competitive with first-mover countries. Fortunately, Canada is showing promising early signs for the creation of a vibrant CDR industry given private sector activities and the presence of some supportive public policies,[74] but sustaining these positive trends over time is only likely if Canada actively chooses to lead on this issue through bold government action.

Action from governments, researchers, and innovators will also be necessary to help address ongoing challenges across the nascent CDR industry. One major current challenge includes the relatively high costs of longer-duration

Three Canadian companies — Planetary Technologies, Carbon Engineering and CarbonCure Technologies — were among the earliest commercial entrants onto the global stage in the CDR fields of ocean alkalinity enhancement, DAC and CO_2 utilization through carbon mineralization, respectively, and embody the possibilities of Canadian-led innovation in this new industry.

CDR projects that can span hundreds to thousands of dollars per tCO_2 captured for early-stage projects, which will require widespread innovation and learning by doing to help reduce costs. Energy requirements also pose challenges to various CDR methods, such as DAC, which require an abundance of clean and cheap energy (electrical and thermal) that must also be used to reduce emissions across the economy. Relatedly, CDR projects should seek to reduce their energy consumption needs to the greatest extent possible. A third challenge is the lack of robust measurement, monitoring, reporting and verification (MMRV) frameworks to help validate the scientific efficacy of CDR methods across the full life cycle of a project. Robust MMRV frameworks, some of which are in the early development phase, will be crucial to establishing trust within the marketplace between CDR project developers, investors, carbon credit purchasers and the public. A fourth challenge includes potential ecological risks associated with the storage and transportation of CO_2, and the need for strategies to avoid CO_2 leakage or other environmental impacts. A final major challenge involves the need for more targeted community engagement and social science research to help inform all aspects of project planning and execution that respects local community needs and concerns. None of these challenges can be fully resolved in a lab, and require proof-of-concepts at a scale that can generate valuable lessons for a diverse set of stakeholders and inform further CDR development.

Thriving innovation ecosystem

A growing number of companies are ready to capitalize on the economic opportunity of a comprehensive, supportive policy and regulatory environment for CDR (**Table A-3**). As of October 2023, there were an estimated 69 CDR companies in operation at varying levels of commercial readiness and project types across several provinces in Canada (**Figure 7**). The bulk of these companies are focused on CO_2 utilization[75] and BiCRS, with other notable project types including DAC and mineralization or enhanced rock weathering (**Figure 8**). Three Canadian companies — **Planetary Technologies**,[76] **Carbon Engineering**[77] and **CarbonCure Technologies**[78] — were among the earliest commercial entrants onto the global stage in the CDR fields of ocean alkalinity enhancement, DAC and CO_2 utilization and carbon mineralization, respectively, and embody the possibilities of Canadian-led innovation in this new industry.

Image courtesy of: Planetary Technologies

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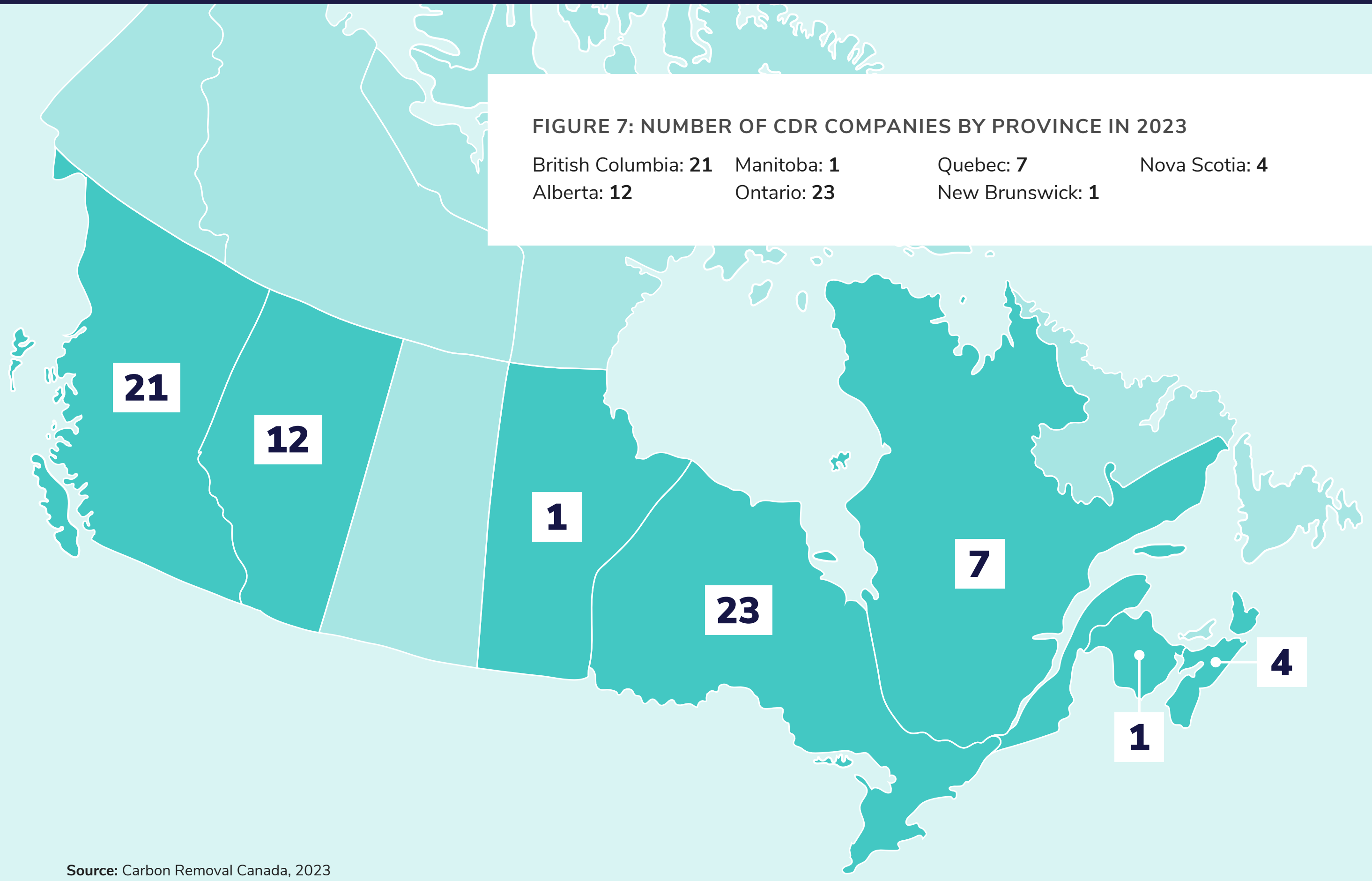
FIGURE 7: NUMBER OF CDR COMPANIES BY PROVINCE IN 2023

British Columbia: **21** Manitoba: **1** Quebec: **7** Nova Scotia: **4**
Alberta: **12** Ontario: **23** New Brunswick: **1**

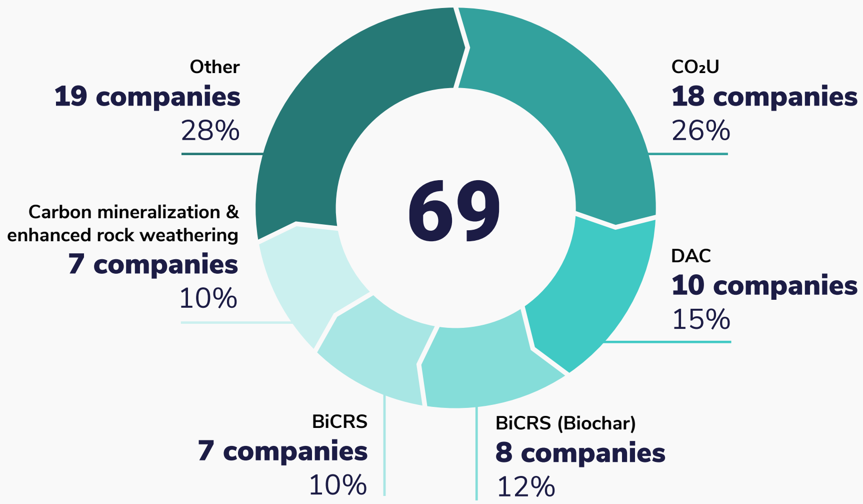


Source: Carbon Removal Canada, 2023

69

total CDR companies in Canada

FIGURE 8: NUMBER AND PERCENTAGE OF CDR COMPANIES IN CANADA BY METHOD IN 2023



Source: Carbon Removal Canada, 2023

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CDR in demand

An estimated 95 companies in Canada have either set or are committed to developing science-based targets as of October 2023.

While the development landscape is still in its infancy, some projects have already been announced in Canada, including **Airex Energy Inc.** (biochar facility in Port-Cartier, Quebec)[79] and **Deep Sky's** partnerships with **Captura** (direct ocean capture pilot facility in Eastern Quebec)[80] and **Mission Zero Technologies** (DAC facility in Quebec).[81] Other Canadian CDR companies such as **CarbonCure Technologies**[82] and **Carbon Engineering**[83] have also begun project development outside of Canada. On the demand side, corporations such as Shopify[84,85] and BMO Financial Group[86] have made commitments to purchase more than 100 thousand tonnes of CDR in total from project developers through the voluntary carbon market.[87,88] An estimated 95 companies in Canada have either set or are committed to developing science-based targets as of October 2023,[89] for which CDR could help meet those targets and further build the demand signal in the market.

Corporations such as Shopify and BMO Financial Group have made commitments to purchase more than 100 thousand tonnes of CDR from project developers providing a catalytic boost to the CDR market.

Burgeoning policy environment

Canada currently has a climate target to achieve a 40 – 45 per cent reduction in GHG emissions by 2030 (from 2005 levels) through its Nationally Determined Contribution (NDC) and a legislative mandate to achieve net-zero GHG emissions by 2050 through the *Canadian Net-Zero Emissions Accountability Act* of 2021.[90] At present, Canada has reduced emissions around eight per cent from 2005 levels and registered an economy-wide emissions level of 670 $MtCO_2e$ in 2021.[91] Through its long-term strategy submitted to the UNFCCC[92] and Carbon Management Strategy,[93] Canada expects CDR to be an important tool in helping achieve net-zero emissions.[94] However, recent policy progress in the United States and the European Union highlight the need for accelerated progress on policy and regulatory support for CDR in Canada.

United States

The U.S. has made huge strides in supporting the development of a domestic CDR industry. Through passage of the *Infrastructure Investment and Jobs Act and Inflation Reduction Act* (IRA), the U.S. government has announced historic commitments to help fund the CDR industry at a level unmatched by any other country to date. Funding of USD$3.7 billion will support several strategic initiatives, including a pre-commercial prize competition for DAC, development of four regional DAC hubs, grants for CO_2 utilization applications and the development of MMRV best practices to help validate CDR methods and promote scientific integrity.[95] The IRA includes another powerful economic incentive: a USD$180 per tonne tax credit for DAC projects that permanently store CO_2. The U.S. Department of Energy (DOE) has also announced USD$35 million in funding for the direct procurement of credits from CDR projects through a purchasing pilot program,[96] which is the first-ever federal procurement program for CDR.

Proposed legislation announced in the U.S. Congress could also bolster these efforts, including the *Carbon Dioxide Removal Research and Development Act* which would establish a 10-year multi-agency research, development and demonstration (RD&D) program for CDR.[97] These initiatives are further underpinned by DOE's Carbon Negative Shot, which seeks to spur innovation in CDR to achieve gigatonne-scale removal at a cost of less than USD$100 per net metric ton of CO_2e.[98]

European Union

The EU is also making remarkable progress in fostering a pan-European CDR industry. Most notably, the EU is developing an industry-leading governmental standards framework to help validate CDR project outcomes through its Carbon Removal Certification Framework. The proposed framework provides a voluntary means to define and certify high-quality CDR projects in a standardized manner.[99] Horizon Europe and the Innovation Fund, two primary funding vehicles for research and innovation in the EU, have historically provided direct and indirect financial support for CDR projects and could play a larger supportive role in the future.[100,101] The European Commission is also required to propose a 2040 climate target for the EU in 2024, which would include specifications for how to treat CDR alongside emissions reduction efforts in pursuit of net-zero emissions.[102] Additionally, the European Commission is expected to determine how CDR could play a formal role in the EU Emissions Trading System.[103]

Image courtesy of: CarbonCure

Section 4

What's next?

While Canada has a strong foundation upon which to build out a CDR sector, policymakers will need to take additional, bold actions to realize Canada's potential as a CDR leader.

Policy development plays an important role at the early stage of the CDR industry. Policies should be inclusive and seek to create a supportive ecosystem across a host of stakeholders including governments, the private sector, academia, non-governmental organizations, cleantech accelerators, philanthropies, Indigenous communities, labour groups and the skilled Canadian workforce. Policies that encourage active community engagement that seeks permission to undertake CDR projects, promote environmental justice, and provide guidance on equitable arrangements for sharing costs and benefits will be crucial to the success of this new industry.

Building on a strong foundation

Fortunately, Canada already has several policy incentives and regulatory frameworks that can serve as the foundation for a robust domestic CDR industry.

Industrial carbon pricing

Industrial carbon pricing was first developed in Alberta in 2007. It has a long history of support across Canada, and serves as the backbone of Canadian industrial climate policy. The system uses a performance-driven output-based pricing mechanism to provide a price incentive for industrial emitters to reduce GHG emissions and allows jurisdictions to either adopt the federal pricing system or develop their own pricing systems.[104,105] By 2030, the federal carbon price is scheduled to hit $170 per tonne of CO_2e which could provide a powerful incentive for decarbonization including CDR.

Carbon Management Strategy

Released in September 2023, this strategy recognizes the importance of CDR in compensating for residual emissions and addressing historical emissions. It also acknowledges the need to promote storage durability and focuses on technology-based CDR approaches that are in need of crucial government support (including oceans-based methods). Looking ahead, the strategy defines key focus areas, including advancing RD&D objectives, driving down costs, expanding CO_2 utilization applications, developing standards and detailed mapping of geologic storage options.[106]

CCUS Investment Tax Credit

Budget 2023 announced the government's intention to consult on the development of a CCUS Investment Tax Credit (ITC). The draft legislative proposal for the CCUS ITC includes support for CDR projects by providing tax credits at the level of 60 per cent for qualifying expenses through 2030 and 30 per cent through 2040.[107] Final design of the CCUS ITC is expected to be completed soon.

GHG offset protocols

Government-led efforts are underway to include CDR projects in published federal offset protocols through the development of new protocols.[108] The federal government is currently developing a protocol for DAC, with consideration of BECCS and other methods for future protocol development.[109]

Existing carbon storage regulations

Several provinces have CO_2 storage regulations in place, including Alberta, British Columbia, and Saskatchewan (with efforts underway to develop a regulatory protocol for Ontario).[110,111] These provinces are thus eligible for the CCUS ITC and could serve as early deployment locations for various CDR projects.

Mission Innovation initiative

The Canadian government is a co-lead of the Carbon Dioxide Removal Mission area through Mission Innovation alongside the United States and Kingdom of Saudi Arabia, which can help promote technological innovation in CDR on a global scale. The goal of this mission area is to scale CDR to 100 $MtCO_2$ per year globally by 2030 with an initial focus on BiCRS, carbon mineralization and DAC.[112,113]

We recommend policymakers create a concrete goal for building out CDR this decade, with a target in the range of 5 $MtCO_2$ of CDR capacity being actively developed by 2030.

Closing the policy gap

Most CDR technologies are still in their early stages of development. To reach the scale needed by mid-century, CDR will need to follow the path travelled by other successful low-carbon technologies like solar photovoltaic (PV) – only it will need to scale in even less time than solar. Policymakers could draw and adapt lessons from the growth of the solar industry to potentially realize similar breakthroughs in cost declines and learning curves utilizing technology push, knowledge flows and demand-pull policy mechanisms.[114]

To better understand what specific CDR policies Canada should pursue, Carbon Removal Canada conducted over 70 stakeholder interviews with civil society, academia, Indigenous leaders and CDR companies while drawing from lessons in scaling up other fast-growing low-carbon technologies.

An overall goal for the CDR sector this decade must be to responsibly build-out the first set of at-scale projects that act both as proof of concept and begin to create momentum that can bring costs down as the industry begins to scale up. If Canada is to play a leadership role in CDR, we recommend policymakers create a concrete goal for building out CDR this decade, with a target in the range of 5 $MtCO_2$ of CDR capacity being actively developed by 2030. As mentioned in Section 1, without developing this range of CDR capacity by 2030, it is hard to see how Canada could reach the scale of CDR needed by 2050.

Based on our research, Carbon Removal Canada recommends that policymakers take action to support the CDR sector in three key areas:

1. stimulating market demand;
2. accelerating technology supply and advancement; and
3. enabling rapid and responsible CDR project deployment.

Policymakers should pursue these policy areas in cooperation with provinces, territories and Indigenous communities. Below, we offer starting points for policy in each category, and intend to expand on these ideas in future work.

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1. STIMULATING MARKET DEMAND

The CDR market in Canada has very few buyers, largely because even technologies like DAC remain very expensive (anywhere from USD$600 to $1,000 per tonne).[115] While there have been a few notable examples from companies such as Shopify and BMO, CDR will require a much larger pool of demand beyond what these first-mover companies can offer. As with most other early-stage technologies, government support is needed to help establish the industry and bring CDR methods down the cost curve. It also provides a necessary bridge to prepare CDR solutions for scale and for their ultimate inclusion in compliance markets and other regulatory regimes.

Canada can utilize several policy levers to create the market demand needed to scale CDR, including:

Direct procurement

The Government of Canada should directly purchase CDR services from projects that can be built in Canada. Such a procurement program would stimulate demand, generate price discovery (especially if run through reverse auctions), unlock project financing, and help the Government of Canada address some of its own residual emissions (e.g., military-related emissions). A CDR procurement program would also be in line with recommendations made by the Greening Government Strategy already put forward.

Carbon contracts for difference

Carbon contracts for difference (CCfDs) provide industrial emitters with more certainty around the economic incentives from carbon pricing in future years. CCfDs would provide up to a $170 per tonne economic benefit to firms for purchasing CDR, which would be a big boost to the case for prospective buyers, and help Canada close much of the incentive gap[116] on DAC with the United States.

Tax credits

The federal government should strengthen the CCUS investment tax credit and create a complementary production tax credit for CDR. While carbon pricing paired with CCfDs and an investment tax credit for DAC would be a powerful incentive, there would still be an incentive gap compared to the 45Q tax credit available in the United States. Analysis by Clean Prosperity and the Transition Accelerator demonstrated that, in addition to CCfDs, an investment tax credit supplement or an additional production tax credit worth approximately $55 per tonne would be needed to close this gap.[117]

2. ACCELERATING TECHNOLOGY SUPPLY AND ADVANCEMENT

The Government of Canada — working with international partners such as the United States, can play a pivotal role in enhancing innovation in the CDR industry, helping new technologies move from lab to market. Developing new CDR methods and helping to improve existing ones will be essential if the sector is to reach the scale needed to achieve Canada's net-zero by 2050 targets.

Canada has a strong track record when it comes to supporting new technology development and can leverage that same ecosystem to support CDR. Encouragingly, Canada has already taken some notable steps including through the Budget 2021 commitment of $319 million over seven years for Natural Resources Canada's Energy Innovation Program, which can be used in part for CDR.

We recommend Canada build on its work to date through:

CDR technology RD&D

The Government of Canada should specifically earmark funds for CDR allocated from the existing money within the NRCan Energy Innovation Program and/or from new money. Canada should pursue a CDR RD&D agenda that is complementary to research priorities in partner countries that could strategically position Canada for leadership in emerging technologies in the rapidly evolving CDR field. Additionally, the federal government should continue to invest in research in partnership with provincial and territorial governments to identify and characterize suitable CO_2 storage sites, particularly in Central and Eastern Canada.

Financing support

CDR projects require huge outlays of capital. A 0.5 $MtCO_2$ DAC plant, for example, may cost over USD$1B to build and operate based on current technology.[118] The government can reduce the costs of CDR projects, and help attract private capital, by offering diverse types of financing support, including concessional lending and/or loan guarantees through existing financing mechanisms such as the Canada Infrastructure Bank, the Canada Growth Fund and potentially granting mechanisms like the Net-Zero Accelerator Fund.

CDR hub creation

The federal government, in partnership with provinces and territories, should support multiple "CDR hubs" that can kickstart the Canadian CDR industry and demonstrate the potential of this suite of technologies. Importantly, CDR hubs can bring together multiple actors across the value chain (CDR suppliers, transport providers, storage facilities, labour, community groups and more) that are needed to make CDR projects viable.

3. ENABLING RAPID AND RESPONSIBLE DEPLOYMENT

For a robust CDR market to develop in Canada, government policy must create an environment that enables the rapid and responsible deployment of CDR technologies.

Some of the most important concerns include:

CDR protocols

The Government of Canada should continue development of a DAC protocol that can generate CDR credits under the Canadian Greenhouse Gas Offset Credit Market. It should also begin to develop protocols for other CDR methods, such as BiCRS, carbon mineralization and enhanced rock weathering, as well as ocean-based CDR methods such as ocean alkalinity enhancement (OAE). These protocols should be developed in a way that ensures projects meet stringent scientific standards and maximize the likelihood that credits generated from CDR projects in Canada can be traded across provinces and international borders. Enabling the trading of credits is key to the growth of the industry.

Opportunities for Indigenous community participation and partnership

Government policies should facilitate arrangements involving CDR projects that create equitable partnership opportunities for Indigenous communities. Additionally, the federal government should work with stakeholders to develop robust engagement and social acceptance frameworks. This includes industry standards on the need to obtain free, prior, and informed consent from Indigenous communities, engaging communities on what constitutes co-beneficial CDR projects based on Traditional Ecological Knowledge to help inform project location, type, and scale, and the establishment of community benefit agreements and plans between CDR project developers and communities.

Siting, permitting, and liability

For Canada to be a CDR leader, the siting and permitting process for large CDR infrastructure will need to be streamlined. The government should apply sensible recommendations[119] for prioritizing low-carbon infrastructure to CDR projects, enforce established regulations and permitting timelines more strongly, and increase public visibility and accountability around these processes. Further, the government should establish best practice guidelines for how to handle the long-term liability associated with carbon storage following project closure. Alberta's current system for how to handle the long-term liability could be drawn from to encourage consistent rules nationally.

While each of these recommendations will require thoughtful consideration and in-depth analysis to create policies that can spur CDR scale up in Canada, they constitute a strong starting point for Canadian leadership in this nascent field. The importance of acting now cannot be overstated. This is a decisive decade that will determine the future of CDR in meeting climate goals by mid-century and beyond.

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Section 5

Appendix

Table A-1: Overview of CDR methods

Category	Method	Description	Storage Characteristics	Technology Readiness Level (TRL) (1 – 9)	Est. Removal Potential ($GtCO_2$/yr)	Est. Cost at Scale ($US/$tCO_2$)
Forestry	Afforestation / reforestation (AF/RF)	Planting trees in new areas where they did not previously exist (afforestation) or replanting trees in areas where they once existed (reforestation).	***Classification***: Biological (biotic) ***Type***: Organic (trees, roots, soils) ***Est. durability***: Decades to centuries	8 – 9[a]	0.5 – 10[a]	0 – 240[a]
	Agroforestry	Purposeful integration of agricultural and forestry systems to promote positive synergistic benefits across economic, social, and environmental factors.	***Classification***: Biological (biotic) ***Type***: Organic (trees, roots, soils) ***Est. durability***: Decades to centuries	8 – 9[a]	0.3 – 9.4[a]	Insufficient data[b]
	Improved forest management (IFM)	Active forest management techniques that seek to improve the health of forests and maintain or expand carbon stocks such as protective mechanisms against disease and pest infestation.	***Classification***: Biological (biotic) ***Type***: Organic (trees, roots, soils) ***Est. durability***: Decades to centuries	8 – 9[a]	0.1 – 2.1[a]	Insufficient data[b,c]
	Reducing emissions from deforestation and forest degradation (REDD+)	Reducing or preventing deforestation and promoting sustainable forest management.	***Classification***: Biological (biotic) ***Type***: Organic (trees, roots, soils) ***Est. durability***: Decades to centuries	8 – 9	0.4 – 5.8[g]	0 – 50
Soils	Soil carbon	Pursuing a variety of soil management techniques that seek to maintain or expand carbon stocks such as no-till farming and planting cover crops.	***Classification***: Biological (biotic) ***Type***: Organic or inorganic (soils) ***Est. durability***: Decades to centuries	8 – 9[a]	0.6 – 9.3[a]	-45 – 100[a]

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Category	Method	Description	Storage Characteristics	Technology Readiness Level (TRL) (1 – 9)	Est. Removal Potential ($GtCO_2$/yr)	Est. Cost at Scale (US/tCO_2$)
Other	Coastal blue carbon	Preserving or expanding ecosystems in coastal and oceanic areas including mangroves, salt marshes and seagrass meadows that store carbon in plants and soils.	*Classification*: Biological (biotic) *Type*: Organic (trees, roots, soils) *Est. durability*: Decades to centuries	2 – 3[a]	<1[a]	Insufficient data[b,c]
	Peatlands & wetlands	Preventing the destruction of peatlands or wetlands and seeking to restore such ecosystems through techniques such as re-wetting.	*Classification*: Biological (biotic) *Type*: Organic (trees, roots, soils) *Est. durability*: Decades to centuries	8 – 9[a]	0.5 – 2.1[a]	Insufficient data[b,c]
Biomass carbon removal and storage (BiCRS)	Biochar	Plant biomass and organic waste that is heated in the absence of oxygen (or in a limited-oxygen environment) through pyrolysis to form a stable, carbon-rich solid that is more resistant to natural decay.	*Classification*: Hybrid *Type*: Organic (biomass) *Est. durability*: Centuries to millennia	6 – 7[a]	0.3 – 6.6[a]	10 – 345[a]
	Biofuels (2nd Generation with CCS)	Transforming non-food plant biomass and organic waste into biofuels through various processes and capturing attendant CO_2 emissions for storage or use.	*Classification*: Hybrid *Type*: Dependent upon use of captured CO_2 *Est. durability*: Millennia (geologic storage)	Unknown	Unknown	Unknown
	Biomass to H_2 with CCS	Transforming plant biomass and organic waste into hydrogen through various processes and capturing attendant CO_2 emissions for storage or use.	*Classification*: Hybrid *Type*: Dependent upon use of captured CO_2 *Est. durability*: Millennia (geologic storage)	Unknown	Unknown	Unknown
	Bio-oil	Plant biomass and organic waste that is heated in the absence of oxygen (or in a limited-oxygen environment) through pyrolysis to form a carbon-rich oil that can be injected into the Earth's subsurface, where it transforms into a stable solid.	*Classification*: Hybrid *Type*: Organic (biomass) *Est. durability*: Millennia	Unknown	Unknown	Unknown
	Biopower with CCS	Using plant biomass and organic waste feedstocks to generate electricity and capturing attendant CO_2 emissions for storage or use.	*Classification*: Hybrid *Type*: Dependent upon use of captured CO_2 *Est. durability*: Millennia (geologic storage)	Unknown	Unknown	Unknown
	General (BECCS)	Using plant biomass and organic waste feedstocks to produce electricity, heat, or fuels and capturing attendant CO_2 emissions for storage or use.	*Classification*: Hybrid *Type*: Dependent upon use of captured CO_2 *Est. durability*: Millennia (geologic storage)	5 – 6[a]	0.5 – 11[a]	15 – 400[a]

Category	Method	Description	Storage Characteristics	Technology Readiness Level (TRL) (1 – 9)	Est. Removal Potential ($GtCO_2$/yr)	Est. Cost at Scale (US/tCO_2$)
	Green biomass burial	Burial of biomass resources in specially-engineered pits that slow the process of natural decay.	*Classification*: Biological (biotic) *Type*: Organic (biomass) *Est. durability*: Insufficient data	Insufficient data	Insufficient data	Insufficient data
	Harvested wood products (HWP)	Carbon that is embedded into wood products that can be used for purposes such as building construction after biomass feedstocks are harvested and processed.	*Classification*: Biological (biotic) *Type*: Organic (built environment) *Est. durability*: Decades to centuries	8 – 9[a]	0.2 – 1.3[a]	Varies
Mineralization	Carbon mineralization	Reacting certain rocks and minerals with CO_2 to form solid carbonates above or below the Earth's surface.	*Classification*: Non-biological (abiotic) *Type*: Inorganic (rocks and minerals) *Est. durability*: Millennia	6 – 7[d]	1 – 10[d]	10 – >1,000[d]
	Enhanced rock weathering (ERW)	Processing CO_2-reactive rocks and minerals into a small grain size (to accelerate the natural weathering process of rocks) and spreading the alkaline substance on agricultural or other land areas to store CO_2 in soils or form bicarbonates that eventually are transported to the oceans via waterways for storage.	*Classification*: Non-biological (abiotic) *Type*: Inorganic (rocks and minerals, bicarbonate ions) *Est. durability*: Millennia	3 – 4[a]	2 – 4[a]	50 – 200[a]
Oceans	Direct CO_2 injection: Seawater	Injection of liquid CO_2 into the deep ocean under certain temperature and pressure conditions to promote dissolution into carbonate and bicarbonate ions.	*Classification*: Non-biological (abiotic) *Type*: Inorganic (bicarbonate and carbonate ions) -Inorganic (dissolved gaseous CO_2, carbonic acid, carbonate ions, bicarbonate ions) -Inorganic (dissolved gaseous CO_2) → organic (CO_2 uptake by marine flora via photosynthesis) *Est. durability*: Millennia	Insufficient data	Insufficient data	Insufficient data
	Direct CO_2 injection: Sub-seafloor geologic storage	Injection of CO_2 below the seafloor for the purpose of storage in various geologic formations through various trapping mechanisms.	*Classification*: Non-biological (abiotic) *Type*: Inorganic (rocks and minerals) *Est. durability*: Millennia (geologic storage)	Insufficient data	Insufficient data	Insufficient data

Category	Method	Description	Storage Characteristics	Technology Readiness Level (TRL) (1 – 9)	Est. Removal Potential ($GtCO_2$/yr)	Est. Cost at Scale (US/tCO_2$)
	Direct ocean capture	Use of electrochemical techniques to remove carbon from seawater and possibly introduce a produced chemical base to surface waters to convert dissolved CO_2 into bicarbonate ions.	***Classification***: Non-biological (abiotic) ***Type***: Inorganic (bicarbonate and carbonate ions) Inorganic (*but could ultimately result in organic carbon storage if the captured CO_2 is used for certain applications such as greenhouses to grow plant biomass) ***Est. durability***: Millennia	Unknown	0.1 – >1[e]	100 – >350[e]
	Macroalgae cultivation	Growing macroalgae (seaweed) in marine environments to capture CO_2 dissolved in seawater through photosynthesis.	***Classification Type*** ***Est. durability*** -Biological (biotic) Type: Organic or inorganic (buried in marine sediments or remineralized [biomass sinking]) -Organic (biomass sinking) -Organic (biomass as a non-energy bioproduct such as biochar or human and animal feed) -Organic (biomass as an energy feedstock) → inorganic (CO_2 is captured from an emitting process or facility as the biomass is being transformed into an energy product (electricity, heat, fuel) ***Est. durability***: Centuries to millennia (biomass sinking)	Unknown	0.1 – 1[e]	25 – 125[e]
	Nutrient fertilisation	Addition of macro- and/ or micro-nutrients to ocean surface waters to stimulate phytoplankton blooms.	***Classification***: Biological (biotic) ***Type***: Organic (marine biomass) ***Est. durability***: Centuries to millennia	1 – 2[a]	1 – 3[a]	50 – 500[a]
	Ocean alkalinity enhancement (OAE)	Addition of various alkaline substances to the surface layers of the ocean to help combat local ocean acidification and convert dissolved CO_2 into bicarbonate ions.	***Classification***: Non-biological (abiotic) ***Type***: Inorganic (bicarbonate and carbonate ions) ***Est. durability***: Millennia	1 – 2[a]	1 – 100[a]	40 – 260[a]

Category	Method	Description	Storage Characteristics	Technology Readiness Level (TRL) (1 – 9)	Est. Removal Potential ($GtCO_2$/yr)	Est. Cost at Scale (US/tCO_2$)
Other	Upwelling / downwelling	The artificial movement of ocean waters through large vertical pipes or other means between the surface layer and deep ocean. Upwelling would transport cold, nutrient-rich waters from the deep ocean to the surface to stimulate phytoplankton activity that consumes CO_2. Downwelling would transport CO_2–saturated waters from the surface to deep ocean to promote long-term carbon storage. Note that pumping surface-water acidity to the deep ocean at various depths to promote carbon storage is also being explored.	***Classification***: Hybrid ***Type***: Organic or inorganic (buried in marine sediments or remineralized or marine biomass) ***Est. durability***: Decades to centuries	Unknown[f]	0.1 – 1[f]	>100[f]
	CO_2 utilization (CO_2U)	Use of captured CO_2 to serve as a feedstock for carbon-based products such as chemicals, fuels, and building materials to promote CO_2 circularity and store it on varying timescales depending on the product.	Dependent upon capture mechanism and use of captured CO_2	Varies	Varies	Varies
	Direct air capture (DAC)	Use of special chemicals and materials that selectively bind CO_2 from ambient air for subsequent storage or use.	***Classification***: Non-biological (abiotic) ***Type***: Dependent upon use of captured CO_2 ***Est. durability***: Millennia (geologic storage)	6[a]	5 – 40[a]	100 – 300[a]

[a] Smith, S. M., Geden, O., Nemet, G., Gidden, M., Lamb, W. F., Powis, C., Bellamy, R., Callaghan, M., Cowie, A., Cox, E., Fuss, S., Gasser, T., Grassi, G., Greene, J., Lück, S., Mohan, A., Müller-Hansen, F., Peters, G., Pratama, Y., Repke, T., Riahi, K., Schenuit, F., Steinhauser, J., Strefler, J., Valenzuela, J. M., and Minx, J. C. (2023). The State of Carbon Dioxide Removal - 1st Edition. The State of Carbon Dioxide Removal. doi:10.17605/OSF.IO/W3B4Z

[b] "Carbon Dioxide Removal," Intergovernmental Panel on Climate Change, IPCC AR6 WG3: CDR Factsheet, https://www.ipcc.ch/report/ar6/wg3/downloads/outreach/IPCC_AR6_WGIII_Factsheet_CDR.pdf. Accessed 22 Aug. 2023.

[c] M. Pathak, R. Slade, P.R. Shukla, J. Skea, R. Pichs-Madruga, D. Ürge-Vorsatz,2022: Technical Summary. In: *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.002.

[d] David Sandalow, Roger Aines, Julio Friedmann, Peter Kelemen, Colin McCormick, Ian Power, Briana Schmidt, Siobhan (Sasha) Wilson, Carbon Mineralization Roadmap (ICEF Innovation Roadmap Project, November 2021).

[e] "Ocean-Based Carbon Dioxide Removal: Road Maps," Ocean Visions, https://www2.oceanvisions.org/roadmaps/. Accessed 22 Aug. 2023.

[f] National Academies of Sciences, Engineering, and Medicine. 2022. A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration. Washington, DC: The National Academies Press. https://doi.org/10.17226/26278.

[g] "REDD+", https://unfccc.int/topics/land-use/workstreams/reddplus#:~:text=The%20IPCC%20identifies%20REDD%2B%20as,goals%20in%20countries%20and%20globally. Accessed 23 Aug. 2023.

Source: Carbon Removal Canada, 2023

Table A-2: Selection of literature estimates for CDR need in Canada by 2050

Entity	2030	2040	2050
Buck, 2023			
N/A	**N/A**	**N/A**	**Total: 149**
Canadian Climate Institute, 2021[122,123]			
Available	Unknown (BECCS) 0 (DAC) 80 (LULUCF) **Total: ≥80**	Unknown (BECCS) 0 – 221 (DAC) (median = 111) Unknown (LULUCF) **Total: 0 – 221** (median = 111)	Unknown (BECCS) 0 – 426 (DAC) (median = 213) 105 (LULUCF) **Total: 105 – 531** (median = 318)
Clean Energy Canada, 2023[124]			
Net-Zero	Unknown (DAC) 30 (LULUCF) **Total: ≥30**	Unknown (DAC) Unknown (LULUCF) **Total: Unknown**	0 – 250 (DAC) 105 (LULUCF) **Total: 105 – 355** (median = 230)
Canada Energy Regulator, 2023[125]			
Canada Net-zero	Unknown (BECCS[a]) 0 (DAC) 30 (LULUCF) **Total: 30+**	25 (BECCS) 2 (DAC) 40 (LULUCF) **Total: 67**	60 (BECCS) 55 (DAC) 50 (LULUCF) **Total: 165**
Clean Prosperity, 2023[126]			
Net-Zero pathways by 2050 (select)	0 (DAC)	0 (DAC) 30 (LULUCF) **Total: 30**	13 – 70 (DAC) 50 (LULUCF) **Total: 63 – 120 (**median = 91.5)
Environment and Climate Change Canada, 2022[127]			
Current Assumptions	Unknown (BECCS) Unknown (DAC) Unknown (LULUCF) **Total: Unknown**	Unknown (BECCS) Unknown (DAC) Unknown (LULUCF) **Total: Unknown**	16 – 73 (BECCS) (median = 45) 20 – 133 (DAC) (median = 77) 100 (LULUCF) **Total: 136 – 306** (median = 221)
Electric Power Research Institute, 2021[128]			
Net-Zero	Unknown (DAC) **Total: Unknown**	Unknown (DAC) **Total: Unknown**	114 (DAC) **Total: 114**

*Values are presented in megatonnes of CO_2 per year

[a] Sum of 'Electricity' and 'Low or Non-emitting Hydrogen Production'[129]

Note: Additional studies have been published in the literature that were either out of scope for a Canada net-zero emissions scenario or did not have known data available. Those studies are shown in the footnotes below for reference.[130,131,132,133,134]

Source: Carbon Removal Canada, 2023

Table A-3: CDR companies in Canada (not exhaustive)

No.	Name	Location	Founding Year	CDR Method
1	ADC Technologies	Montreal, Quebec	2013	Direct air capture (DAC)
2	Airex Energy	Laval, Quebec	2014	Biomass with carbon removal and storage (BiCRS): Biochar
3	Arca	Vancouver, British Columbia	2023	Carbon mineralization
4	BC Biocarbon	McBride, British Columbia	2011	Biomass with carbon removal and storage (BiCRS)
5	Bella Biochar	Hamilton, Ontario	2019	Biomass with carbon removal and storage (BiCRS): Biochar
6	Blue Sky Minerals	Vancouver, British Columbia	2023	Carbon mineralization
7	Canada Nickel	Toronto, Ontario	2019	Carbon mineralization
8	Canada's Forest Trust	Toronto, Ontario	2019	Forestation (AF / RF)
9	Canadian Wollastonite	Kingston, Ontario	2001	Enhanced rock weathering (ERW)
10	CarbiCrete	Lachine, Quebec	2016	CO_2 utilization (CO2U)
11	Carbon Alpha	Calgary, Alberta	2021	Geologic storage
12	Carbon Cantonne	Calgary, Alberta	2021	CO_2 utilization (CO2U)
13	Carbon Corps (C2CNT)	Calgary, Alberta	2022	CO_2 utilization (CO2U)
14	Carbon Engineering	Squamish, British Columbia	2009	Direct air capture (DAC)
15	Carbon Lock Technologies	Winnipeg, Manitoba	2020	Biomass with carbon removal and storage (BiCRS): Biochar
16	Carbon Streaming	Toronto, Ontario	2022	Various
17	Carbon Upcycling	Calgary, Alberta	2014	CO_2 utilization (CO2U)
18	Carboclave	Kitchener, Ontario	2016	CO_2 utilization (CO2U)
19	CarbonCure Technologies	Halifax, Nova Scotia	2012	CO_2 utilization (CO2U)
20	CarbonRun	Halifax, Nova Scotia	2022	Ocean alkalinity enhancement (OAE)
21	Cascadia Seaweed	Sidney, British Columbia	2019	Macroalgae cultivation
22	Cbiochar	Sutton, Quebec	2020	Biomass with carbon removal and storage (BiCRS): Biochar
23	CERT Systems	Toronto, Ontario	2019	CO_2 utilization (CO2U)
24	CHAR Technologies	Toronto, Ontario	2011	Biomass with carbon removal and storage (BiCRS): Biochar
25	Clean Carbon Energy	Calgary, Alberta	Unknown	Biomass with carbon removal and storage (BiCRS)
26	CleanO2	Calgary, Alberta	2013	CO_2 utilization (CO2U)

No.	Name	Location	Founding Year	CDR Method
27	CO2 Lock	Vancouver, British Columbia	2021	Carbon mineralization
28	CO2L Technologies	Kingston, Ontario	2022	CO_2 utilization (CO2U)
29	CO280	Vancouver, British Columbia	2022	Project developer
30	Cvictus	Calgary, Alberta	2018	Hydrogen production
31	Deep Sky	Montreal, Quebec	2022	Project developer
32	Drax Canada	Richmond, British Columbia	1989	Biomass with carbon removal and storage (BiCRS)
33	Emergent Waste Solutions	Richmond, British Columbia	2009	Biomass with carbon removal and storage (BiCRS): Biochar
34	Ensyn	Renfrew, Ontario	1984	Biomass with carbon removal and storage (BiCRS): Biochar
35	E-quester	Toronto, Ontario	2021	Direct air capture (DAC)
36	Exhale Aerosystems	Toronto, Ontario	2021	Direct air capture (DAC)
37	Exterra Climate Solutions	Montreal, Quebec	2021	Carbon mineralization
38	First Gigaton	Nanaimo, British Columbia	Unknown	Macroalgae cultivation
39	Flash Forest	Toronto, Ontario	2019	Forestation (AF / RF)
40	Gaia Refinery	Saint John, New Brunswick	2020	Direct air capture (DAC)
41	Huron Clean Energy	Vancouver, British Columbia	2009	Direct air capture (DAC)
42	Hydragas Energy	Vancouver, British Columbia	Unknown	Unknown
43	Hydrogen Naturally	Calgary, Alberta	Unknown	Biomass with carbon removal and storage (BiCRS)
44	Hyperion Global Energy	Ottawa, Ontario	2021	CO_2 utilization (CO2U)
45	Invert	Ottawa, Ontario	2022	Unknown
46	Ionomr Innovations	Vancouver, British Columbia	2017	CO_2 utilization (CO2U)
47	Kanata Clean Power	Vancouver, British Columbia	2020	Direct air capture (DAC), Hydrogen, CDR infrastructure
48	Minera Systems	Squamish, British Columbia	2021	Unknown
49	New Acre Project	Toronto, Ontario	Unknown	Ecosystem restoration
50	Ocean Wise	Vancouver, British Columbia	1956	Macroalgae cultivation
51	ONT Holdings Inc.	Richmond, British Columbia	Unknown	Microalgae cultivation
52	Phycus Biotechnologies	Markham, Ontario	Unknown	CO_2 utilization (CO2U)
53	Planetary Technologies	Dartmouth, Nova Scotia	2019	Direct ocean capture (DOC)
54	Pond Technologies	Markham, Ontario	2008	CO_2 utilization (CO2U)
55	Project Forest	Edmonton, Alberta	2020	Forestation (AF / RF)
56	Sargent Group	Toronto, Ontario	Unknown	CO_2 utilization (CO2U)

No.	Name	Location	Founding Year	CDR Method
57	Scotia BioChar	Bedford, Nova Scotia	2022	Biomass with carbon removal and storage (BiCRS): Biochar
58	SeeO2 Energy	Calgary, Alberta	2018	CO_2 utilization (CO2U)
59	Skyrenu Technologies	Sherbrooke, Quebec	2021	Direct air capture (DAC)
60	Solid Carbon	Victoria, British Columbia	2020	Carbon mineralization
61	Solistra	Toronto, Ontario	2018	CO_2 utilization (CO2U)
62	Svante Inc.	Burnaby, British Columbia	2007	Direct air capture (DAC)
63	Takachar	Vancouver, British Columbia	2012	Biomass with carbon removal and storage (BiCRS)
64	Taking Root	Vancouver, British Columbia	2007	Forestation (AF / RF)
65	Tandem Technical	Ottawa, Ontario	Unknown	CO_2 utilization (CO2U)
66	TerraFixing	Ottawa, Ontario	2020	Direct air capture (DAC)
67	Vortis	Calgary, Alberta	Unknown	CO_2 utilization (CO2U)
68	Vyterra Renewables	Ottawa, Ontario	2021	Biomass with carbon removal and storage (BiCRS)
69	ZS2 Technologies	Calgary, Alberta	2020	Direct air capture (DAC)

Source: Carbon Removal Canada, 2023

Methodology

Residual emissions: A literature review was performed to survey previous studies that modelled net-zero pathways for Canada by 2050. For relevant studies that had representation of CDR in net-zero scenarios, total CDR needed in 2050 was used as an estimate for residual emissions. In the event that only data ranges were provided for various CDR technologies, median values were used for those particular instances.

1.5 °C Target: Based on the estimated cumulative need for CDR globally from 2020 – 2100 by Smith et al., 2023,[120] a proportion of the CDR needed for both 1.5 °C scenarios was calculated by dividing Canada's historical emissions from Friedlingstein et al., 2022[121] by the global total for both economy-wide emissions (fossil fuel use and land-use change) and only fossil fuel use. Those percentages (3 per cent for its share of economy-wide emissions and 2 per cent for its share of fossil fuel emissions) were multiplied by the total removal needs from Smith et al., 2023 to arrive at an absolute share that would need to be removed beyond (assumed) net-zero emissions during the time period 2050 – 2100. The absolute share of emissions was then divided by 50 (years) to arrive at estimated annual removal rates during the time period 2050 – 2100. The lower bounds of the removal ranges for each 1.5 °C scenario represent fossil fuel emissions only and the upper bounds represent economy-wide emissions.

Endnotes

1 Friedlingstein, Pierre, et al. "Global Carbon Budget 2022." *Earth System Science Data*, vol. 14, no. 11, Nov. 2022, pp. 4811–900. *Copernicus Online Journals*, https://doi.org/10.5194/essd-14-4811-2022.

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7 Note: Inclusive of fossil fuel use and industrial activity, land use, land-use change, and forestry. Source: Friedlingstein, Pierre, et al. "Global Carbon Budget 2022." Earth System Science Data, vol. 14, no. 11, Nov. 2022, pp. 4811–900. Copernicus Online Journals, https://doi.org/10.5194/essd-14-4811-2022.

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11 Note: Mitigation deterrence describes the potential risk of society not prioritizing emissions reduction and instead opting for CDR to compensate for emissions that should otherwise be eliminated directly. It is important that CDR is not used as an excuse to continue emitting GHGs that could be eliminated in a cost-effective manner.

12 Note: Currently there is no scientific consensus on what should qualify as a 'residual emission' and assigning such a definition may involve value judgments.

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17 Note: Overshoot describes a period of time when the global average surface temperature of the planet exceeds 1.5°C or 2°C above pre-industrial levels as established in the Paris Agreement. In the event of warming that exceeds these temperature thresholds, CDR provides the potential to reduce global average surface temperatures back below these thresholds through sustained net-negative emissions.

18 Note: There is still some overlap and interdependencies between these different sets of technologies for applications such as DAC and BECCS.

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21 Note: This report defines durable CDR as operating on timescales ranging from centuries to millennia through storage mediums that are less vulnerable to physical reversal events.

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25 Note: Additional opportunities for CDR (which are not covered in this report) could include the full elimination of national historical emissions and/or pursuing a CDR-as-a-service model where CDR is undertaken in one country on behalf of another country that does not have access to adequate resources and therefore acts as a 'host country' for such projects.

26 United Nations, Climate Change, Long-term strategies portal, https://unfccc.int/process/the-paris-agreement/long-term-strategies. Accessed 25 July 2023.

27 Note: This figure excludes emissions from the land use, land-use change and forestry or LULUCF sector.

28 Note: CO_2 equivalent (CO_2e) refers to bundling the global warming potential of different types and amounts of greenhouse gasses into a single, common metric that equates to the amount of CO_2 molecules that would have a similar warming effect.

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30 Note: This would be roughly equivalent to taking 28 – 109 million passenger vehicles off the road per year from an emissions standpoint. Source: Government of Canada, Natural Resources Canada. Greenhouse Gas Equivalencies Calculator. 13 June 2017, https://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/calculator/ghg-calculator.cfm?_gl=1*ig0dur*_ga*MTUyMjE4OTM5NS4xNjk2MjUzNDc4*_ga_C2N57Y7DX5*MTY5NjM1OTg5My4xLjAuMTY5NjM1OTg5NS4wLjAuMA#results.

31 Note: This may be especially true given that some models may only optimize on cost rather than a suite of variables that would affect deployment prospects for CDR such as land use requirements and clean energy availability.

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34 Note: This is particularly important given the inherent uncertainty associated with the performance of the LULUCF sector operating as a net sink or source of CO_2 in any given year (particularly with worsening climate impacts to natural systems in the future).

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36 Note: Net zero is a precondition for net-negative. Any CDR deployment from the present through the achievement of net-zero emissions therefore would not contribute to the removal of historical emissions given that it would simply be compensating for ongoing emissions into the atmosphere.

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40 Note: More specifically, the emissions breakdown includes 34 $GtCO_2$ from fossil fuel use and 39 $GtCO_2$ from land-use change.

41 Note: These figures exclude non-CO_2 greenhouse gases.

42 Note: Higher levels of certainty beyond >50 per cent would be desirable for both 1.5°C scenarios but such data were not available for this analysis.

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