The Potential for Marine Carbon Dioxide Removal in Canada

Executive Summary

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Prepared by RMI for use by Canada's Ocean Supercluster

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Introduction

According to the IPCC, Carbon Dioxide Removal (CDR) is a critical component of a long-term climate aligned future.

One of the most promising deployment options for CDR, if done safely and effectively, is in marine environments, which have natural advantages of scale, potential for rapid growth, lack of competition with terrestrial activities, and the potential for a wide range of co-benefits.

The amount of CDR needed to reach climate goals, such as limiting global temperature rise to 1.5 °C, is significant. Global needs are on the scale of 7-9 GtCO2/y by 2050. A recent report by Carbon Removal Canada suggested a range of 300-500 MtCO2/y needed by 2050 for Canada to manage its residual emissions. The analysis in this report summarized below shows a potential capacity of more than 100 MtCO2/y for Canada's marine CDR (mCDR) industry by 2050, representing a significant contribution towards this national need.

Canada is uniquely positioned to pursue mCDR. It has abundant natural resources, the longest coastlines of any country in the world, access to the Atlantic, Pacific, and Arctic Oceans, a robust history of marine activities, and a strong research community, each of which would be assets in its aspirations to deploy. Both coastal provinces of British Columbia and Nova Scotia are already home to mCDR companies, and both show initiative toward increased climate action.

Today, mCDR deployments are mostly all still at the pilot stage. For the field of mCDR to succeed and serve its important role as part of the climate solution, it must be incubated now with real-world deployments. This makes today a great time of opportunity for mCDR, with early leaders gaining opportunities for investment as well as climate impact.

This report is not intended to be an exhaustive assessment of mCDR potential in Canada, a forecast of the future mCDR industry in Canada, or a roadmap for implementing mCDR in Canada. It is intended as an assessment of what is possible, to set aspirations and highlight opportunities and co-benefits available.

If you would like to review the detailed mCDR study report, please email contact@oceansupercluster.ca to request access.

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Economic Opportunity Assessment of Canada's mCDR Industry

The opportunity for the deployment of mCDR in Canada comes from two levers: environmental goals and economic growth.

Marine CDR has significant potential to contribute to Canada's global climate-related goals. As shown in Table ES1, this report estimates that mCDR has the potential to remove ~90-170Mt CO_2/y from the atmosphere by 2050. To put this number into perspective, Canada's current emissions are ~700 MtCO_2/y. This mCDR potential therefore represents about a 1/6th of Canada's current emissions.

A recent analysis undertaken by Carbon Removal Canada furthermore estimates that Canada will need at least 300Mt/y of carbon removal capacity by 2050 to be in line with Paris Agreement's 1.5 °C goal.[1] mCDR has the potential to contribute ~ 40% of this future removal capacity need. In addition, Canada's latest submission to UNFCCC for 2035 Nationally Determined Contributions (NDCs) targets is to reduce emissions by 45-50% below 2005 levels, requiring ~ 250Mt/y of reductions.[2] If removals are allowed to be included in NDCs in the future, mCDR could significantly help Canada contribute to meeting its NDC commitments.

Finally, mCDR also has the potential to restore marine environments within Canada, for example, by reducing acidification of its oceans, improving marine habitats, and enhancing coastal resiliency.

Assessment of deployment potential

This report's methodology for determining future deployment potentials of mCDR in Canada involved four key steps:

1
Selecting mCDR approaches

2
Determining key constraining factors for the deployment of each approach

3
Investigating available resources for each approach in the target region

4
Upscaling the assumptions to determine a pathway for deployment potential

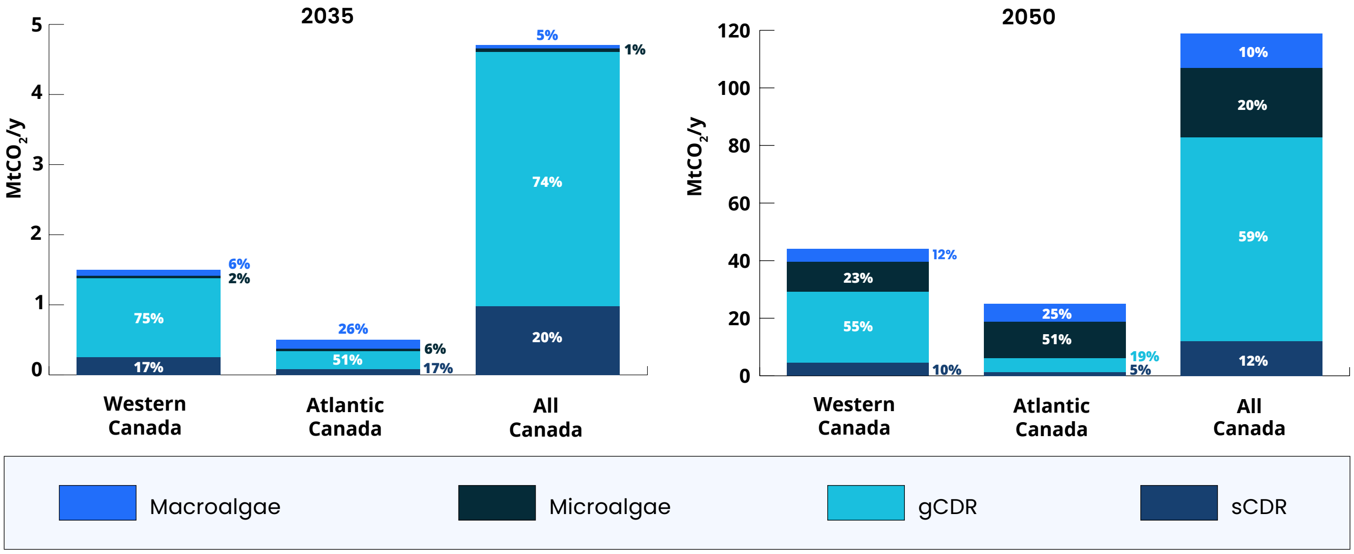
Approaches were divided into three main categories based on key constraining factors:

- **Biogenic CDR (bCDR)**. These approaches involve cultivating either macroalgae or microalgae in the ocean and sinking it. Their key limiting factor is the extent of available coastline. Macro and microalgae potentials were modelled separately, as microalgae-based mCDR is more nascent; it has a large potential for scale in the future, but only if ongoing research proves it to be effective in the next few years.
- **Geochemical CDR (gCDR)**. These approaches involve adding alkaline (basic) rocks to react with acidic CO2 in the ocean or along coastlines, reducing the ocean's acidity and thus increasing its capacity to draw down CO2 from the atmosphere. Their key limiting factor is the availability of alkaline mineral feedstocks.
- **Synthetic CDR (sCDR)**. These approaches involve powering machines to extract CO2 or acid from the atmosphere using ocean water's ability to absorb CO2. Their key limiting factor is the availability of low-carbon electricity.

Table 1
mCDR deployment potentials

		Western Canada		Atlantic Canada		All Canada
values in ktCO2/y		Pooled	BC only	Pooled	NS only	Pooled
Macroalgae	2035	70-200	70-200	80-200	40-100	150-400
	2050	3,500-9,000	3,500-9,000	4,000-10,000	2,000-5,000	8,000-20,000
Microalgae	2035	20-40	20-40	20-50	10-20	40-100
	2050	7,000-17,000	7,000-17,000	8,000-20,000	4,000-9,000	16,000-40,000
gCDR	2035	1,000-1,500	500-700	200-300	100-150	3,000-4,000
	2050	20,000-30,000	8,000-13,000	4,000-6,000	2,000-3,000	60,000-90,000
sCDR	2035	100-400	50-150	40-100	10-30	500-1,500
	2050	2,000-6,000	800-2,000	600-2,000	150-500	7,000-20,000
Total	2035	1,000-2000	600-1,000	300-700	150-300	3,500-6,000
	2050	30,000-60,000	20,000-40,000	15,000-40,000	7,000-15,000	90,000-170,000

Figure 1
mCDR deployment potentials (mid-range values)



Note: All the potential for marine CDR in "All Canada" is not simply the sum of Western and Atlantic Canada as it also includes the potential for imports of low carbon energy and alkaline minerals from interior provinces to coastal provinces.

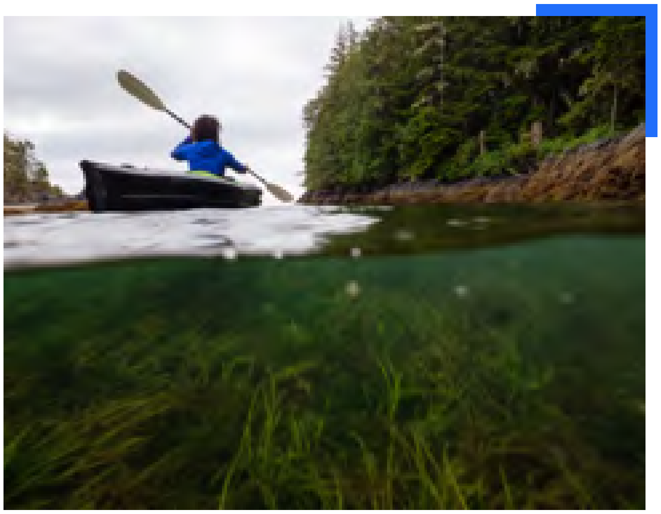
Deployment potentials

As shown in Table 1 and Figure 1, Canada's significant natural resources, current level of industrial activity, and extent of clean energy generation provide significant growth opportunities in the mCDR industry in the coming decades. By 2050, total deployment may exceed 100 MtCO2/y of removals and thus play a significant role in fulfilling Canada's CDR needs.

The deployment potentials within the provinces of British Columbia (20-40 MtCO2/y by 2050) and Nova Scotia (7-17 MtCO2/y) are based on their coastlines as well as forecasts of their production of alkaline minerals and low-carbon electricity within their borders. A key uncertainty associated with these potentials is the degree to which resources for these processes can be imported from other provinces. If additional minerals and energy are imported, the potential for gCDR and sCDR in NS and BC could be much higher. The modelled potential using resources sourced across Western and Atlantic Canada is also included in Table 1 and the calculations of economic impacts to follow.

Regional potentials

Western Canada shows a greater total potential, influenced by the region's larger population and current extent of industrial activity. In proportion to its size, however, Atlantic Canada has only 20% of the population of Western Canada and generates 15% as high of a GDP, and yet its mCDR potential stands at 30% of Western Canada's by 2035 and over 50% by 2050. This means Atlantic Canada's mCDR



potential is more than twice as large relative to its size, and any impacts, such as generated GDP and related workforces, will be significant proportional to current activities.

Distribution across approach categories

The mid-range 'All Canada' total potential shown in Figure 1 shows significant additional gCDR potential compared to the sum of Western and Atlantic Canada's potentials. This is due to the additional potential for mCDR deployment that may be unlocked by importing feedstock extracted within Central Canada if efficient transportation networks are developed. If microalgae-based mCDR approaches, which are currently at early stages of development and scientific validation, are proven by 2050, they will contribute more significantly to total potentials by 2050. Proportionally, this would be a particularly significant impact for Atlantic Canada.

Globally significant impact

Canada's mCDR industry could play a significant part in global deployment. Compared to RMI's previous work on success stories of total global CDR scale by 2050, Canada's mCDR potentials outlined in this report represent 5-10% of a global total. In particular, the capacity for gCDR deployment is significant thanks to Canada's extensive mineral resources, with modelled potentials reaching 15-20% of global total geochemical mCDR deployment by 2050. The estimates presented here show that, assuming winning conditions are met, mCDR has considerable potential in Canada, and would help the country attain its net-zero targets while also positioning Canada as an early leader in this growing industry, with significant potential economic benefits.

Assessment of economic impact

Significant economic potential

mCDR can also provide a meaningful contribution to Canada's economic growth prospects via job creation, GDP growth, capital investment and transitioning of workforce. An mCDR industry operating on scales of tens of millions of tons of CO2 removed each year would represent a significant new marine industry. If winning conditions are established to unlock this potential, this report estimates that the new industry would provide up to almost 100,000 jobs across Canada, contribute $7-20 billion to its total GDP, and generate $50-140 million in federal and provincial tax revenues. By share of total GDP, this represents up to 40% of the current scale of Canada's ocean economy.

To put the economic projections of mCDR in perspective, Canada's electricity utility sector currently employs approximately 100,000 people throughout Canada, attracts more than $22 billion in capital investment and contributes $35 billion to Canada's GDP – numbers similar to mCDR potentials by 2050.

Regional impacts

From a regional perspective, the proportional impacts of this industry on coastal provinces are significant. Based on distributions of resources across provinces, including province-specific projected growths in the generation of clean electricity, 20% of Canada's mCDR deployment potential is based on resources sourced within Atlantic Canada. By 2050, depending on the fraction of regional resources that are used for deployment within Nova Scotia compared to neighboring Atlantic provinces, this represents the creation of 4,000-22,000 jobs in Nova Scotia and a contribution of $0.6–4B to the GDP (which reflects 1.5-9% of Nova Scotia's current GDP). Similarly, with access to energy and feedstock resources sourced from across Western Canada, British Columbia could benefit from $2-8B of GDP impact (0.7-3% of British Columbia's current GDP) and the creation of 11,000-35,000 jobs by 2050.

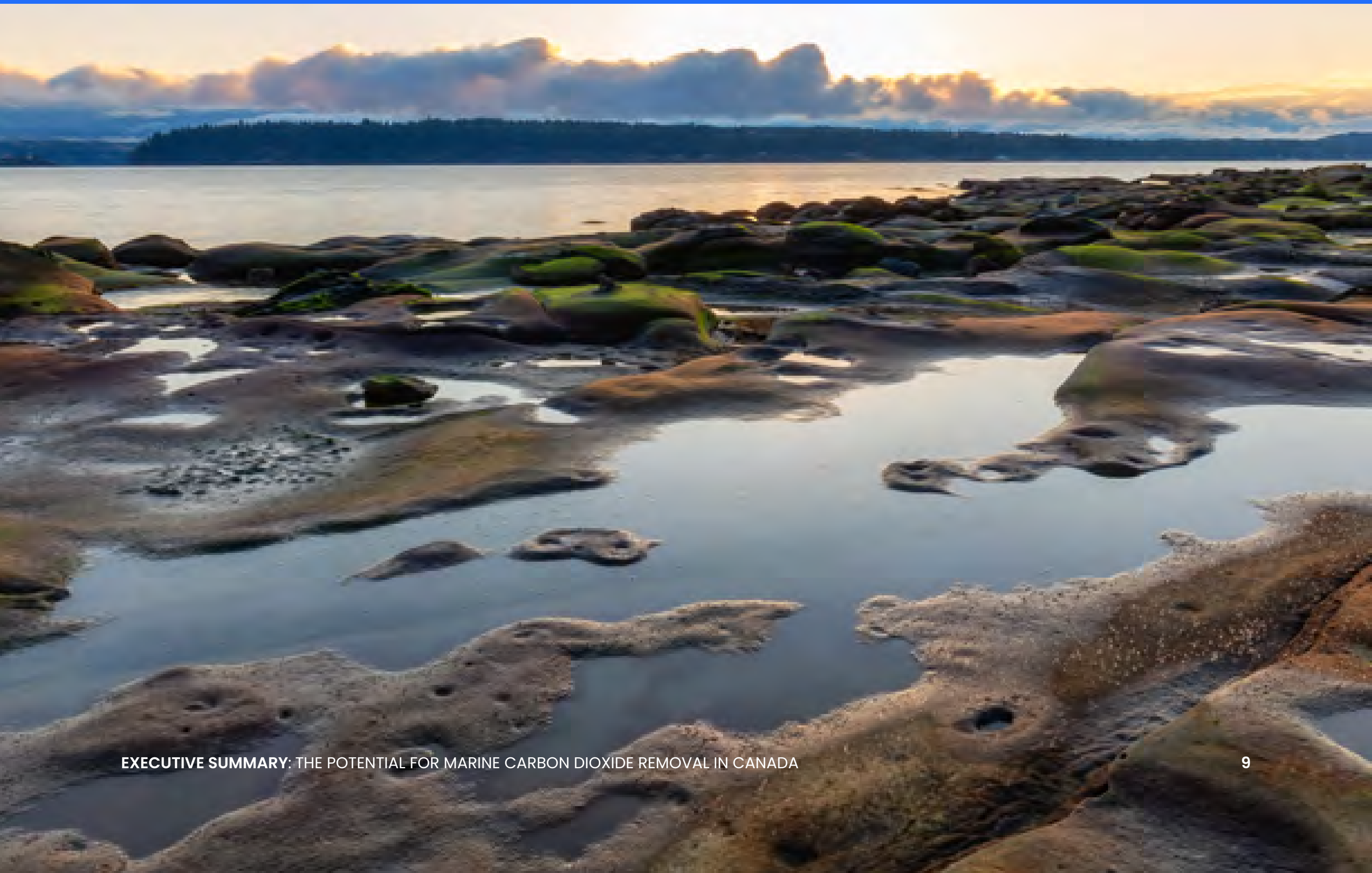
> Deployment of CDR using different approaches involves distinct industrial and economic activities and were modelled separately.

Table 2
CAPEX + OPEX funding needs across mCDR approaches at scale

	Western Canada		Atlantic Canada		All Canada
$M/y	**Pooled**	**BC only**	**Pooled**	**NS only**	**Pooled**
2035	200-600	90-300	600-1,500	20-70	70-1,800
2050	4,000-13,000	2,500-7,500	2,500-7,000	1,000-3,000	12,000-36,000

Total market volume

The total investment need for a scaled mCDR industry was estimated using interview data on current CAPEX and OPEX costs of operating mCDR projects, in combination with analysis of the possibility of future cost improvements as projects deploy at scale. This estimated cost to deploy mCDR in Canada is $0.7-1.8B in 2035 and $12-36B in 2050. The sum total costs presented in Table 2 present an estimation of the total market volume of mCDR deployment if credits are sold at prices close to the cost of deployment.



Workforce

Removing thousands of tonnes of CO2 each year by 2035 and more than a hundred thousand tonnes per year by 2050 will require a significant workforce, summarized in Table 3, involved in activities including feedstock extraction, processing, transportation, and deployment; synthetic CDR plant operation; and seaweed aquaculture, processing, and sinking. This report estimates that the mCDR industry could generate more than 3,000 jobs by 2035, growing to almost 100,000 jobs by 2050. The total numbers of people employed in the provinces of BC and NS are 3 and 0.5 million, respectively, meaning the total full-time equivalent workforce generated by the mCDR industry at scale could represent as much as 1% and 2% of BC and NS' current employment totals. These estimates were based on RMI company survey data on workforce intensities per unit of deployment capacity, combined with proportions of permanent and seasonal jobs in analogous industries.

The new jobs created as part of the mCDR industry by 2050 include a four-fold growth in the aquaculture workforce for bCDR projects based on macroalgae sinking alone, with even larger growth anticipated as a result of scaled deployment of microalgae sinking approaches if these are proven to be effective in the coming decade. The expansion of quarrying operations by 50% compared to current levels, to provide feedstock for gCDR projects, would generate more than 10,000 new jobs related to feedstock extraction and processing alongside up to 40,000 jobs related to deployment and ancillary project operations. Current workers in Canada's fishing industry, which has faced increasing unemployment close to 30% in recent years, will likely be able to reskill into these industries. Constructing and operating plants deploying sCDR projects will require a workforce equivalent to approximately 5% of the current size of the renewable energy labor pool.

Table 3
Total workforce needs for mCDR deployment at scale

		Western Canada		Atlantic Canada		All Canada
		Pooled	**BC only**	**Pooled**	**NS only**	**Pooled**
Permanent	2035	600-1,000	300-500	150-300	70-150	1,800-3,000
	2050	15,000-27,000	8,000-17,000	7,000-15,000	3,000-7,000	40,000-75,000
Part-time	2035	200-300	100-200	60-100	30-60	600-900
	2050	6,000-12,000	4,000-9,000	4,000-9,000	2,000-4,000	16,000-31,000
FTE	2035	700-1,300	400-600	200-400	100-200	2,000-4,000
	2050	19,000-35,000	11,000-24,000	10,000-22,000	4,000-10,000	52,000-95,000

Tax takes

At scale, a billion-dollar mCDR industry would generate significant regional and federal tax revenues. Based on comparisons to tax takes per employee or GDP unit observed in analogous industries, the analysis shown in Table 4 shows that the total tax take including both corporate and income tax revenues generated by the mCDR revenue could exceed $100 million by 2050. Initially, tax takes from the industry will remain low, as early-stage technology development will not be profit-generating, and supportive markets such as carbon markets need to continue to develop alongside mCDR technologies. In other cleantech and climate industries, tax incentives are historically a critical scaling policy tool. Such tax breaks would necessarily reduce the near-term tax take, but in so doing incubate the accelerated growth of an industry towards large taxable scale in the future. Tax incentives specific to operation within or sourcing of resources from certain provinces will affect the proportion of tax take across federal and provincial taxes.

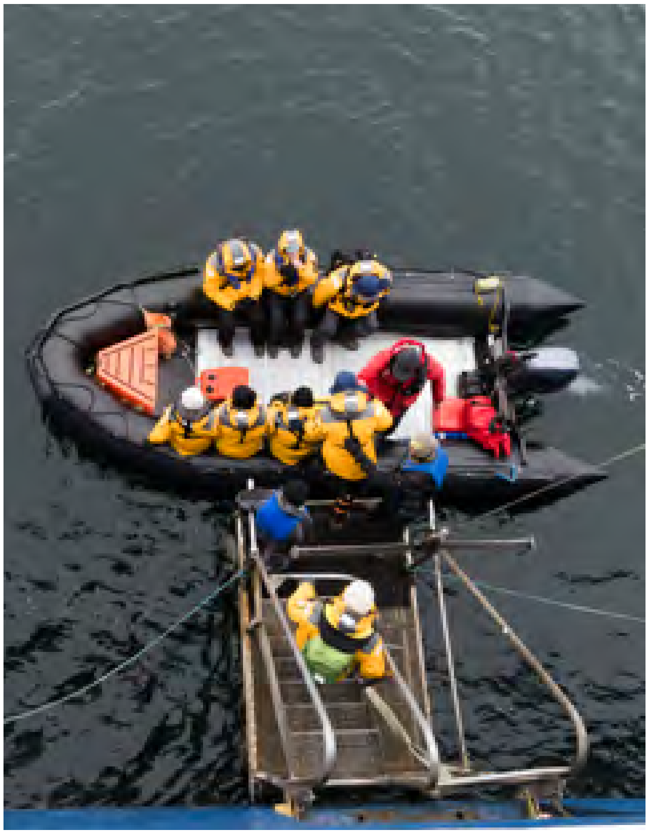


Table 4
Total tax take potentials across mCDR approaches at scale

	Western Canada		Atlantic Canada		All Canada
$M/y	**Pooled**	**BC only**	**Pooled**	**NS only**	**Pooled**
2035	0.7 – 2	0.4 – 1	0.2 – 0.6	0.1 – 0.3	2 – 6
2050	20 – 50	10 – 30	10 – 30	5 – 10	50 – 140

GDP contribution

Activities related to the establishment and operation of a scaled mCDR industry, including investment spending, employment, and generated revenues, stand to contribute significantly towards national and regional GDP. The estimated ranges were based on comparisons to analogous industries in terms of GDP contributions relative to their scale measured by total workforce size and total capital investment. This scale of deployment would make mCDR a significant Canadian industry, contributing the equivalent of 0.3-1% of Canada's current $2.3 trillion GDP, or up to 50% of the current GDP contributions of Canada's marine economy, which totaled about $50 billion in 2023. For regionally specific context, in 2023, the GDP of BC and NS, respectively, was $410B and $60B, meaning the GDP impacts of a scaled mCDR industry using resources from within these provinces by 2050 represent 0.3-1% of BC's current GDP, and 1-3% for NS.

Table 5
Total GDP impact potentials across mCDR approaches at scale

	Western Canada		Atlantic Canada		All Canada
$M	**Pooled**	**BC only**	**Pooled**	**NS only**	**Pooled**
2035	100 – 300	50 – 150	30 – 80	10 – 40	300 – 900
2050	2,500 – 7,500	1,500 – 5,000	1,500 – 4,000	600 – 2,000	7,000 – 20,000

Return on investment

The expected rate of return on the total investment summarized in Table 2 is difficult to quantitatively model at this early stage in the absence of mCDR companies that have reached commercial scale, or cases where the technology has been proven safe, scalable, measurable, and bankable. Assessments across other cleantech sectors have shown average rates of return near 8%, with significant fluctuations as different industries underwent periods of stagnation or success. Some technologies behind mCDR, especially gCDR and bCDR approaches, are physically quite simple by comparison to other cleantech. These are not complicated technical processes. The potential for commercial deployment is largely contingent on demand and public policy.

Impacts on ancillary industries

A billion-dollar mCDR industry would be significant not only in terms of the direct economic impacts of generated revenue and employment; it also represents a significant physical scale in terms of the production and transportation of materials. Expected impacts on ancillary industries include the generation of new demand for materials and infrastructure, such as mineral feedstock, sensors and environmental impact monitoring solutions, membranes and raw materials for sCDR processes, rail and barge transportation, and shipping infrastructure for deployments. Many CDR approaches, especially sCDR approaches, will require the provision of significant low-carbon electricity. This can create stable demand form and spur development of renewable generation and grid transmission projects, but also poses the risk of competition with other demands for low-carbon electricity. Forward planning for new generation deployments and allocation of electricity across regions will be essential. Ongoing and increasing efforts for the generation of additional renewable electricity, such as plans for offshore wind projects in Nova Scotia, will contribute significantly to regional sCDR potentials.

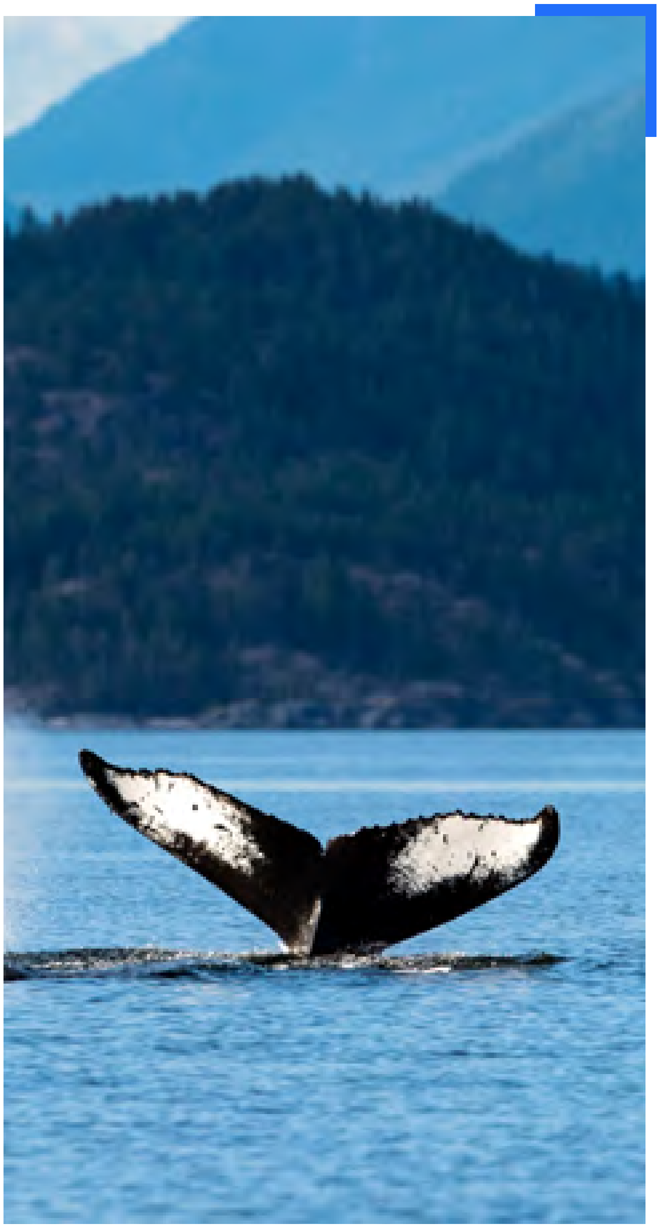
Global leadership

Canada is well-positioned to become an early global leader in mCDR. Doing so creates the opportunity for it to export not only raw materials and resources used for mCDR deployment in other geographies, but also the expertise involved in mCDR technology development, project planning, and impact monitoring. Canada's strength in research, from academic research through engineering of novel technologies, places it in an advantaged position to cultivate work on mCDR impacts, including open system modelling and monitoring. Support for work in this space could establish Canada as a world leader in the scientific and engineering aspects of mCDR, exporting project expertise, sensor and deployment technologies, and physical equipment as MRV solutions for mCDR approaches are developed and standardized.

Opportunities for community engagement and partnerships

Finally, and critically, the rapid development of a new industry will have varied impacts on communities throughout Canada, including people participating in the mCDR workforce, coastal communities whose local areas and ecosystems are impacted by project deployment, and Indigenous communities whose territories and cultural ties and knowledge extend across Canada's coastal landscapes. Effective two-way community engagement, including partnership and co-ownership in project deployment, is an essential component of responsible CDR deployment. A scaled mCDR industry will require a large number of projects unique in their geography, project details, local ecosystems, and each will require proactive and inclusive engagement with and participation of diverse local communities.

Canada's Regional Advantages for mCDR



Canada's developed coastlines and active marine industries are key advantages positioning the country as an ideal host for the nascent mCDR industry.

Its two most populous coastal provinces, British Columbia and Nova Scotia, possess the majority of developed, accessible coastlines. Together, the two provinces account for more than 38,000 km of coastlines, about one sixth of the country's total.

Both provinces are well-suited to the development of ocean economies. Nova Scotia's land mass never extends more than 70km from the Atlantic Ocean, and the province is committed to clean energy development and emissions reductions, as showcased in its plans for substantial offshore wind development and commitments to source more than 75% of all power from renewables by 2030. British Columbia accounts for roughly half of Canadian commercial fishing operations as part of the country's biggest maritime sector with $4 billion in total output, and also has ambitious climate targets, planning to reduce its overall emissions 40% by the year 2030.

Both Nova Scotia and British Columbia are already hubs for the development of various CDR technology, including mCDR companies and their pilot projects. These provinces are home to a wealth of academic, non-profit, and governmental organizations focused on the development and scaling of marine technology. They already host the regional networks and infrastructure necessary for supporting the accelerated build-out of critical climate technology like mCDR. Existing carbon management and pricing policy provides support for initial demand for removal credits for companies pursuing deployment in Canada's waters.

> By leveraging these advantages and supporting the winning conditions needed for the industry's development, the provinces will be well-positioned to lead global deployment of mCDR technologies.

Winning Conditions for Deployment of a Scaled mCDR Industry

Although significant potential exists for marine CDR to deliver environmental and economic benefits to coastal provinces and Canada as a nation, there are a wide array of social, technical, regulatory, and financial winning conditions that must be prioritized to reach successful scaled deployment.

The removal potentials and economic impacts identified in this study are highly dependent on a variety of policy and practical actions. These conditions and challenges are, for the most part, well known in the CDR industry, but have proven difficult to overcome. To that end, the following discussion is intended to highlight those conditions in the context of Canadian provinces and provide recommendations for how to unlock them.

In order to highlight the most important conditions that must be met by Canada to achieve significant growth and scaled removals of marine CDR approaches, Table 6 describes the most critical actions for the industry to thrive, both by 2035 and 2050, across all three mCDR categories.

Table 6
Near and long-term conditions for a scaled mCDR industry in Canada.

Marine CDR Approach	2035 Winning Conditions	2050 Winning Conditions
Across All Marine Approaches	• Science behind impacts and co-benefits is clarified, creating clear permitting pathways • Specific, scalable government procurement for marine CDR has been established • Early mCDR pilots prioritize collaboration and approach socialization with coastal populations and Indigenous peoples	• Mandatory baselines for government purchase of mCDR credits have been legislated nationally • A variety of mCDR approaches are operating with community support, employing a diverse array of ownership models • Jurisdiction for permitting the deployment of various approaches is centralized and streamlined
gCDR	• Partnerships with commercial industries and feedstock suppliers have been established to utilize existing infrastructure • Impacts of coastal deployment on ecosystems and durability of open-system removals are proven with high-efficacy trials • Transportation networks (rail and barge) have been established to reduce feedstock cost and emissions intensity	• Industry growth creates demand for investment in port infrastructure specifically designed for gCDR approaches • Coastal quarrying operations to serve gCDR facility demand are stood up. • Canada's government has engaged other nations to establish guidelines on credit generation, environmental management, and deployment in international waters.
bCDR	• Ideal deployment sites are characterized based on depth, temperature, and tidal currents • Permitting for marine dumping of microalgae fertilizers and biomass sinking is clarified with ECCC and DFO • Co-products derived from biomass produce revenue streams to ensure early financial stability	• Seedbanks of ideal species for bCDR approaches are established for long-term security • Efficacy of open-ocean deployment and removal durability are clarified by early pilots and demonstrations • Infrastructure, in the form of fleets equipped with technology for seeding and deployment and coastal processing plants, are established in ideal deployment zone alongside industries that utilize byproducts
sCDR	• ECCC, DFO, and industry have collaborated to address pH marine dumping barrier to maximize removal efficiency and energy usage. • The build out of a wide variety of low-cost, low-carbon energy sources are prioritized in coastal provinces • Early workforce training programs are mobilized to avoid bottlenecks in megatonne scale up	• Synthetic marine CDR reaches sufficient demand to justify the establishment of critical supply chains • Long-term impacts of localized pH increases are understood to avoid negative impacts on ecosystems and population centers. • Projects are co-located with industrial partners interested in the by-products of synthetic mCDR, including green hydrogen and desalination remediation

Cross-cutting winning conditions and recommendations

Canada already hosts legislative and geographic conditions that are uniquely suited to fostering an impactful marine CDR industry. It thus has the potential to lead globally in solving the most critical challenges that the mCDR and, more broadly, the CDR industry must overcome to reach an impactful scale by mid-century. By leveraging a favourable system of carbon management mechanisms and policies, as well as its robust academic research ecosystem and network of NGOs that support CDR development, Canada can meet the following winning conditions and deliver meaningful economic and environmental impacts through mCDR before 2050.

Near-term benchmarks (2025-2035)

By 2035, the most critical step for unlocking the monetization of mCDR, clarify supply chain needs, and create effective permitting structures will be proving the efficacy of mCDR approaches. This requires adequate funding for fundamental research as well as pilot and demonstration-scale facilities to study long-term impacts, co-benefits, and safety under a range of local conditions. Open data-sharing with industry and communities will encourage shared learnings and allow project developers to adjust approaches to preempt and mitigate any risks.

Establishing specific government procurement funds for mCDR and amending existing carbon management policies to include CDR would also support growth of the industry. Canada is already the first country to allocate national funds towards the purchase of CDR pathways, and this initiative must continue to scale, and include mCDR, in order to create stable demand. By doing so, Canada's government can set a baseline demand for CDR, mitigate industry wide risk and curb uncertainty about long-term funding for startups and operations with high CapEx and front-end costs. Canada can also encourage private industry support for CDR, including mCDR, by successfully integrating CDR credits into Canada's national carbon trading system. The current Output-Based Pricing System sets an escalating price for carbon emissions per tonne, reaching $170/tonne by 2030. By integrating CDR as a means to supplement a percentage of these direct OBPS payments, private industry would contribute to CDR demand. As technology advances and costs for CDR become competitive with the $170/tonne 2030 OBPS price, companies would be financially motivated to purchase credits

Finally, early Canadian mCDR pilots can and must prioritize engagement and collaboration with coastal communities, including Indigenous communities, to ensure long-term success and ongoing social license. In Nova Scotia, engagement with first nation communities, such as the 13 Mi'kmaq first nations, are now mandated for any activities that impact their land[3]. In British Columbia, first nations will play a key role in accelerating deployment and creating autonomously operating project. This means the adoption of new and innovative models for project governance that incorporate community decision making early in project planning and encourage joint ownership. Agreements should create structures that share project benefits and socialize the science, necessity, and potential risk around mCDR deployments with coastal populations through early education and collaboration.

Long-term benchmarks (2035-2050)

The long-term requirements for mCDR scale up and overall CDR success in Canada build upon the necessary near-term achievements outlined above. They follow the same themes of monetization, supply chain development, community involvement, and regulatory clarity.

By 2050, Canadian government must have a role in purchasing carbon credits directly from industry. This will require the legislation of mandatory purchases at both federal and provincial levels that create baselines for government purchases of CDR based on national residual emissions. Canada's national government should legislate that emissions resultant from government activities, including manufacturing and construction, be offset with purchases directly from CDR providers, creating anticipatory demand that will complement existing private investment and spur growth. The legislation should also incentivize credit purchases from provincial governments that exceed the national standard.

In addition to sustained and consistent demand, mCDR across a variety of pathways will need to operate with community ownership and be promoted by local advocates. By 2050, projects must seek to employ a diverse array of ownership models that prioritize community autonomy and decision-making power. This includes providing coastal communities and Indigenous peoples in mCDR hotspots with resources and trainings to assist or lead in project deployment. Industry-community partnerships that promote technology licensure, revenue sharing, and co-determination for siting locations will create foundational support for the industry.

To enable the acceleration of responsible mCDR deployment, regulatory clarity is critical. Authority for permitting the deployment of various approaches may need to be centralized across provincial and national agencies. Clarifying regulatory jurisdictions alleviates lead times and resource drains for mCDR companies and ensures that as new learnings, scientific findings, or technologies emerge, they can be evaluated and incorporated into existing regulations swiftly.

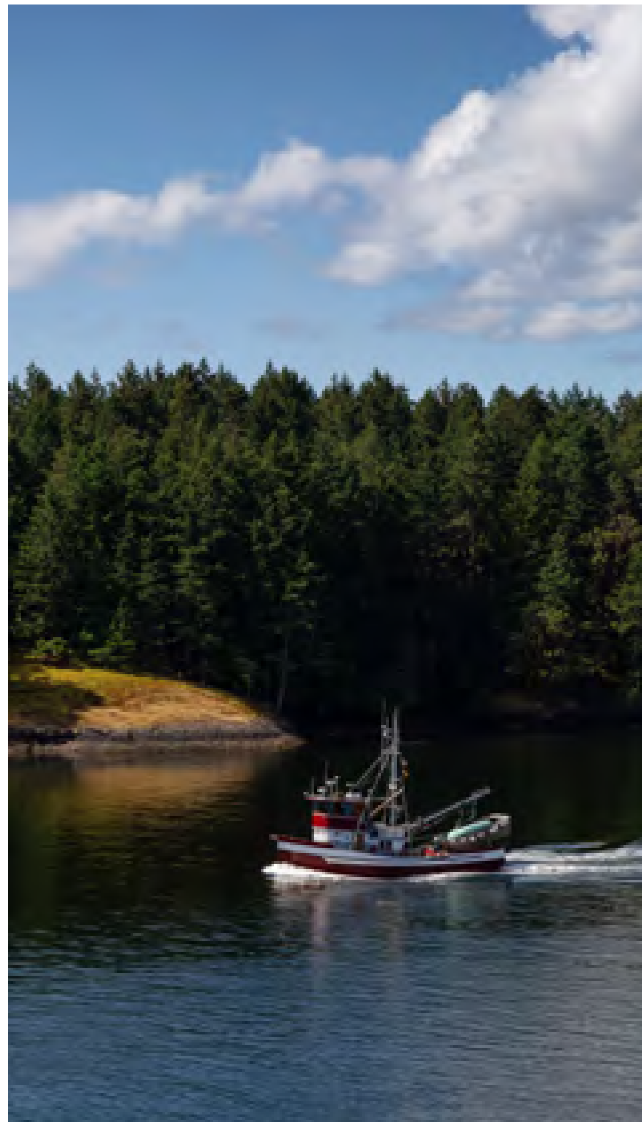
Finally, to avoid bottlenecks in scale up by mid-century, and to mitigate potentially negative impacts of near-shore deployment, Canada's government should prioritize engagement with other nations around deployment in international waters. A scaled mCDR industry may identify ideal siting locations which require included projects to extend into international and shared jurisdictions. Agreements and guidelines on project monitoring, credit generation, and environmental remediation and management will be needed.

Finally, to avoid bottlenecks in scale up by mid-century, and to mitigate potentially negative impacts of near-shore deployment, Canada's government should prioritize engagement with other nations around deployment in international waters. A scaled mCDR industry may identify ideal siting locations which require included projects to extend into international and shared jurisdictions. Agreements and guidelines on project monitoring, credit generation, and environmental remediation and management will be needed.

Approach-specific winning conditions and recommendations

In addition to the winning conditions that must be met across the marine CDR field highlighted above, the synthetic, biogenic, and geochemical mCDR industries must each achieve a set of field-specific conditions to achieve scaled removals.

For biogenic mCDR, success will require the characterization of ideal deployment sites, validation of removal durability, and valorization of biomass byproducts. Siting decisions are critical as they are a key factor in minimizing potential environmental harms from deployment. To secure long-term funding, the validation of removal durability is also a necessary condition for attracting the investment needed to scale the industry to megaton deployment. Finally, bCDR companies should prioritize creating alternative revenue streams that utilize cultivated biomass for production of soil fertilizers, bio-stimulants, and agricultural feed as this can foster scale up in the near term. By prioritizing these three actions, biogenic mCDR companies can create a pathway towards scaled deployment, acknowledging that success is ultimately dependent on removal quality, durability, and adequate funding.



For geochemical mCDR, success will require early collaboration with coastal industries and feedstock suppliers, clarity on the overall impacts of coastal deposition on marine ecosystems, and the establishment of low-carbon transportation networks for feedstock materials. Early startups and deployments will need to partner with mining companies and existing quarries to secure adequate feedstocks for pilots and demonstration facilities. The utilization of existing coastal infrastructure, including shipping and fisheries, will be necessary for increasing early deployment viability and reducing overall capital expenses. As adequate means for deployment is procured, industry and academics should be collaborating with government agencies (E.g. ECCC, DFO) to address risks and create permitting structures around depositing alkaline materials into marine environments to allow projects to move forward as materials and deployment methods are procured. To ensure projects can continue to secure feedstocks and operate under net-negative carbon balances, gCDR approaches will need to create low-carbon transportation corridors. Transport will be primarily through rail and barge systems, which facilitate the movement of large quantities of alkaline feedstock at low cost, from both a financial and emissions perspective.

Finally, for synthetic mCDR, success will require significant build out of low-carbon energy infrastructure, the establishment of acceptable permitting for sCDR processes, and the creation of approach-specific supply chains. The development of new solar, nuclear, wind, and solar energy, as well as the accompanying scale up of transmission infrastructure will be critical for scaling energy-intensive sCDR technologies. Such electricity scale up is also necessary to ensure that demand for sCDR removals does not compete with residential, commercial, and industrial decarbonization. Permitting clarity is also necessary to ensure that operations are not required to rebalance their basic (High pH) effluent. The rebalancing process to meet current pH limits leads to increases in material and energy usage and reduces removal rates. And finally, to minimize cost associated with energy usage and technology efficacy, sCDR companies and manufacturing industries should work to establish new supply chains and products. This is particularly important for specialized membrane technology which will allow for larger scale construction and higher-quality removal efficiency.

For all three approaches discussed above, an in-depth discussion on additional winning conditions, as well as recommendations on how to achieve those described here, can be found in the exhaustive discussion of the report. While meeting these conditions does not provide a guarantee of scale up, they do address the baseline requirements that will need to be met to give each approach the best chance of success before mid-century. The more exhaustive discussion of the report aims to support and justify, in greater detail, the importance of the aforementioned conditions to each of the three approach categories effective to scale up.

List of Acronyms

CDR
Carbon Dioxide Removal

mCDR
Marine CDR

bCDR
Biogenic CDR

gCDR
Geochemical CDR'

sCDR
Synthetic CDR

MAE/OAE
Mineral/ocean alkalinity enhancement

DOC
Direct ocean capture, also known as CO2 stripping

EA
Electrochemical alkalinity production, also known as electrochemical OAE

DAC
Direct air capture, a type of sCDR which may be deployed coastally or inland

CCS
Carbon capture and storage

ktCO2
Kilotonne, i.e. one thousand metric tonnes, of CO2. 1 kt is equivalent to 1,000,000 kg.

MtCO2
Megatonne, i.e. one million metric tonnes, of CO2. 1 Mt is equivalent to 1,000 kt.

GtCO2
Gigatonne, i.e. one billion metric tonnes, of CO2. 1 Gt is equivalent to 1,000 Mt.

$
All $ values in this report represent $CAD, unless stated otherwise.

IPCC
Intergovernmental Panel on Climate Change

CER
Canada Energy Regulator

DFO
Fisheries and Oceans Canada

ECCC
Environment and Climate Change Canada

NASEM
U.S. National Academies of Science, Engineering, and Medicine

Endnotes

1 Carbon Removal Canada, Ready for Removal: A Decisive Decade for Canadian Leadership in Carbon Dioxide Removal (2023), https://carbonremoval.ca/wp-content/uploads/2023/11/CRC_ResearchReport_ReadyForRemoval.pdf

2 Canada's Nationally Determined Contribution. https://unfccc.int/sites/default/files/2025-02/Canada%27s%202035%20Nationally%20Determined%20Contribution_ENc.pdf

3 The Confederacy of Mainland Mi'kmaq. (n.d.). About. https://cmmns.com/about/

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