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the Carbontech Innovation System *in Canada*

An evaluation of national carbon conversion technology development competitiveness

Abstract

The *Carbontech Innovation System in Canada* report investigates Canada's role in the growing global markets for carbon capture and utilization technologies. With its early carbon capture and storage project experience and considerable public and private investment, Canada is positioned to be a leader in the sector but only if we move quickly to overcome the barriers to technology development and commercialization.

The Carbontech Innovation System in Canada:
An evaluation of national carbon conversion technology development competitiveness

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A Message from:

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The world is a vastly different place than it was a few months ago. The twin crises of COVID-19 and the collapse of world oil prices have left global economies heading toward a recession. As we ready to publish this report, no one knows what shape the recovery will take.

The challenge of climate change may not be at the forefront of many people's minds, but it remains a looming threat. Although CO_2 emissions have contracted sharply as economies shrink and energy demand drops, recovery will bring with it renewed growth and an associated rebound in GHG emissions.

As Canada looks toward post-COVID-19 economic recovery, it is crucial to evaluate and implement strategies that will lead to sustained emissions reductions in alignment with Canada's Paris and mid-century carbon commitments. These commitments can only be achieved by deploying a multitude of strategies (including energy efficiency programs, electrification, expansion of renewable power, absolute reductions in production and consumption, and deployment of carbon removal solutions) while being guided by social, economic and environmental considerations.

> **Climate models show CCUS will likely play an important role in mitigation, particularly in hard to decarbonize industrial sectors.**

Climate models show carbon capture, utilization and storage (CCUS) will likely play an important role in mitigation, particularly in hard to decarbonize industrial sectors. As a consequence, there has been growing interest among decision makers and investors in CCUS. Global attention will be focused on Canada's CCUS activities by the NRG COSIA Carbon XPRIZE which will be awarded in the fall of 2020.

This report, a collaborative effort led by CMC Research, assesses Canada's strengths in CCUS with a focus on competitiveness in emerging technologies that convert carbon to commercial goods, known as carbontech. It provides a fresh perspective on the sector and demonstrates that if policy and resources are focused, Canada can 'own the podium' in carbontech, building on its early leadership in CCUS.

We have the unprecedented opportunity to design Canada's post-COVID-19 recovery to position our economy for future success. Which bets should decision-makers make? This report provides a compelling empirical case for why Canada can compete and win in the trillion-dollar global race to capture and convert carbon to create value.

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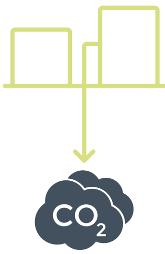
Executive Summary

The *Carbontech Innovation System in Canada* report investigates Canada's role in the growing global markets for carbon capture and utilization technologies. The need to keep global warming to below 1.5 degrees demands multiple industrial strategies including the deployment of CCUS technologies. Carbontech is a way to reframe CO_2 from a costly problem to a revenue generating feedstock with a potential trillion dollar global market value. Acknowledging the potential of carbontech to spur deployment and drive down costs of carbon capture and storage does not remove the need for high-emitting sectors to find other emission reduction opportunities or to develop low-carbon alternatives for their products.

Carbontech has the potential to contribute to Canadian economic development, job growth and to decarbonization.

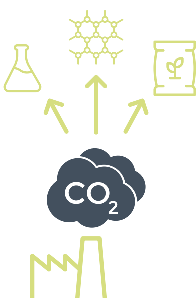
The prospect of a new trillion-dollar industry is attracting widespread investment interest, stimulating an international race in technology research, development, and demonstration (RD&D) and deployment. With its early carbon capture and storage project experience and considerable public and private investment in relevant technologies and projects, Canada is positioned to be a leader in the emerging carbontech sector if we move quickly to overcome the current barriers to technology development and commercialization.

This report provides the basis for a fact-based dialogue around Canada's strengths and weaknesses and the priority actions necessary to establish the country as a global leader in the carbontech industry. Some highlights and key learnings include:



1. All credible scenarios for remaining below 1.5 degrees include carbon capture, utilization and storage (CCUS) technologies.

To reduce the impacts of climate change and stabilize temperature change below 1.5°C, global greenhouse gas emissions must be reduced to net zero by 2050. Models mapping pathways to these steep reductions show a critical role for CCUS technologies alongside energy efficiency programs, electrification, expansion of renewable power, absolute reductions in production and consumption, and deployment of other carbon removal solutions.



2. Global attention is focused on a new generation of technologies that capture and convert carbon into commercial goods.

Interest in carbontech is growing with the market for products forecasted to grow to $1 trillion annually by 2030. These technologies have caught the attention of entrepreneurs, technology developers and governments because they offer twin benefits: 1) the goods produced store carbon and can help sequester emissions; and 2) carbon-to-value pathways offer operators a way to recoup costs.

3. Canada is well-positioned to be a global leader in carbontech.

Canada has strengths in engineering capacity, test and scale-up facilities, and public finance support for early stage research and development. It has leading academic research centres and scale-up facilities for carbon capture and utilization, particularly in Alberta, British Columbia, Ontario, and Saskatchewan. It has policy support in the form of a rising carbon price, emerging lifecycle-based GHG product regulations (e.g. the Canadian Clean Fuel Standard), and other mechanisms. **This study finds Canada is among the top four countries globally in both carbontech patents and carbontech ventures.**

4. **There are challenges to overcome if Canada is to be a leader in the development and export of carbontech.** Support for a thriving carbon technology industry should focus on further development of market mechanisms to promote adoption; regulatory measures to enable and incent project development; and communication efforts to increase awareness of and investor support for these technologies.

5. **Lessons for success can be drawn from Canada's carbon capture and storage sector.** Canada is a recognized leader in the development of carbon storage facilities and accompanying regulatory frameworks and is home to one in five of the world's largest CCS projects. Approximately 1 in 6 of all tonnes of anthropogenic CO_2 that have been sequestered globally to date have been injected in Canada according to the Global CCS Institute. In 2019, one of the world's largest CO_2 pipelines capable of transporting over 15 megatonnes per year began operations in Alberta. Although transport and storage operations are vastly different from carbon conversion processes, the technologies share strong similarities in barriers and enablers which can inform a path forward.

Carbontech has the potential to contribute to Canadian economic development, job growth and to decarbonization resulting from increasing the pace of carbon capture project development. But with rapid acceleration of the sector taking place in China, the U.S. and the EU, Canada risks falling behind. To help this young industry flourish, a comprehensive national strategy should be developed to guide policy makers, industry, small- and medium-size enterprises, and the finance community as they make decisions that will impact growth of the sector. We hope this report will serve as a guide to focus attention and resources as stakeholders create a roadmap for development of CCUS within achievable and effective decarbonization pathways.

1. Introduction

Concerns about climate change have resulted in global agreement on the need for collective action to reduce anthropogenic greenhouse gas (GHG) emissions [1]. Stabilizing atmospheric temperature change below 1.5°C requires achieving net zero emissions by 2050 and net-negative emissions thereafter [2-5].

Negative emissions technologies (NETs) are essential tools in our multifaceted tool box (which includes energy efficiency programs, electrification, expansion of renewable power and absolute reductions in production and consumption) for meeting climate stabilization targets [6, 7]. While differing in terms of the volume of mitigation that can be delivered through various pathways [8], there is broad agreement across numerous studies that industrial production pathways leveraging carbon capture, utilization and storage (CCUS)[1] can result in significantly lower emissions compared to conventional technologies [9-11], and in some cases negative emissions over product life cycles [12, 13]. While CCUS does not relieve the pressure on high emitting sectors to find other innovative ways to decarbonize or find lower carbon alternatives for their products, the majority of

Global decarbonisation targets require widespread deployment of CCUS.

1 In the current study, CCUS refers to the whole industry including carbon capture, utilization and storage. Where needed, distinction is made to emphasize subsectors: CCS (carbon capture and storage), carbontech (carbon capture and utilization) and CCS-EOR (Carbon capture and storage for enhanced oil recovery).

credible scenarios for achieving global decarbonisation targets require widespread deployment of CCUS on the scale of 5-10 Gt per year by 2050-2080 [14-16]. Assuming economies of scale and learning curves in terms of execution costs, widespread deployment of CCUS could potentially halve the costs of meeting climate targets internationally [2, 17].

Since the implementation of the first carbon capture and storage (CCS) project in Texas in 1972, 21 large-scale capture facilities (>1 Megatonne per annum (Mtpa)) have been constructed and are in operation worldwide with a total capture capacity of approximately 40 Mtpa. The global cumulative capacity of these large-scale CCS and CCS for enhanced oil recovery (CCS-EOR) facilities is expected to roughly double to 97 Mtpa given the 51 facilities that were in operation or are in the planning or construction phase in 2019 (Figure 1)[18]. And while there are indicators of acceleration, the current and projected pace of CCS project development remains far below what is required to achieve less than 1.5 of temperature increase [6, 7]. There are several factors, such as economic performance and social acceptability, that adversely impact the deployment rate of CCS.

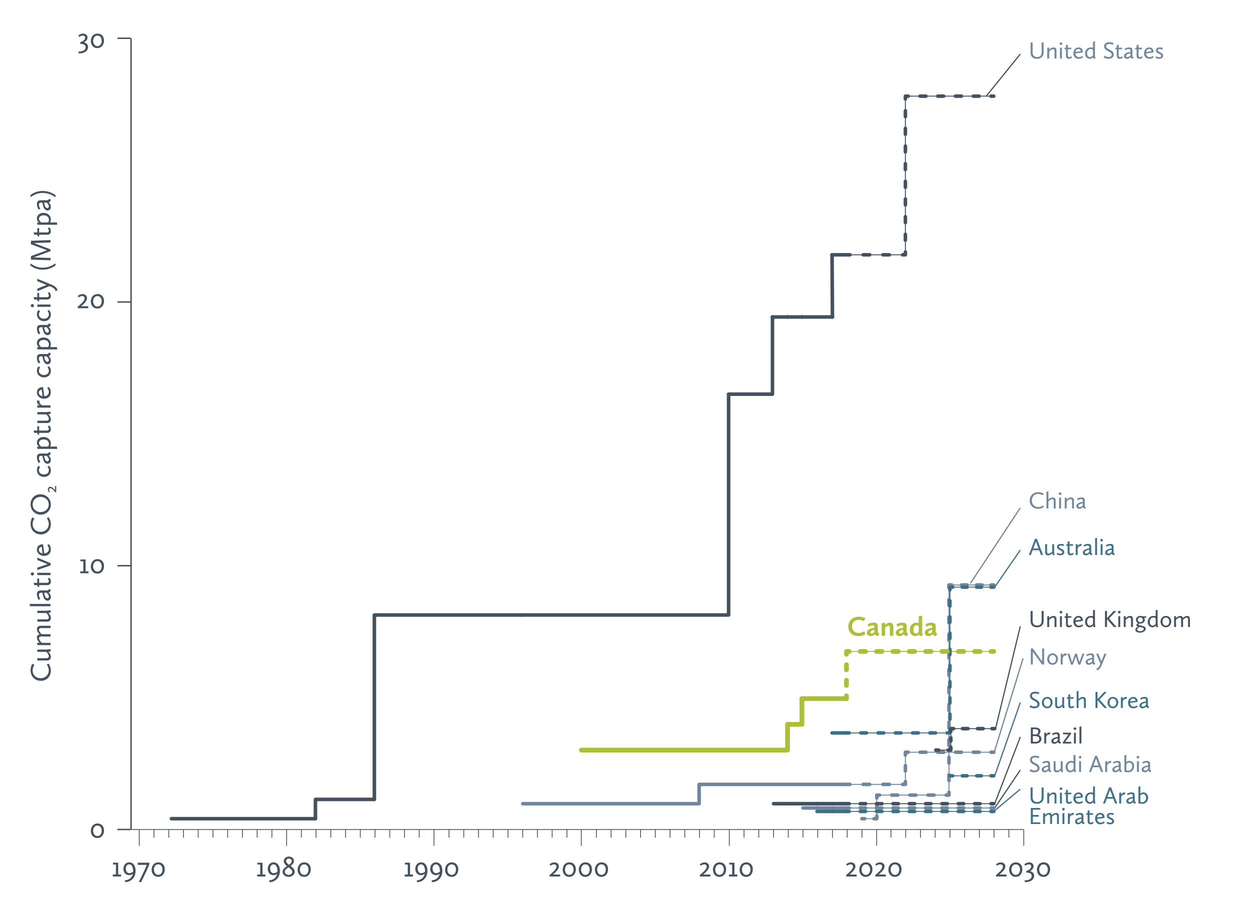


FIGURE 1: Historical trends and short-term future trends of large-scale CCS facilities.[2]

Source: Global CCS Institute. [18]

2 In Figure 1, the solid line shows the operational large-scale CCS facilities and the dashed lines shows the projects which are in various stages of implementation (i.e., from planning to construction)

A new generation of technologies focus on reframing the CO_2 problem by transforming carbon dixode from a waste product into a feedstock for generating value add products (e.g., CO_2 to fuel [19-21], CO_2 to methanol [22, 23], formic acid [24, 25] and nanotubes [26]). The resulting emerging sector of technologies, collectively referred to as carbontech, encompasses both technologically-mature CO_2 utilization pathways (e.g., for food processing) and emerging pathways such as utilization of CO_2 for fuel production, mineralization, concrete curing, etc.

Carbontech is gaining increased attention in national and regional climate policy because these technologies may offer benefits when compared to geological CO_2 storage including: environmental benefits (i.e., permanence of storage), economic development (i.e., value add products), sustainability of supply (captured CO_2 can be used instead of fossil fuels to produce almost any hydro-carbon based product), stakeholder acceptance [27], and applicability across a wider set of industries and emission sources [28-30].

In a 2016 study by the Global CO_2 Initiative, annual revenue from the global carbontech sector was forecast to grow to as much as US$800 Billion by 2030 [31]. Developing an industry that moves 5-10 Gt per year of CO_2 by 2050 would likely require the construction of capture facilities, pipelines and related value-add infrastructure on the same scale as today's global oil industry, which took over 100 years to develop and moved 4 Gt of hydrocarbons in 2016 [32]. The establishment and growth of an industry of this size and scope offers significant economic opportunity for technology leaders, project developers, financiers and shareholders. As a result, a global race is underway in carbontech research, development, demonstration and deployment [33, 34]. This is underscored by recent commitments to carbon negative investment by leading tech companies including Stripe, Shopify, and Microsoft [159]. From a policy-making perspective, carbontech is becoming mainstream, with a move to include it in global climate agreements [35] and in the European Emissions Trading System's (EU ETS) innovation fund [36].

A global race is underway in carbontech research, development, demonstration and deployment.

Canada was an early leader in conventional CCS project development and deployment. Today it hosts five of the 21 CCS facilities in operation worldwide; and is home to several globally significant carbontech innovation prizes that will be described below. Backed by this history of CCS project experience as well as considerable public and private investment[3], Canada could be a global leader in carbontech development and market creation.

To date, minimal literature (peer-reviewed and grey) has focused specifically on Canadian competitive positioning in the carbontech development and commercialization system. This study addresses this knowledge gap by analyzing the attributes of Canada's carbontech innovation system. It seeks to empirically assess Canada's competitiveness in the development and deployment of CCUS technologies, with a specific focus on carbontech. Specific objectives are:

- To identify the barriers and enablers for the development and widespread adoption of carbontech in Canada;
- To assess Canada's existing strengths based on different elements of the CCUS innovation system; and
- To evaluate gaps which need to be filled to enable the emergence of a thriving Canadian carbontech industry.

This study provides a comprehensive overview of the current status of the Canadian carbontech industry as well as enabling policies and technology support programs.

Leveraging both new research and existing literature, this study provides a comprehensive overview of the current status of the Canadian carbontech industry as well as enabling policies and technology support programs. The results are relevant to academics, industry stakeholders, technology investors as well as policy makers, and it provides the basis for a dialogue around the prospects and priority actions necessary to establish Canada as a global leader in the carbontech industry.

3 Anecdotally, Canada and its provincial innovation funds have spent more on CCUS technology development than the US Department of Energy.

2. Global Competitiveness of Canada's Carbontech Sector

Identifying Canada's competitive position in an emerging technology sector like carbontech has several dimensions. The research team sought to understand Canada's global carbontech competitiveness by reviewing CCUS literature, studying CCS-specific technology development and project implementation obstacles, and hosting expert workshops on CCUS in Toronto, Calgary and Vancouver.

Identifying Canada's competitive position in an emerging technology sector like carbontech has several dimensions.

Despite the differences between conventional CCS and emerging carbontech, both sets of technologies share strong similarities in terms of policy and regulatory barriers and enablers, customers, investors, technology development pathways and associated expertise areas, though development of conventional CCS technology has nearly 50 years of experience behind it. Given this history, we used observed barriers and enablers to conventional CCS technology and project development to inform our examination of national carbontech competitiveness.

Generally, conventional CCUS projects face concerns and barriers associated with technology maturity, enabling laws and regulations, economics and cost of implementation, and social acceptability both by project host communities and other key stakeholder groups [37, 38]. Key barriers to CCUS development include:

- **Lack of public financial support and private investment.** The greatest impediment to deployment of CCUS technologies has been the difficulty in financing projects [39]. Analyzing 22 CCUS projects that were canceled in Europe, Vögele et al., (2018) suggest that financial barriers were among the main factors resulting in cancelation of nearly two-thirds of the projects [40].
- **Absence of supportive national and regional policies and regulation.** The primary cause for cancellation of nine CCUS projects in Europe was the absence of regulatory frameworks [40]. Specific regulatory barriers in CCUS projects include legal uncertainties (e.g., uncertainties about the ownership of the pore space into which CO_2 is injected) [41], long-term liability ownership risks, and lack of comprehensive regulations [43]. Specific social acceptability barriers include concerns regarding the long-term safety of the technology, the human health hazards associated with CO_2 and the permanence of underground storage [44].
- **Deficiency of domestic CCUS technology expertise.** The development of a thriving sector of carbontech entrepreneurs, project developers and operators requires ample technology R&D experience [39], relevant project execution experience, and access to technology development facilities to enable field-based pilots and scale-up opportunities [41, 42].

In addition to our literature review, we researched factors impacting Canadian technology and market development by hosting a series of three workshops in Vancouver, Calgary and Toronto between 2018 and 2019. Participants included Canadian and international experts from federal and provincial governments, heavy industry (cement, petrochemicals, power generation), investors, carbontech ventures, environmental non-governmental organizations, academics and think tanks. To position Canada for global leadership in this sector, workshop participants highlighted the need for a national carbontech strategy to address carbon pricing, stable political support, a clear communications strategy, and public support for a CO_2 transportation network.

Based on these inputs, we have defined the following dimensions for assessing national competitiveness in carbontech industry development:

- **Domestic Expertise:** A thriving network of academic technology research and development centres, technology pilot/scale-up facilities, and of large-scale CCUS projects;
- **Access to capital:** Capital availability, which includes public and private investment in CCUS technology research, development, project finance and venture capital;
- **Regulatory Framework:** Supportive national and regional policies and regulation to enable and incent project development. These must address legal uncertainties including ownership of pore space, management of long-term liability, barriers to social acceptability including host community consultation and benefit-sharing, monitoring to address long-term safety, human health risks, etc. Regulatory incentives may include recognition of CCUS-related carbon benefits in domestic offset markets and compliance accounting.
- **Public Acceptability:** Factors including a domestic history of successful project development and operation experience, effective benefit sharing arrangements, positive perceptions about projects among host communities and wider publics, and trust in mechanisms to mitigate project-related risks that include geological storage and CO_2 transport safety. These positive indicators are underpinned by trust in authorities and in the processes for securing operating permits and permission from the host community, and by perceptions regarding the origin and urgency of climate change.
- **Effectiveness of the innovation system:** While ecosystem investment, domestic expertise, financial support, enabling regulatory frameworks, and public acceptability are critical ingredients to a thriving CCUS industry, they are not necessarily enough to ensure the success of the innovation system and market creation. Evidence of CCUS venture growth, technology development, and commercialization activities can be used to gauge the overall effectiveness of the innovation system.

3. *Domestic Expertise*

Typical to new technology development, the carbontech commercialization process involves several steps including basic research, feasibility research, technology development, technology demonstration and large-scale deployment (Figure 2). The competitive position of Canada in each stage of the carbontech development chain is discussed in this section.

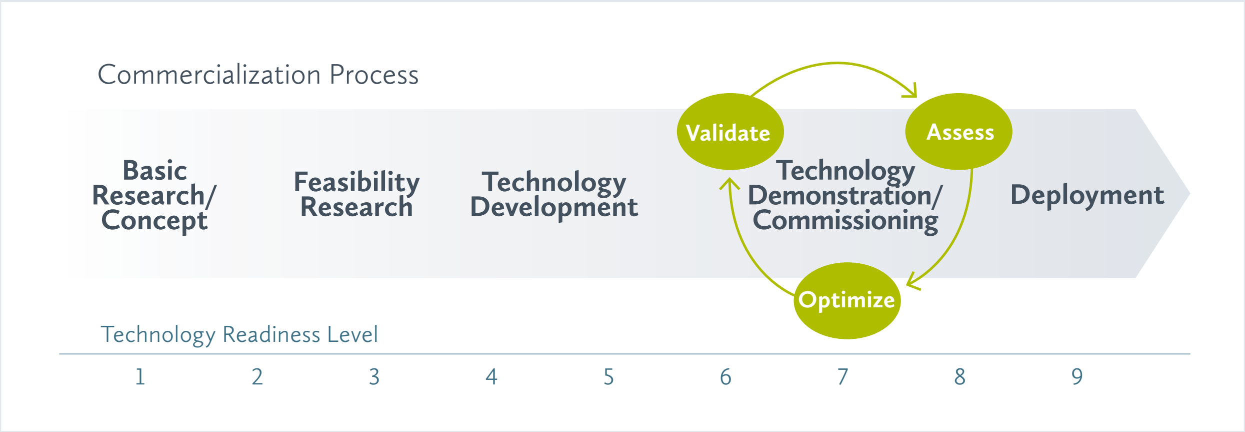


FIGURE 2: Technology commercialization process.
Source: National Renewable Energy Laboratory. [45]

3.1 *Research and development centers*

Canada's world class academic research centres give Canada a competitive advantage in carbontech R&D and technological innovation – the first step in the technology commercialization process. Table 1 provides an overview of Canadian research and development centers in the CCUS sector.

TABLE 1: Canadian CCUS research centers

Province	CCUS research center		Activities
ON	University of Toronto	Sargent Laboratory	CO_2 Utilization (CO_2 to fuel) [46]
BC	University of British Columbia	Clean Energy Research Center (CERC)	CERC is active in different areas of the CCUS chain: CO_2 capture (CO_2 solid sorbents for pre- and post-combustion systems, chemical looping combustion system, gas hydrate crystals for pre-combustion capture of CO_2); conversion, (electrochemical conversion of CO_2 to produce valuable chemicals and fuels, co-polymerization of CO_2 to increase the molecular weight of polymers while increasing CO_2 utilization); and storage (CO_2 storage in mines and mineral precipitates, and in depleted natural gas reservoirs) [47].
BC	CMC Research Institutes	Carbon Capture and Conversion Institute	The Carbon Capture and Conversion Institute offers scale up, validation and development services to take technologies to the pre-pilot – 1 tonne CO_2/day - stage. The facility focuses on carbon capture technologies ranging from solvent, solid sorbents, membrane, and cryogenic-based systems and, in the utilization stream, processes that include thermal, chemical and electrochemical technologies.
AB	University of Calgary	Carbon Capture Initiative	CO_2 capture (academic research and technology development) [48].
AB	University of Calgary	Global Research Initiative (GRI) in sustainable low carbon conventional resources	Among others, research activities include fluid flow and transport phenomena in porous media, CO_2 storage in geological media, and upscaling and parameter estimation [49].
AB	University of Calgary	Gas Hydrates Laboratory	Assessment of using hydrates to sequester CO_2 and the potential of natural gas production from hydrates [50].
AB	University of Alberta	Future Energy Systems	Advanced Electrochemical System for Energy Storage Through Conversion [51], Advancing Effective Geological Storage [52], Adsorption mechanism of potassium promoted hydrotalcite [53], CO_2 Dissolution in Saline Pore Fluids and CO_2 EOR [54], Integrated Carbon Capture and (Photo) Reduction Systems [55], Mitigation of climate forcing materials [56], Post Combustion Capture using Solid Sorbents [57], Thermal Impacts for Geological Storage [58], Transforming Fossil Fuels into Heat or Hydrogen [59], Value-add Conversion [60].
AB	CMC Research Institutes	Containment and Monitoring Institute	The Containment and Monitoring Institute is an applied research, development and commercialization site for the development of CO_2 monitoring technologies, and for testing and validating methane emissions detection technologies.
SK	University of Regina	Dr. Yongan Gu's research group	The four primary research areas include CO_2 EOR, solvent vapour extraction (VAPEX), asphaltene precipitation and deposition, and fluid phase behaviour and PVT studies.
SK	University of Regina	Clean Energy Technologies Research Institute (CETRI)	The research mainly focuses on CO_2 capture technologies and procedures for reducing technology costs.
SK	International CCS Knowledge Center (ICCSKC)		With the ultimate objective of accelerating the deployment of CCS technology globally, the ICCSKC provides services from planning and design through policy advice for CCUS project implementation [61].

3.2 Test and scale-up facilities

Implementation of carbontech technologies at test and pilot scale is the next key step in the technology commercialization process. In Canada, there are several world-class testbed and pilot demonstration facilities which can be used by technology developers in various stages of the CCUS chain (i.e. capture, transport, use, storage and monitoring) (Table 2). These testbed facilities provide innovators the opportunity to test their technologies in pilot and semi-commercial settings, and often under variable weather conditions that commercial technologies are exposed to when operating outdoors in Canada's diverse regional climates and seasons. Canada is home to several CO_2 capture facilities that use oxy-fuel, pre- and post-combustion techniques to simulate the capture of CO_2 from industrial flue gas. The stream of CO_2 from many of these facilities is identical to the real-world flue gas from carbon-intensive industries and electricity generation plants and can be converted for further utilization or used to test the behaviour of CO_2 when sequestered in different media. Canada also hosts facilities to monitor the short to long-term behaviour of sequestered CO_2 in geological formations and aquifers, materials and products, and to assess life cycle concerns regarding permanence.

TABLE 2: Testbed and scale-up facilities

Province	Facility	Area of focus	Service
BC	CMC Research Institutes' Carbon Capture & Conversion Institute (CCCI) [62]	Capture and conversion	The Carbon Capture and Conversion Institute offers scale up, validation and development services to take technologies to the pre-pilot – 1 tonne CO_2/day - stage. The facility focuses on carbon capture technologies ranging from solvent, solid sorbents, membrane, and cryogenic-based systems and, in the utilization stream, processes that include thermal, chemical and electrochemical technologies.
AB	InnoTech Alberta's Alberta Carbon Conversion Technology Centre (ACCTC) [63]	Capture and conversion	This facility provides flue gas from a natural gas combined cycle gas turbine to CU technology developers, to enable testing of their capture and utilization technologies. The center has 5 testing bays for concurrent testing and it is suitable for technologies with a utilization rate of between 1-25 tonnes CO_2 per day.
AB	CMC Research Institutes' Containment and Monitoring Institute (CaMI) [64]	Monitoring for containment	The institute operates a 200-hectare field research station which functions as an applied research, development and commercialization site for CO_2 injection and monitoring, and methane detection technology validation.
ON	Natural Resources Canada's Oxy-fuel/G2 Group of CanmetENERGY [65]	Capture and utilization	The Oxy-fuel/G2 Group of CanmetENERGY is a leader in oxy-fuel combustion and CO_2 capture and utilization. Its focus is developing advanced fossil fuel combustion technologies with CO_2 capture and conversion to value-add products.
SK	SaskPower Shand Carbon Capture Test Facility (CCTF) [66]	Capture	Flue gas from the Shand Coal Power Station is fed to a test facility for post combustion capture technology evaluation and refinement. The facility can accommodate different test configurations and amine-based solvents and has a capture capacity of 120 tonnes of CO_2 per day.

3.3 Large-scale carbon capture and storage facilities

CCS and carbontech (capture and utilization technologies) have similarities in their capital-intensive infrastructure requirements, long project lifecycles, and technical requirements. The most common similarity is that carbontech and CCS both use CO_2 capture technology. The historical development of CCS is an important learning opportunity to overcome challenges of an emerging carbontech sector. This paper uses Canada's leadership in CCS commercialization to assess carbontech's national market strengths and weaknesses.

Canada is among leading countries hosting commercial scale CCS projects. Among the global pool of 51 large-scale CCS facilities currently in operation or under development/construction that are tracked by the Global CCS Institute[4], five are located in Canada[5] (Table 3) [18]. Roughly 1 in 6 tonnes of CO_2 that have been sequestered globally have been injected in Canada according to the Global CCS Institute in 2018.

TABLE 3: Canadian large-scale CCS facilities

Facility	Company	Development status	Province	Capture capacity (Mtpa)	Operation date	Industry	Transport length (km)	Storage type
Great Plains Synfuel Plant and Weyburn-Midale [67]	Dakota Gasification Company	Operating	SK	3.0	2000	Synthetic natural gas	329	EOR
Boundary Dam Carbon Capture and Storage [68]	SaskPower	Operating	SK	1.0	2014	Power generation	66	EOR
Quest [69]	Shell/CNRL	Operating	AB	1.0	2015	Hydrogen production	64	Dedicated geological storage – onshore deep saline formations
Alberta Carbon Trunk Line ("ACTL") with Agrium CO_2 Stream [70]	Agrium/ Enhance Energy	Operating	AB	0.3-0.6	2020	Fertilizer production	240	EOR
Alberta Carbon Trunk Line ("ACTL") with North West Sturgeon Refinery CO_2 Stream [71]	North West Sturgeon Refinery/ Enhance Energy	Operating	AB	1.2-1.4	2020	Oil refining	240	EOR

Canada, the United States and Norway are the only three countries worldwide which have large-scale CCS facilities both in electricity generation and in large-scale industrial plants [18]. The knowledge and expertise gained through the implementation of commercial-scale CCS projects can be transferred in the development of new CCS plants, arguably enabling learning effects including cost reduction. Such an advantage could position Canada ahead of many emerging competitors in carbontech development, since carbontech and CCS both share capture technology and require similar processes to plan for, build and execute commercial projects.

4 According to the Global CCS Institute, large-scale CCS facilities are categorized as those involving capture, transport and storage (either in geological sites or for enhanced oil recovery) at a capture scale of at least 0.8 Mtpa CO_2e from coal-based power plants, or at least 0.4 Mtpa from emissions-intensive industrial facilities, respectively. There are 51 projects in the Global CCS Institute's project database: 21 are in operation, two are under construction and 28 are in various stages of development.

5 Operational large-scale CCS facilities exist in only six countries worldwide.

4. Financial Support

Canadian CCUS technology innovators and developers have benefited from significant support programs offered both by the government (at federal, provincial and municipal levels) and by the private sector. Below we review two categories of CCUS technology support programs in Canada: federal and provincial financial incentives, and public & private innovation challenges.

4.1 Financial incentives

Financial incentives and subsidies have played a crucial role in the development and improvement of the economic-performance of emerging energy technologies.

Historically, financial incentives and subsidies have played a crucial role in the development and improvement of the economic-performance of emerging energy technologies [72]. The literature suggests that given the long commercialization cycle in novel industrial and energy technologies, critical enabling ingredients include patient, non-dilutive finance (generally from public sources), and corporate strategic partners willing to work collaboratively with entrepreneurs [73].

Canadian public investment in CCUS as a distinct focus began ramping up substantially in 2008 following the work of Alberta-Canada Task Force on CCS, which was mandated to advise government and industry on how to support Canadian CCS technology development and commercialization.

Through initiatives such as the ecoENERGY Innovation Initiative (ecoEII) [74], Clean Energy Fund (CEF) [75] and Clean Energy Innovation (CEI) [76], the Canadian federal government has contributed to numerous CCUS projects at different commercialization stages (See Appendix A) [77]. Provincial funding for CCUS projects in Alberta, Saskatchewan, British Columbia and Nova Scotia was on a financial scale comparable to federal funding [78]. In some cases, the province was the main investor for the CCUS project and the federal funding was marginal. For example, shares of Government of Alberta and Government of Canada in the total projects costs for Shell's Quest project were 57% and 9%, respectively [79, 80]. Similarly for the Alberta Carbon Trunk Line [81] and Boundary Dam [82] projects, provincial funding was much higher than federal funding (see Table 4).

Canadian public investment in CCUS peaked in 2013-14 at $409 million, largely because of the public-private cost-sharing associated with the construction of the multi-billion-dollar Shell Quest and SaskPower Boundary Dam CCS projects (Figure 3). Although expenditures in CCUS have not reached that level again, the period 2017-18 did see an increase in CCUS spending with total investments of $57 million.

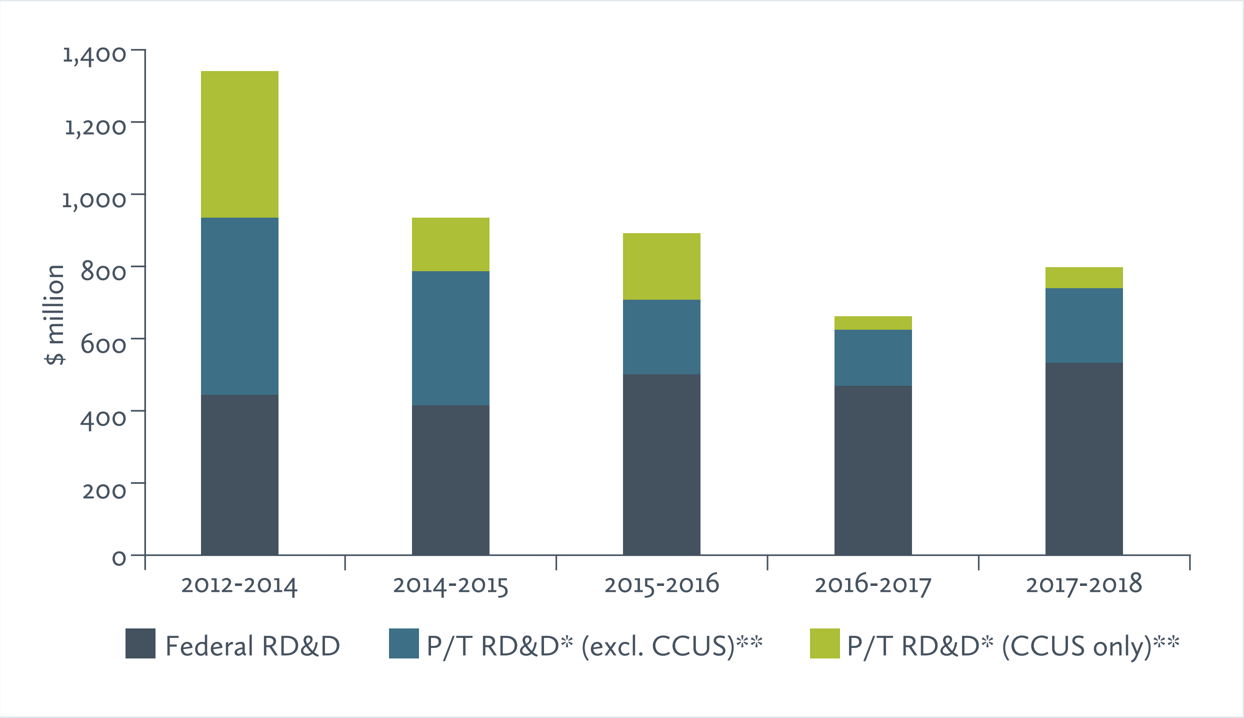


FIGURE 3: Canadian public expenditures on energy RD&D.
Source: Natural Resources Canada. [83]

In 2016, Canadian governments at all levels committed to increasing support for energy-related RD&D (including CCUS) to support the objectives of the Federal-Provincial-Territorial Pan-Canadian Framework on Clean Growth and Climate Change [83], and to meet Canada's commitment under Mission Innovation to double its 2014-15 funding of $387 million for clean energy and clean technology development to $775 million by 2020 [84].

Canadian CCUS technology developers can access financial support and investment through a range of federal and provincial government mechanisms. The federal government's Sustainable Development Technology Canada (SDTC) has invested over $1.3 billion in pre-commercial cleantech projects since 2001. At the provincial level, Emissions Reduction Alberta has invested $375 million in pre-commercial clean tech projects since 2009 and Alberta Innovates invests roughly $100 million annually in early stage clean technology RD&D. Additional financial support will likely emerge through the newly-established $35 billion Canada Infrastructure Bank, whose mandate is to build "a portfolio of investments that make a substantive contribution to supporting Canada's greenhouse gas reduction goals" [85].

Canadian CCUS technology developers can access financial support and investment through a range of federal and provincial government mechanisms.

Membership organizations also provide support for carbontech research and development. For example, Canada's Oil Sand Innovation Alliance (COSIA) member companies contributed to the NRG COSIA Carbon XPRIZE, a $20M international competition searching for breakthroughs in carbon conversion technologies.

Canadian public incentives for CCUS have successfully mobilized substantial investment from other sources, including from the U.S. Department of Energy and from the private sector (Table 4). Our analysis suggests that historically each $2 of Canadian public funding has mobilized roughly $1 of complementary investment in CCUS projects in Canada (Table 4).

TABLE 4: **Government funding for CCUS projects in Canada**

Project	Total CAPEX cost	Government of Canada funding	Provincial funding	Other public/ international funding	Private sector funding	Federal and Provincial funding as % of total project costs
	Million CAD					
Demonstration and commercial projects						
Alberta Carbon Trunk Line (ACTL) [81]	1200	63.2	495	-	-	46.5
Shell Quest [79, 80]	1310	120	745	6.3 Alberta Innovates	-	66.5
Weyburn-Midale CO_2 Monitoring and Storage Project[6] [86]	40.9	15.2	4.9	13.9 US Government	6.9 Industry	49.1
Boundary Dam [82]	1350	240	1110	-	-	100
Spectra Energy Fort Nelson Carbon Capture and Storage (FNCCS) Feasibility Project [87]	34.1	11.7	3.4	7.2 US Department of Energy	11.8 Spectra Energy	44.1
Total (Demonstration and commercial projects)	3935	450.1	2358.3	27.4	18.7	71
Feasibility studies and pilot projects						
Capital Power Corporation-IGCC Front End Engineering Design Study [88]	33	11	11	-	11 private sector	66.7
ARC Resources- Heartland Area Redwater Project (HARP) [89]	3.4	0.8	0.4	-	-	35
Husky Oil Operations Ltd. Heavy Oil CO_2 EOR and Storage in Saskatchewan [90]	67.7	14.1	-	-	53.6	20.8
TransAlta, Capital Power L.P. and Enbridge Inc. Project Pioneer in Alberta [90]	32.4	16.2	5	-	11.2	65.4
Total (Feasibility studies and pilot projects)	136.5	42.1	16.4	-	75.8	43
Total	**4071.5**	**492.2**	**2374.7**	**27.4**	**94.5**	**70**

6 The Great Plains Synfuel Plant and Weyburn-Midale CCS project (Table 3) is a commercial large-scale facility that is funded by private sector only (i.e., Cenovus and Apache) and did not receive any governmental funding at its inception. The Weyburn-Midale Storage and Monitoring project (Table 4) is a distinct project and did receive public funding.

While public and private funding have advanced CCUS technology in Canada, complementary measures are needed, including market creation through recognition of CCUS in offsets markets, carbon pricing to incent investment, and tax credits for project development and operation [91]. In the United States, for example, Section 45Q under the Bipartisan Budget Act of 2018 provides a tax credit of between $50 USD/tonne (for CCS) and $35 USD/tonne (for CCS-EOR) for any CCS plant that commences construction before 2024 [92]. By reducing the economic barrier to deployment of CCUS technologies, such measures are expected to expand the pace and scale of implementation in the U.S. [93].

4.2 Technology innovation challenges and prizes

Innovation challenges and prizes can be effective measures to accelerate innovation and commercialization of novel technologies [94]. Prizes can incentivize R&D as well as mobilize academic, entrepreneurial, investor and corporate interest across the technology innovation cycle in the theme that is at the centre of the prize [95, 96]. Globally, there are several CO_2 removal/reuse innovation challenges, including the Virgin Earth Challenge [97] and the European Union's Horizon CO_2 reuse prize [98]. Comparatively, Canada is hosting some of the most advanced carbontech innovation challenges worldwide (Table 5), and there is evidence to suggest that this is creating the beginnings of a carbontech cluster in Canada focused in Alberta.

TABLE 5: Examples of CCUS innovation challenges with Canadian support

#	Innovation Challenge	Sponsor/ Administrator	Focus	Amount
1	Carbon XPRIZE* [99]	NRG and COSIA	A 4.5-year competition focusing on technologies that convert CO_2 into products with the highest net value to reduce atmospheric CO_2 and convert it to valued add products.	USD$20M
2	ERA Grand Challenge [100]	Emissions Reduction Alberta	The grand challenge funds the innovative technologies which converts CO_2 to carbon-based products and markets.	C$35M
3	Solution 2030 Challenge [101]	Ontario Centres of Excellence/ Government of Ontario	A global challenge focused on accelerating the commercialization of GHG emissions reduction technologies in Ontario by 2030. The programs provide funding for prototype development and technology demonstration.	C$7M

*The NRG COSIA Carbon XPRIZE is supported by U.S. energy company NRG, Canada's COSIA, and is administered by the U.S. XPRIZE Foundation.

While Canada is supporting the CCUS prizes mentioned in Table 5, innovators from around the globe are participating. For example, the 10 NRG-COSIA Carbon XPRIZE finalists come from five different countries (United States, Canada, United Kingdom, China and India). In terms of mobilizing and providing validation to domestic technology developers, Canada is home to three of the XPRIZE finalists, second only to United States with four finalists.

Beyond financial awards, competitions incent the development of supporting infrastructure, including the Alberta Carbon Conversion Technology Center which attracted federal, provincial, municipal and private sector support. Local technology venture accelerators, like the Creative Destruction Labs-Rockies in Alberta, have supported several carbontech ventures, suggesting a reciprocal relationship emerging between competitions and local innovation ecosystems. Regional corporate partners are taking an interest as well: Capital Power, a North American utility headquartered in Alberta, acquired an equity interest in one of the XPRIZE finalists, C2CNT.

5. Regulatory Frameworks and Public Acceptability

5.1 Enabling regulatory measures

Due to the complex nature of the carbontech chain, a comprehensive set of regulatory measures are required to ensure successful large-scale implementation of the technology [102]. While different in nature, both CCS and carbontech share similar regulatory challenges. Existing and emerging regulatory frameworks could be used to support both groups of technologies. With several key regulatory measures in place at provincial and national levels, Canada is a global pioneering country in terms of establishing the necessary regulatory frameworks to enable and incent carbontech project development [102]. Examples include Alberta's Mines and Minerals Act (Carbon Capture and Storage Statutes Amendment Act, S.A. 2010, c. 14) [103] and Carbon Sequestration Tenure Regulation [104], British Columbia's Oil and Gas Activities Act [105] and Petroleum and Natural Gas Act [106] and Saskatchewan's Oil and Gas Conservation Act [107].

A comprehensive set of regulatory measures are required to ensure successful large-scale implementation of the technology.

In 2015, the Global CCS Institute conducted a comprehensive cross-country study to assess the effectiveness and maturity of the globally existing CCS regulations against the following criteria [108]:

- Clarity and efficiency of the administrative process;
- Comprehensiveness of the legal framework in providing for all aspects of a CCS project;
- Appropriate siting of projects and adequate environmental impact assessment processes;
- Stakeholder and public consultation; and
- Long-term liability for closure, monitoring and accidental releases of CO_2.

Of 55 countries investigated in that study, Canada was one of the five nations which possesses CCS-specific laws that are applicable across most part of the CCS cycle. Globally, Canadian CCS regulations were found to be the most effective in managing the administrative process as well as the long-term liability aspects of the CCS project.

On the other hand, results of the analysis suggest that there is opportunity to improve Canadian CCS regulatory regimes. More specifically, CCS legal and regulatory regimes are province-specific (i.e., exist only in Alberta, British Columbia and Saskatchewan) and there is a need to extend these regulations across other provinces and at the federal level. In addition, compared to other countries, Canadian CCS regulations were found to lack strength in terms of environmental impact assessment. Revision of existing regulations in that regard would improve the overall performance of the CCS regulatory regime in the country.

5.2 Public acceptance

Public acceptance can impact the adoption rate of CCS at regional and national levels [109, 110]. Public support itself is influenced by factors such as perception of benefit; trust in authorities; processes undertaken to secure project host community permission and risk perception, including concerns about geological storage and skepticism about human-induced climate change [111]. General public familiarity and acceptance of carbontech as a CO_2 mitigation technology not only varies among countries and demographic groups, but is influenced by regional-cultural differences [112]. For example, a study focusing on three Canadian provinces with different levels of CCS deployment rates show that publics most familiar with CCS are those that reside in provinces where there are already storage projects [113]. Public awareness is also found to positively impact risk perception with respect to CCUS technologies [114].

Less research has been conducted looking at factors that influence public perceptions of carbontech. Given that Canada already hosts several large-scale CCS facilities and people in those provinces are familiar with the technologies, carbontech may find public support for future projects especially in those regions with CCS facilities. A 2009 study found that Canadians view CCS with geological storage as lower-risk for climate mitigation than normal oil and gas industry operations, nuclear power generation or coal-burning power generation [115].

Input from the expert workshops hosted by this study's researchers suggests that carbontech may have greater public acceptability relative to conventional CCS projects. Participants concluded that while Canadians can generally be expected to be receptive to implementation of CCUS projects based on prior project experience, the successful development of a carbontech industry will require government to invest in sustained and benefit-focused communication in addition to investment in the necessary CO_2- transport infrastructure and regulatory frameworks [116, 117].

6. Innovation System

The establishment of various research centres and test bed facilities, public investment mechanisms, regulatory frameworks, widely publicized technology innovation challenges, and reportedly positive public attitudes towards carbontech has built momentum behind the technology in Canada. Proxy indicators for the innovation capacity are the number of for-profit carbontech ventures and patent activities.

6.1 Canadian carbontech venture formation

A list of Canadian carbontech developers active in Canada that includes an assessment of their area of focus and technology development status was complied through a comprehensive desk study, a review of the publicly-available venture databases, and consultation with industry and government stakeholders (see Appendix B). Where data on the commercialization status of technologies were not available, the technology commercialization timeline was validated through in-person interviews with technology developers.

Among the pool of 31 identified Canadian carbontech innovators, four focus solely on CO_2 capture technologies (post-combustion), two are active in both capture and utilization, and one focuses on direct air capture (DAC) and utilization. Figure 4 shows the sectoral distribution of the Canadian carbontech innovators.

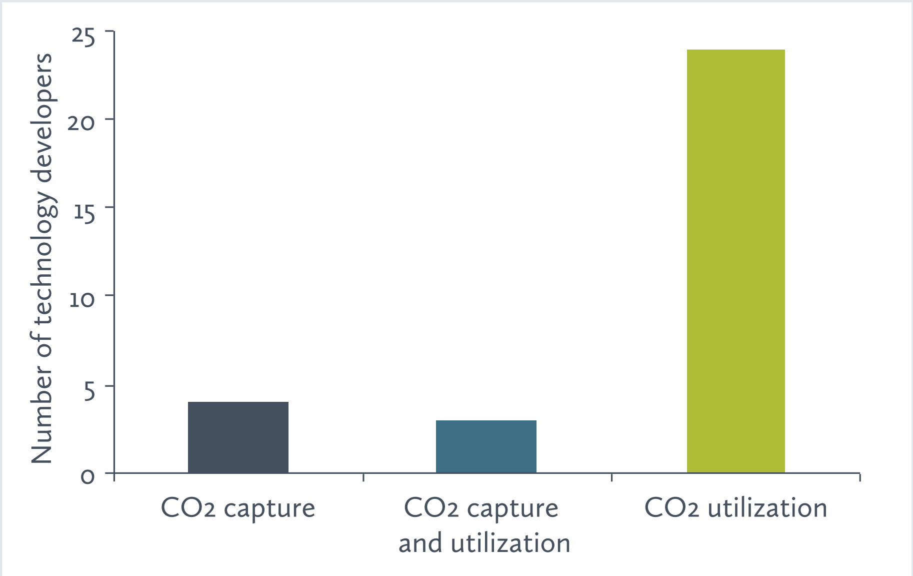


FIGURE 4: Sectoral distribution of Canadian CCUS innovators. (n=31)

Over half of the 27 companies developing carbon utilization technologies focus on CO_2 for fuel production or building materials (eight and seven companies respectively). This is followed by CO_2 to chemicals (three companies) and simultaneous production of fuels and chemicals (three companies). Polymer production from CO_2 accounts for 7% of total CO_2 utilization activities in Canada (two companies). The remaining 15% are active in other CO_2 utilization pathways including production of graphene and graphite and CO_2 utilization in greenhouses among others (four companies). The sectoral distribution of carbontech developers in Canada is shown in Figure 5.

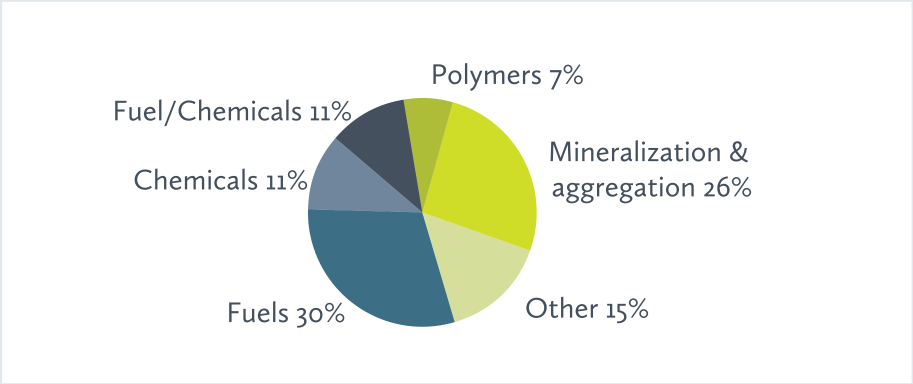


FIGURE 5: Distribution of Canadian CCUS technology development ventures between CO_2 utilization pathways. (n=27)

Analysis of the global pool of 181 carbontech ventures available from the Smart CO_2 Transformation (SCOT) database [118], shows that the global sectoral distribution of carbontech ventures is different than what we observe in Canada (Figure 6). Compared to the global data pool, Canadian carbontech ventures are more active in CO_2 mineralization/CO_2 to solid, and less active than the global average of ventures active in CO_2 to fuel and CO_2 to chemicals.

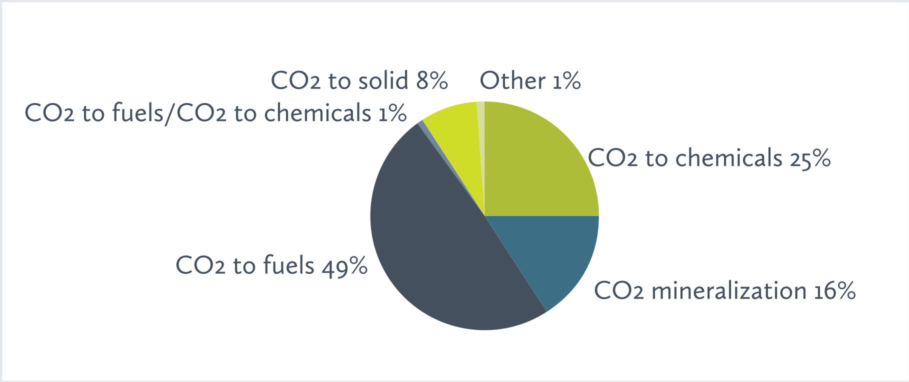


FIGURE 6: Global distribution of CCUS technology development ventures between CO_2 utilization pathways. [118]

Roughly half of Canadian carbontech innovators report that their technologies are in conceptual design and R&D phases with only one project at the pilot stage (Figure 7).

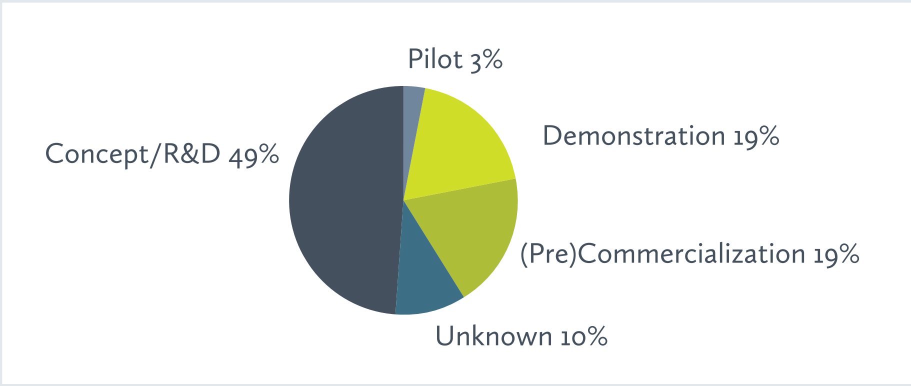


FIGURE 7: Development status of Canadian CCUS technologies. (n=31)

6.2 Canadian CCUS patent activity

Patent activities are indicators of technology R&D and innovation effectiveness [121] and patent data is a useful tool for measuring innovation in technologies [122] and industries [123]. In terms of the number of CCS patents granted, Canada is among the top four jurisdictions globally, with 332 of the world's 2,325 total, or 14% behind the U.S. (708 patents), China (663 patents) and European Patent Office (441 patents) [124]. In CO_2 utilization, (including both EOR and carbontech pathways), Canada holds 253 patents (representing 8% of the global carbontech patent pool as reported in 2017) placing the country third after the United States (1,222) and China (395) [125]. In terms of focus areas, 90% of Canadian carbontech patents are in EOR and in CO_2 to chemicals or fuels, split roughly equally, with the remaining 10% primarily in CO_2 mineralization [125].

7. Results and Discussion

Results of the analysis suggest that while Canada has competitive advantage in several aspects of carbontech technology innovation, there are areas where further improvement is needed to help the country realize its ultimate potential for carbontech technology development and adoption.

7.1 Canada's competitive advantage

Key Canadian areas of competitive advantage include domestic expertise, availability of financial support, effective regulatory framework, public acceptability and proven innovation performance.

As host to one-in-five of the world's large-scale CCS facilities, and with a comparatively-large number of world-class research centers and technology test bed facilities across the CCUS commercialization cycle, Canada is able to transfer technological and engineering expertise into the carbontech sector, as well as reduce the costs of proving out and implementing technologies in the field. The former could be done in the form of technology and knowledge transfer and the latter will be the result of learning by doing.

While Canada has competitive advantage in several aspects of carbontech technology innovation, there are areas where further improvement is needed to help.

In terms of financial support, Canada's large number of carbontech public support programs, financial incentives and public/private innovation challenges are positively mobilizing carbontech development and venture formation. Analysis of historical trends shows that each $2 of public federal and provincial financial support mobilize almost $1 of private investment into CCUS. In addition, Canada has hosted some of the most advanced global carbontech challenges including the NRG COSIA Carbon XPPRIZE and ERA Grand Challenge. Participants in these challenges have access to world-class test and scale-up facilities and to domestic and international sources of funding and investment – resources which could mobilize ventures to relocate to Canada.

The CCS-related regulatory frameworks in Canada are rated among the most comprehensive and effective CCS regulatory regimes globally, particularly in terms of clarity, efficiency of administrative process, and comprehensiveness of the legal framework for various stages of project development. While these regulations are mainly designed for CCS and CCS-EOR, the historical lessons learned could be used to effectively revise existing regulations to cover other sub-sectors of the CCUS chain including emerging carbontech pathways.

Public support is a necessary element in the siting and development of carbon storage and carbontech facilities and operations. Canada has demonstrated public support for CCS projects in regions where there are large-scale storage facilities, suggesting a willingness to host carbontech projects.

> **The CCS-related regulatory frameworks in Canada are rated among the most comprehensive and effective CCS regulatory regimes globally.**

Canada places fourth globally in terms of CCUS patents and third for carbontech -specific patents. The country is home to 27 carbontech innovators relative to a pool of 181 carbontech innovators tracked globally. Canada has a disproportionate share of the total pool of ventures in CO_2 to fuels, chemicals, and building materials/ minerals, suggesting these may be areas where Canada could build a competitive advantage for further technology development and market creation.

7.2 Potential areas of improvement

Canada's current CCUS innovation system has proved to be effective in technology commercialization and to some extent, market creation. However, for the country to become a global leader in the carbontech space a long-term national strategy needs to be developed that addresses improvement in financial support, regulatory frameworks and incentives for commercial adoption, a communications strategy, and innovation performance tracking.

> **For the country to become a global leader in the carbontech space a long-term national strategy needs to be developed.**

To help the economic sustainability of carbontech in Canada, innovative market mechanisms that promote technology adoption are required. Examples of such mechanisms are the inclusion of carbontech in regional and national carbon pricing systems and/or regulations that support eligibility of CCUS for some type of tax credit - similar to the U.S. Section 45Q CCUS tax credit. At this time, for example, only California has the necessary pricing under its Low Carbon Fuel Standard to enable CO_2-to-fuels to be commercially viable [126].

While Canada's CCUS regulatory regime is among the world's most supportive for carbontech implementation, policy uncertainty hinders the sector's development. While existing laws are most-developed in Alberta and Saskatchewan, they could be further extended to other jurisdictions within the country. Policy uncertainty was flagged at our CCUS expert workshops as the primary barrier to carbontech project and venture investment in Canada. Other barriers include recognition of carbon-based products and capture technology integration needs in industrial codes, product standards and green building/infrastructure rating systems.

An effective and unified carbontech communications strategy is necessary to propel the sector into the mainstream. Support for Canadian carbontech can be enhanced by further familiarizing key publics with the benefits of the technology, and by depoliticizing the carbontech opportunity [116]. A comprehensive communications strategy should target policy makers and political influencers to include carbontech in provincial and national climate action plans. It should also reach domestic and international investors to familiarize them with the considerable economic opportunity that carbontech has to offer, and the unique opportunities within the Canadian marketplace.

Finally, federal and provincial governments should provide specific support to carbontech development centres and to commercialization and scale-up efforts that build on the existing strengths (i.e., proven ventures needing scale-up funding in CO_2 mineralization, CO_2 to fuel and CO_2 to chemicals). Governments should track performance systematically, using quantitative indicators including those identified herein (patents, venture formation, public perception, project experience, investment, highly qualified personnel, etc.) as well as monitor emerging opportunities [127]. This is of crucial importance, especially considering the large number of Canadian CCUS patents and the large number of carbontech innovations currently in R&D stage.

8. Conclusions

Carbontech is an emerging technology sector whose economic potential could be on the order of a trillion dollars globally by 2030. While carbontech is limited in terms of its ability to 'soak up' CO_2 from anthropogenic sources, it offers an important economic incentive for wider deployment and cost reduction in carbon capture technology. This is seen as a critical ingredient in meeting global decarbonisation objectives, especially in the hard-to-decarbonise heavy industrial sectors.

Lessons from the regulated implementation of CCS can be used to inform the development of carbontech. In Canada, the experience of the first generation of CCS efforts is illustrative: Canadian academics, governments and corporations were among the global pioneers in CCS project development and today the country is home to one-in-five of the world's large-scale CCS facilities, with significant new projects emerging.

Carbontech is an emerging technology sector whose economic potential could be on the order of a trillion dollars globally by 2030.

Canada's support for efforts such as the Carbon XPRIZE and Emission Reduction Alberta's Carbon Utilization Grand Challenge, and the associated test bed facilities, have placed it among the top four countries globally both in establishment of carbontech patents and in the formation of carbontech ventures.

Carbontech has the potential to contribute to economic development, job growth and to decarbonisation climate targets. But with the rapid acceleration of carbontech development and investment in China, the U.S. and the EU, Canada risks falling behind. To help this nascent industry flourish, a comprehensive national strategy should be developed to guide policy makers, industry, SMEs, and the finance community as they make decisions that will impact growth. We hope this report will serve as a guide to focus attention and resources as stakeholders create a roadmap for future development of CCUS within broader emission reduction pathways.

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Appendix A: Federal financial support for CCUS projects [77]

Project Title	Lead Proponent	Provinces	Innovation	Funding Program*	Funding Status	NRCan funding (M$)	Project value M$)
Air-to-Fuels Development, Feasibility, and pre-FEED Study for First Commercial-Scale Demonstration Plant	Carbon Engineering Ltd.	BC	FEED Study	CEI	Active	1.5	4.2
Alberta Carbon Trunk Line Carbon Capture and Storage Project	Enhance Energy	AB	Demonstration	CEF	Completed	63	1200 [128]
Alberta CO_2 Purity Project (ACPP)	Petroleum Technology Alliance Canada	AB	R&D	ecoEII	Completed	0.525	0.955
Atmospheric leak detection as a tool for bitumen steam chamber and oil well integrity risk analyses	Saint Francis Xavier University	NS	Demonstration	ecoEII	Completed	0.3	0.539
Carbon Nanoplatelet (CNP) Production from Exhaust CO_2 Emissions	Carbon Upcycling Technologies Inc.	AB	R&D	CEI	Active	0.95	1.1
Carbon Storage Onshore Nova Scotia – Injection Site Characterization	CCS Research Consortium of Nova Scotia	NS	R&D	ecoEII	Completed	4.5	7.7
CO_2 Conversion to Methanol	Quantiam Technologies Inc.	AB	R&D	CEI	Active	1.15	2
Development of a Pilot-scale Supercritical-CO_2 Brayton Cycle Demonstration Loop	Carleton University, Mechanical Engineering	ON	R&D	ecoEII	Completed	1.4	2.2
Energy Quest Project	Shell Canada	AB	Demonstration	CEF	Completed	120	1310
Enzymatic Technology for Efficient Carbon Capture from Oil Sands Operations	CO_2 Solutions Inc.	QC AB	R&D	ecoEII	Completed	5.3	8.5
Identification of Options for CO_2 Storage in the Athabasca Area	Alberta Innovates – Technology Futures	AB	R&D	ecoEII	Completed	0.55	0.9
Surface Containment Monitoring for Carbon Capture and Storage	Saint Francis Xavier University	NS	R&D	ecoEII	Completed	0.909	1.6
VeloxoTherm CO_2 Capture Process Demonstration	Svante (formerly Inventys)	SK	Demonstration	CEI	Active	2.6	15.2

Appendix B: Canadian CCUS innovators

Province	Innovator	Focus	Technology/Pathway	Technology status
AB	SEEO2 Energy [129]	CO_2 Utilization	CO_2 to chemicals and fuel	Demonstration
AB	CleanO2 [130]	CO_2 Capture and utilization	Post combustion chemical adsorption	(Pre) commercial
AB	University of Alberta Fuel Cell [131]	CO_2 Utilization	CO_2 to fuel	R&D
AB	Enerkem Inc. [132, 133]	CO_2 Utilization	CO_2 to intermediate products	R&D
AB	Carbon Upcycling Technologies Inc. [134]	CO_2 Utilization	Polymer, Concrete and concrete coating	(Pre) commercial
AB	C2CNT [135]	CO_2 Utilization	CO_2 to polymer (nanofiber/nano tube)	R&D
AB	Quantiam Technologies Inc. [136]	CO_2 Utilization	CO_2 to fuel (Methanol)	R&D
BC	Carbon Futures [137]	CO_2 Utilization	CO_2 to chemicals	R&D
BC	Svante (formerly Inventys) [138]	CO_2 Capture	Intensified rapid cycle temperature swing adsorption (i-TSA) post combustion capture	(Pre) commercial
BC	Carbon Engineering [139]	Direct Air Capture and CO_2 Utilization	CO_2 to fuel	Demonstration
BC	Terra CO_2 Technologies [140]	CO_2 Utilization	Metal carbonation	Unknown
BC	Mantra Energy Alternatives [141]	CO_2 Utilization	CO_2 to fuel and Chemical	R&D
BC	University of British Columbia [142]	CO_2 Utilization	CO_2 to Chemical/ Mineralization	R&D
NS	Carbon Sense Solutions [143]	CO_2 Utilization	Mineralization and building materials	R&D
NS	CarbonCure [144]	CO_2 Utilization	CO_2 to concrete	Commercial
ON	University of Toronto Sargent Group [145]	CO_2 Utilization	CO_2 to fuel	R&D
ON	Capital Carbon Solutions (Energy SMART Group) [146]	CO_2 Capture and Utilization	CO_2 to fuel	R&D
ON	CVMR [147]	CO_2 Utilization	CO_2 to graphene and graphite	Pilot
ON	Tandem Technical [148]	CO_2 Utilization	CO_2 mineralization	Demonstration and scale-up
ON	Pond Technologies [149]	CO_2 Utilization	Various including CO_2 to food, fuel and chemical-Mainly CO_2 to Biofuels	Commercial
ON	CERT [150]	CO_2 Utilization	CO_2 to fuel	R&D
QC	Carbicrete [151]	CO_2 Utilization	Concrete curing	Demonstration
QC	CO_2 Solutions [152]	CO_2 Capture	Using 1T1 enzyme for carbon capture	Demonstration
QC	The Valorisation Carbone Québec (VCQ) [153]	CO_2 Utilization	Various	Demonstration
QC	Saint-Felicien Pulp Mill and Greenhouse [154]	CO_2 Utilization	Greenhouse	Unknown
QC	Shell Cansolv [155]	CO_2 Capture	Post combustion amine-based capture	Commercial
QC	McGill University-Lumenfab [156]	CO_2 Utilization	CO_2 to fuel	R&D & demonstration
QC	McGill University [157]	CO_2 Utilization	Aggregation and Carbonation	R&D
SK	HTC Purenergy Inc. [158]	CO_2 Capture	Post combustion capture	Unknown

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