RESEARCH REPORT

Evaluation of carbon capture and storage potential in Canada

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Executive summary

Carbon capture, utilization, and storage (CCUS) is emerging as an important opportunity in Canada's path towards net zero, necessitating a better understanding of where and how it could be best implemented as part of a comprehensive net-zero strategy.

In this report, we examine the potential of CCUS to address emissions currently produced by Canada's major industrial sectors. We characterize Canada's onshore geological storage potential and CCUS infrastructure by province, focusing on available reservoirs located in British Columbia, Alberta, Saskatchewan, Manitoba, Ontario, and Quebec. Our focus is on the expanded use of saline aquifers for permanent carbon dioxide (CO_2) storage, over the more limited basins currently used for enhanced oil recovery.

In our analysis, we plot the geographical position and the associated emissions of high-emitting facilities that can integrate CCUS. These facilities are then grouped according to a "proximity taxonomy" that we have derived to assess the theoretical potential of applying CCUS to these sectors. This taxonomy is used to group facilities based on their distance to potentially suitable geological storage basins, and/or to currently functioning or planned infrastructure for CO_2 transport and injection.

Although we focus on the application of CCUS in this research report, we recognize that Canada's geological storage resources can also be used by carbon dioxide removal (CDR) technologies[1] to address hard-to-abate and historical emissions.[2]

The results of the spatial analysis draw out practical considerations for large-scale CCUS deployment to address high-emitting sectors in Canada, based on large point-source facility emissions. Results are generated on a regional level to help inform provincial-level policy planning already underway (e.g., Alberta), or expected for this evolving sector (e.g., Ontario).

Key findings

Overall, Canada has rich potential for geological carbon storage. Approximately 389 gigatonnes (Gt) of prospective onshore storage exists, located mostly in Saskatchewan, Alberta, and Manitoba. On a regional basis, our main findings are that:

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[1] Such as for direct air capture, which can also be situated over geological storage to enable the permanent storage of captured CO_2.

[2] Carbon Removal Canada has recently estimated that Canada will need 300 Mt per year of CDR just to offset historical emissions (at the lowest end of the scale to remain within 1.5 °C of warming). This suggests the long-term use of resources for CDR deployment will likely be required to address historical emissions, rather than for the continued offset of residual emissions (Bushman and Merchant, 2023).

1. **British Columbia**'s prospective geological storage — 3,000 megatonnes (Mt) — is located in the sparsely-populated and mountainous northeast region of the province. Only about 1.2 Mt, or 20%, of provincial point-source facility emissions are situated close to known prospective storage. Combined, these factors suggest that the practical application of CCUS is currently limited in the province unless other basins are discovered and developed,[3] new technologies are applied,[4] and/or long pipelines are approved and built over complex terrain.
2. For **Alberta,** there is significant opportunity to leverage abundant geological storage resources (79,000 Mt) and existing CCUS infrastructure to help decarbonize several sectors, most notably the oil sands and utilities sectors. Many high-emitting facilities are located over formations that can store high volumes of CO_2, and are also located close to existing or proposed CO_2 transport and injection infrastructure. The theoretical emissions capture potential from these existing facilities can amount to as much as 104 Mt/year. To realize these projections, proposed infrastructure (e.g., capture facilities, pipelines and injection hubs) would need to be developed, enabling injection into saline aquifers, which represent a much larger storage resource than the more limited formations currently used for enhanced oil recovery (EOR).[5] Development of hubs to access saline aquifers would enable permanent storage of emissions and significantly expand the potential for CO_2 storage in Canada. Existing CCUS assets and storage potential could also support industrial growth and create new economic opportunities.
3. **Saskatchewan** overlies 290,000 Mt of prospective storage, which represents 70% of Canada's estimated total geological storage potential. The province also has a history of developing CCUS infrastructure. Although there is opportunity in Saskatchewan to explore these formations for CCUS, the scattered locations of existing point-sources may present economic challenges for the development of shared infrastructure. On the other hand, if Canada is to invest heavily in a CDR sector, Saskatchewan is likely to be a particularly attractive destination for carbon sequestration. CDR technologies are not predicated on the capture occurring at a point-source and can play an important role in addressing Canada's historical emissions. We suggest that a CDR-focused carbon

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[3] Such as the Nechako Basin in central British Columbia and the Georgia Basin on the West Coast (near Vancouver).

[4] Though northeast British Columbia is a primary area of interest for CCUS, the British Columbia Energy Regulator has indicated that other areas of the province have geology which may be suitable for CCUS projects that utilize slightly different technology, see: https://www.bc-er.ca/stories/carbon-capture-and-storage/

[5] In Western Canada, these formations have the smallest storage potential of all options (Hares *et al.*, 2022). For example, ACTL-Clive and Weyburn-Midale sites are significantly limited in their CO_2 storage capacity — with only about half of the estimated 87 Mt capacity remaining at Weyburn-Midale and less than 18 Mt remaining at the Clive site. Small storage capacity can negatively impact the long-term economics of EOR-based CO_2 storage and limit the practicability of EOR formations for large-scale CCUS deployment.

management strategy may be an area of interest for Saskatchewan to explore given its significant geological assets.

4. For **Ontario**, the lack of existing CCUS infrastructure means that significant resources and investment would be needed to make use of geological storage to address large facility emissions (estimated at 31 Mt CO_2/year), among other considerations. Notably, Ontario's CCUS potential is also significantly constrained by the province's limited geological storage, estimated at 730 Mt. This value has not been comprehensively evaluated — Ontario's actual geological storage capacity may be smaller than initial estimates have suggested,[6] with reservoirs possibly crossing the province's jurisdictional boundaries. Considering the available storage potential estimates together with the province's point-source emissions, we find that the Ontario basin could reach capacity by 2060-2075 even under fairly optimistic assumptions. This highlights the need for a selective CCUS development strategy that is balanced with other industrial emissions reduction measures in Ontario.[7]

5. Lastly, **Quebec** has significant geological storage resources (up to 3,200 Mt), with 44%, or 6.4 Mt, of point-source emissions located above prospective storage. Like Ontario, Quebec currently lacks carbon management infrastructure. Given the relatively low volume of emissions from large point-sources in the province (less than half of those of Ontario), the development of CCUS should be evaluated alongside other decarbonization opportunities, or in tandem with CDR, to take full advantage of geological assets while achieving higher "emissions return on investment" for this province.

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GIS mapping by C. Noyahr.

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[6] The storage efficiency of basins has been standardized at 2% of the bulk storage on average, which has been applied to characterize the British Columbia, Alberta, Saskatchewan, and Quebec reservoirs noted in this report. In contrast, Ontario's early reservoir calculation uses values of 10% for storage efficiency, which implies that Ontario's reservoir capacity may be significantly lower than what is reported in the earlier literature. Further expounded in *Box 5*.

[7] This noted, leveraging geological storage from other regions (such as Quebec or Michigan) may be an opportunity for further exploration. There are already examples of cross-jurisdictional CO_2 trade, such as Whitecap Resources purchasing CO_2 from North Dakota-based Dakota Gasification Company for sequestration in Saskatchewan's Weyburn oil field.

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1. Introduction

In 2022, Clean Prosperity launched a policy-focused modelling project with Navius Research to explore pathways to achieving net-zero emissions across the Canadian economy by 2050. Our research objectives are to model the broader energy-system outcomes of a net-zero transformation across sectors, geographies, and technologies, and examine the types of policies and infrastructure required to achieve these outcomes. This multi-year effort builds upon the work and findings of other Canadian and international net-zero studies.

One of the novel approaches that we are applying is performing spatial analysis on and downscaling[8] of select modelling results using geographic information systems (GIS) tools. This requires the integration of mapping assets with data that can be used to evaluate different net-zero pathway projections. The work detailed in this report explores the deployment context for one particular net-zero pillar identified in our work to date: carbon capture and removal. This report is intended to help provide a more specific understanding of the role that carbon capture and storage technologies can play in reducing Canada's carbon dioxide (CO_2) emissions, as well as identify considerations associated with a high level of deployment.

In this research report,[9] we examine CO_2 emissions from sectors with major emission point-sources across Canada (i.e., high-emitting sectors), and identify five provinces — British Columbia, Alberta, Saskatchewan, Ontario, and Quebec — that have geological formations that can potentially be used for CCUS (with a focus on saline aquifers). We then assess the potential application of CCUS to these high-emitting sectors, based on facility proximity to (1) geological formations that can permanently sequester carbon (storage), and to (2) currently built and/or planned infrastructure to transport this carbon and inject it underground.

In select provinces, we further examine certain implications of deployment, such as the risk of limited geological storage assets being exhausted within a short timescale (Ontario). Based on currently available geological studies, this work identifies a number of key considerations for large-scale CCUS deployment in Canada, recognizing that in

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[8] Downscaling refers to the procedure of using large-scale model results to make inferences at finer spatial (and/or temporal) scales for application to local-level analysis and planning. The spatial data analysis deployed in this report will support our future downscaling work.

[9] In June 2023, we released our first comprehensive modelling report which documents our current climate policy trajectory to 2050, and introduces the five net-zero pathways (Felder and Hervas, 2023 with companion methodology report: Navius Research, 2023). In December 2023 we published our Pillars of Decarbonization report (Felder, Hervas, and Noyahr, 2023, and also viewable at https://cleanprosperity.ca/net-zero-pillars-of-decarbonization/). Our upcoming work will look at renewable energy deployment, as well as identifying regional opportunities to operationalize net zero.

many regions further studies are required to meet the necessary contingencies[10] to determine commercially viable storage capacity.

Box 1: Understanding carbon dioxide capture, utilization, and storage vs. carbon dioxide removal

Carbon capture, utilization, and storage (CCUS) is typically employed to address point-source emissions for large-emitting facilities. CCUS typically involves “scrubbing” greenhouse gases (primarily carbon dioxide, or CO_2) from vent streams as they are emitted from a facility. Such systems are usually installed by large industrial emitters,[11] such as steel and cement production plants, or are applied in fossil fuel- or biomass- based power generation facilities.[12] CCUS systems can capture a significant portion (as high as 90% or more[13]) of CO_2 from flue gas at the point-source (noting that the flue gas itself may have low CO_2 concentrations, as low as 3%). Following capture, the CO_2 can be permanently stored in deep geologic formations such as saline aquifers, or used in various applications including enhanced oil recovery (EOR)[14] to produce oil. In this report we recognize that many current projects — including two operating hubs in Western Canada — are used for EOR, however, these are limited in total storage potential.[15] To enable permanent storage of large quantities of CO_2, we focus on the storage potential of Canada’s saline aquifers.

Carbon dioxide removal (CDR) technologies differ from CCUS in that they are designed to capture greenhouse gases directly from the air, without being tied to a point-source. A forerunning technology in this area is direct air capture (DAC), whereby chemical and physical processes are used to extract CO_2 from ambient air (with a CO_2 concentration of ~0.04%). DAC systems can theoretically be placed anywhere and capture any amount of CO_2 (including what was emitted in the past, which is referred to as historical or legacy emissions). Following capture, the carbon can be diverted to derive other marketable products or put in long-term or permanent storage, usually via injection deep underground (>800 m depth). In our modelling work, we have focused on the placement of DAC facilities near permanent geological storage.

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[10] Storage is deemed commercially viable (and termed “storage capacity”) once it meets all contingencies, which can be technical, regulatory, economic, or social. Prior to meeting all contingencies, it is referred to as “contingent storage”. See the Society of Petroleum Engineers terminology in Appendix B.

[11] Having emissions greater than 0.2 Mt CO_2e/year.

[12] The use of biofuels in combination with CCUS, usually termed bioenergy with carbon capture and storage (BECCS), can result in net-negative emissions since biofuels are considered low- or zero- carbon fuels. While we do not examine BECCS in this report, the role of BECCS in net-zero pathways is discussed in Felder, Hervas, and Noyahr, 2023.

[13] The capture proportion can differ depending on factors including the technology used for capture and the characteristics of the flue gas (Kearns *et al.*, 2021).

[14] Enhanced oil recovery (EOR) is a technique for enhancing oil extraction, where CO_2 is injected into an oil reservoir to increase pressure and improve the flow rate of oil, thus increasing the yield of that reservoir. EOR can also be performed using other gases, chemical injection, and heat (USDE, 2023).

[15] Estimations suggest that there are around 870 Mt of potential CO_2 storage (cumulative) in EOR formations in Alberta (Hares, 2020), approximately 240 Mt in Saskatchewan (Jensen, 2022), and about 30 Mt in northeastern British Columbia, (Geoscience British Columbia, 2023, Appendix C). Furthermore, the storage capacity of individual pools can be very low (a few megatonnes), raising additional challenges for scalability and long-term investment (Hares *et al.*, 2022).

DAC technology is currently in the very early stages of development, with 27 DAC plants having been commissioned worldwide to date, capturing only about 0.01 Mt of CO_2 per year (IEA, 2023a). Other forms of CDR are under development, including carbon mineralization and modification of ocean alkalinity, which do not necessarily require access to deep underground storage.[16]

2. Understanding Canada's potential for CCUS

The CCUS process involves the capture of CO_2 at the emissions point-source, transport of the captured CO_2 to an injection site, and its injection into a suitable underground geological storage formation. Captured CO_2 can also be utilized for a commercial purpose, with enhanced oil recovery (EOR) being the main commercial use of CO_2 to date. When used for EOR, nearly all of the CO_2 that is injected underground during the extraction process remains underground and is considered to be sequestered.[17] In this report we do not specifically assess EOR-suitable formations[18] and instead focus more broadly on the potential for large-scale permanent storage.

In this section, we describe Canada's potential and outlook for CCUS deployment based on three major parameters, which are:

1. The availability of suitable geological storage formations in different regions.
2. The presence of existing and/or planned infrastructure that can support the transport and injection of CO_2 into storage formations.
3. The current geographic distribution of major point-source emitters (e.g., fossil fuelled power plants and industrial facilities) that can utilize CCUS.

2.1 Introduction to geological formations for CO_2 storage

A number of characteristics are used to assess a reservoir's adequacy for CO_2 storage, such as: available pore space (capacity), injectivity[19], permeability, depth, and formation

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[16] Mineralization is a natural (but slow) process that occurs when CO_2 in moist air reacts with rock to form a solid mineral. CDR approaches involving mineralization aim to accelerate this natural process, for example, by increasing the surface area of exposed rock (Hills *et al.*, 2020). Similarly, ocean alkalinization is an approach that aims to enhance the ocean carbon sink by increasing the alkalinity of seawater (American University, 2023).

[17] Some of the CO_2 that is injected during the EOR process comes back up with the recovered oil, at which point it is typically separated and re-injected to extract more oil. In the end about 90-95% of the CO_2 remains geologically sequestered (Melzer, 2012).

[18] EOR potential is treated at length in the 2022 report by the Transition Accelerator on CO_2 storage potential in Western Canada (Hares *et al.*, 2022)

[19] The formation must be able to accept the CO_2 at a sustainable rate.

seal integrity (NETL, 2023). Suitable onshore[20] geological storage formations are usually at least two kilometres below surface and can include mature and/or depleted oil and gas reservoirs, basalt formations, and deep saline formations described in *Box 2.*

Once injected underground, the CO_2 is trapped via several processes operating at different time scales. Physical or structural trapping is the primary mechanism in which supercritical[21] CO_2 is retained by the structure and the stratigraphic features of the formation (Kelemen *et al*., 2019). Secondary processes, which include capillary trapping, solubility trapping, and mineral trapping, function at longer time scales and trap the CO_2 more permanently.[22]

The risk of leakage (CO_2 escaping from the storage formation into its surroundings and/or back into the atmosphere) is generally highest during the active injection phase.[23] Mitigation of leaks is conducted through measurement, monitoring, and verification (MMV) programs, which can include plume modelling, groundwater monitoring, satellite and atmospheric monitoring, and seismic monitoring.[24]

Box 2: Geological storage for captured CO_2

Deep saline aquifers: Saline aquifers are large porous formations that are filled with brine. To be suitable for CO_2 storage, the porous aquifer must be overlain by a layer of caprock or seal. Saline aquifers are usually penetrated by fewer wells than oil and gas reservoirs and therefore have a relatively low risk of leakage. However, they are also not as well characterized, implying that more work is needed to determine their capacity and other key attributes (Hares et al., 2022).

Mature oil fields: CO_2 can be injected into oil fields that have been producing oil for many years in order to increase oil recovery (i.e., enhanced oil recovery). In Western Canada, these formations have the smallest storage potential of all geological storage options (Hares et al., 2022).

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[20] Our current analysis is limited to onshore storage due to higher readiness for onshore CCUS expansion in the near-term, given the already functioning projects and available/planned infrastructure in parts of Canada. However, we recognize that offshore storage may become feasible in the future, opening up possibilities for carbon capture development in regions that are not considered in this report.

[21] A supercritical fluid has properties of a liquid (density) and a gas (viscosity and tension) simultaneously. CO_2 reaches the supercritical state when temperatures are higher than 31.1 degrees Celsius and pressures are above 7.28 MPa. These conditions occur deep underground, as both temperature and pressure are correlated with depth (Bachu, 2008).

[22] Capillary trapping is the process in which CO_2 is rendered immobile in the pore space, where it can remain stable for decades to centuries (Krevor *et al*., 2015). Solubility trapping is when the CO_2 dissolves in the water or brine and moves with deep water cycles on the scale of thousands to millions of years (Leslie *et al*., 2020). Mineral trapping occurs when CO_2 reacts with mineral and organic matter and is incorporated into a stable mineral phase. This is a very slow process that only becomes significant on a geological time scale (Zhang and Song, 2014).

[23] There is also some leakage risk during the transportation and storage phases.

[24] See the Shell Quest MMV Plan for example (Shell Canada, 2017).

Depleted oil and natural gas reservoirs: These are porous rock formations previously containing oil and gas. Because these formations held oil and gas trapped for thousands of years, they are considered to have the right conditions for CO_2 storage. However, these reservoirs tend to have low pressure and weak or no aquifer support, which presents challenges for injection and well integrity (Hoteit et al., 2019).

Basalt formations: Acidic CO_2-rich solutions (usually CO_2 dissolved in water) or liquid/supercritical CO_2 are injected into alkaline igneous rocks (e.g., porous basalt formations). The acidic solution neutralizes alkaline igneous rocks and forms precipitate minerals which fill the pore space, thus trapping the carbon dioxide permanently in solid form. This process occurs at short time scales (months to years) and the offshore storage potential (under the sea floor) is potentially high (180,000–250,000 Gt). However, to date the process has only been demonstrated in lab settings and in a few onshore field projects (Snæbjörnsdóttir et al., 2020).

Ocean storage: In this type of storage, CO_2 is injected directly into the ocean water column (below 1,000 m depth) where it dissolves and disperses, becoming part of the global carbon cycle, likely to remain out of the atmosphere for several hundred years. Ocean-based storage remains in the research stage, with questions remaining about long-term effects of this approach, including impacts on ocean pH and ecosystems (Caldeira et al. 2018).

2.2 Geological formations for onshore CO_2 storage in Canada

In this report, we focus on Canada's deep saline aquifer formations as these formations have very large storage potential[25] and are therefore most relevant to large-scale CCUS implementation.

Our analysis covers three major geologic regions, as mapped in *Figure 1*. The largest of these is the Western Canadian Sedimentary Basin (WCSB), which spans northeast British Columbia, most of Alberta, southern Saskatchewan and southwestern Manitoba. A subset of formations within this large sedimentary basin have sufficient size, depth, and other geological characteristics to be considered for long-term CO_2 storage.

Ontario and Quebec are located above the Appalachian Basin and St. Lawrence Lowlands Basin. These basins are relatively small and only have cursory evaluation estimates available, as detailed assessments have not yet been conducted.

Table 1 below describes the primary onshore formations in Canada that are illustrated in *Figure 1* and that have been evaluated (to varying degrees). These are mostly

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[25] Storage potential includes resources that are contingent (potentially accessible) and prospective (undiscovered and estimated). See *Appendix B* for further information.

prospective onshore storage[26] estimates (see *Appendix B* for storage resource classification), which suggest that these basins can support substantial quantities of CO_2 injection for long-term storage. In total 389,000 Mt (389 Gt) of prospective onshore storage is estimated to be available in Canada. For comparison, Canada's total greenhouse gas emissions in 2021 were estimated to be around 670 Mt CO_2e (ECCC, 2023b) — not including emissions from land use change and forest fires.

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[26] Prospective storage is understood in terms of chance of discovery and chance of development (see *Appendix B*). Storage capacity is used as a resource term, defined in (SPE, 2017), and reserved for pore space that is discovered, characterized, injectable, and classified as commercially viable (Hares *et al.*, 2022).

Figure 1: Basins in Canada that contain potential reservoirs for CCUS storage, demarcated by provincial boundaries. Formations in blue are deep saline aquifers that have been evaluated to provide prospective storage estimates (per *Table 1*).

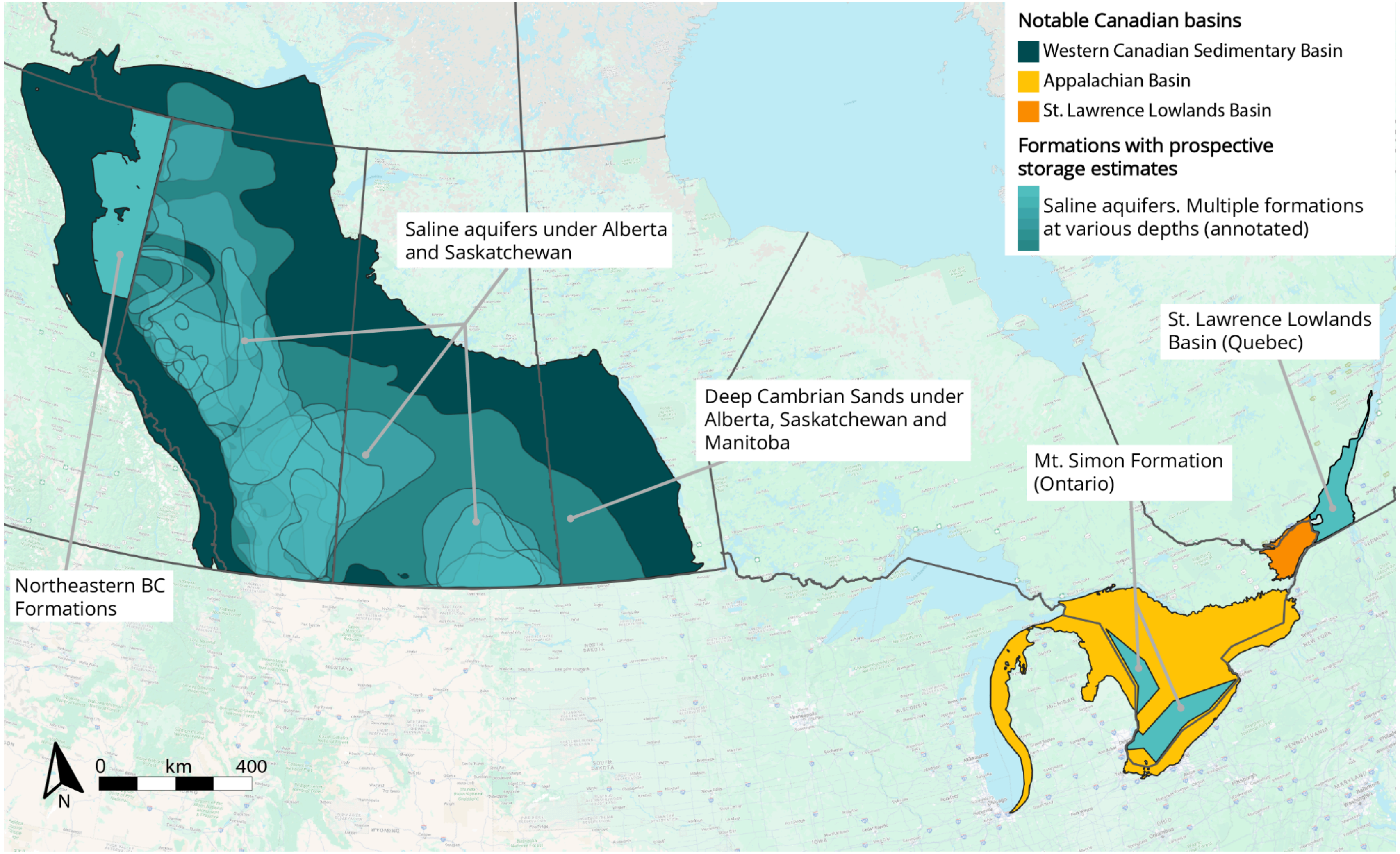

Table 1: Canadian saline aquifer formations and onshore CO_2 storage potential.

Basin; storage formation(s)	**Storage potential (Mt)**	**Description**
British Columbia: Western Canadian Sedimentary Basin (WCSB); Northeastern British Columbia saline formations[27]	**3,000 Mt** of prospective saline aquifer potential	These are saline formations that offer potential storage in carbonate and sandstone reservoirs in northeast British Columbia (Geoscience BC, 2023). Currently none of these reservoirs are being developed for storage.
Alberta: WCSB; Deep Cambrian Sands and other saline formations	**37,000 Mt** of prospective storage from Deep Cambrian Sands saline aquifers **42,000 Mt** of prospective storage from other saline aquifers under Alberta	Deep Cambrian Sands are the largest saline formations in Canada which span from Alberta into Manitoba and are composed of porous sandstones. These formations are the subject of many ongoing storage evaluations, and are also the target for the Shell Quest hydrogen plant that deploys CCUS. Other saline aquifers include formations stretching from Alberta into Saskatchewan at depths > 800 m and composed of porous sandstones or porous carbonates.[28] Many of these aquifers are targets for ongoing carbon sequestration evaluation.
Saskatchewan: WCSB; Deep Cambrian Sands and other saline formations	**268,000 Mt** of prospective storage from the Deep Cambrian Sands **22,000 Mt** prospective storage from other saline aquifers	
Manitoba: WCSB; Deep Cambrian Sands	**13,500 Mt** of prospective storage from the Deep Cambrian Sands	

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[27] There are other basins in the province that may be evaluated in the future (Geoscience BC, 2023).

[28] Extracted directly from the NATCARB Atlas Saline Basin 10 km grid shapefile (NETL, 2015). Other characterized aquifers in Alberta and Saskatchewan include: Beaverhill Lake Group, Elk Point Group, Mission Canyon Formation, Rundle Group, Viking Formation, Woodbend Group, and Winterburn Group.

Ontario: Appalachian basin; Mt. Simon formation	**146 to 1104 Mt** (730 Mt mid-range estimate) of prospective storage	Assessment has been performed on the Mt. Simon formation within the Appalachian basin, composed of porous sandstones. The formation reservoir is segmented into a northern and southern part[29] (Shafeen *et al.*, 2004a). The lower estimate (closer to 146 Mt) is derived using a lower storage efficiency assumption that is used by the U.S. Department of Energy (Goodman *et al.*, 2011).[a] No storage projects have been implemented to date.
Quebec: St. Lawrence Lowlands basin; Cairnside and Mt. Covey formations	**2,800 to 3,200 Mt** of prospective storage	The assessment has been performed on the Cairnside and Mt. Covey formations within the basin. Both formations are composed of porous sandstones (Bedard *et al.*, 2013). No storage projects have been implemented to date.
Total (approx.)	**389,000 Mt (389 Gt)** prospective storage	About 70% of this prospective storage is in Saskatchewan, followed by Alberta (20%).

[a] The U.S. Department of Energy has developed a Carbon Storage Atlas that provides information on CCUS developments across North America (Goodman et al., 2011). The atlas includes an equation to generate the static volume of pore space that can be displaced by CO_2, or the "storage resource estimate".[30] To obtain the "usable" storage of the reservoir, the bulk storage value is multiplied by a storage efficiency factor (to simulate losses due to real world fluid dynamics in the reservoir). The storage efficiency (also called sweep efficiency) has been standardized at 2% of the bulk storage in the average case. This value is used when characterizing British Columbia, Alberta, Saskatchewan, and Quebec reservoirs (the values noted in *Table 1* above). However, Ontario's early reservoir calculation (also shown in *Table 1*) uses values of 10% for efficiency.[31] This implies that Ontario's reservoir capacity may be significantly lower than the top estimate (730 Mt), the implications of which are further examined in *Box 5*.

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[29] Around 442 Mt are located in the southern segment of the reservoir and the remaining 289 Mt are located in the northern segment of the reservoir (Shafeen *et al.*, 2004).

[30] A CO_2 storage resource estimate is defined as the fraction of pore volume of porous and permeable sedimentary rocks available for CO_2 storage and accessible to injected CO_2 via drilled and completed wellbores (NETL, 2015).

[31] 10% sweep efficiency (Shafeen *et al.*, 2004a). Sweep efficiency is the fraction of the reservoir or pore volume that is invaded by the displacing fluid. Studies have explored a variety of methods to increase sweep efficiency to increase storage potential (Kim and Santamarina, 2014).

2.3 Existing and planned infrastructure that can support CCUS in Canada

The CCUS sector is under active development in Canada, principally in Alberta and Saskatchewan. Up to 4 Mt per year of CO_2 is currently captured for use and geological storage, and the federal *Carbon Management Strategy* estimates that 16 Mt per year can be stored by 2030 based on existing policy commitments and assumptions regarding the timing of project investment decisions, approvals, and construction (NRCan, 2023).

As it is often not technically and/or economically feasible to inject and store CO_2 at all capture sites (i.e., at every point-source), shared transport and injection infrastructure is needed to enable capture and storage at a more extensive scale. Infrastructure that is currently in use and under development aims to allow emitters to transport CO_2 via pipeline[32] to wells that inject it into deep storage.

Moreover, many first-of-a-kind CCUS projects have been “full-chain” (from capture to injection) infrastructure builds involving a single developer. However, this model suffers from high investment, risk, and liability burdens that must be shouldered by the developer (Dewar *et al.*, 2020). More recent projects have focused on “splitting up the CCUS value chain,” with shared access to underground injection and long-term storage via CCUS “hubs”. In this format, injection can still occur at a single site, but the CO_2 is sourced and transported from a number of different point-source emitters at various locations. This type of model offers many advantages, including lowering risk and costs for individual developers, and facilitating specialization at different points on the value chain (which allows new specialized players to emerge and boost innovation and investment in the sector). However, the hub model is not without challenges as it can add complexity to projects in the current regulatory environment. Issues including the seamless transfer of carbon credits between entities, transfer of liability, and jurisdictional irregularities will need to be addressed as the carbon market matures, to ensure fair distribution of benefits and risks along the value chain (Havercroft and Macrory, 2014).

As of 2021, over 140 CCUS hubs were under development around the world (IEA, 2023b). In Canada, the “open hub” model is currently the most common form of CCUS infrastructure proposed for future development. The open hub model entails open access and affordable use of the CCUS transport and saline aquifer injection infrastructure by emitters (see Alberta’s process for accelerating CCUS development at Government of Alberta, 2023b).[33]

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[32] While other forms of transport, such as truck, ship, and rail, are also possible, they are generally used for moving relatively small quantities of CO_2 and are not well-suited for large-scale deployment (Global CCS Institute, 2018; Equinor ASA, 2024).

[33] Notably, all the sequestration leases in the cited Alberta document are for saline aquifers.

Table 2 details the CO_2 injection sites that are currently operating in Canada. Six of the sites are dedicated to their associated projects and are thus not contenders for open hubs. The remaining two sites, Weyburn-Midale and Alberta Carbon Trunk Line (ACTL) - Clive (shaded in grey in *Table 2*), both EOR sites, follow a model that is closer to an open hub[34] as they accept CO_2 from multiple emitters.

CO_2-EOR can serve an important role as an anchor for infrastructure development by boosting the immediate economics of carbon capture and spurring further investment (e.g., per Hares *et al.*, 2022, International CCS Knowledge Centre, 2021). However, individual EOR formations tend to have a small storage potential, even if the combined potential of the formations may be large (Hares *et al.*, 2022). For example, ACTL-Clive and Weyburn-Midale sites are significantly limited in their CO_2 storage capacity — with only about half of the estimated 87 Mt capacity remaining at Weyburn-Midale and less than 18 Mt remaining at the Clive site (Hares *et al.*, 2022). Small storage capacity can negatively impact the long-term economics of EOR-based CO_2 storage and limit the practicability of EOR formations for large-scale CCUS deployment. Infrastructure buildout to enable access to saline aquifers would be required for large-scale CCUS development.

As incentives have continued to mature for permanent CO_2 storage, interest in developing high-capacity saline aquifer storage has increased. *Figure 2* shows large land areas that have been recently leased by different operators for assessment of CCUS storage. The majority of these areas are under evaluation for hub development using saline aquifers (grey areas in *Figure 2*). The blue-hatched areas are being evaluated for dedicated CO_2 storage for oil sands emissions from a conglomerate of six oil sands operators known as Pathways Alliance;[35] and Shell facility emissions from plants near Edmonton (Shell Polaris) (Shell Canada, 2021). Other evaluation leases include Reconciliation Energy (green area in *Figure 2*) for the development of a reservoir to capture and store emissions from renewable biodiesel production (Reconciliation Energy, 2023). The blue shaded area has been evaluated by Shell Quest and is being used to inject CO_2 generated from their blue hydrogen (steam methane reforming) plant (Site 7 in *Figure 2*).

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[34] The operational model of the Weyburn-Midale and ACTL-Clive projects follows that of a hub. However, they are not technically defined as open hubs as per Alberta's regulations, which exclude CO_2 sequestration projects associated with hydrocarbon recovery from the open hub designation (Government of Alberta, 2022).

[35] Pathways Alliance is a group of six oil companies who have committed to reaching net-zero emissions from their operations (Pathways Alliance, 2022).

Table 2: CO_2 injection sites currently operating in Canada.

Currently operating CO_2 injection sites	**Description**
1. Aquistore Deep Saline Aquifer Project	Dedicated deep saline storage site that provides CO_2 storage for SaskPower Boundary Dam 3 Carbon Capture and Storage facility (International CCS Knowledge Centre, 2021).
2. Weyburn-Midale EOR (takes multiple emitters)	EOR is conducted at the Weyburn and Midale oil fields using CO_2 that is piped in from the Great Plains Synfuels plant in North Dakota as well as SaskPower's Boundary Dam 3 CCUS facility in Estevan.[36] The total CO_2 storage capacity in the pools used at this location is estimated to be around 87 Mt[36], with over 45 Mt already being stored as of 2022 (Hares *et al.*, 2022; Cardinal Energy Ltd, 2022).
3. Hays Gas Plant - Enchant EOR	Dedicated injection site operated by Canadian Natural Resources Ltd (CNRL) which sources carbon from the Hays gas plant (CNRL, 2022).
4. NOVA Chemical Plant - Joffre EOR	Dedicated injection site operated by Whitecap Resources. They source carbon from the nearby NOVA chemical manufacturing plant (Whitecap Resources Inc., 2023).
5. Alberta Carbon Trunk Line - Clive EOR (Hub)	Clive Enhance Oil Recovery project. Enhance is currently the only organization in Alberta that manages sequestration of CO_2 from multiple sources — the "hub" model (Origins CCS, 2023). The storage pool at this site has an estimated capacity of 18.8 Mt, with around 4 Mt already stored as of 2024 (Government of Alberta, 2024; Hares *et al.*, 2022).
6. MEGlobal Chemical Plant - Chigwell EOR	Dedicated injection site operated by Alphabow Resources. They source carbon from the MEGlobal chemical manufacturing plants (Alberta Carbon Registries, 2019).
7. Shell Quest Scotford Upgrader Hydrogen Plant	Dedicated deep saline injection site for the Scotford Upgrader plant, which produces hydrogen via steam methane reforming, which is then combined with bitumen to produce synthetic crude oil (Government of Alberta, 2022).
8. Advantage Glacier CCS Gas Plant	Dedicated deep saline injection site for the Advantage Glacier gas plant (Entropy Inc., 2022).
Projects shaded in grey operate as hubs as they accept emissions from multiple sources via pipeline for injection at a single site. Currently, these sites inject CO_2 for EOR but it is anticipated that ACTL will be adapted to include saline aquifer storage.	

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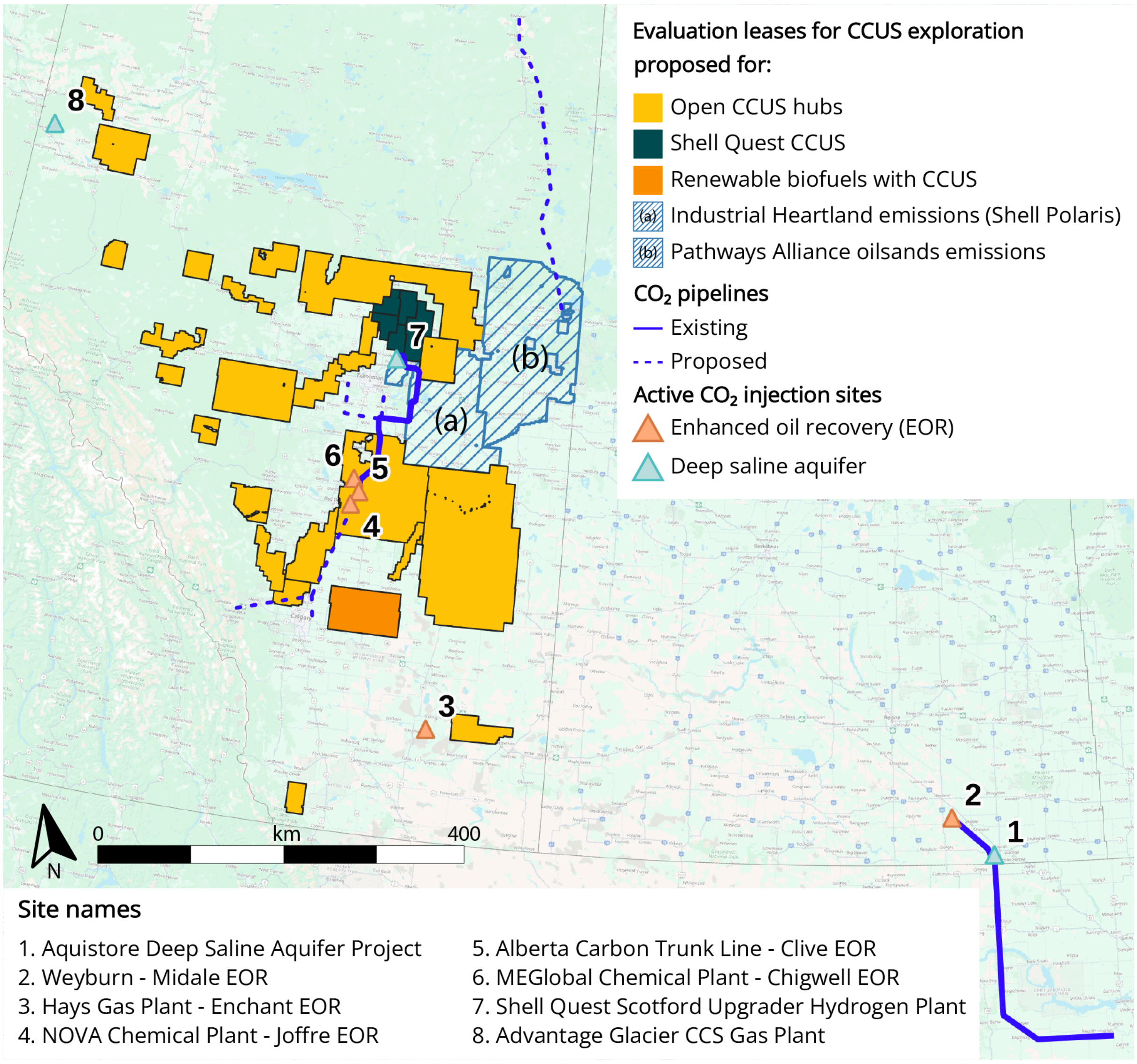
[36] Whitecap Resources suggest that potential storage could be higher at these sites, estimating around 115 Mt CO_2 for Weyburn (Whitecap Resources Inc., 2024).

Figure 2: Currently operational and proposed CO_2 transport and injection infrastructure in Canada.



Numbered injection sites are labelled in the "Site names" legend with corresponding triangles denoting site type. A full description of sites is available in *Table 2*. CO_2 pipelines are represented as solid blue lines for existing pipelines and hatched blue lines for proposed pipelines. Land areas in yellow correspond to leases for proposed open carbon hubs, and blue hatched leases are intended for specific projects: (a) Shell's industrial heartland emissions and (b) Pathways Alliance oil sands emissions via a proposed pipeline. The area in dark green represents the CO_2 storage area for Shell's Quest Hydrogen facility. The orange area is leased by Reconciliation Energy for storage of emissions from a proposed renewable biofuels plant.

2.4 Large emissions point-sources that can integrate CCUS

In Canada, large point-source emitters are generally industrial operations or power plants that rely on fuel combustion for electricity generation and/or heat for industrial processes.[37] In this report we segregate industrial emitters by subsector as different subsectors can carry unique opportunities and challenges for CCUS implementation. We have identified 11 sectors[38] where CCUS can be theoretically applied to capture point-source emissions. These include:

1. Chemical manufacturing
2. Lime and cement manufacturing
3. Metal manufacturing
4. Other large manufacturing
5. Mining
6. Pulp and paper
7. Utilities (electricity and heat generation)
8. Oil sands operations
9. Other types of oil and gas extraction
10. Petroleum refining
11. Pipeline transport of natural gas

Figure 3 shows Canada's emissions from major point-sources in 2021, based on the 11 sectors listed above. The values provided are adapted from Environment and Climate Change Canada (ECCC)'s facility emissions inventory (2021).[39] The magnitude of CO_2 emissions is represented by circle size. The totals are also documented in *Table 4*.

The figure shows that the largest emission clusters are located in the northwest Albertan oil sands. There is also a large industrial cluster in northern Alberta (near Edmonton) which corresponds to oil and gas extraction, utilities, and manufacturing facilities. Significant point-source clusters are also located in southern Ontario and southern Quebec, comprising utilities and various types of manufacturing.

Other sizable emitters corresponding to utilities, mining, and manufacturing, are scattered across the country, including parts of British Columbia and Atlantic Canada.

Previous studies, including the International CCS Knowledge Centre's CO_2 guided map for Canada (International CCS Knowledge Centre, 2021) and Boston Consulting Group (BCG)'s analysis for scaling up Canada's carbon capture (Green *et al.*, 2021) have identified significant opportunities across the country, based on clusters of industrial emitters that could take advantage of hub development to help lower sequestration

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[37] The primary mode of carbon capture applied to these sectors is the integration of post-combustion capture units to their heat, cogeneration, and electricity generation operations. The CCUS units are then able to capture up to 90% of CO_2 from flue gas. Other technologies involving pre-combustion carbon capture are also in development, which may capture an even higher proportion of CO_2 emissions (Ihejirika, 2021).

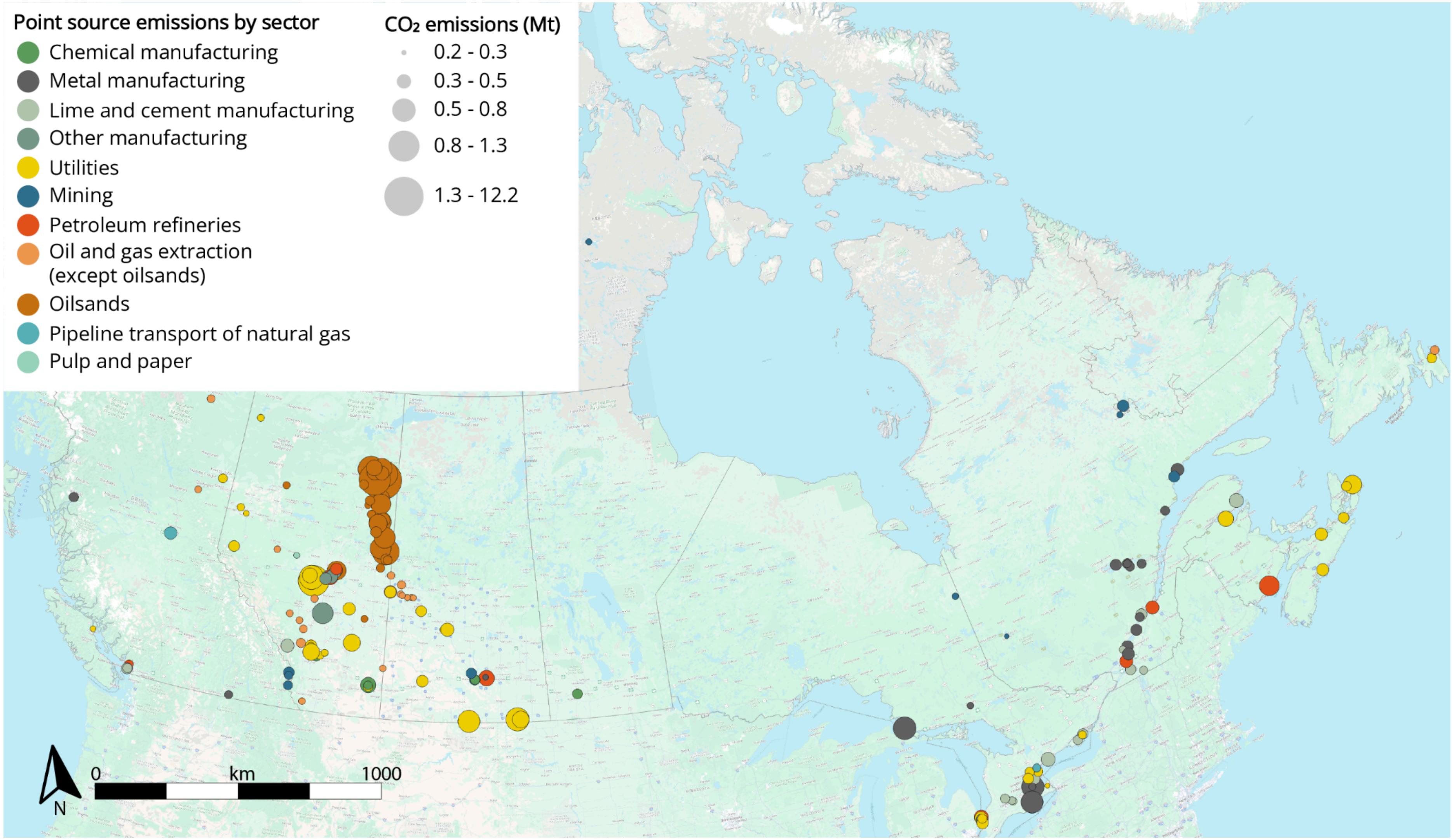
[38] Using the National Inventory Report categorization previously described (ECCC, 2023a).

[39] The large final emitter (LFE) point-source data included on the map is from Environment and Climate Change Canada's facility emissions inventory from 2021. Large Final Emitters (LFE) emissions are classified by NAICS code and are aggregated into 11 sectors. Each dot on the map represents one LFE above 0.2 Mt CO_2e/year. The colour of the dot indicates the sector and the size indicates the magnitude of annual emissions in 2021.

costs. Our analysis aligns with the work by BCG, which shows many of these same point-sources grouped by region (per Exhibit 1 in Green *et al.*, 2021), as well as with H2GO Canada's hydrogen studies and Geofirma's CCUS roadmap for Ontario, which recognize similar spatial distribution of industrial clusters in Ontario (H2GO Canada, 2023; Geofirma Engineering, 2023). Our work also builds on the International CCS Knowledge Centre report (see Figures 3 and 4 in International CCS Knowledge Centre, 2021), however we apply more recent large final emitter data from 2021.

In addition to mapping total emissions by facility point-source, our analysis provides further resolution on the contributing sectors and subsectors that make up these emissions across Canada. As discussed in subsequent sections, the source of emissions can carry material implications for the costs of CCUS implementation (e.g., due to differential CO_2 concentrations from flue gas streams, see *Box 3*), and consequently has a bearing on the type of support that would be most relevant given a particular region's industrial context. Our analysis also leverages existing/proposed CO_2 transport and injection infrastructure as a starting point for CCUS expansion, and further elaborates on the role (and limitations) of regional geology in supporting CO_2 storage.

Figure 3: CO_2 emissions (2021) for large point-source emitters across Canada that can integrate CCUS.



3. Methods and materials

In our analysis, we describe the sector-based CCUS potential in select provinces based on geological characteristics, large point-source emissions (2021), and the current state of the region's carbon management infrastructure.

This approach connects three interrelated aspects that we consider important to informing provincial CCUS planning: (1) regional major emissions point-sources that are candidates for CCUS, (2) available onshore[40] subsurface formations (saline aquifers) that can support CO_2 sequestration, and (3) CO_2 transport and injection infrastructure that is currently in place, or under consideration for future development.

3.1 Mapping of spatial layers

With input from our modelling partner, Navius Research, we compiled a set of spatial layers corresponding to the locations of major point-source emitters of CO_2, current/planned CO_2 transport pipelines and injection sites, and geological conditions relevant to carbon capture, transport, and storage. This source data is largely from government agencies and listed in *Appendix A*.

Using geographic information systems (GIS) tools, we overlaid point-source emissions data with datasets on geological storage, CCUS pipelines, CO_2 injection sites, evaluation lease areas, and other existing and planned CCUS infrastructure projects.[41] These spatial layers were integrated using GIS to assess the relative spatial distribution of point-source emitters across Canada, aggregated by province and by economic sector.

3.2 Classification of point-source emitters by proximity to infrastructure and geological storage

We next formulated five categories (detailed in *Table 3*) to reflect a point-source's location with respect to suitable regional geology for long-term sequestration (per *Figure 1),* and its proximity to existing or proposed CCUS transport and injection infrastructure (per *Figure 2)*. This approach allows us to understand which large emitters could be well-positioned for CCUS deployment based on their spatial attributes, and in turn help provinces understand where CCUS deployment would likely be of benefit and interest to pursue.

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[40] Offshore and ocean storage are active areas of research (see *Box 2*), with potentially large resources available off the coasts of Canada and the United States. While promising in terms of technical feasibility, ocean storage development is currently less ready than onshore storage, having unique ecological, logistical, regulatory, legal, and cost challenges (Webb and Gerrard, 2019; Wong, 2023).

[41] Datasets were checked against available secondary sources and in some cases updated manually.

1. For Category (1), a 50 km buffer was applied around existing CO_2 pipelines and operating injection hubs (per *Table 3*). We use 50 km to define "close" proximity. This distance roughly corresponds to that of more economic, lower diameter, and lower volume feeder pipelines that would connect emission sources to higher capacity trunk lines (LaFrenz *et al.*, 2021; CER, 2023; Wei *et al.*, 2022; USDE, 2015).[42]
2. For Category (2), a 50 km buffer was applied around proposed CO_2 pipelines and merged with evaluation leases for sequestration projects (per *Figure 2*).
3. For Category (3), saline aquifer geology shapes for British Columbia, Alberta, Saskatchewan, Manitoba,[43] Ontario, and Quebec were merged into a single layer from their respective sources (with exclusion of areas under Categories 1 and 2).
4. For Category (4), a 50 km buffer was applied to Category (3) areas.
5. Category (5): areas outside of those under Categories 1-4.

Large emissions point-sources (defined as those facilities emitting more than 0.2 Mt of CO_2 per year) were compared against these categories to generate proximity-based results. In this analysis and as noted in *Table 3***,** we assume that:

1. Point-sources located in the vicinity of existing infrastructure could potentially connect to this infrastructure. Connecting to existing pipelines lowers the overall time to implementation and overall investment.[44]
2. Point-sources located in areas that are under evaluation for potential hubs, or that are near proposed pipelines, may be able to take advantage of infrastructure in the near future, pending the buildout of the proposed projects.
3. Point-sources located further away are likely to face more logistical challenges, higher costs, and longer timelines for realizing their CCUS potential, and are therefore likely to be less economic or less feasible in many instances.

We highlight that to successfully harness existing and planned pipelines, it is essential to build more injection hubs with high geological storage capacity (i.e., saline aquifers), as

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[42] Although there is no exact rule defining pipeline length with respect to diameter/volume, CO_2 pipelines of up to and around 50 km in length are typically considered "short" (e.g., LaFrenz *et al.*, 2021) and cost-effective (e.g., Wei *et al.*, 2022). Similarly, large oil and gas transmission pipelines crossing provincial borders, which are overseen by the Canada Energy Regulator, are over 50 km long (CER, 2023). In the United States, a 50 mile threshold is often used to denote shorter lateral pipelines (USDE, 2015).

[43] Aquifers for Manitoba are technically included in the mapping but not examined herein.

[44] Historically, long pipelines (both for natural gas and CO_2) have been built as mainlines, with subsequent extensions to the pipeline being built off the mainlines (Argonne National Laboratory, 2007; USDE, 2015). In Alberta, backbone infrastructure routes, such as the ACTL, were identified as major transmission lines for emitters to connect to (Angevine and Hrytzak-Lieffers, 2007; Government of Alberta, 2009). Wolf Midstream has also recently entered an agreement to extend the trunk line 40 km to capture CO_2 from additional industrial sources (Wolf Midstream, 2023).

the currently functioning (EOR) hubs are significantly limited in capacity (as detailed in *Table 2*)**.**

Table 3: Point-source emitter categories with respect to proximity to CO_2 transport, injection, and geological storage.

Category	**Description**	**Significance/rationale**
(1) Within 50 km of existing infrastructure	Emission point-source is located within 50 km of existing CO_2 transport pipelines (i.e., Alberta Carbon Trunk Line and cross-border pipeline between Saskatchewan and the U.S.) and injection sites functioning as open hubs.[45]	Sites can theoretically link into existing pipelines, which can lower the overall required time for implementation and level of investment.
(2) Within 50 km of proposed CO_2 pipelines, or within land areas for proposed storage hubs	The point-source is located within a land lease area that is currently under evaluation for storage hub development; or the point-source is within 50 km of a proposed CO_2 pipeline.	Storage infrastructure may become accessible to these locations in the near future, pending full build-out of proposed projects. There is uncertainty with regard to which projects will be fully built, as well as their exact locations and timelines.
(3) Above storage geology (no infrastructure)	The point-source is located above suitable storage geology, but there is no operational or proposed CO_2 transport or injection infrastructure within 50 km of the site.	Storage may become accessible to these locations in the future with more infrastructure development. However, higher uncertainty and longer timelines are implied due to lack of current infrastructure plans or distance to storage. These areas could be considered for targeted infrastructure development in the future, especially in regions where there is a concentration of emitters.
(4) Within 50 km of storage geology (no infrastructure)	The point-source is not located near infrastructure, but is within 50 km of suitable storage geology. Emissions could be transported to wells that are located above a storage basin.	
(5) Far from infrastructure and storage geology	The point-source is located further than 50 km from suitable storage or infrastructure, making the emission stream more difficult to transport and store.	CCUS implementation could face significant logistical and cost challenges.

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[45] Glacier CCS, Aquistore, Joffre EOR, Chigwell EOR, Enchant EOR, and Shell Quest currently capture with dedicated storage for their respective point-sources. As such they are not considered as nodes for current infrastructure for storage.

4. Findings: CCUS by region and sector, Canada

The following findings are intended to inform: (1) which regions in Canada are best positioned for CCUS development based on access to underground storage and established/planned CO_2 transport and injection infrastructure; and (2) which sectors could be contenders for CCUS deployment, based on the specific geographical position of their associated large emitters.

4.1 CCUS potential by region across Canada

As per the mapping result displayed in *Figure 4,*[46] our analysis shows that even though the largest volume of geological storage space is located in Saskatchewan (see *Table 1***)**, the most immediate opportunity for CCUS expansion is in Alberta, where major geological storage resources are already supported by both existing and developing infrastructure. Alberta also has the most advanced regulatory regime for CCUS, which is critical for enabling expansion and encouraging further investment (Hares *et al*, 2022).

Based on emissions and basin storage potential, development opportunities for CCUS exist in Saskatchewan, Manitoba, British Columbia, southern Ontario, and southern Quebec. However, each province faces unique geographic, geological, and/or infrastructure challenges. For instance, British Columbia's abundant geological storage is distant from the majority of provincial point-source emissions (*Figure 4*). Saskatchewan's emissions are scattered over large areas in the south of the province with many located far from existing transport and injection infrastructure. However, it is worth noting that 100% of Saskatchewan's large point-source emissions occur above storage geology, highlighting the province's potential for CCUS development, possibly in conjunction with CDR.

Further, Ontario, Quebec, and Manitoba currently lack CCUS infrastructure. Ontario, which has significant point-source emissions, is also significantly limited by its geological storage potential. This is further explored in Section 5.4**.**

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[46] Our findings illustrated in *Figure 4* are well aligned with an earlier study by the International CCS Knowledge Centre, who conducted a similar analysis but with 2018 emissions data (International CCS Knowledge Centre, 2021). Our work builds on this initial analysis by the application of a proximity taxonomy to assess sector-based CCUS potential.

Figure 4: Mapping result of overlaying point-source emissions with carbon dioxide storage potential in Canada.

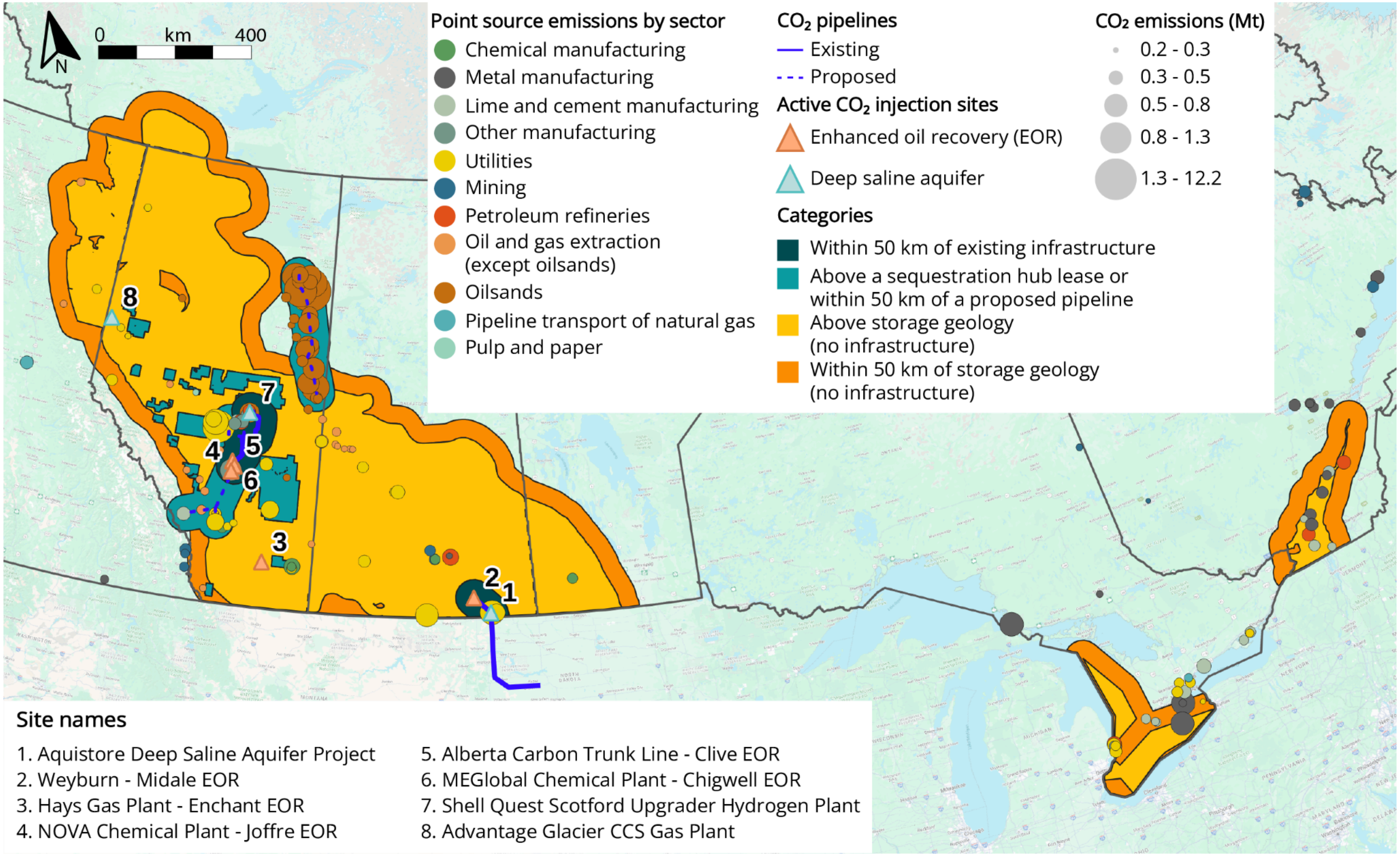

Table 4 below quantifies the data points shown in *Figure 4.* This table illustrates that continued CCUS buildout can help address Alberta's significant point-source emissions from large industrial facilities (i.e., facilities that emit more than 0.2 Mt CO_2/year[47]), which, at 122.5 Mt/year, are much higher than those in other provinces (see *Row 1*). Of this total, 99.8% of emissions occur within 50 km of potential geological storage. Furthermore, about 15% of Alberta's point-source facility emissions occur within 50 km of existing CO_2 pipelines, and 79% are located within 50 km of proposed pipelines or within land areas that are under evaluation for potential storage hubs. This reflects a total of 104 Mt/year of theoretical capture in these two categories assuming a 90% capture efficiency, among other assumptions.

It is worth noting that small point-sources (less than 0.2 Mt CO_2/year) are not included in the ECCC emissions inventory dataset used in this report. However, in some provinces the sum total of emissions from smaller point-sources can comprise a significant proportion of industrial emissions. For instance, the 2021 total point-source emissions in Quebec amounted to about 22.6 Mt CO_2, with only 14.8 Mt (65%, per *Table 4*) coming from larger emitters. Similarly, total point-source emissions in British Columbia in 2021 were estimated to be 15.5 Mt CO_2, only 6.3 Mt (41%) of which were from sources emitting over 0.2 Mt CO_2/year (ECCC, 2021).

4.2 CCUS potential by sector across Canada

Table 5 below breaks down point-source emissions across Canada by economic sector. In this table the oil sands sector stands out as the highest emitting sector at nearly 74 Mt of CO_2 emissions per year (*Row 1*). Utilities are another high-emitting sector with 56.4 Mt/year of CO_2 emissions across the country[48]. Notably, both of these sectors show significant potential for near-term CCUS deployment, as over 40% of utilities and nearly all (96%) of oil sands point-source emitters are located close to proposed pipeline infrastructure, or are within land leases under evaluation for storage hub development. Over 13% of utility and close to 4% of oil sands point-source emissions are within 50 km of already existing pipelines.

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[47] In our analysis we include all facilities that report emissions to the ECCC emissions inventory, which uses the 0.2 Mt CO_2/year threshold for reporting. Some researchers use a higher threshold in their analysis (e.g., 0.4 Mt CO_2/year is often used by the International CCS Knowledge Centre) to account for capture cost considerations with currently commercially available technology.

[48] Of the 50 electricity and cogeneration plants in Canada, 13 power plants are coal or fuel-oil based, where CCUS is a lower priority compared to fuel-switching. Two coal facilities are located in Alberta, emitting a total of 12.6 Mt CO_2/year; and three coal facilities are located in Saskatchewan, emitting a total of 10.2 Mt CO_2/year. The remaining facilities are located in the Maritime provinces, away from onshore storage.

Table 4: Total emissions (CO_2) by province from large point-source emitters in relation to existing/proposed carbon capture infrastructure and storage geology, Canada. Yellow boxes show the greatest value for each sector, and blue boxes show the second-highest value.

	BC	AB	SK	MB	ON	QC	NB	NL	NS	NT
Total emissions from large point-sources (Mt CO_2) in 2021*	6.3	122.5	21.5	0.6	31.1	14.8	5.5	2.8	6.0	0.2
Number of facilities	14	81	21	1	34	22	4	5	5	1
Within 50 km of existing infrastructure	0%	15.4%	29.4%	0%	0%	0%	0%	0%	0%	0%
Within 50 km of proposed CO_2 pipelines, or within land areas for proposed storage hubs	0%	79.2%	0%	0%	0%	0%	0%	0%	0%	0%
Above storage geology (no infrastructure)	14.2%	4%	70.6%	100%	28.8%	44%	0%	0%	0%	0%
Within 50 km of storage geology	4.6%	1.1%	0%	0%	33.5%	10.9%	0%	0%	0%	0%
More than 50 km away from infrastructure and storage geology	81.2%	0.2%	0%	0%	37.7%	45.1%	100%	100%	100%	100%

* The 2021 data provided here is illustrative of current conditions, recognizing that emissions values (with associated proportion values) will likely change over time, especially if more mitigation measures are implemented (data source: 2021 ECCC facility emissions inventory which includes facilities with annual emissions of over 0.2 Mt CO_2/year). Note that only CO_2 emissions are considered, not other greenhouse gases, as CCUS is largely designed for capture and sequestration of CO_2.

Other sectors of interest include petroleum refining, lime and cement, chemical manufacturing, oil and gas extraction (except oil sands), and other manufacturing. Significant proportions of these emissions are located near existing pipelines, proposed pipelines, or within storage hub evaluation areas.

While our results point to oil sands, utilities, and several types of manufacturing as optimal sectors for CCUS expansion from a geographic standpoint, further analysis is required to understand the sector-specific challenges and costs. For example, one important cost determinant of CCUS is the concentration of CO_2 in flue gases, which can differ widely between sectors and subsectors (summarized in *Box 3*). Generally, a higher concentration and purity of CO_2 in flue gases leads to lower costs of capture. Other determinants include the types of technology used for capture, and the scale of CCUS deployment (see Kearns *et al.*, 2021 for detailed discussion on these topics).

Table 5: Total sectoral emissions (CO_2) from large point-source emitters in relation to existing/proposed carbon capture infrastructure and storage geology, Canada. Yellow boxes show the highest value for each sector, and blue boxes show the second-highest value(s).

	Sectors associated with major point-source emitters										
	Chemical manufacturing	Lime and cement manufacturing	Metal manufacturing	Mining	Oil and gas extraction (except oil sands)	Oil sands	Other manufacturing	Petroleum refineries	Pipeline transportation of natural gas	Pulp and paper	Utilities
Total emissions (Mt CO_2) in 2021*	6.5	12.4	21.2	5	7.9	73.8	9.6	16.4	1.2	0.4	56.4
Number of facilities	9	17	20	11	22	31	11	13	2	2	50
Within 50 km of existing infrastructure	24.6%	4.8%	1.4%	0%	3.8%	3.7%	75%	29.3%	0%	0%	13.7%
Within 50 km of proposed CO_2 pipelines, or within land areas for proposed hubs	9.2%	9.7%	0%	0%	15.2%	95.5%	0%	0%	0%	50%	41.5%
Above storage geology (no infrastructure)	50.8%	15.3%	34.4%	28%	57%	0%	5.2%	37.8%	0%	0%	20.4%
Within 50 km of existing infrastructure	15.4%	14.5%	19.8%	0%	7.6%	0.4%	15.6%	11.6%	0%	0%	4.3%
Far from infrastructure and storage geology	0%	55.6%	44.3%	72%	16.5%	0.4%	4.2%	21.3%	100%	50%	20.2%

* The 2021 data provided here is illustrative of current conditions, recognizing that emissions values (with associated proportion values) will likely change over time, especially if more mitigation measures are implemented (data source: 2021 ECCC facility emissions inventory).

Box 3: CCUS at point-sources and flue gas concentration

Point-source capture cost plays an important role in CCUS planning. Sectors that produce high concentrations of CO_2 in flue gas are preferred, as this allows for CO_2 to be captured with cheaper, smaller, and less specialized units.[49]

Sectors that generate flue gases with a high CO_2 concentration include natural gas processing,[50] chemical manufacturing,[51] and hydrogen production.[52] When specific technologies are applied, metal manufacturing[53] and cement manufacturing[54] can also produce flue gas with high CO_2 concentrations. However, flue gas concentrations can also vary within sectors and between specific facilities and processes.

Sectors that burn natural gas for heat or electricity produce more dilute CO_2 streams. These sectors include utilities and oil sands.[55] Dilute streams need larger capacity equipment and specialized solvents to separate CO_2 from the flue, which can drive up costs. However, in these sectors, economies of scale can help lower the overall price of capture. For example, larger capacity units can be deployed to capture higher volumes of CO_2 (Kearns *et al.*, 2021).

Although it can be costly, Alberta Innovates recommends implementing commercial-scale capture at oil sands and power generation facilities to bring the costs down and continue to make incremental improvements in all aspects of the CCUS process (Alberta Innovates, 2022). Upcoming commercial CCUS projects in Alberta include capture from hydrogen production (e.g., Air Products Hydrogen, 2023) and cement manufacture (Heidelberg Materials, 2023).

In Ontario, decarbonization through CCUS is currently not a high priority for many sectors due to cost and uncertainty, however CCUS storage for hydrogen production is being evaluated (Sarnia-Lambton Economic Partnership, 2022). Many steel manufacturers consider CCUS as a distant possibility, though Stelco intends to capture CO_2 from their (blast-furnace) steel manufacturing and utilize the captured CO_2 for development of marketable products such as bioplastics (Warrian and Afshar, 2023).

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[49] This is due to higher partial pressures of CO_2 which allow CO_2 to more readily transfer to a solvent (Kearns *et al.*, 2021).

[50] Natural gas processing is the purification of raw natural gas to remove solids, water, and various gases including CO_2. The partial pressure of the CO_2 impurity can range, but is usually very high (96%–99%) (Bains, Psarras, and Wilcox, 2017).

[51] Specifically the production of ethanol, ethylene products, and fertilizer have 95%–99% flue concentrations of CO_2 (Bains, Psarras, and Wilcox, 2017).

[52] Hydrogen is produced either by steam methane reformation (SMR) or autothermal reformation (ATR). SMR plants produce 30%–60% CO_2 flue streams, while ATR produces up to 95% flue concentrations of CO_2 (Korski, Jutt, and Wu 2021).

[53] Blast furnaces for steel can produce up to 20% flue concentrations of CO_2. Newer technologies such as direct reduction of iron (DRI) can produce up to 90% flue concentrations of CO_2 (Bains, Psarras, and Wilcox, 2017).

[54] Cement manufacturing generates CO_2 as a process emission. Current production processes generate 18%–30% flue concentrations of CO_2. Newer technologies enhance the ability for cement manufacture to inherently capture up to 90% (Kearns *et al.*, 2021).

[55] In utilities the flue concentration of CO_2 ranges from 4% (natural gas) to 15% (coal) (Bains, Psarras, and Wilcox, 2017). A case study from the oil sands suggests that in-situ, mining, and upgrading equipment ranges from 4% to 11% CO_2 concentrations (Kilpatrick *et al.*, 2014).

5. Findings: Provincial CCUS potential

In the following sections, we extend the analysis to five provinces[56] — British Columbia, Alberta, Saskatchewan, Ontario, and Quebec — to better understand the regional challenges, opportunities, and possible limitations for the expanded deployment of CCUS.

5.1 British Columbia

British Columbia has a significant prospective storage resource, with 3,000 Mt of storage potentially available. This resource is located in the sparsely-populated northeast region of the province *(Figure 5).* Other basins to the south and southwest of the province may be evaluated in the future, including the Nechako Basin in central British Columbia and Georgia Basin on the West Coast (near Vancouver) (Geoscience BC, 2023).

At 6.5 Mt/year, British Columbia has fewer large point-source emissions of CO_2 in comparison to other large provinces like Alberta (122.5 Mt/year), Ontario (31 Mt/year), and Quebec (14 Mt/year). Only about 14% (0.9 Mt) of these emissions are located above known suitable storage geology in the northeastern region of British Columbia, and an additional 5% (0.3 Mt) are situated near appropriate geology (*Figure 6*).

Remaining large emitters are scattered mostly across the southern portion of the province. British Columbia also currently lacks CO_2 transport and injection infrastructure, which presents additional challenges even in areas near geological storage.

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[56] We do not include Manitoba in this discussion due to low large point-source emissions in the province (0.6 Mt).

Figure 5: Map of emissions point-sources and prospective storage geology and infrastructure in British Columbia.

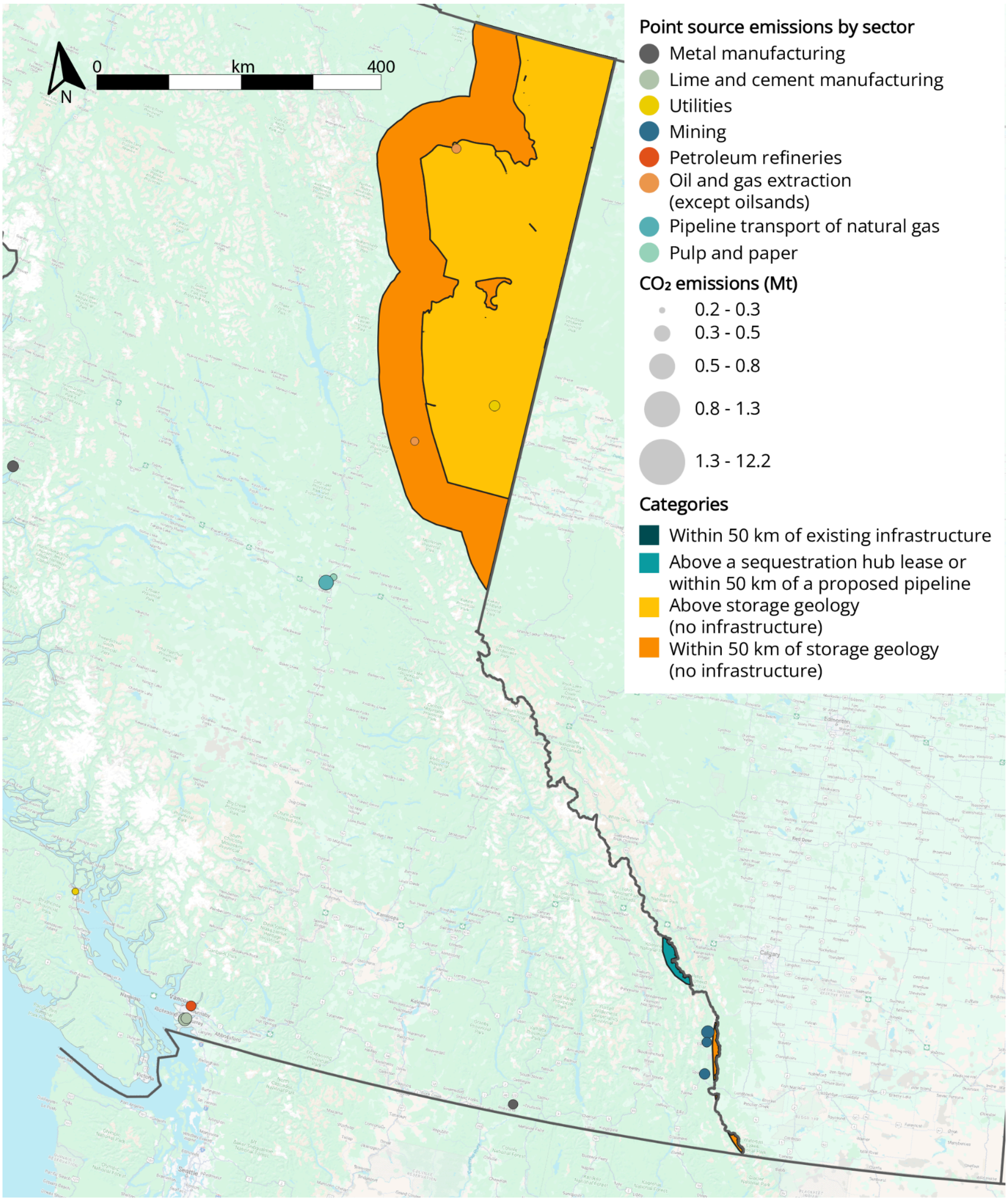


Figure 6: Breakdown of large point-source CO_2 emissions by proximity category in British Columbia.

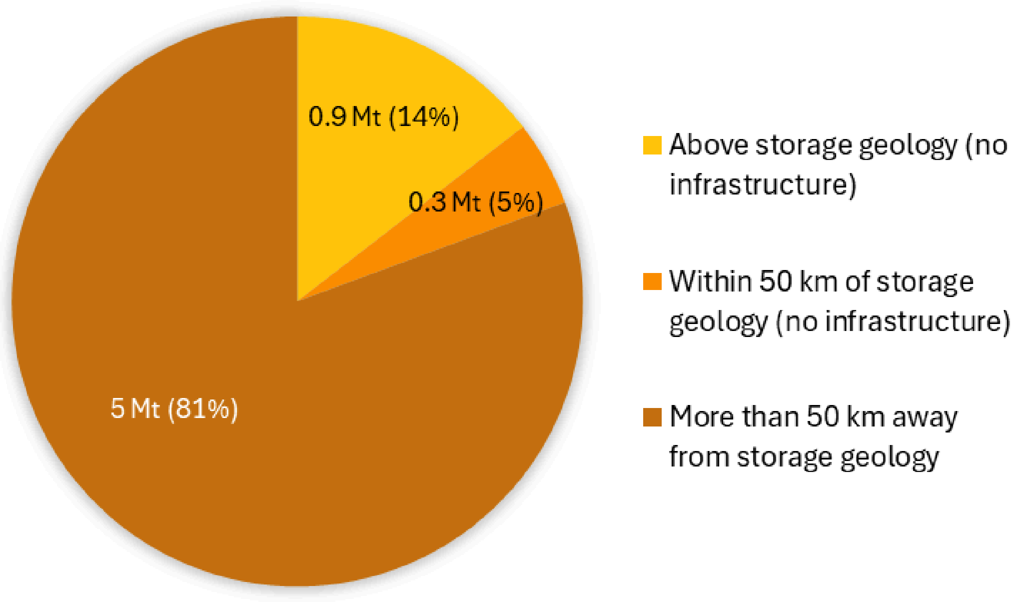
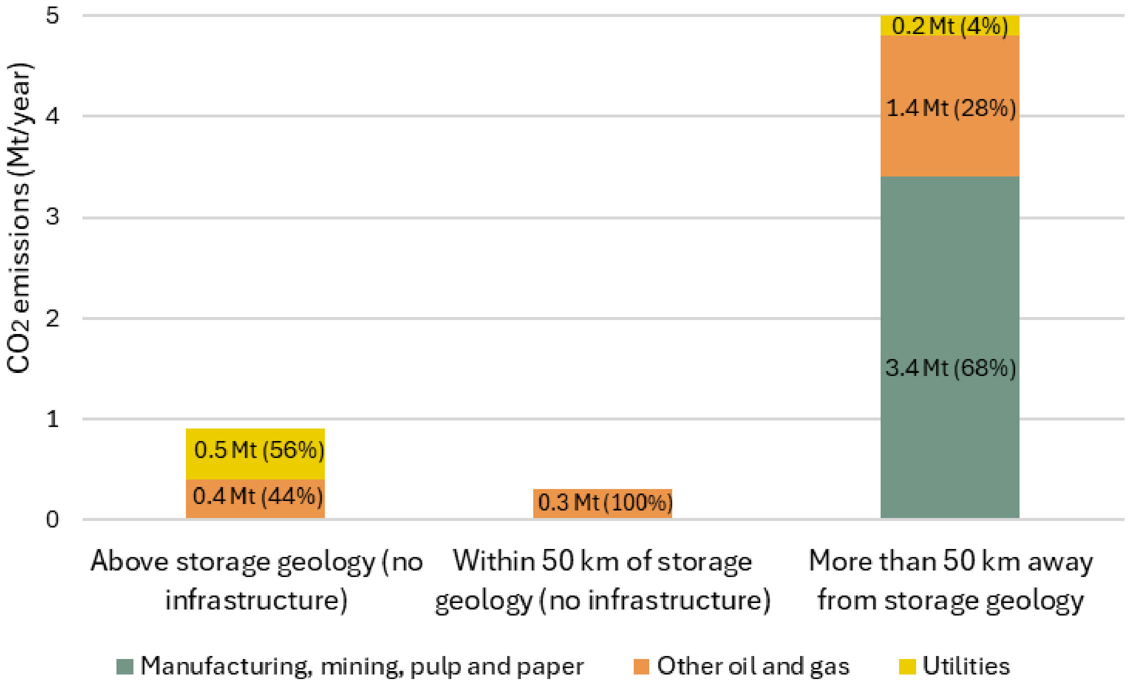


Figure 7: Proximity of large point-source sector emissions to CCUS geology / infrastructure in British Columbia.



When examined by sector, CO_2 emissions in areas above or near geological storage formations largely relate to oil operations. Approximately 0.7 Mt of oil and gas extraction point-source emissions occur above or near geological storage, and an additional 0.5 Mt of emissions above storage are from utilities (*Figure 7*). Overall, 83% of British Columbia's current point-source emissions are situated some distance from the northeastern basin, which has been characterized for prospective storage. The factors identified to date — remote geological storage located in mountainous terrain, combined with limited nearby point-source emissions that can make use of this asset — suggest that the practical application of CCUS is currently limited in the province unless other basins are discovered and developed,[57] new technologies are applied,[58] and/or long pipelines are approved and built, in some cases over complex terrain.

5.2 Alberta

Alberta has a vast geological storage resource for CO_2 (~79,000 Mt) as well as the most developed CCUS infrastructure of any province, illustrated in *Figure 8*. Alberta also has by far the highest emissions from large point-sources of all provinces (122.5 Mt/year of CO_2 in 2021, which is followed by Ontario at 31 Mt/year). Approximately 60% of these emissions result from oil sands operations (74 Mt/year). A sizable 27 Mt/year is also emitted from utilities (electricity and cogeneration plants), followed by another 13.7 Mt/year from various types of manufacturing facilities.

When we plot the point-source emissions shown in *Figure 8* against our proximity taxonomy, we see that 16% (18.9 Mt) of the province's large point-source emissions are located near existing CO_2 pipelines or injection hubs, and another 79% (97.1 Mt) are located near proposed pipelines or sequestration hubs indicated by evaluation leases (*Figure 9).* Combined, this suggests a theoretical capture potential of 104 Mt/year at a 90% capture rate and assuming that all proposed CCUS infrastructure is fully developed.[59]

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[57] Such as the Nechako Basin in central British Columbia and the Georgia Basin on the West Coast (near Vancouver).

[58] Though northeast British Columbia is a primary area of interest for CCUS, the British Columbia Energy Regulator has indicated that other areas of the province have geology which may be suitable for CCUS projects that utilize slightly different technology (see BCER, 2021).

[59] Theoretical capture is the total capturable emissions multiplied by the theoretical capture capacity (115 Mt x 90% = 104 Mt). Additional pipeline capacity may be needed to support this volume of CO_2 transport.

Figure 8: Map of emissions point-sources and prospective storage geology and infrastructure in Alberta.

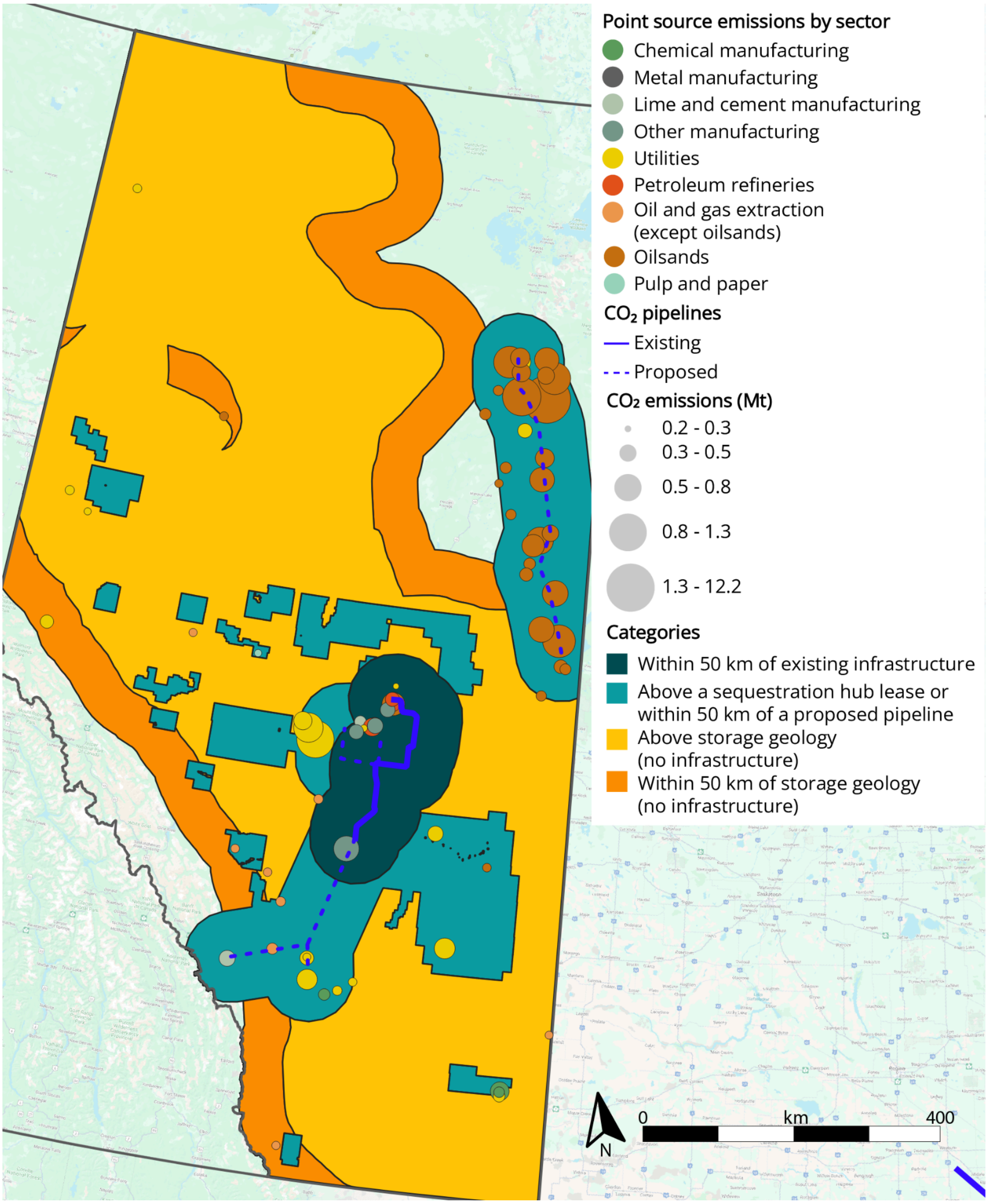


Figure 9: Breakdown of large point-source CO_2 emissions by proximity category in Alberta.

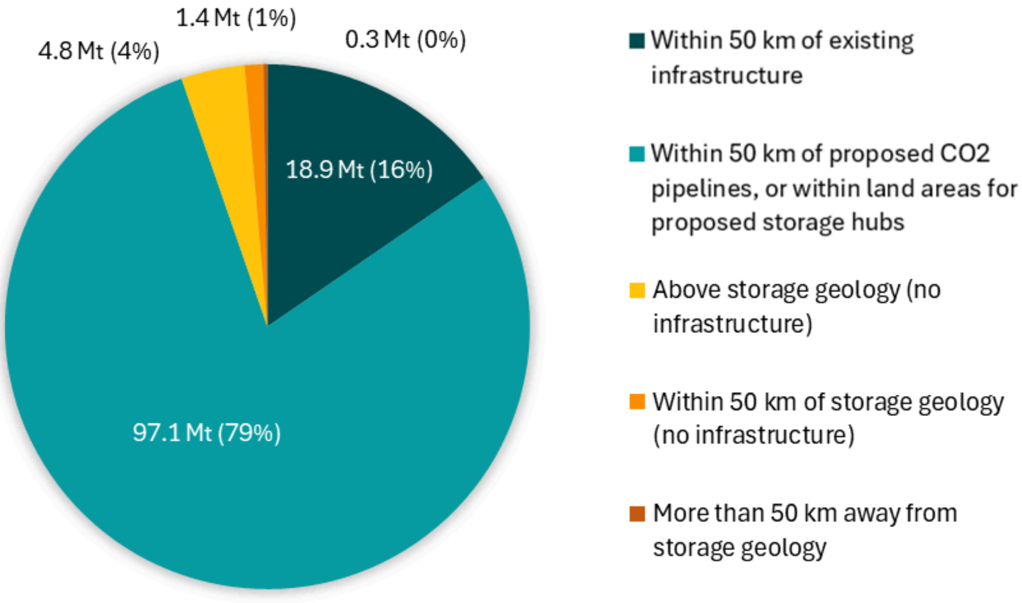
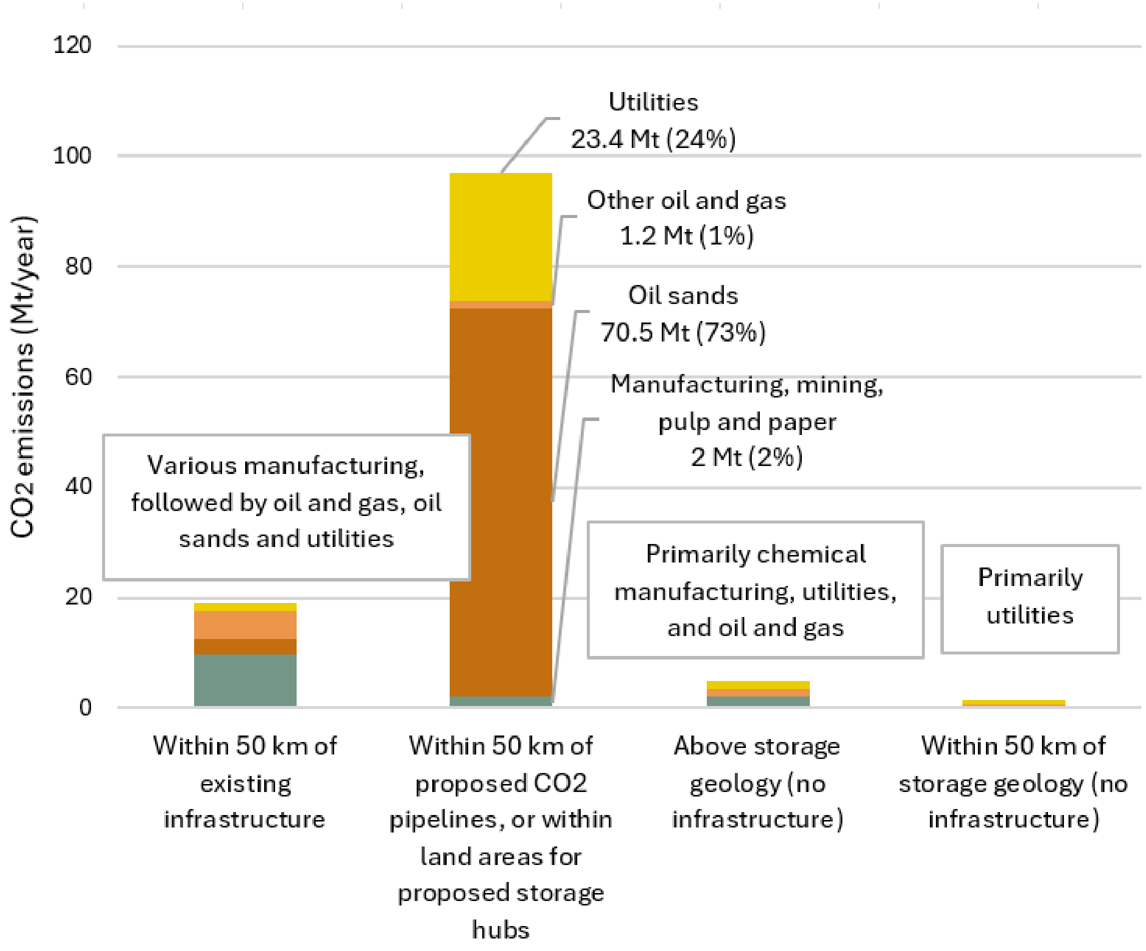


Figure 10 shows that most of the emissions occurring near already existing pipelines or injection hubs are from metal, chemical, lime/cement, and other manufacturing, as well as utilities and oil sands facilities (a total of 18.9 Mt).

Furthermore, nearly all (96%) of oil sands point-source emissions (70.5 Mt of CO_2 emissions) are currently within 50 km of a proposed CO_2 pipeline or within land areas for proposed storage hubs. Over 86% (23.4 Mt) of point-source emissions from utilities are also located near these proposed pipelines, or within land areas for proposed storage hubs (*Figure 10*).

Figure 10: Sectoral breakdown of large point-source emissions by proximity category in Alberta.



The analysis brings out four key points:

1. Up to 17 Mt/year (assuming a 90% capture rate) of emissions can be mitigated in the near-term by implementing CCUS in facilities that are located near existing infrastructure.

2. The currently proposed CCUS infrastructure projects could play a key role in reducing emissions in Alberta in the near term, given that a total of 97.1 Mt of point-source CO_2 emissions are located near proposed pipelines or within evaluation lease areas.

3. Combined, existing and proposed storage hubs can address 104 Mt/year of existing point-source capture at a 90% capture rate. Harnessing this scale of capture would entail the extension of existing CCUS infrastructure to access

Alberta's vast storage reserves in saline aquifers, as EOR storage potential is much more limited (refer to Section 2).[60]

4. Nearly all of Alberta's major point-source emissions are located above storage geology (with or without infrastructure), which suggests that CCUS could be an option for emissions reduction in many heavy-emitting sectors, pending infrastructure buildout.

Although the potential for CCUS in Alberta is significant from the standpoint of geological sequestration and the respective locations of major point-source emitters, other factors (not examined in this report) will play a role in calculating the full extent of costs and trade-offs associated with the scale of CCUS deployment described here. These factors include, but are not limited to: the stages of existing facilities in their prescribed lifecycles; the operational energy requirements of CO_2 capture, transport, and injection; supply chain, labour, and technological constraints relating to infrastructure development; competing land uses; and potential environmental and socio-economic implications and risks associated with large-scale infrastructure development. As a climate mitigation strategy, CCUS must also be evaluated in comparison to alternative measures that may yield more lasting and transformative benefits.[61]

5.3 Saskatchewan

Saskatchewan has abundant geological resources for carbon storage (~290,000 Mt, which comprises approximately 70% of Canada's overall prospective storage estimates). Like Alberta, Saskatchewan stands out as having CO_2 transport and injection infrastructure in place in the southeast of the province, which includes two injection sites (one being a hub) and a cross-border pipeline that currently transports CO_2 from U.S. sources for injection into the Western Canadian Sedimentary Basin. As illustrated in the *Figure 11* map, the majority of Saskatchewan's point-source emissions are located a large distance from this existing infrastructure and scattered throughout the province. The total emissions from these large point-sources is about 21.2 Mt/year, which is a fraction of those in Alberta (122.5 Mt/year).

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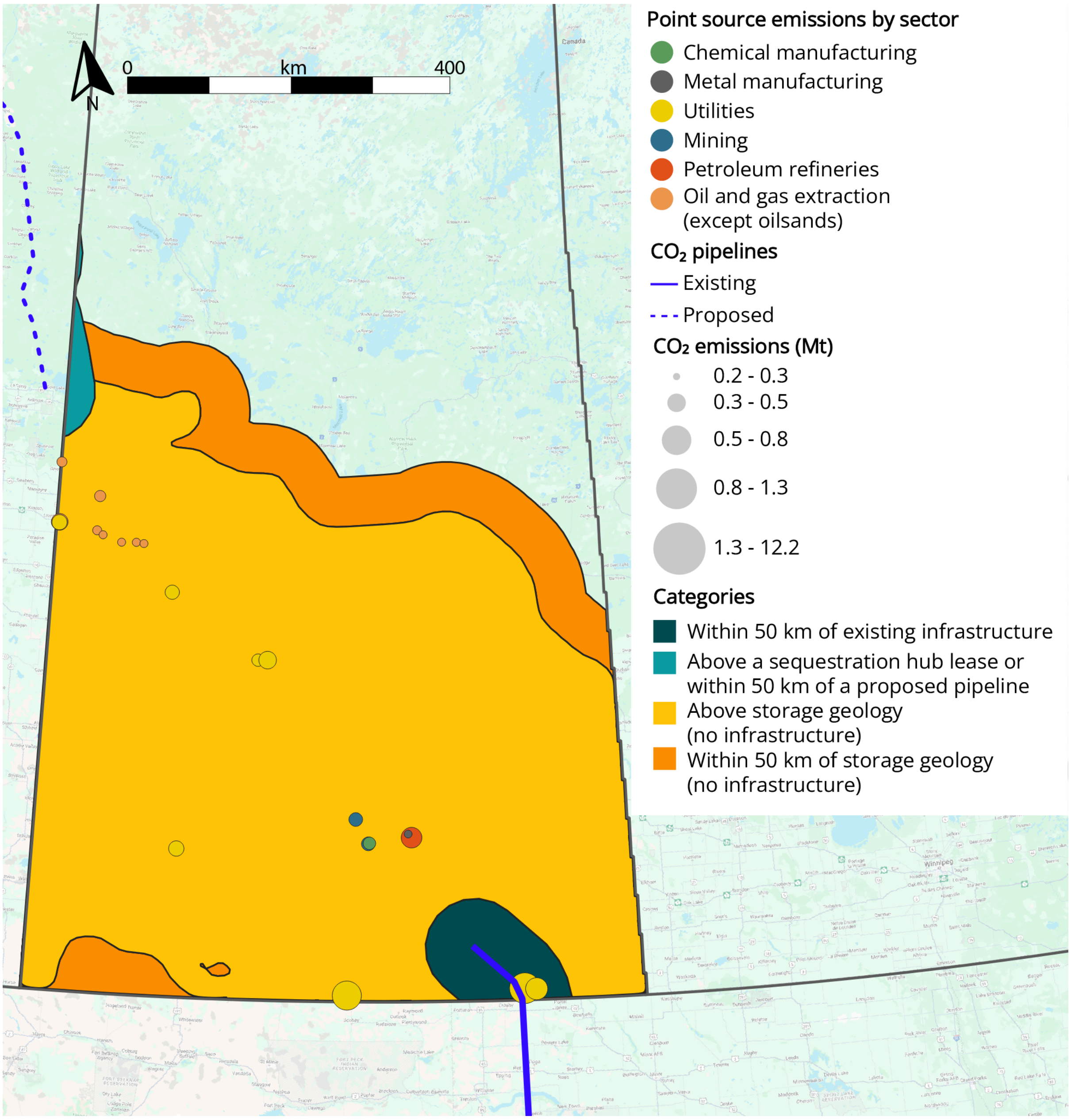
[60] Per previous footnotes, estimations suggest that there is around 870 Mt of potential CO_2 storage (cumulative) in EOR formations in Alberta (Hares, 2020), approximately 240 Mt in Saskatchewan (Jensen, 2022) and about 30 Mt in northeastern British Columbia (Geoscience British Columbia, 2023, Appendix C).

[61] For example, shifting utilities to clean electricity generation may be a better long-term investment strategy than focusing on continued fossil-based generation with CCUS abatement.

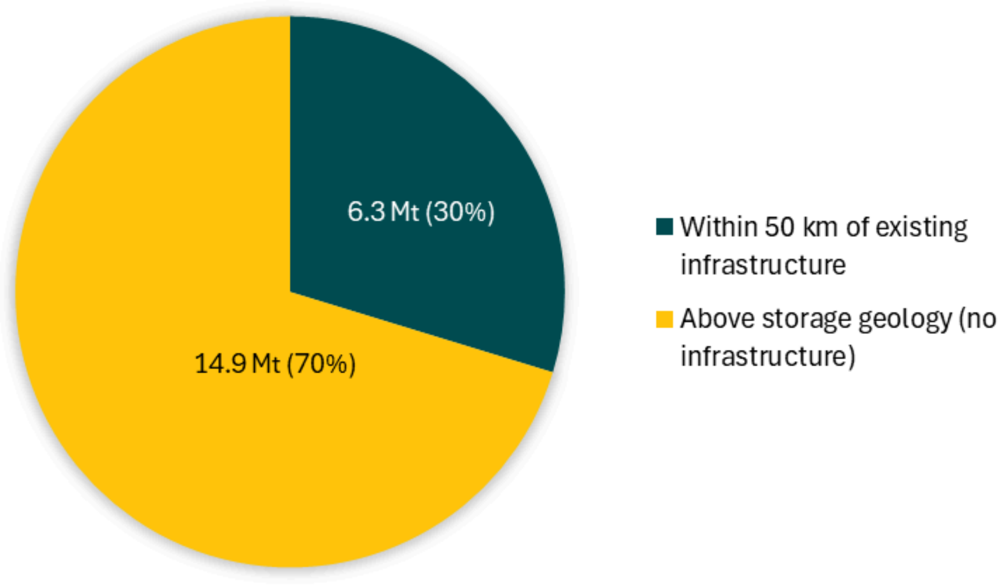
Figure 11: Map of emissions point-sources and prospective storage geology and infrastructure in Saskatchewan.



Nearly 30% of large emissions sources in Saskatchewan are located within 50 km of the existing CO_2 pipeline (*Figure 12*, 6.3 Mt). All of these are utilities adjacent to the existing CCUS facility at Boundary Dam (*Figure 13*). The remaining emissions are located above suitable geological storage (*Figure 12,* 14.9 Mt) and are associated with several sectors — the largest being utilities, followed by oil and gas (except oil sands), and mining.

A key challenge for CCUS expansion in Saskatchewan is that current emission sources are scattered across large swathes of the province. Extensive transport or injection/facility infrastructure buildout would be required to facilitate carbon capture for many of these emission sources. However, some concentrations of emitters are distinguishable in regions near Regina, Saskatoon, and Lloydminster, indicating potential opportunities for hub development.[62] Notably, the province has expressed interest in exploring hub development in central Saskatchewan (near Regina-Moose Jaw), near the Weyburn EOR field in the southeast, and near Lloydminster (Government of Saskatchewan, 2021).

Figure 12: Breakdown of large point-source CO_2 emissions by proximity category in Saskatchewan.



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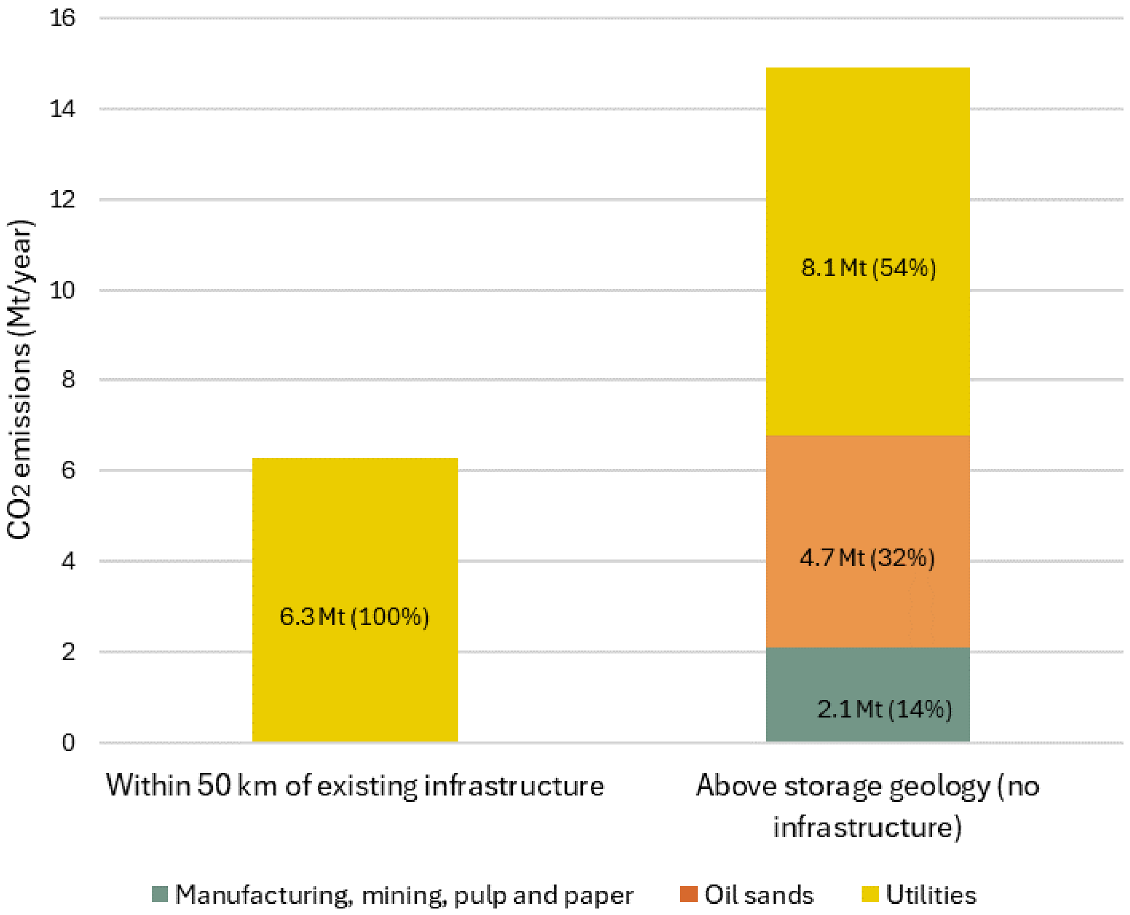
[62] Echoing earlier work from International CCS Knowledge Centre, 2021 and the Boston Consulting Group (BCG) (Green *et al.*, 2021) identifying similar clusters.

Figure 13: Sectoral breakdown of large point-source emissions by proximity category in Saskatchewan.



Box 4: Considering carbon dioxide removal in Saskatchewan

Carbon dioxide removal (CDR) technologies can play a significant role in achieving net zero. In the second interim report of Clean Prosperity's Net-Zero Pathways for Canada project (Felder, Hervas, and Noyahr, 2023), direct air capture (DAC) CDR plays a role across all net-zero pathways. Our results project that in order to meet net zero, 13–70 Mt/year of capture through DAC by 2050 may be required, and possibly much more if fossil fuel consumption is not significantly reduced across the economy. This does not include the very large additional amounts of CDR that are likely to be needed after Canada reaches net zero, to address historical emissions.

If DAC is developed in tandem with CCUS, such projections will likely require large quantities of dedicated saline aquifer storage. This observation becomes especially important when we consider the potential application of CDR to address historical emissions, which is an even more challenging goal to achieve than net zero. Organizations such as Carbon Removal Canada have estimated that Canada will need around 300 Mt per year of CDR to offset historical emissions and keep in alignment with global climate targets (Bushman and Merchant, 2023).

DAC systems can theoretically capture and inject CO_2 without the need for significant transport infrastructure development since they can be placed anywhere above proven storage, as long as a nearby non-emitting energy source is available for operation. In Saskatchewan's case, a number of challenges would need to be addressed. For example, DAC deployment would require extending the province's grid capacity with carbon-free electricity sources. Further advances in DAC technologies are also needed to develop units that can function well in Saskatchewan's climate. Nevertheless, the analysis conducted herein shows that Saskatchewan has a large amount of prospective storage (290 Gt) which spans about half of the province**.** We suggest that this sizable storage potential could be leveraged to enable future CDR development**,** which may be an attractive opportunity to grow Saskatchewan's carbon management industry (in addition to addressing the province's point-source emissions).

5.4 Ontario

Ontario has relatively limited geological storage potential characterized to date, and no current or planned infrastructure for CO_2 transport and sequestration. Although estimated provincial storage potential (between 146 and 1104 Mt, see *Box 5*) is more limited relative to other regions reviewed, there is opportunity for targeted CCUS development in southern Ontario. Nearly a third (9.2 Mt) of large point-source emissions from manufacturing industries are located above this potential storage basin, and an additional 10.4 Mt of point-source emissions are located within 50 km of the basin (*Figures 14* and *15*).

Figure 14: Map of emissions point-sources and prospective storage geology in Ontario.

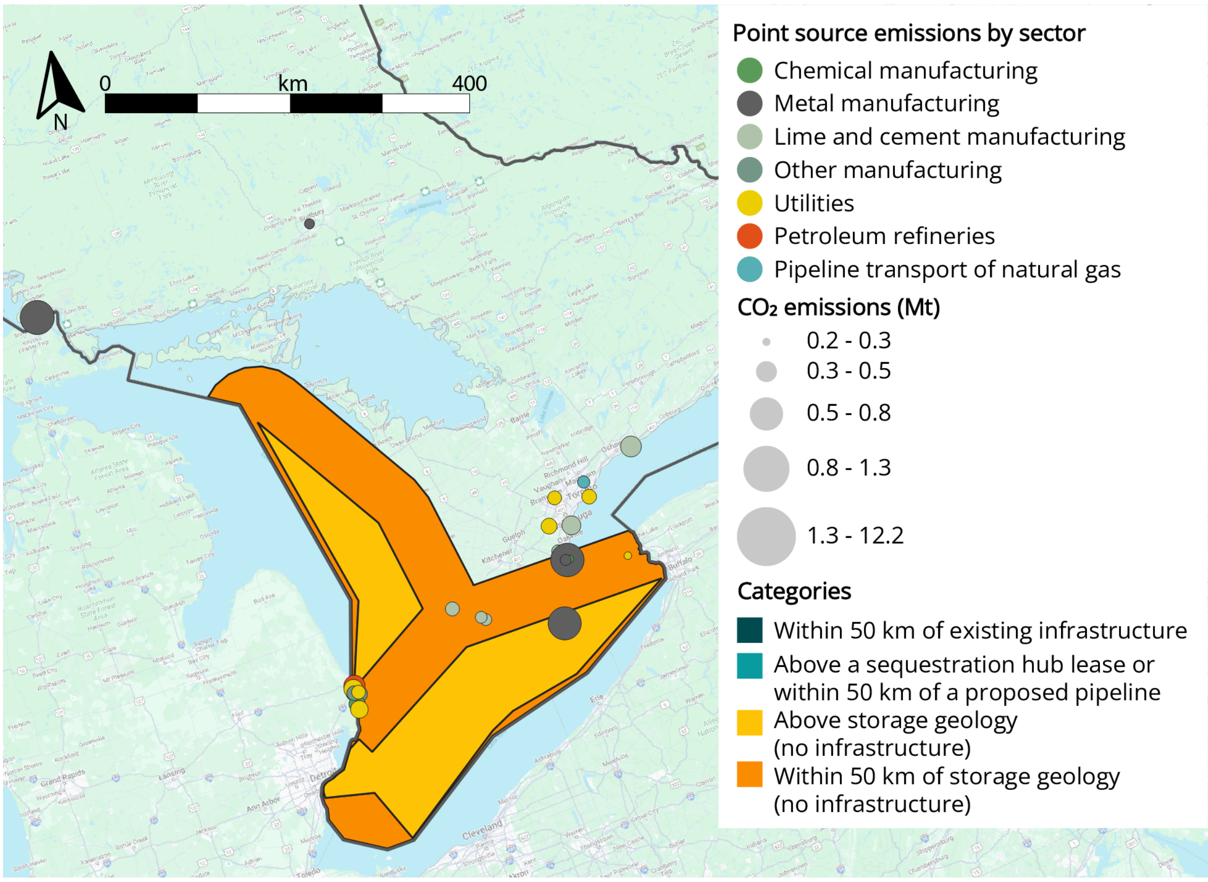
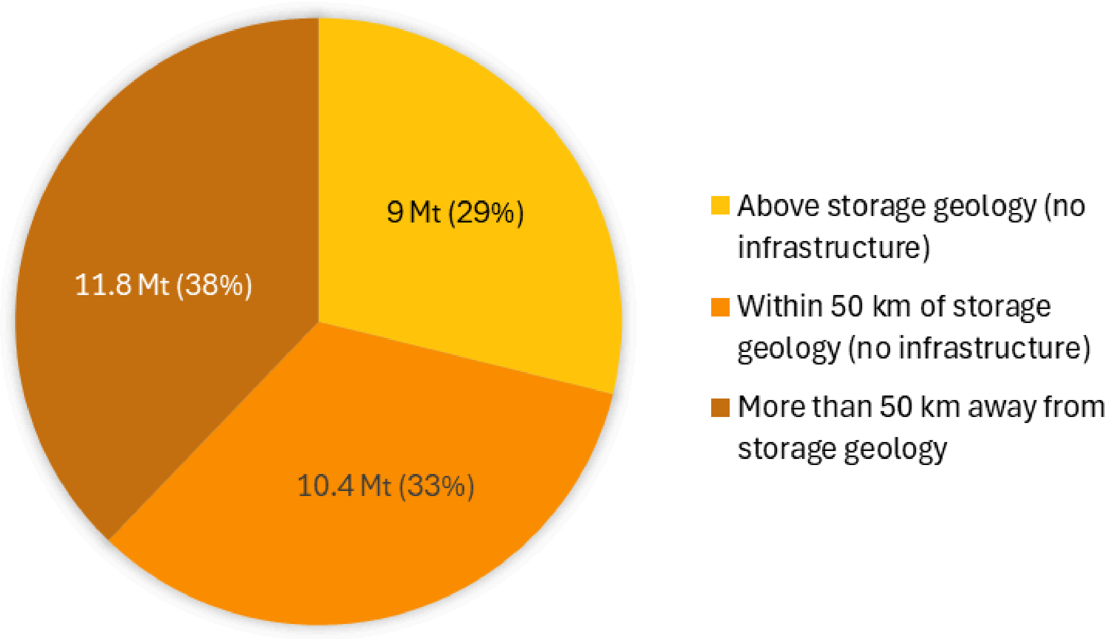


Figure 15: Breakdown of large point-source CO_2 emissions by proximity category in Ontario.



Ontario's metal manufacturing sector facilities could be well-positioned to take advantage of CCUS deployment, alongside other actions underway to mitigate emissions.[63,64] The sector currently emits about 12.5 Mt of CO_2 annually, of which 3.9 Mt are located above suitable storage geology. An additional 4.2 Mt of emissions are located within 50 km of storage[65] (these values are shown as a subset of "Manufacturing, mining, and pulp and paper" category in *Figure 16*). There is also notable opportunity in lime and cement, chemical, and other manufacturing, which have a combined 4 Mt of CO_2 emissions located either above or within 50 km of storage geology. Similarly, petroleum refineries and utilities emit around 4 Mt and 3 Mt of CO_2, respectively, and are sited either directly above or within 50 km of potential storage geology.

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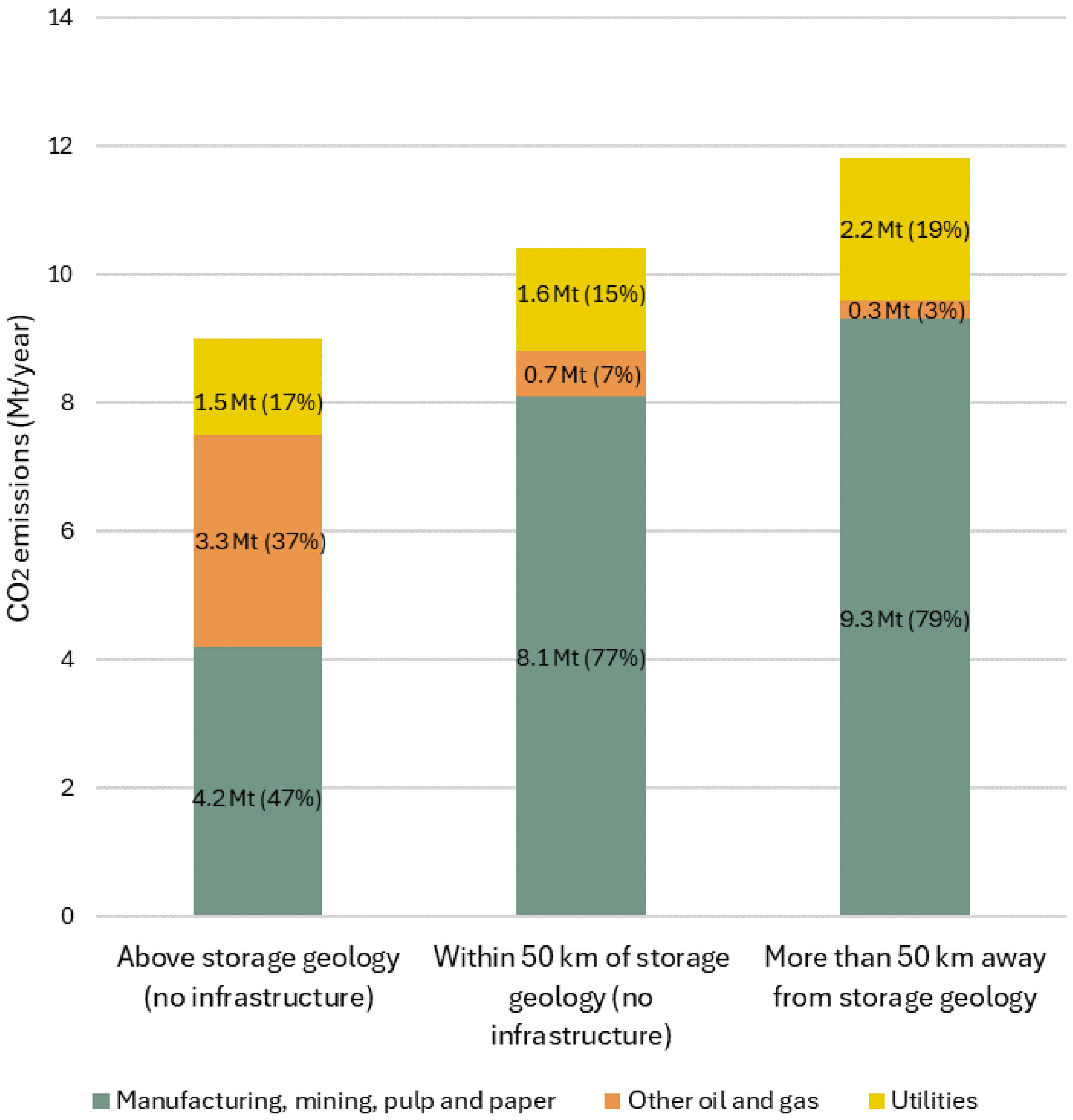
[63] Ontario's steel sector is already taking steps to reduce emissions by improving energy management practices, optimizing operations, and switching to lower-emission furnaces among other measures (CSPA, 2021; Khan *et al.*, 2023).

[64] The economics of capture in metal manufacturing subsectors would need to be considered as costs of capture differ based on the manufacturing processes being deployed (see *Box 3*; Kearns *et al.*, 2021).

[65] This total is estimated to decline due to the transition of the steel company ArcelorMittal Dofasco's blast furnace facility to electric arc technology. See notes below *Figure 16* and in *Box 5*.

Figure 16: Sectoral breakdown of large point-source emissions by proximity category in Ontario.



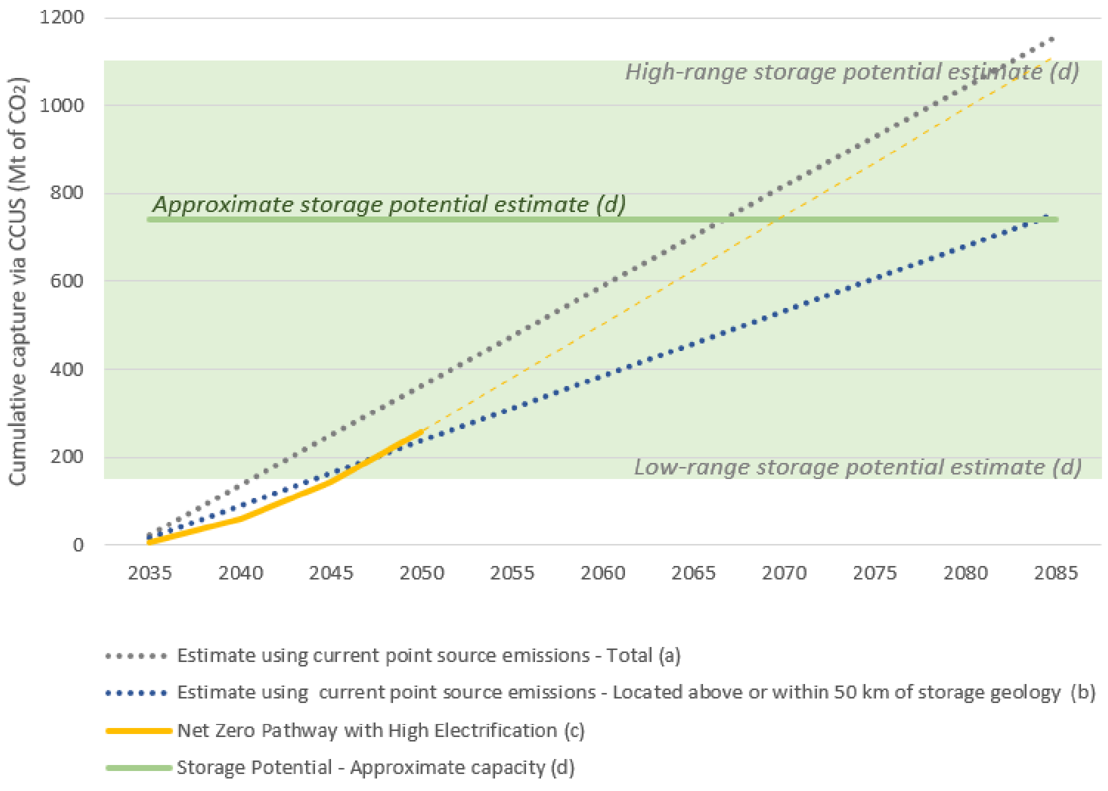
* We note that this total is expected to decline due to the transition of the steel company ArcelorMittal Dofasco's blast furnace facility to electric arc technology, announced in 2022. This Hamilton-based project is expected to come online in 2028 and reduce the plant's emissions by 3 Mt annually. As the Hamilton site is situated within 50 km of available storage, the emissions reductions anticipated for the ArcelorMittal Dofasco development have been accounted for in our forward-looking projections in *Box 5*. Algoma Steel, another major steel company situated in Sault Ste. Marie, has also commenced work on upgrading its steel plant, however this facility is sited outside of the prospective geological storage area. In our net-zero modelling work, both projects are modelled in the pathways to achieve about a 6 Mt reduction in GHG emissions in 2030 relative to 2020.

Box 5: Examining Ontario's prospective storage over time

One of the key challenges for large-scale CCUS development in Ontario is the geographically and geologically limited underground storage. In general, the Ontario and Quebec basins have not been well studied for CO_2 storage compared to those in Western Canada. Early estimates have pegged Ontario's total CO_2 prospective storage at around 730 Mt (Shafeen *et al.* 2004a). More recent estimates suggest storage could actually be a fraction of that (closer to 146 Mt, based on 2% sweep efficiency[66] from Goodman *et al.*, 2011).

The geographic location of these storage basins may add further complications. The optimal injection zone may be in the middle of Lake Huron[67] or Lake Erie, with the possibility that the injected CO_2 will spread outside of the borders of Canadian pore space into U.S. formations (Shafeen *et al.*, 2004b; AECOM and Itasca Consulting, 2011).

Figure: Cumulative CO_2 capture via CCUS (Mt) in Ontario estimated using 2021 point-source emissions estimates, compared to a net-zero pathway with high electrification, and geological storage potential estimates.



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[66] Sweep efficiency is the fraction of the reservoir or pore volume that is invaded by the displacing fluid.

[67] Similar to land, access to water involves agreement with Indigenous peoples (e.g., Fasken, 2023).

Even assuming the highest basin capacity estimates, theoretically applying CCUS to address all industrial point-source emissions extended over time suggests that Ontario's storage basins will reach their capacity by 2065 to 2085 (See the figure above). If other net-zero measures for industry are also deployed, such as those applied in a high electrification pathway, storage capacity in the province may serve another three to five years, but will still reach its limits well before the end of the century.

Figure notes

(a) Estimate assumes full deployment of CCUS (at 90% capture rate) to capture all large point-source emissions, totalling 25.2 Mt/year (accounting for expected emissions reduction from ArcelorMittal Dofasco and Algoma Steel plants in 2030). Point-source emissions and their locations with respect to geological storage are assumed to remain constant and equivalent to 2021 values, and all required infrastructure is assumed to be in place by 2035.

(b) Estimate assumes deployment of CCUS (at 90% capture rate) to capture all large point-source emissions currently located either above or within 50 km of storage geology, totalling 16.4 Mt/year (accounting for expected emissions reduction from ArcelorMittal Dofasco steel plant in 2030). Point-source emissions and their locations with respect to geological storage are assumed to remain constant and equivalent to 2021 values, and all required infrastructure is assumed to be in place by 2035.

(c) Based on net-zero modelling to 2050 in Felder, Hervas, and Noyahr, 2023. The High Electrification pathway is characterized by low costs of wind and solar power, EV batteries, and heat pumps, as well as availability of a variety of energy storage options. After 2050 it is assumed that the CCUS rate remains constant and equivalent to the 2050 value of 24.5 Mt/year.

(d) Based on Shafeen *et al*., 2004a, where the CO_2 storage capacity in Ontario is approximated at 730 Mt. Lower- and higher-range estimates are based on sensitivity analysis of sweep efficiency, where the highest estimate (1104 Mt) assumes sweep efficiency of 25%. The lower estimate in Shafeen *et al.*, 2004a is 220 Mt, which assumes sweep efficiency of 5%. More recent estimates including by the National Energy Technology Laboratory have used even lower (below 5%) sweep efficiency in their estimates. The lower-range estimate (146 Mt) in this figure corresponds to 2% sweep efficiency (see Goodman *et al.*, 2011).

Geological storage potential is a key limiting factor for CCUS deployment in Ontario, especially when considering cumulative usage over time (*Box 5*). Geological storage resources in the province, as currently estimated, are only able to support around 30 to 50 years of widespread CCUS deployment (depending on the scale of deployment and assuming a median storage capacity estimate of 730 Mt), with significant uncertainties regarding actual storage efficiency, differential aquifer depths that can impact injection suitability, and other factors. For example, Shafeen *et al.* 2004a, which is the main preliminary estimate available for Ontario to date, only applies the Mt. Simon formation in characterizing Ontario's basin potential. The Eau Claire formation (which is located directly above the Mt. Simon formation) is excluded in this analysis, due to the assertion that this formation is non-porous. Ontario's basin potential estimate could be revised if the Eau Claire formation was found to be more porous than initially considered, per Armstrong and Carter, 2010. Exploring this possibility would require more characterization and, if the formation is found to be promising, the prospective capacity may be increased. However, other studies consider Eau Claire primarily as a sealing formation and not applicable to storage (Leetaru et al., 2009).

The limited storage resources in the province, as presently estimated, imply that investment in CCUS infrastructure must be weighed against investment in other emissions reduction measures and targeted to address emissions that are otherwise difficult to abate. A selective CCUS deployment strategy that is balanced with other mitigation measures may be pragmatic over the longer term as it will help extend the operational timeframe of any CCUS infrastructure that is developed. Thus, our main observations on Ontario’s CCUS potential to date are that:

1. Based on current estimates, Ontario’s limited storage resources and their associated geographies (e.g., possible injection sites within water bodies) imply that the potential scale of CCUS deployment and the long-term viability of CCUS in the province is constrained.
2. The prospective storage basin constraint needs to be carefully considered when investing in emissions reduction strategies for the province. For example, CCUS may be best applied to hard-to-abate sectors (e.g., cement), while other sectors (e.g., utilities) may be better served by transitioning to low-carbon fuels and/or renewable energy.
3. Further study of storage basins is required to obtain a more accurate approximation of storage potential in Ontario, as well as to provide a more complete understanding of the risks and challenges that may be posed by the geology and geographic location of the basins. Leveraging geological storage from nearby regions (such as Quebec,[68] as discussed in the following section) may also provide opportunities for further exploration.

5.5 Quebec

Similar to Ontario, Quebec currently lacks CO_2 transport and injection infrastructure, but, in contrast, has significant storage potential, estimated to be between 2,800 Mt and

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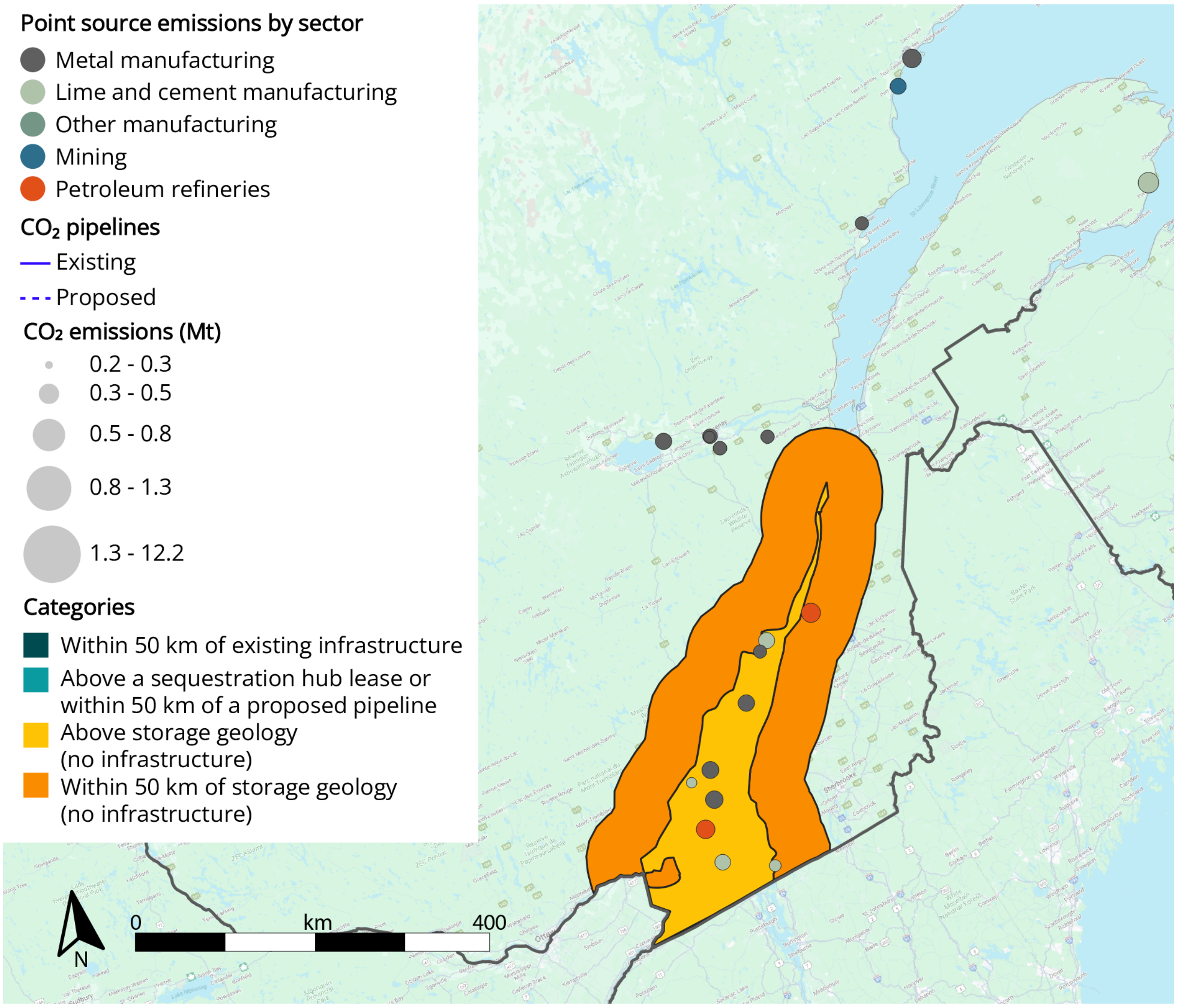
[68] The prospect of storing some of the emissions captured in Ontario may be of benefit to explore given Ontario’s limited geological storage and Quebec’s limited emissions from large point-sources.

3,200 Mt. In addition to the storage basins previously listed in *Table 1*, Quebec may have access to offshore geological storage (e.g., Malo and Bedard, 2012). None of the province's potential geological storage (on- or offshore) has been well studied to date.

Total CO_2 emissions from large point-sources in Quebec currently stand at around 15 Mt/year (about half of those in Ontario). Given the relatively low (though not insignificant) point-source emissions, Quebec's geological storage would be far from exhausted with complete CCUS deployment, even with offshore storage excluded.

Figure 17 illustrates that the locations of many large emissions point-sources coincide with potential storage basins in southern Quebec. The sectoral distribution of emissions is similar to that of Ontario, with metal manufacturing, lime and cement, other manufacturing, and petroleum refineries located either above or close to geological storage.

Figure 17: Map of emissions point-sources and prospective storage geology and infrastructure in Quebec.



Over 43% (6.4 Mt) of emissions are located above storage geology, and another 11% (1.6 Mt) within 50 km of storage *(Figure 18).*

Of emissions currently occurring above potential storage geology, 3.2 Mt are from metal manufacturing, 1.9 Mt are from lime and cement manufacturing, and 1.1 Mt are from petroleum refining. Another 1.2 Mt of petroleum refinery emissions and 0.4 Mt of lime and cement manufacturing emissions are located within 50 km of storage geology *(Figure 19).*

In Quebec, the evaluation to date indicates that:

1. Quebec is in a good position for CCUS deployment given the province's abundant geological storage resources, and due to the relative location of emissions from large point-sources (particularly in manufacturing and petroleum refining). The province's storage resources can also be utilized for CDR and/or in support of storage needs emerging from other nearby regions like Ontario.
2. Given the relatively low overall volume of emissions from large point-sources in Quebec currently, investment in CCUS infrastructure should be evaluated alongside other decarbonization opportunities and CDR to achieve higher environmental return on this investment.

Figure 18: Breakdown of large point-source CO_2 emissions by proximity category in Quebec.

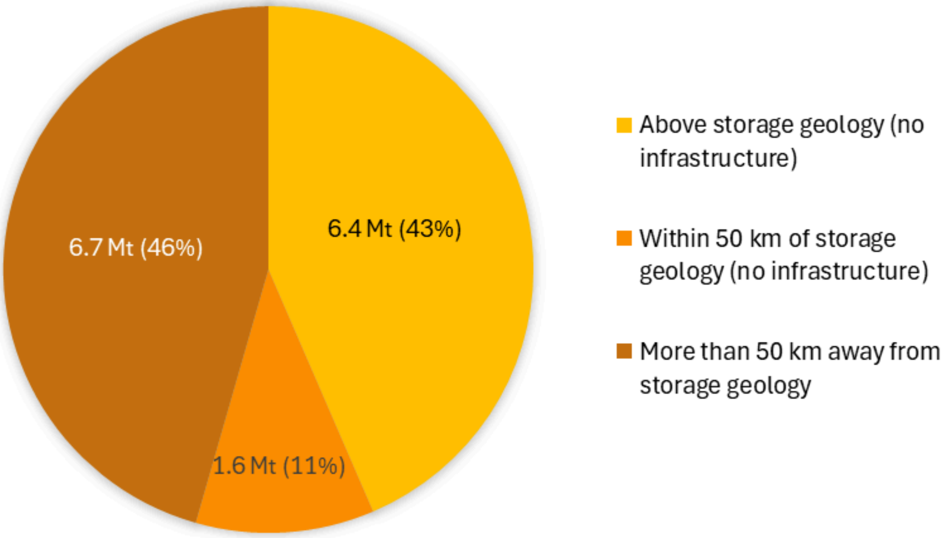
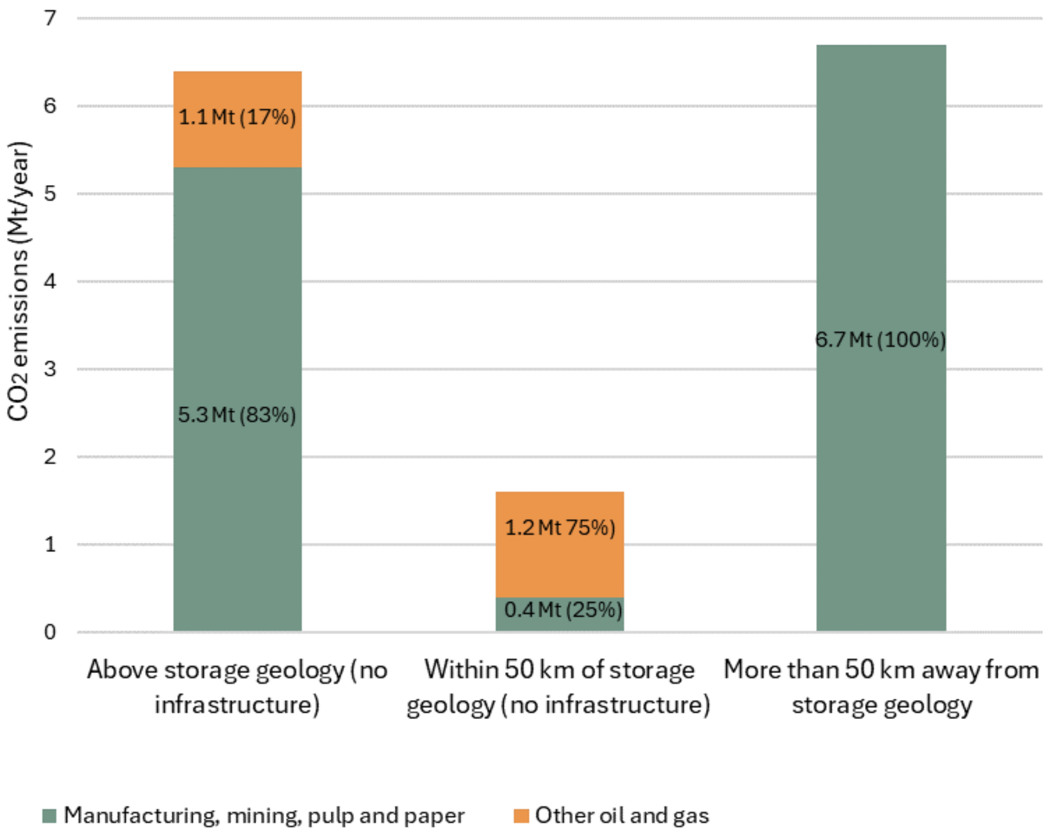


Figure 19: Sectoral breakdown of large point-source emissions by proximity category in Quebec.



6. Conclusions

Our results show that Canada has rich geological potential for long-term carbon storage in its saline aquifers, and the beginnings of larger-scale infrastructure for CO_2 injection and pipeline transport. Canada's geology is projected to be able to support nearly 400 Gt of prospective storage, 99% of which is in the deep Cambrian sands spanning large parts of Alberta, Saskatchewan, and Manitoba.

The CCUS opportunity varies significantly by province and thus should be assessed at the provincial, rather than national, level. Alberta has a large CCUS opportunity. It currently has the most developed carbon management infrastructure of all of the provinces. This infrastructure can support deployment of CCUS for permanent carbon storage at a number of major point-source emission sites, as well as serve as the basis for expansion to other emitters located in relatively close proximity to these assets. In Saskatchewan, which has 70% of Canada's prospective onshore storage potential, the relative paucity of existing point-source emissions — and the fact they are dispersed across the province — makes the economics and logistics of shared storage sites more challenging (though these challenges would be less applicable to CDR). For Ontario, the limited basin potential characterized to date — along with the lack of existing CCUS infrastructure — suggests that the province may need a selective approach to CCUS development that is coupled with alternative means to address large point-source emissions.

In terms of sectors, our GIS analysis shows that the most near-term opportunity for CCUS exists for oil sands and electricity/cogeneration facilities in various regions across Canada, given the proximity of these sectors' facilities to onshore geological storage and, in some regions, to existing CCUS infrastructure. However, the oil sands and utilities sectors have lower concentrations of CO_2 in their emissions streams, which raises the cost of capture for emitting facilities. For these facilities to be able to apply CCUS most economically, lowering the cost of transportation and storage will be important to help balance these higher capture costs. The open hub models (that can connect a number of diverse point-sources into centralized injection sites) can help enable the economies of scale required to support CCUS capture for such sectors.

Carbon capture technologies can also play a modest role in the short- to medium-term decarbonization of other economically important sectors, including oil and gas extraction outside the oil sands, manufacturing, and mining. Although total emissions from these sectors are much lower than from oil sands and utilities (see *Table 5*), analysis indicates that in some regions, developing CCUS for these sectors may be of interest. We note, however, that capturing these emissions would require added infrastructure buildout, due to their distance from existing/planned infrastructure.

Overall, there is significant untapped potential in Canada for CCUS deployment with respect to infrastructure and geology — particularly for the utilities and oil sands sectors. Development of this CCUS potential will require careful consideration of costs, risks, and other factors at each specific location. Such work will help better inform the role of carbon capture in Canada's near-term emission reduction opportunities and net-zero future.

7. Study assumptions and limitations

- This study is limited by the available published knowledge on deep saline geology and is mainly based on prospective storage potential.[69] Real storage capacity is likely much lower[70] and would require localized study to adequately assess.
- The analysis assumes that all currently proposed CCUS infrastructure (i.e., all proposed pipelines and evaluation leases) can be deployed, regardless of any technical, socio-economic or environmental factors that can impact feasibility. Overall, we do not evaluate the costs associated with deployment and infrastructure buildout; the material use, supply chain, and labour constraints that would be associated with large-scale construction; as well as the land use considerations and/or trade-offs with other mitigation measures. Much more further study and engagement is needed to understand the impacts and implications associated with carbon capture and storage deployment.
- The analysis is focused on the capture of current emissions from Canada's high-emitting facilities, and uses this as a starting point to estimate potential emission sources into the future. This approach is applied so as to leverage the spatial data available on the present position of current high-emitting facilities in Canada. This allows us to explore CCUS deployment within a scenario akin to business-as-usual, where major industrial emissions remain largely similar to the current day picture. The approach is limited in that emission values (and their proportion by sector) will change over time, commensurate with economic growth and/or mitigation measures (including those that could affect fossil fuel production and other emissions into the future), among other factors. Nonetheless, the work provides a theoretical illustration of the emissions capture potential of full CCUS deployment based on prospective geological storage assets.
- This work is primarily focused on the geographic, spatial, and technical aspects of CCUS deployment. In practice, and as with all large-scale development projects, we note that meaningful civic and community engagement will be critical in ensuring the success of carbon capture and storage projects, and ideally result in the equitable distribution of benefits associated with such

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[69] "Prospective storage potential" refers to a resource where estimates have been made about the resource potential but are prospective based on stage of discovery and development. "Storage capacity" is a term used for storage formation that have been shown to be commercially viable as supported by numerical evidence of storage capacity (Per: SPE, 2017, see *Appendix B*).

[70] Real storage capacity is based upon provable results and also has additional economic and regulatory constraints. For example, the Quest CCUS project is "proven" (based on injection data and modelling) to have a storage capacity of 27 Mt, injecting at 1.1 Mt/year for 25 years, (e.g., Shell Canada, 2015). This differs from the prospective storage capacity for the aquifer area derived by numerical methods (~900 Mt, NATCARB Atlas Saline Basin 10 km grid shapefile (NETL, 2015).

large-scale infrastructure development. Although our research focus is on the energy system implications of various pathways to achieve net zero, this is a paramount consideration and will ultimately determine the success or failure of net-zero interventions.

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Appendix A: GIS layer descriptions and data sources

Layer	Detail	Layer provider
Net-zero pathway results from gTech-IESD[71] model	Generated as pie charts and for CCUS/DAC per net-zero pathway; sector emission sources.	Navius Research, with pathway design by Clean Prosperity
Emission point-sources	Sorted by NAICS,[72] and modified by Navius research to match NIR[73]	Environment and Climate Change Canada
Ontario and Quebec basin shapes	The shape and size of the subsurface basin under the provinces of Québec and Ontario	Navius Research, (modified herein based on reservoir shapes generated in research papers for Ontario and Quebec respectively (Shafeen *et al.*, 2004a; Bedard *et al.*, 2013)
Sequestration hubs	A map of carbon sequestration land leases, the leaseholder, and the formations under investigation	Government of Alberta, 2023a
Saline aquifer shapes for Canada	Saline aquifer shapes for Canada	National Energy Technology Laboratory NATCARB Atlas Saline Basin 10km Grid (NETL, 2022)
Depleted oil and gas reserve shapes for Alberta	Depleted oil and gas reserve shapes for Alberta	National Energy Technology Laboratory NATCARB Atlas Saline Basin 10km Grid

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[71] gTech is a computable general equilibrium model developed by Navius Research. The model was customized to meet the specific goals of this project. IESD is Navius' integrated electricity dispatch model that is partly coupled with gTech to represent the dynamics of sector-specific electricity consumption and generation on a finer scale (Navius Research, 2023).

[72] North American Industry Classification System (NAICS) Canada (Statistics Canada, 2022).

[73] National Inventory Report (NIR) categorization of economic sectors Canada's official greenhouse gas inventory (ECCC, 2023a).

NEBC CO_2 storage formations shapes	Saline Aquifer and depleted oil and gas reserve shapes for Alberta	Geoscience BC (Canadian Discovery Ltd., 2023, see Appendix E).
Active sites and proposed pipelines	Approximated locations of existing and proposed CO_2 trunk lines	Current location of CO_2 pipelines (Government of Alberta 2021) Origins project for future ACTL pipeline extensions (Origins 2022) Location of the Pathways Alliance proposed pipeline (Canadian Energy Center, 2022) All active sites located on Openstreetmap

Appendix B: Storage resource classification framework summary (SPE, 2017)

Storage resource classification	**Description**	**Notes**
Storage capacity	Discovered, commercial; can be sub-classified as “proved” (low uncertainty), “probable” (medium uncertainty), and “possible” (higher uncertainty). Key contingencies have been met. Contingencies can be technical, regulatory, economic, and social.	“Capacity” is only used for commercially viable storage formations
Contingent storage resources	Discovered, but sub-commercial; has uncertainty-based subclassification.	One or more contingencies have not been met.
Prospective storage resources	Undiscovered — deemed to be potentially accessible within undiscovered geologic formations or uncharacterized parts of discovered formations; understood in terms of chance of discovery and chance of development.	Currently most storage assessments are for prospective sources, for which suitability of storage has not been ascertained.