Report

Carbon capture and storage and the Canadian oil sands

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About this report

Since 2009, IHS Markit has provided research on issues surrounding the development of the Canadian oil sands. This report focuses on carbon capture and storage and the Alberta oil sands. The Canadian oil sands announced their Pathways to Net Zero initiative to accelerate their emission reduction ambition. Carbon capture and storage (CCS) is a critical opportunity that could make large scale emission reductions in the oil sands. This report will explore CCS and its potential in the Alberta oil sands. What are its components and what are the unique opportunities and challenges in relation to the oil sands.

Context. This report is part of a series of reports from the IHS Markit Canadian Oil Sands Dialogue. The dialogue convenes stakeholders to participate in an objective analysis of the benefits, costs, and impacts of various choices associated with the development of the Canadian oil sands. Stakeholders include representatives from government, regulators, oil companies, and nongovernmental organizations.

This report and past Canadian Oil Sands Dialogue reports can be downloaded at www.ihsmarkit.com/oilsandsdialogue

Methodology. IHS Markit conducted its own extensive research and analysis on this topic, both independently and in consultation with stakeholders. The work was completed in late 2021 prior to recent changes in federal policy, which could alter some of the key insights.

Contents

Oil sands emissions

Where do emissions come from?

What is the scale and how has that changed over time?

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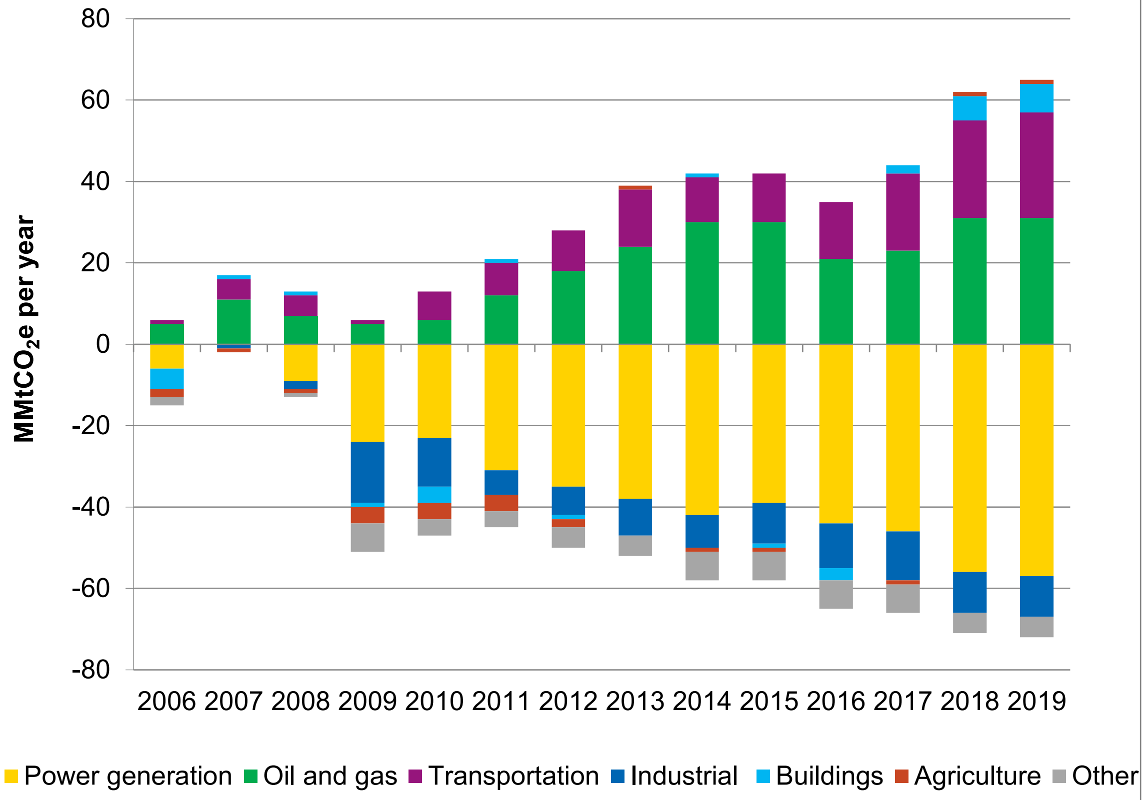
Key messages

- **Pressure to accelerate the energy transition is building and domestically Canada is seeking a 40–45% reduction in greenhouse gas (GHG) emissions by 2030 from 2005 levels.** However, few reductions have been achieved to date leaving only eight years for Canada to make very sizeable reductions in order to meet its ambition. This will require actions from across the economy, including oil and gas, which has historically been a source of GHG emissions growth.
- **Over the past decade oil sands growth made it a major economic engine, but that growth also outstripped GHG intensity reductions, leading to a rise of absolute emissions.** Since 2009 (the earliest IHS Markit can accurately estimate oil sands emissions), oil sands production more than doubled, GHG intensity fell by 21%, and absolute emissions rose by 29 million metric tons (MMt).
- **Oil sands operations share many similarities with industrial plants, relying heavily upon stationary combustion sources that make them aimable for carbon capture and storage (CCS).** IHS Markit estimates about 85% of oil sands emissions come from stationary combustions with varying degrees of CO_2 concentration, which impacts capture cost.
- **There are multitude of factors that influence the relative attractiveness and opportunities for CCS in the oil sands.** This includes not only the purity of CO_2 found in flue gas streams, but also retrofitability, as well as transportation cost. Although emissions from hydrogen production may have the highest concentration of CO_2 in the oil sands, ease of access may be a challenge in comparison to free standing boilers for example.

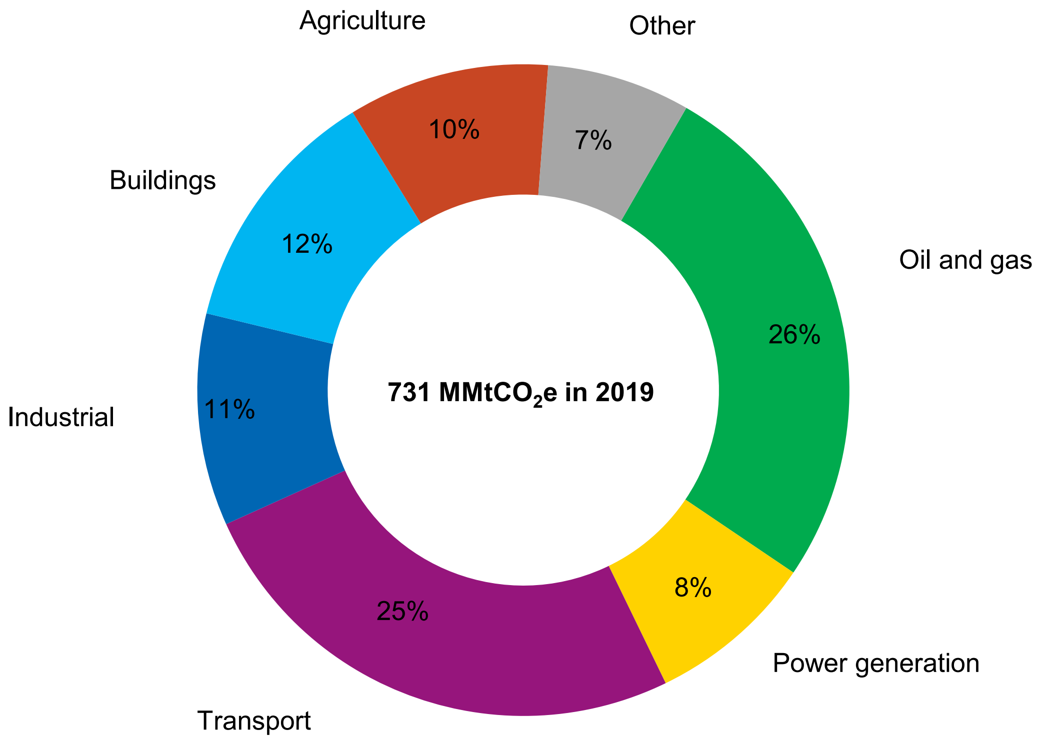
Canada's emission composition

Change in Canada's National Inventory from 2005 to 2019 ($MMtCO_2e$ per year)



Source: Environment and Climate Change Canada National Inventory Report 1990–2019: Greenhouse Gas Sources and Sinks in Canada

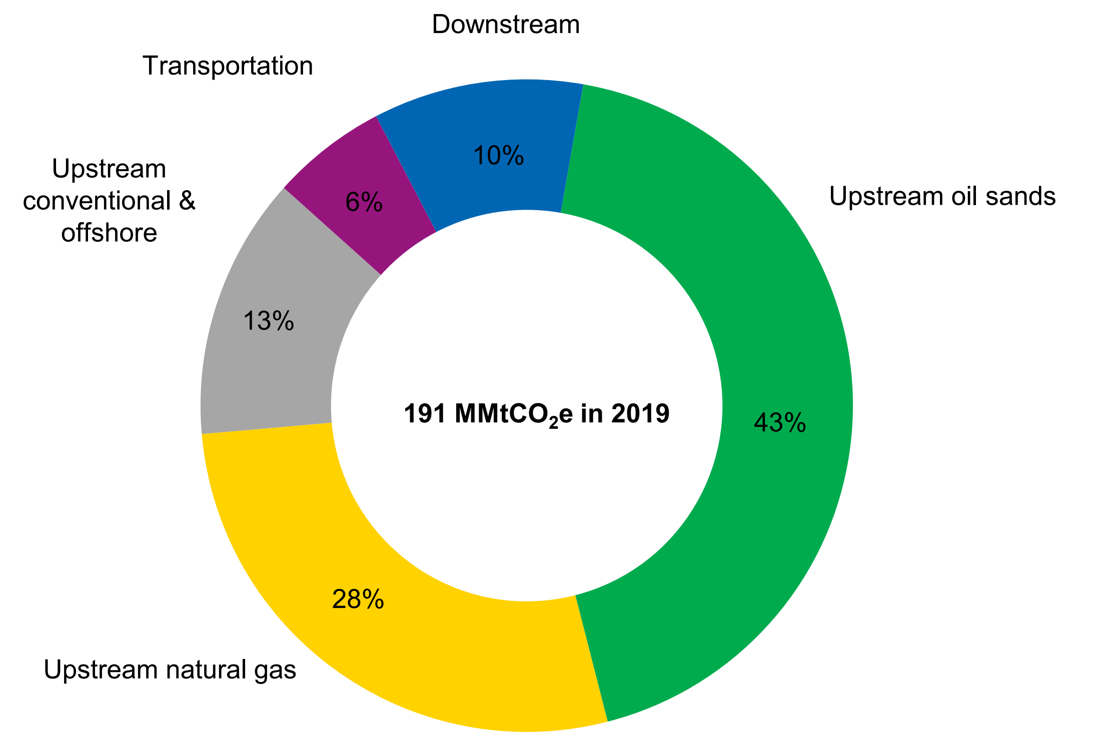
Composition of Canada's National Inventory in 2019



Source: Environment and Climate Change Canada National Inventory Report 1990–2019: Greenhouse Gas Sources and Sinks in Canada

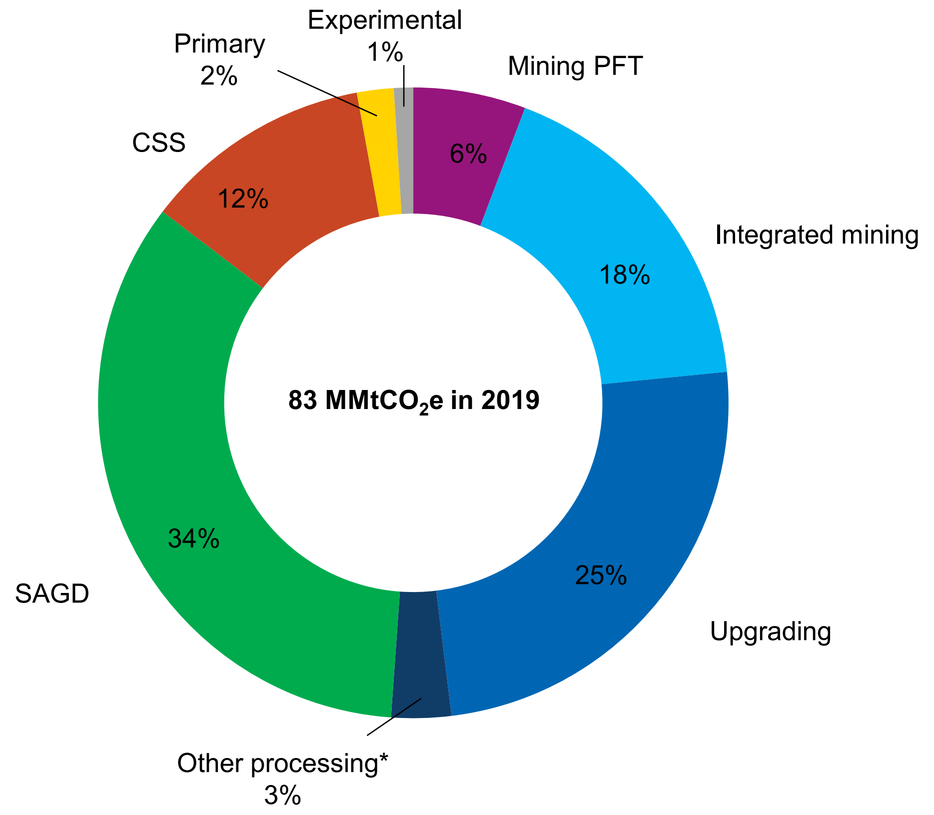
Composition of oil and gas sector GHG emissions in 2019

Canada’s oil and gas sector emissions in 2019



Source: Environment and Climate Change Canada National Inventory Report 1990–2019: Greenhouse Gas Sources and Sinks in Canada

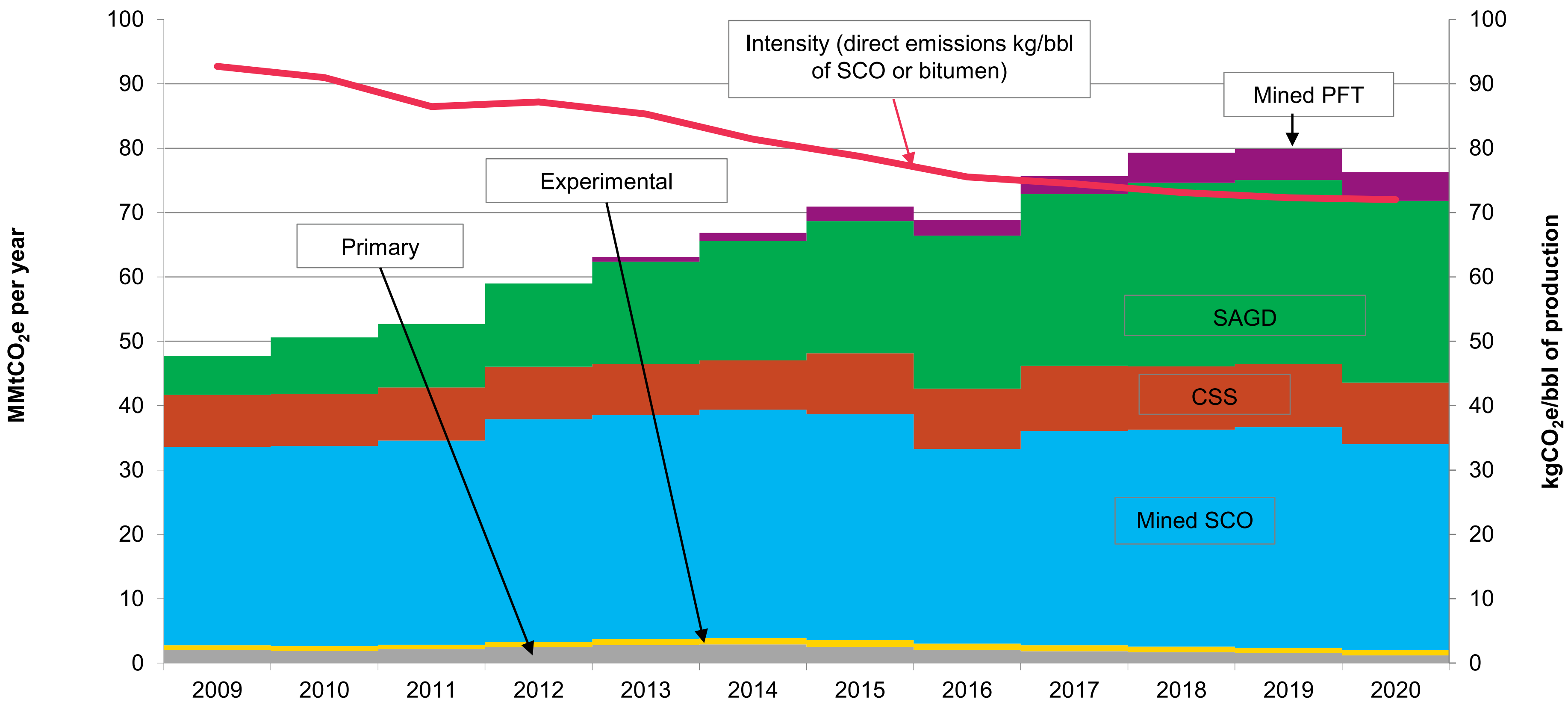
Canada’s oil sands sector emissions in 2019



Note: *Other processing includes emissions from the Bi-provincial upgrader and Northwest Redwater Refinery both part of oil sands in Canada's National Inventory.
Source: IHS Markit, Environment and Climate Change Canada National Inventory Report 1990–2019: Greenhouse Gas Sources and Sinks in Canada

Change in oil sands emissions (intensity, absolute, and production)

Composition of IHS Markit base case absolute oil sands emissions (MMtCO_2e per year)



Change 2009–20

Production
>100% 1.5 million b/d

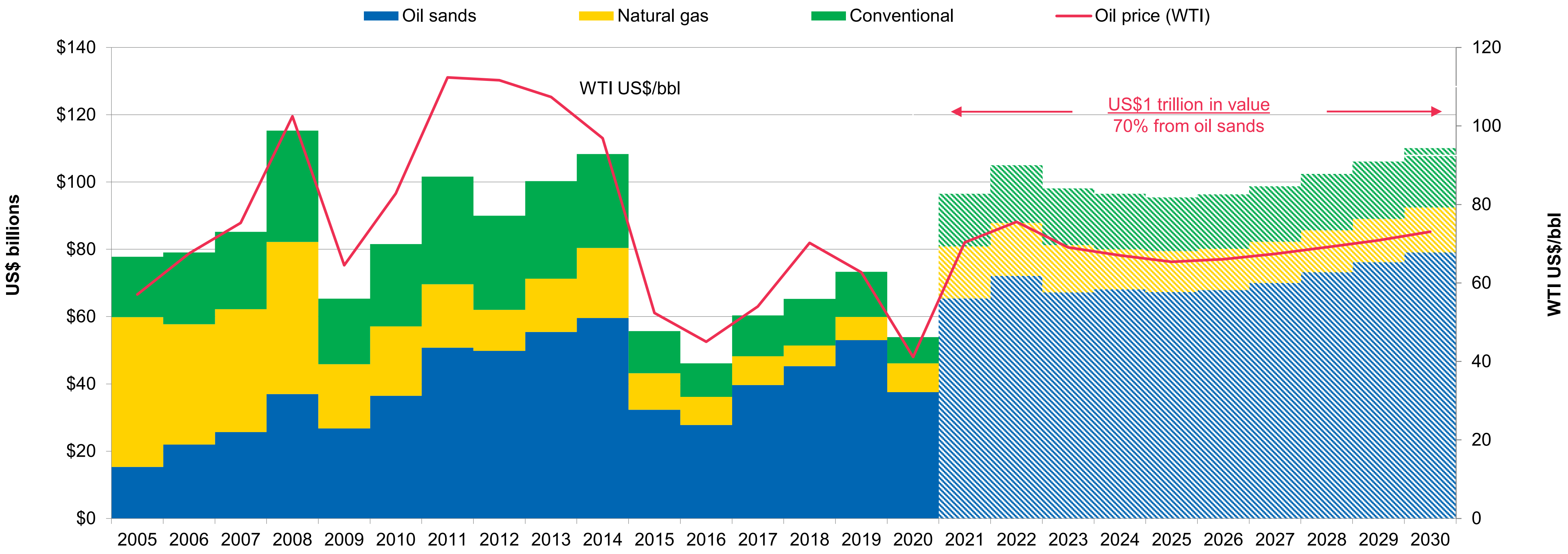
GHG intensity
20% or 17 kgCO_2e/bbl

GHG emission
60% or 29 MMtCO_2e

Note: SCO = Synthetic crude oil. SAGD = Steam-assisted gravity drainage. CSS = Cyclic steam stimulation. PFT = Paraffinic froth treatment.
Source: IHS Markit

The value of Canada's hydrocarbon sector has grown along side production growth with significant potential value forecast

Estimated value of key western Canadian hydrocarbon streams

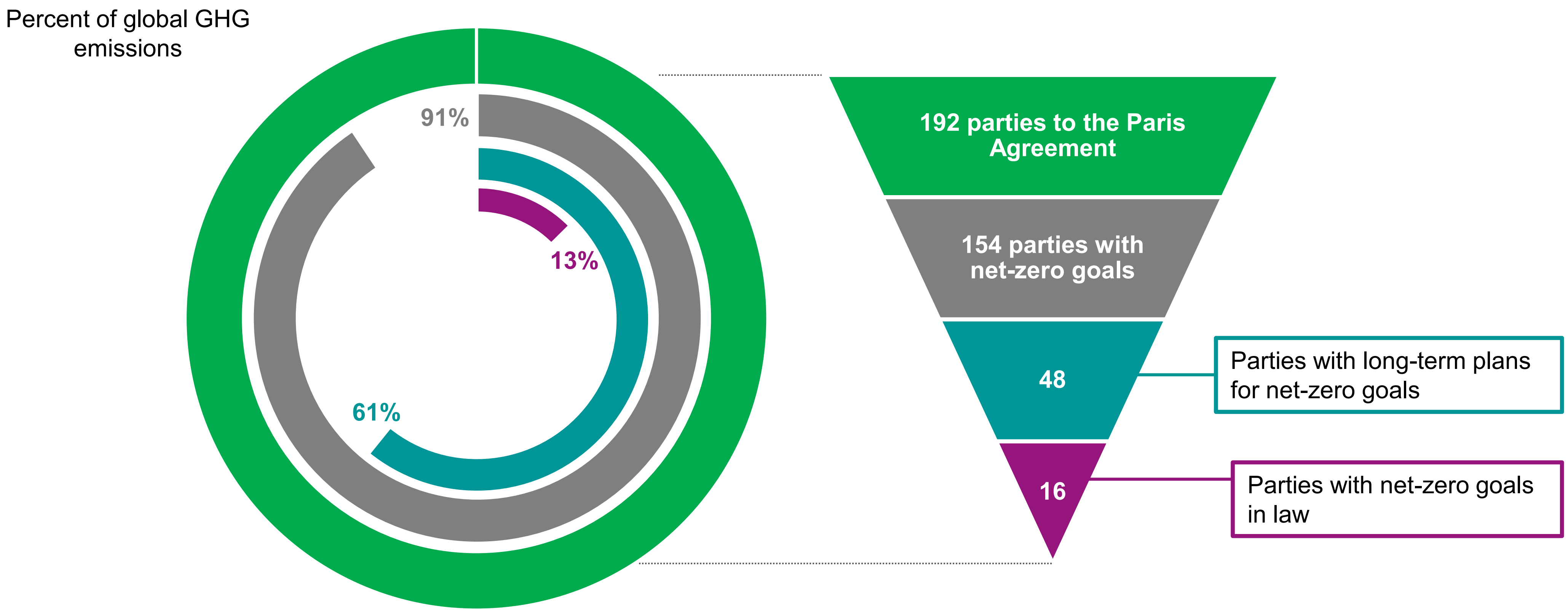


Note: WTI = West Texas Intermediate
Source: IHS Markit

The pace of global action to tackle climate change has been accelerating

Nations have announced a net-zero target for all GHGs, but others (notably, mainland China and India) are targeting only CO_2

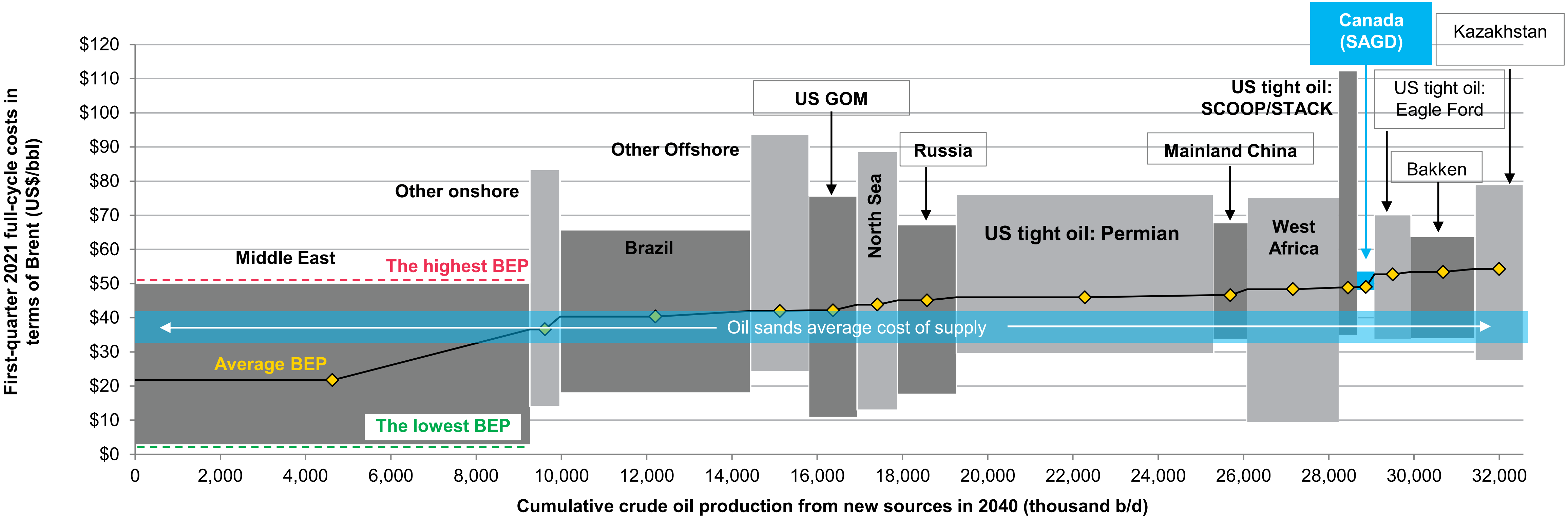
Net-zero ambitions outpace actions



Note: As of 5 November 2021.
Source: IHS Markit

Low decline rate and operating costs below the incremental supply cost of most of the rest of the world may make oil sands resilient in lower-demand scenarios

Cost curve of new global crude oil supply in select areas in 2040

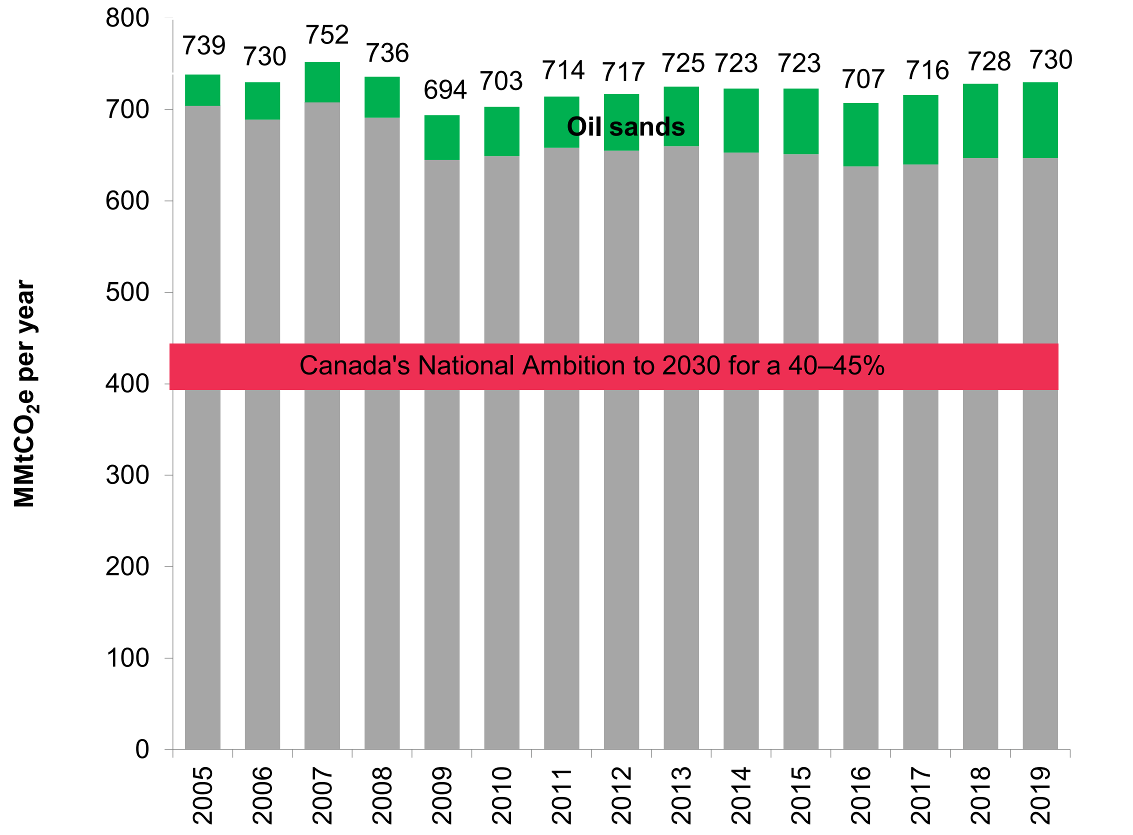


Note: The cost curve's horizontal axis shows production in 2040 from new projects expected to start production between 2021 and 2040. For a selected country/region/play, the upper side of the bar corresponds to the highest BEP, the lower side of the bar to the lowest BEP, while the width of the bar represents crude oil production from new sources in 2040. New sources of oil equal any volumes from projects that were not producing as of 2020, including sanctioned projects, unsanctioned projects, and assumed discoveries. GOM = Gulf of Mexico. The Middle East includes both offshore and onshore projects in Saudi Arabia, Kuwait, the United Arab Emirates, Iraq, Iran, Oman, Qatar, and Bahrain. West Africa includes both offshore and onshore projects in Angola, the Republic of the Congo, Equatorial Guinea, Ghana, and Nigeria. Rest of the world–Onshore and Rest of the world—Offshore categories include all production from respective projects, not included in other countries or regions. The global supply shown does not include all producing areas (in part so as not to reduce clarity of the supply stack figure) and represents 89% of total global production from new projects. The cost curves were completed in mid-2021. BEP = breakeven point.

Source: IHS Markit

Canada’s national ambition

Change in Canada’s National Inventory from 2005 to 2019 ($MMtCO_2e$ per year)



Source: IHS Markit, National Inventory Report

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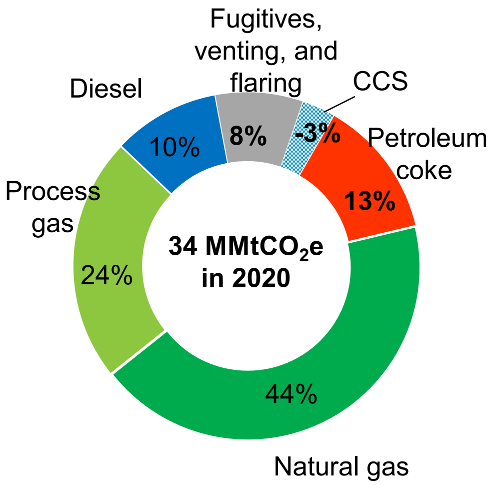
- Numerically Canada’s GHG emissions have remained relatively flat between 700 MMt to 730 MMt over the past 15 years
- Within eight years Canada would require between 280 to 320 MMt eliminated.
- Achieving Canada’s ambition will require significant reductions from across its economy, including oil and gas.
- The Oil Sands Pathways to net zero have set a collective ambition of 22 MMt reduction from 2018 by 2030, which represents a significant change from the past.

The source of oil sands emissions vary by operation

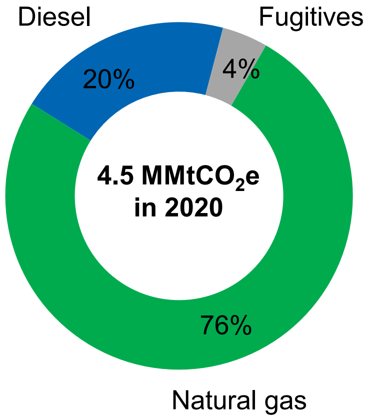
Integrated mining (Mines with upgraders that market synthetic crude oil)	**Unintegrated mining (PFT)** (Mines without upgraders that market diluted bitumen)	**Steam-assisted gravity drainage (SAGD)** (Thermal in situ facilities that drill horizontally for bitumen and market diluted bitumen)	**Cyclic-steam stimulation (CSS)** (Thermal in situ facilities that drill vertically for bitumen and market diluted bitumen)

Sources of integrated mining GHG emission in 2020



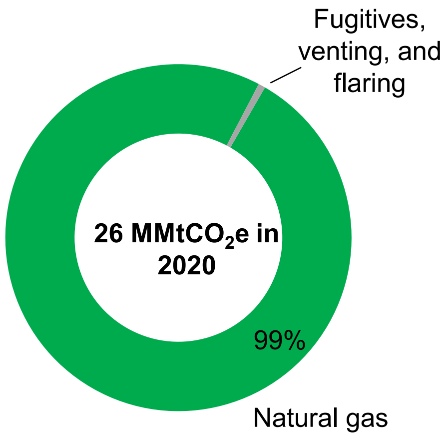
Source: IHS Markit

Sources of unintegrated mining (PFT) GHG emissions in 2020



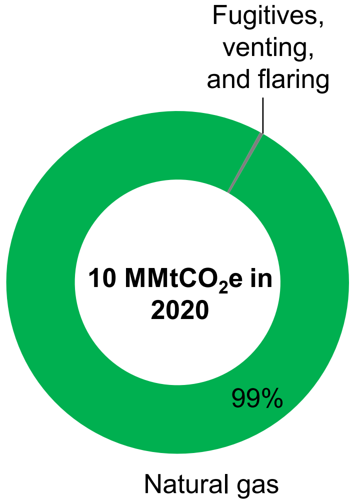
Source: IHS Markit

Sources of SAGD GHG emissions in 2020



Source: IHS Markit

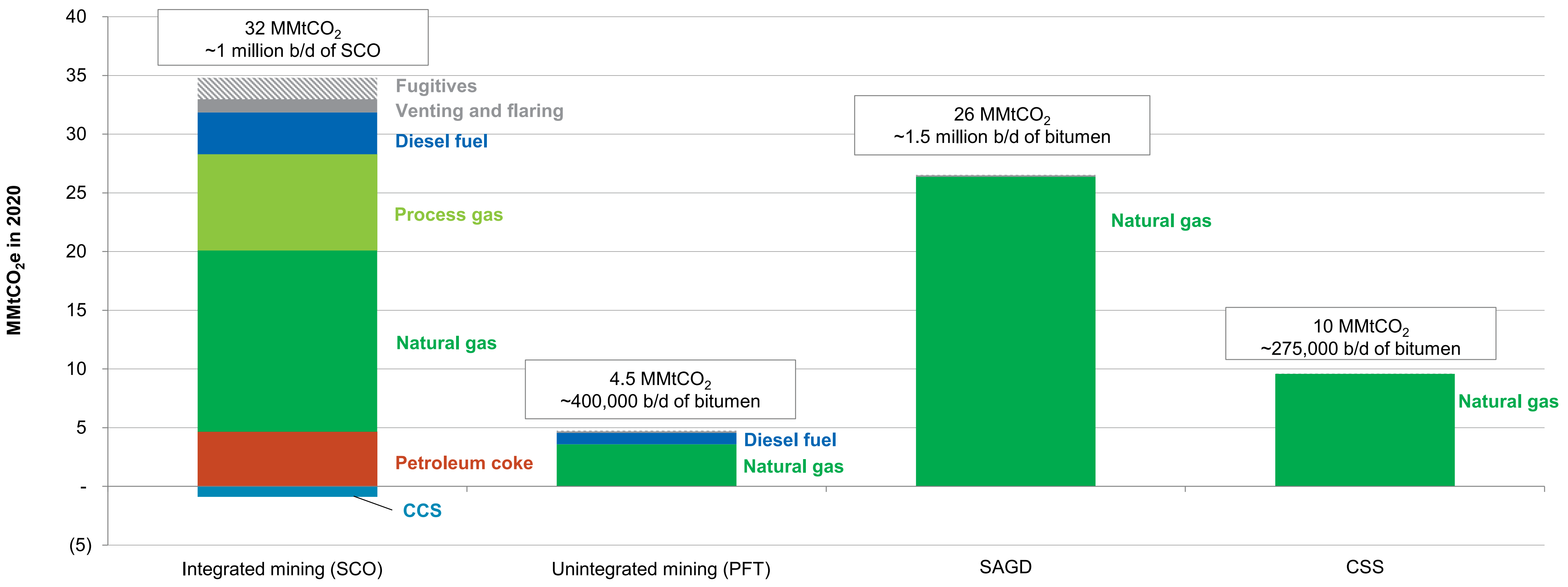
Sources of CSS GHG emissions in 2020



Source: IHS Markit

Most emissions come from the use of hydrocarbons, most notably gas, but also diesel for the mine fleets, and petroleum coke …

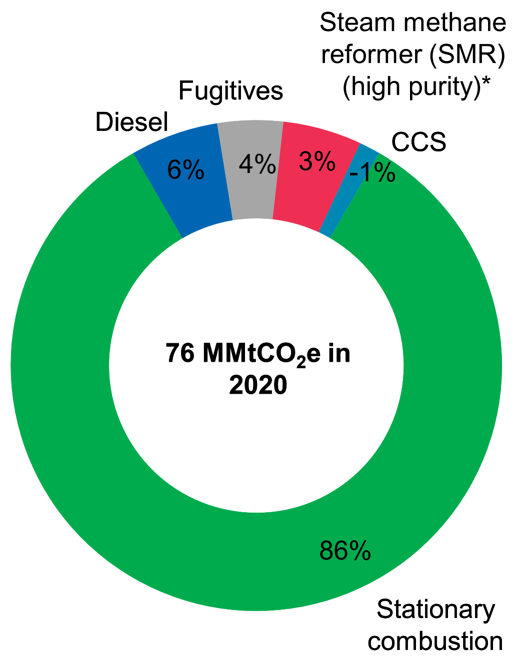
Oil sands GHG emissions by fuel or type in 2020



Source: IHS Markit

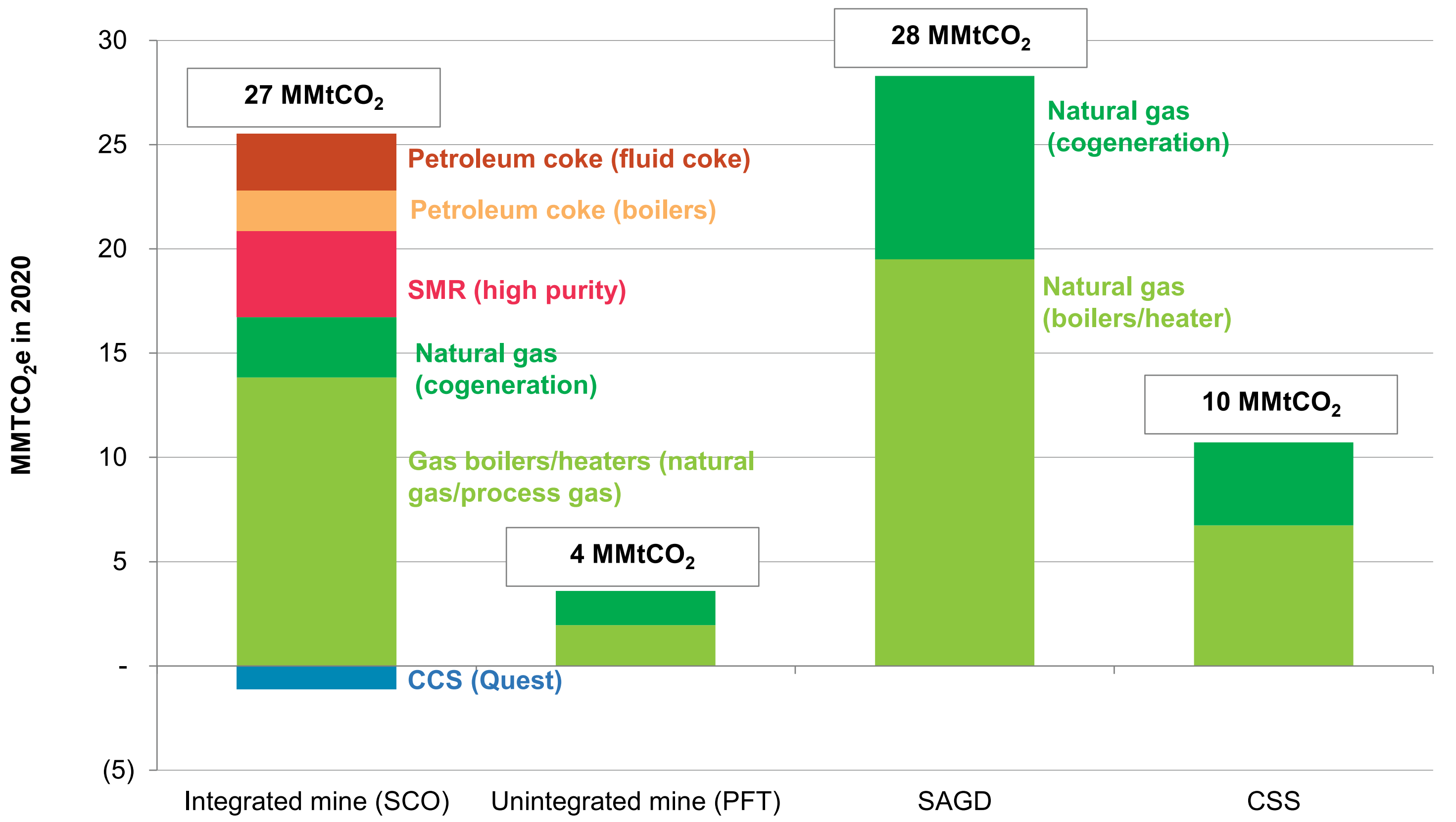
… with most GHG emissions occurring from stationary combustion sources, particularly, heaters, boilers, and cogeneration

Oil sands GHG emissions by type of combustion in 2020



Note: CCS is assumed to come from SMR high purity.
CCS = carbon capture and storage
Source: IHS Markit

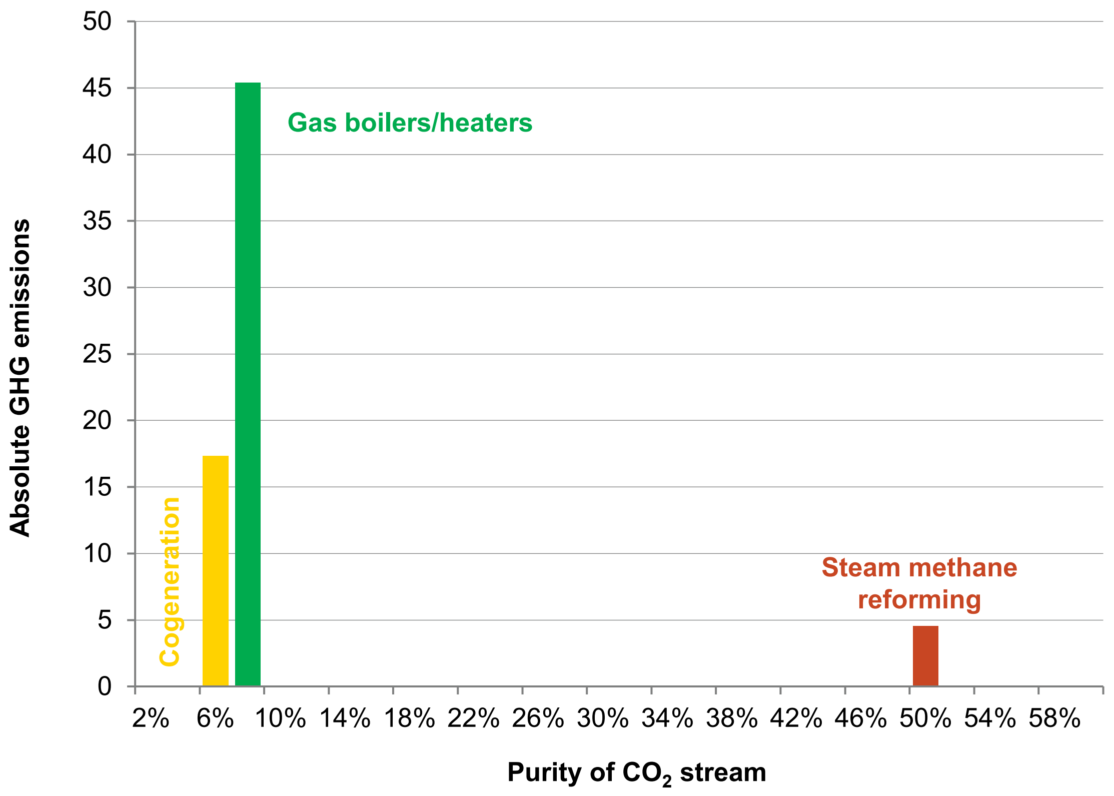
Composition of stationary combustion sources in 2020



Source: IHS Markit

Different concentrations of CO_2 emission sources influence capture cost, with lower purity streams having high costs to dehydrate and compress

Concentration of CO_2 flue gas streams of oil sands facilities (represents about 88% of oil sands GHG emissions)



Source: IHS Markit

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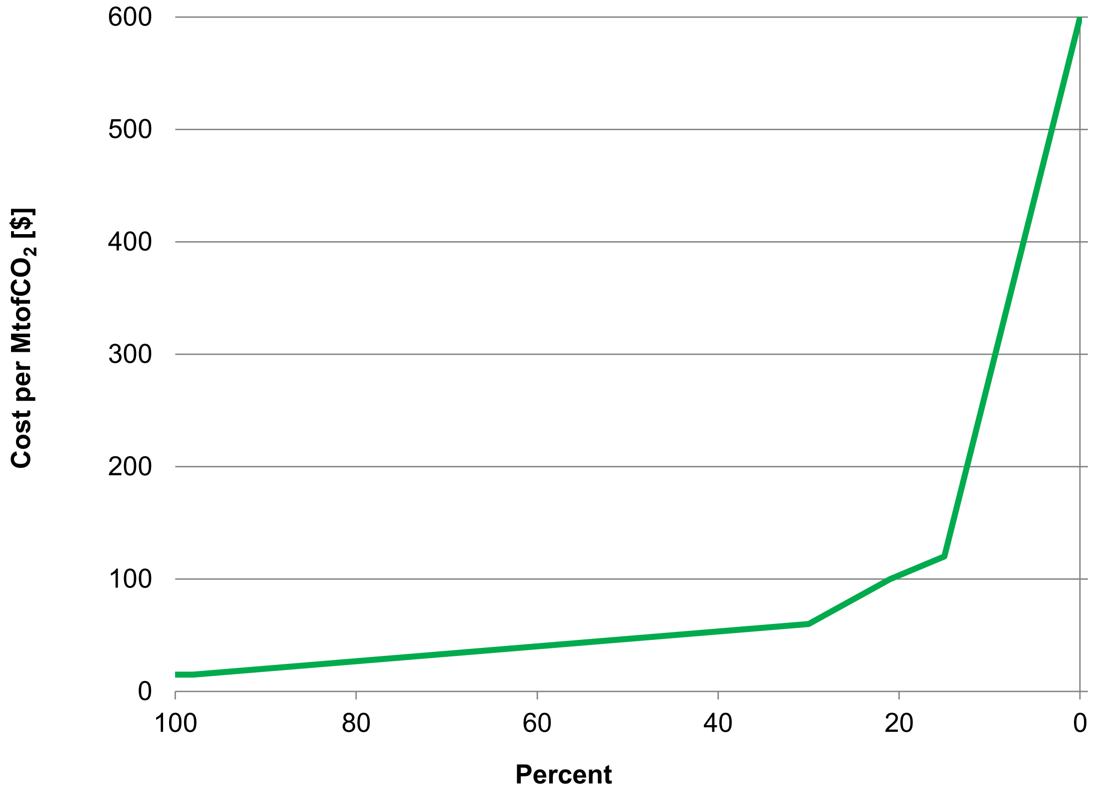
Capture cost in function of CO_2 concentration



Note: Based on zeroemissionplatform.eu
Source: IHS Markit

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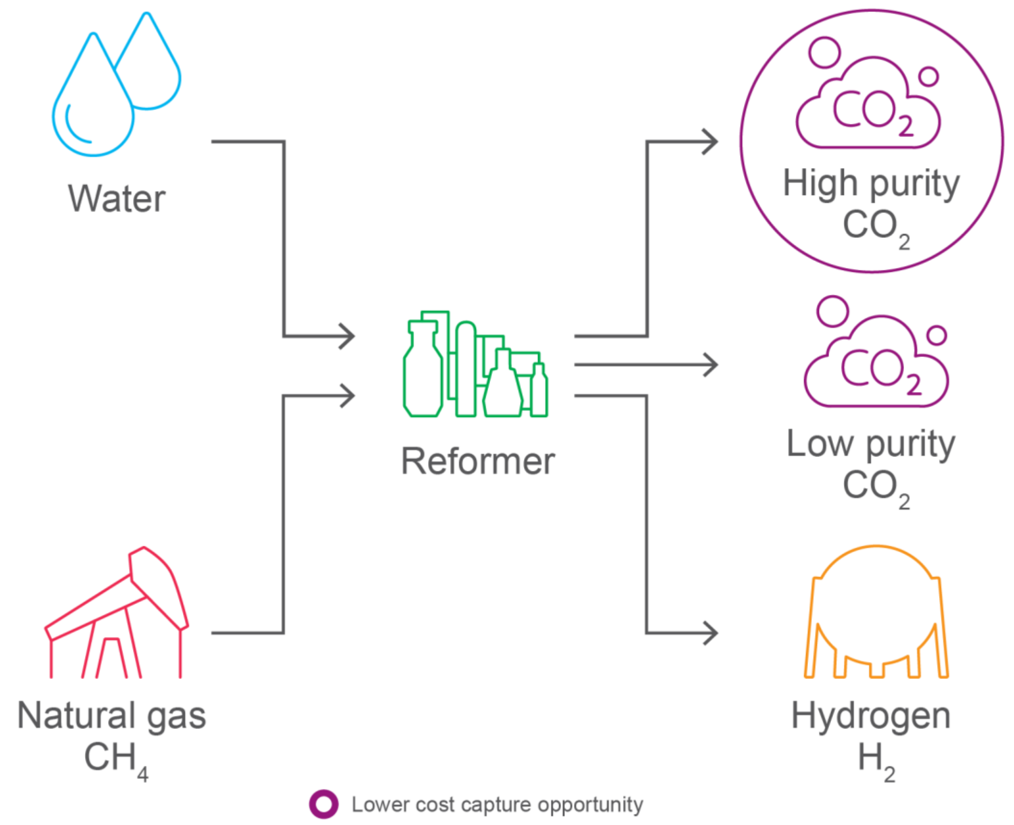
Capture opportunities from steam methane reforming would be among the lowest opportunities in the oil sands

Illustration of CO_2 streams from methane reforming



Source: IHS Markit

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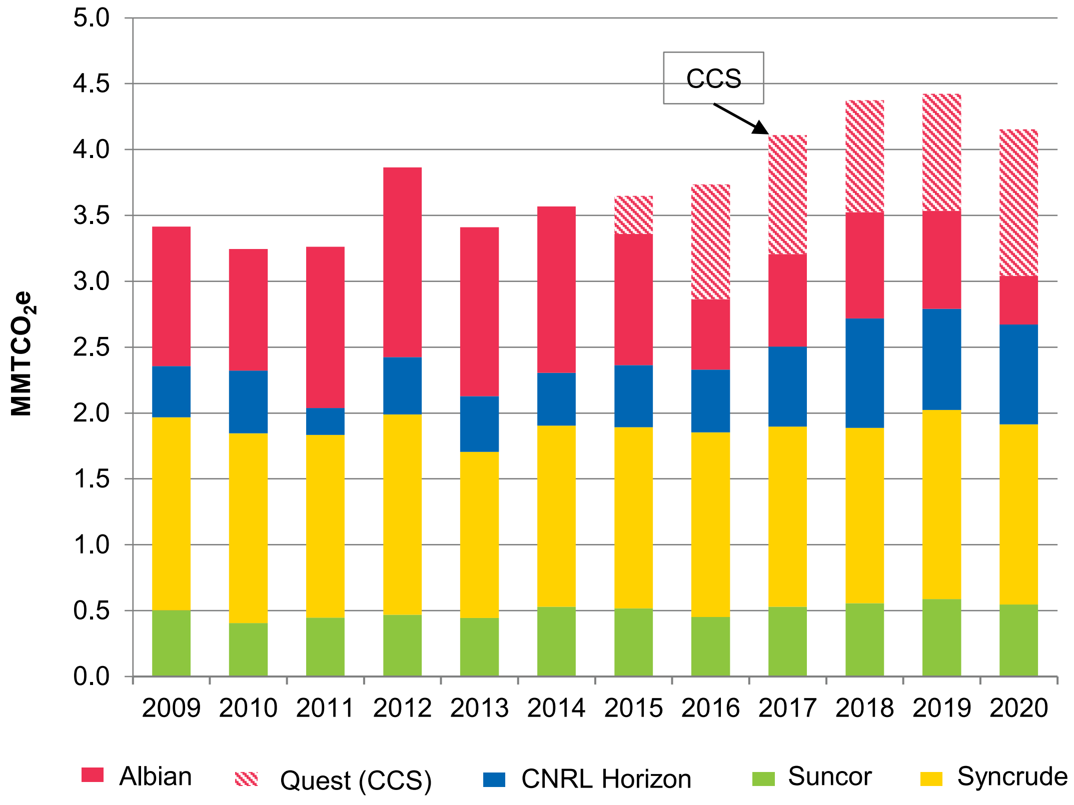
IHS Markit estimate of higher purity CO_2 emissions from steam methane reforming in the oil sands (natural gas into chemical process)



Source: IHS Markit

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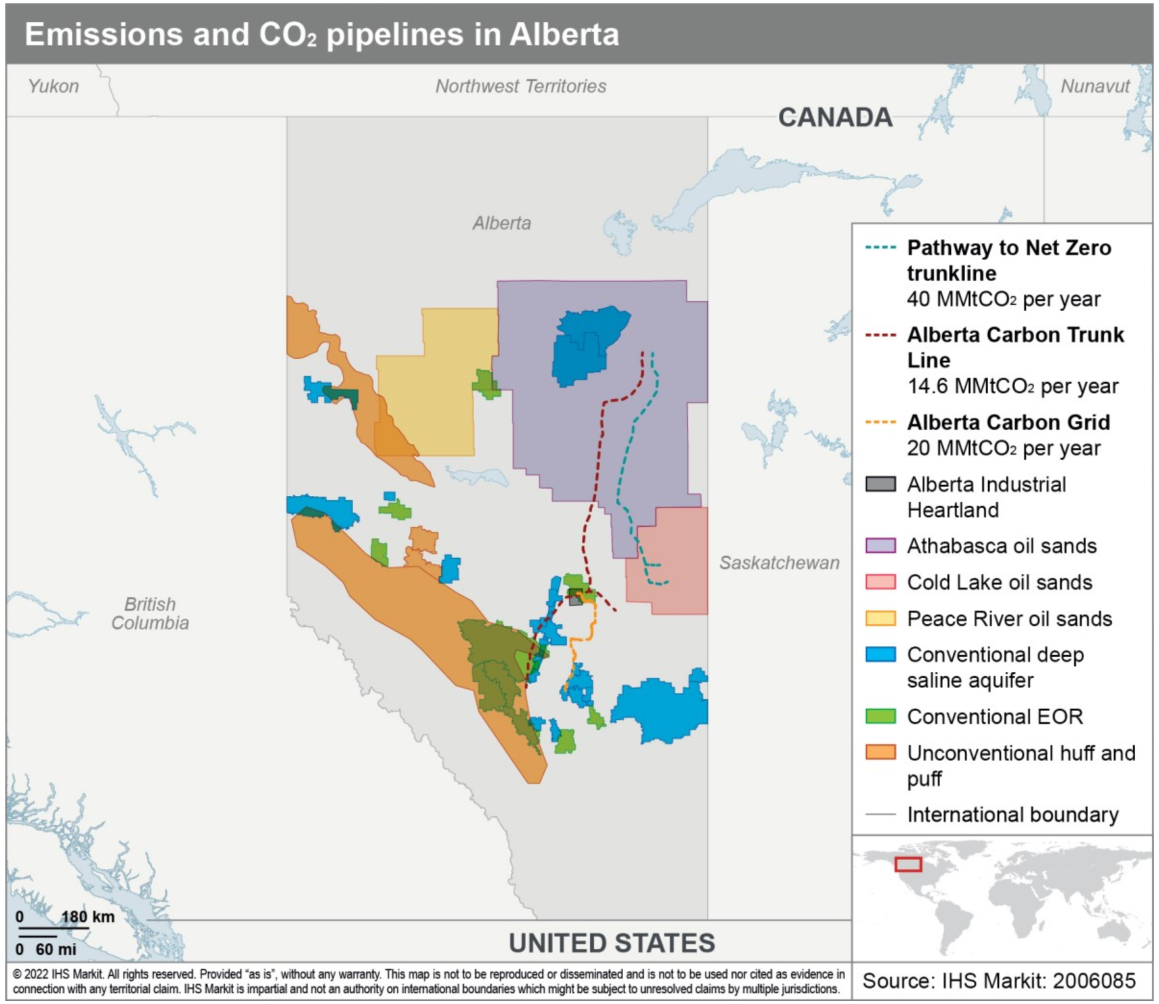
Key consideration is also the need to transport captured CO_2 to potential use or sequestration sites



- Alberta already has an established carbon trunk line connecting industrial facilities near Red Deer and in Fort Saskatchewan with sequestration near Edmonton.
- Most oil sands operations are far from sequestration opportunities and long-distance transportation infrastructure is already being proposed.

The global experience with carbon capture and storage (CCS)

What is CCS, how does it work, and what are the opportunities and challenges?

CCS is advancing around the world. What are these various projects, their objectives, and contexts?

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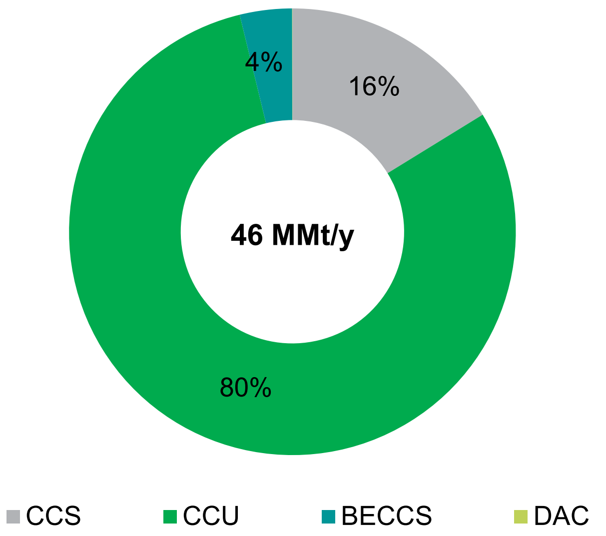
Key messages

- **CCS hubs are becoming an important piece of the future of carbon capture development.** Carbon capture clusters and shared transportation and storage could reduce costs through economies of scale and decrease leverage risk.
- **The United States and United Kingdom are anticipated account for approximately 70% of carbon capture capacity in the next five years.** The United States is expected to account for 50% of the global capacity, nearly half of which is CCS capacity. The United Kingdom is looking toward primarily CCS capacity.
- **Many CCS projects currently announced to proceed has received governmental support to reach financial viability.** The inability to monetize captured carbon through CCS projects suggests government support via subsidies, tax credits, carbon credits, and/or grants is needed to make the project financially viable.

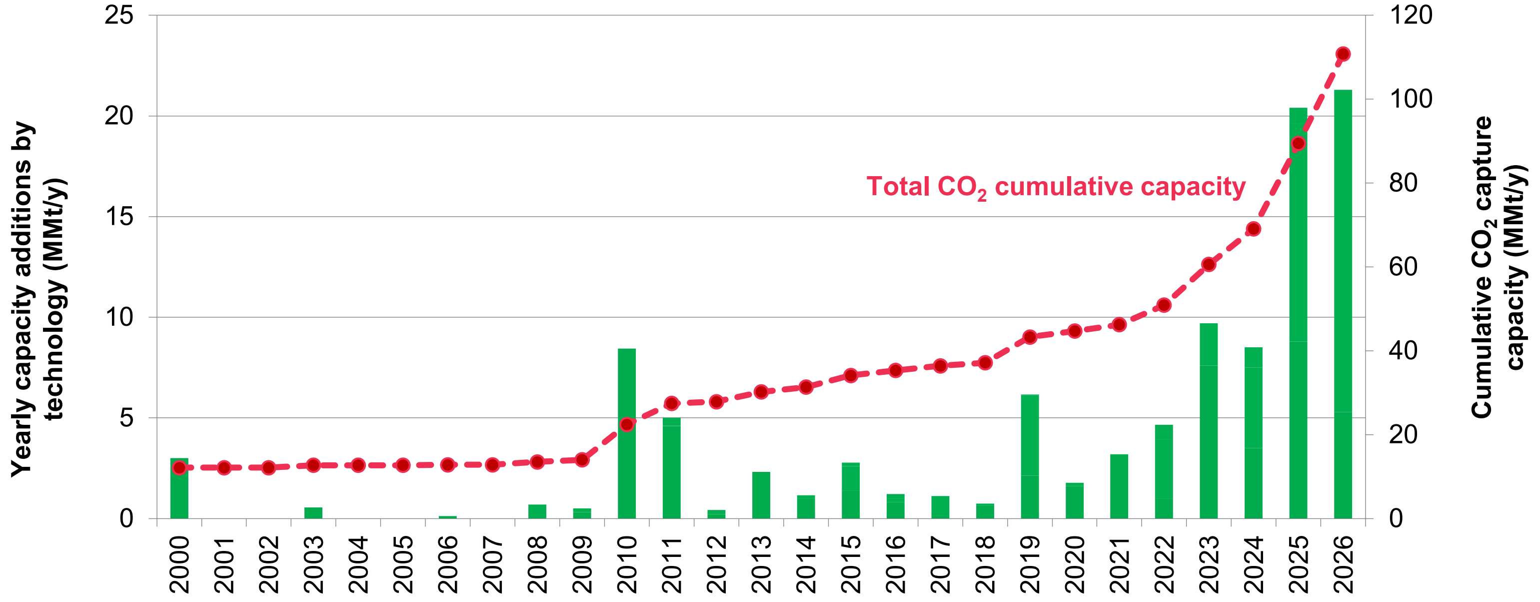
During 2021, two large-scale new projects started operations, increasing total capture capacity to around 46 MMt/y

Current CO_2 capture capacity* by solution



Note: *Capacity only includes commercial projects (large-scale and small commercial). This chart does not include "storage or transportation only" projects. CCS = Carbon capture and storage. CCU = Carbon capture and utilization. BECCS = Bioenergy carbon capture and storage. DAC = Direct air capture.
Source: IHS Markit

Evolution of CO_2 capacity—All technologies

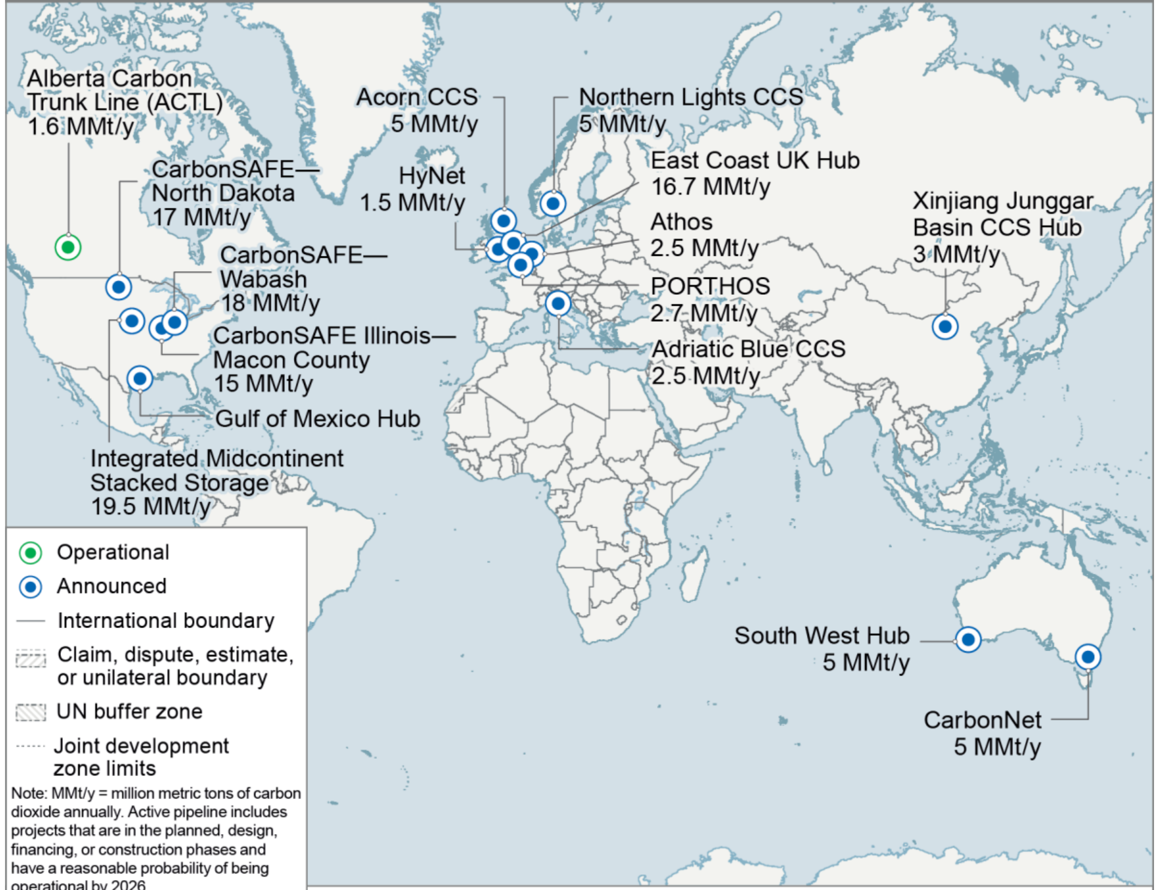


Note: *Others include cement and Iron production, water to energy and direct air capture. **2027 and 2028 compile the projects that have been announced but don't have a defined project timeline
Source: IHS Markit, The Global CCS Institute, NETL CCUS Database, MIT Carbon Capture and Storage Project Database

- Carbon capture and utilization (CCU) projects have been the main driver for capacity growth in the past 10 years. These projects have mainly been using CO_2 for enhanced oil recovery (EOR) activities led by oil and gas companies. IHS Markit expects to see a shift toward CCS projects in the next five years.
- CCS projects only account for 16% of the current capacity; however, this solution has a significant potential to grow as characterization of storage sites improves in different regions.

Capture, transport, and storage hubs are becoming important drivers for future carbon-capture development

CCUS hubs in operation or active pipeline



Note: MMt/y = million metric tons of carbon dioxide annually. Active pipeline includes projects that are in the planned, design, financing, or construction phases and have a reasonable probability of being operational by 2026

Source: IHS Markit: 2005619

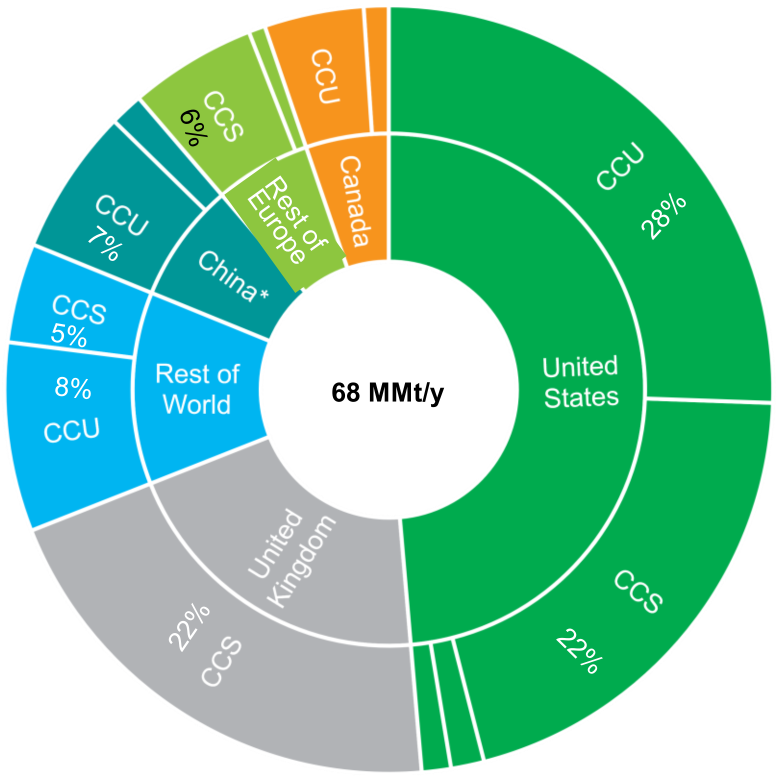
- One approach gaining traction is to identify or establish industrial "clusters" where an at-scale carbon-capture infrastructure buildout can be leveraged to capture emissions and transport them to an offsite storage area or "hub." While clusters are associated to multiple emitting facilities located in the same geographic location, hubs are associated to shared transportation infrastructure and storage. Hubs are a game changer because they decrease the investment risk and could reduce costs through economies of scale. Examples of hubs:
  - East Cost UK hub in the United Kingdom
  - Porthos in the Netherlands
  - Alberta Carbon Trunk Line (ACTL) in Canada
  - CarbonNet in Australia
  - Xinjiang Junggar Basin CCS hub in mainland China
- Norway's Northern Lights—Longship and the Netherlands' Port of Rotterdam CO_2 Transport Hub and Offshore Storage (Porthos) are in an advanced stage of development.
  - Storage hubs are also garnering interest in the United States as evidenced by continuing work funded by the US DOE and the recent announcement of the Gulf of Mexico hub
- ACTL is the first hub currently operating, with two capture facilities closely located and a shared transportation and storage infrastructure this project is the first of its kind in the region.

United States and United Kingdom are expected to account for around 70% of the capture capacity in the next five years

- The United States will continue to be the leader of the market accounting for 50% of the capture capacity expected in the next five years from the active pipeline* of projects.
- United Kingdom is a new player in the market. The country's decarbonization strategy identified CCS as a key technology to meet its net-zero target.
- Mainland China's project pipeline is driven by CCU projects using the CO_2 captured for EOR.
- Capture capacity for the rest of Europe is expected to more than double in the next five years mainly driven by the projects in Norway.
- Government support from European countries has been critical for the development of a solid pipeline of CCS projects for the next five years; however, the high costs of these projects could limit the growth in the long term.

Note: *Active pipeline includes projects that are in the planned, design, financing, or construction phases and have a reasonable probability of being operational by 2026.

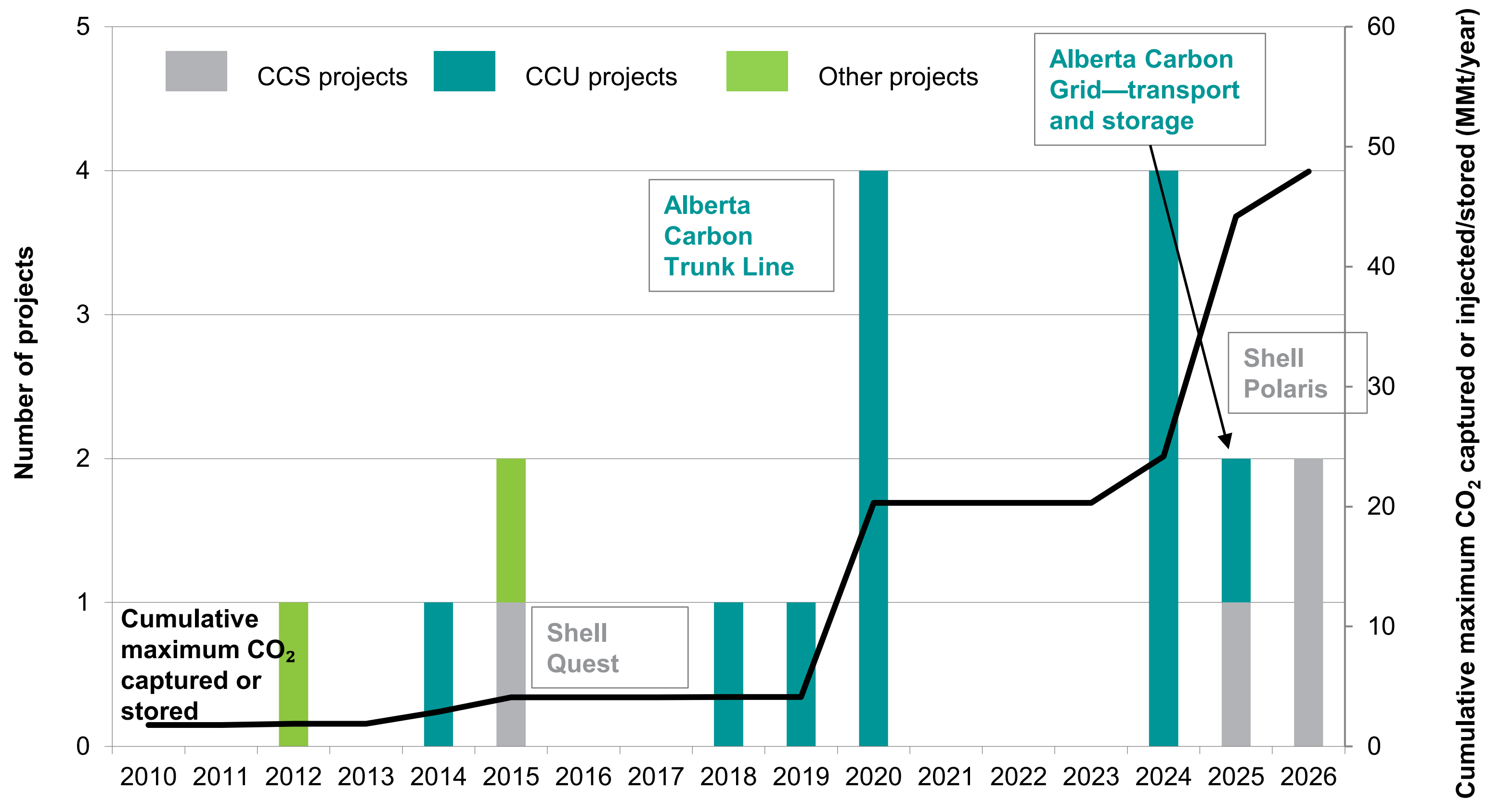
Active pipeline capture capacity by geography, 2021–26 (MMt/y)**



Note: *Refers to mainland China. **Canada is not included in the active pipeline; however, shown in this graph for a representative portion should the projects be deemed active projects in the future. All capture projects are included (large-scale and small-pilots).
Source: IHS Markit

An influx of announced CCUS projects was seen in 2021, larger in scale than projects completed in the prior decade

Canadian CCUS projects 2010–26



Source: IHS Markit

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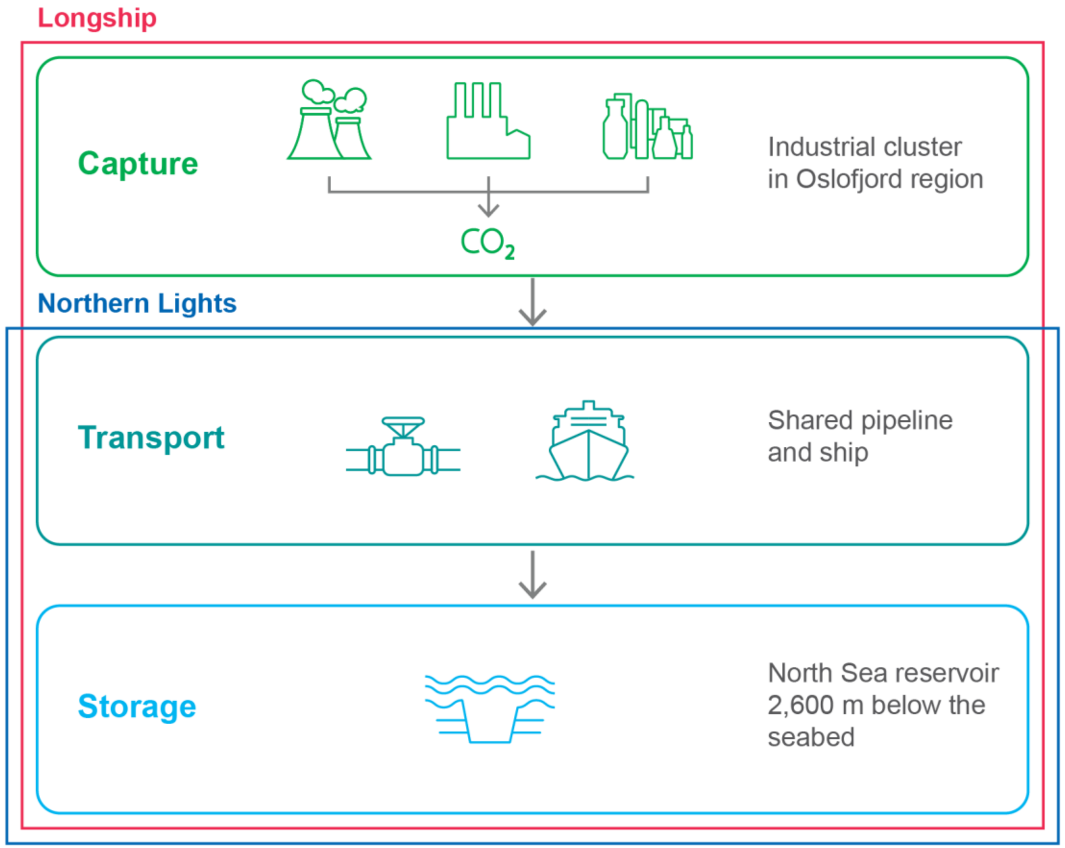
- Canadian CCUS projects prior to 2020 were relatively small scale; however, they have been important in the development of CCUS globally.
- The Alberta Carbon Trunk Line came into service in 2020, which was the first hub project completed globally.
- A number of CCUS projects were announced in 2021 with anticipated start-up dates of 2024–26.
  - In March 2022, the government of Alberta selected six projects to work with the government to evaluate the location suitability of storing carbon
  - TC Energy and Pembina announced the Alberta Carbon Grid, which aims to transport up to 20 $MMtCO_2$/year.
  - Shell's Polaris CCS aims to capture 750,000 metric tons of CO_2/year from the Scotford refinery and chemicals plant.

Shell Quest CCS experience

- Quest is located at the Scotford upgrader and is part of the Athabasca Oil Sands Project.
- CO_2 is captured at the Scotford upgrader, then transported 65 km via pipeline to three injections wells to be permanently stores 2 km underground.
- Captures and stores approximately 1 $MMtCO_2$/year.
  - Estimated to be one-third of the CO_2 emissions from the Scotford upgrader.
- Planning and preliminary design began in 2009 with completion of the project in in September 2016.
- Awarded C$120 million from Canadian Energy Fund and C$745 million from the Province of Alberta.
  - Total cost of approximately C$1.35 billion.

Longship—Northern Lights located in Norway with estimated storage of 1.5 MMtCO_2/year

Longship–Northern Lights CCS project in Norway



Source: IHS Markit

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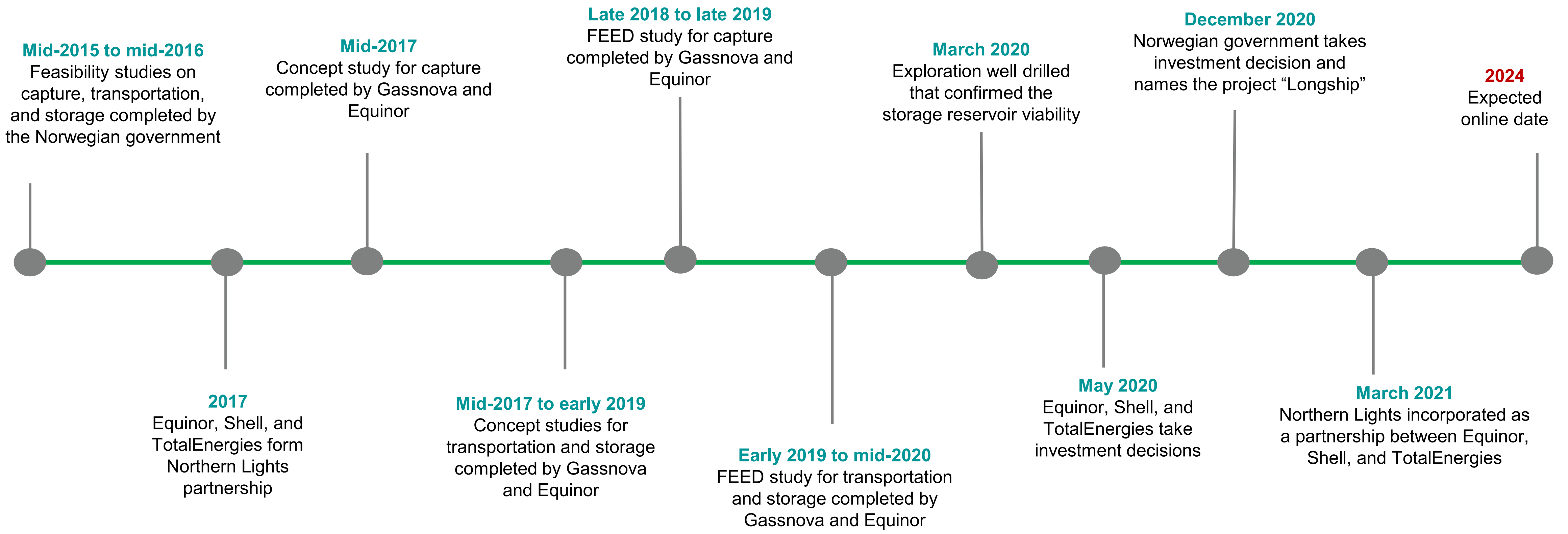
- **The project is a collaboration between state and private firms.** Gassnova coordinated the overall project schedule and managed cross-chain risks and functionality, while Equinor, Shell, and TotalEnergies partnership is responsible for Northern Lights transport and storage design, construction, and operation, and Norcem and Fortum Oslo Varme will be capturing the carbon.
- **State aid provided the individual companies secured sufficient and funding from the European Union and their own funding to meet total cost.**
  - State aid is for construction and first 10 years of operation
- **State funding is estimated to be 40–85% of total capital cost for each portion of the project.** Northern Lights, Norcem, and Fortum Oslo Varma estimated to receive state aid covering over 70%, 80%, and 40% of the costs, respectively.
- **Estimated cost for the CCS chain is C$185/metric ton***
  - Nearly half is for storage and transport (capture is 700 km away from storage and needs to go on a ship).
- **Norway Climate Change Act aims for 50% reduction by 2030 compared to 1990 levels.**
  - 2018—Climate Change Act (legally binding)
  - Oct 2019—Norway, Iceland, and the European Union formally agreed to cooperate on fulfilling respective emissions targets by 2030
  - Part of the EU ETS (emissions trading system)

Note: *Gassnova report "Developing Longship—key lessons learned"

Helped along by government funding and coordination, the project will take nearly a decade to reach an in-service date

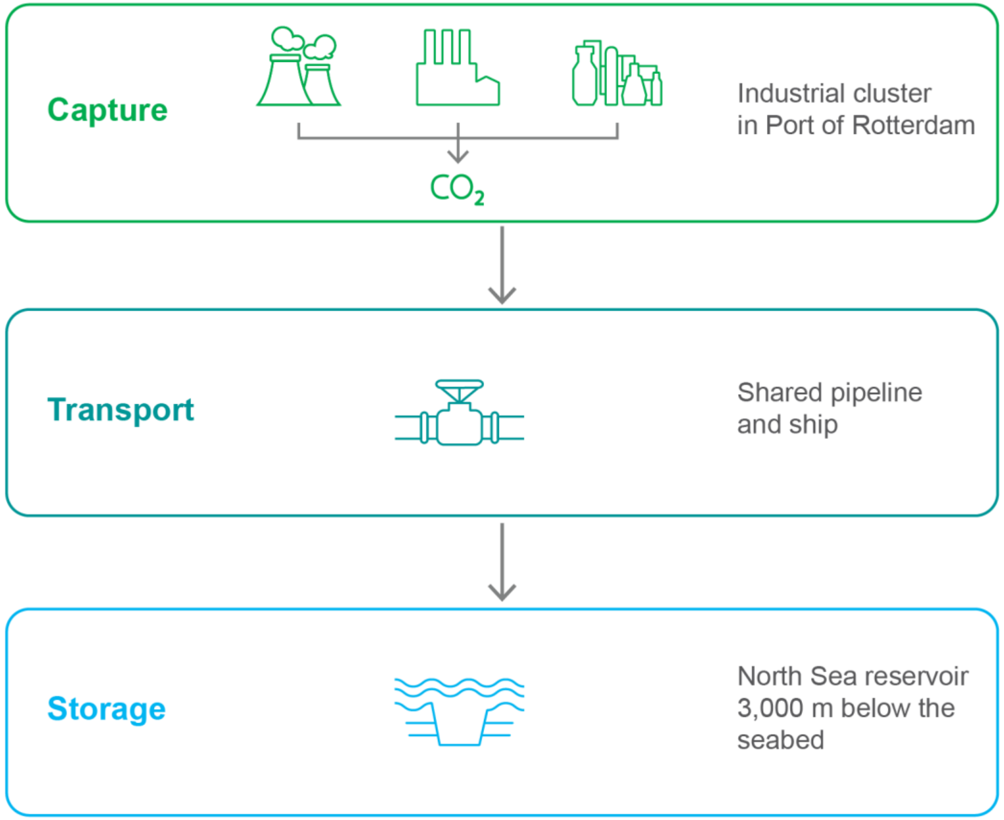
Timeline of key events in the Longship—Northern Lights CCS project



Source: IHS Markit

Porthos—Port of Rotterdam, Netherlands CO_2 Transport Hub and Offshore Storage with estimated storage of 2.5 $MMtCO_2$/year

Porthos CCS project in the Netherlands



Source: IHS Markit

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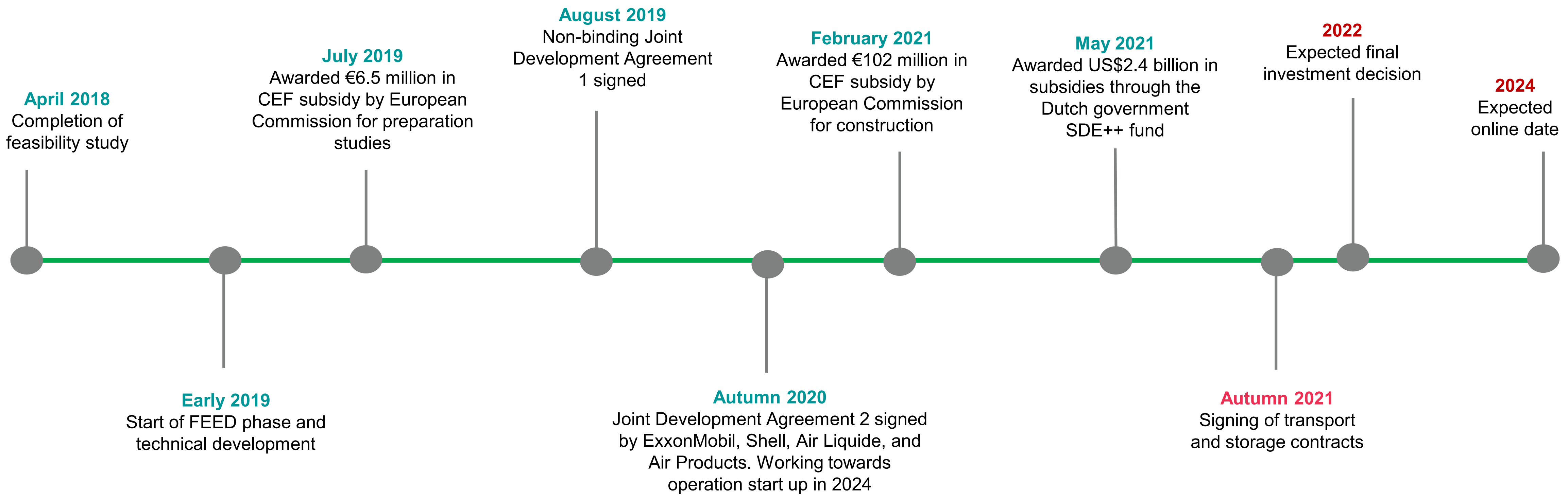
- **Private, public, and non-profit companies come together in this integrated project.** Porthos is a joint venture between EBN (European Business and Innovation Center Network), Gasunie (energy network operator), and Port of Rotterdam Authority. Air Products refinery, Air Liquide refinery, ExxonMobil refinery, and Shell refinery and chemical plant will be the capture sources.
- **Funding awarded in May 2021 from the SDE++ fund*.** Combined, the companies have requested nearly US$2.4 billion in subsidies.
- **Netherlands Climate Act aims for a 49% reduction in emissions by 2030 compared to 1990 levels.**
  - 2019—Netherlands Climate Act (legally binding). Plan to stimulate industry to reduce emissions with a CO2 tax and the SDE++ subsidy.
  - 2019—Norway, Iceland, and the EU formally agreed to cooperate on fulfilling respective emissions targets by 2030.
  - Part of the EU ETS (emissions trading system).

Note: *SDE++ = Sustainable Energy Transition Scheme

Porthos nearing the finish line for investment decision

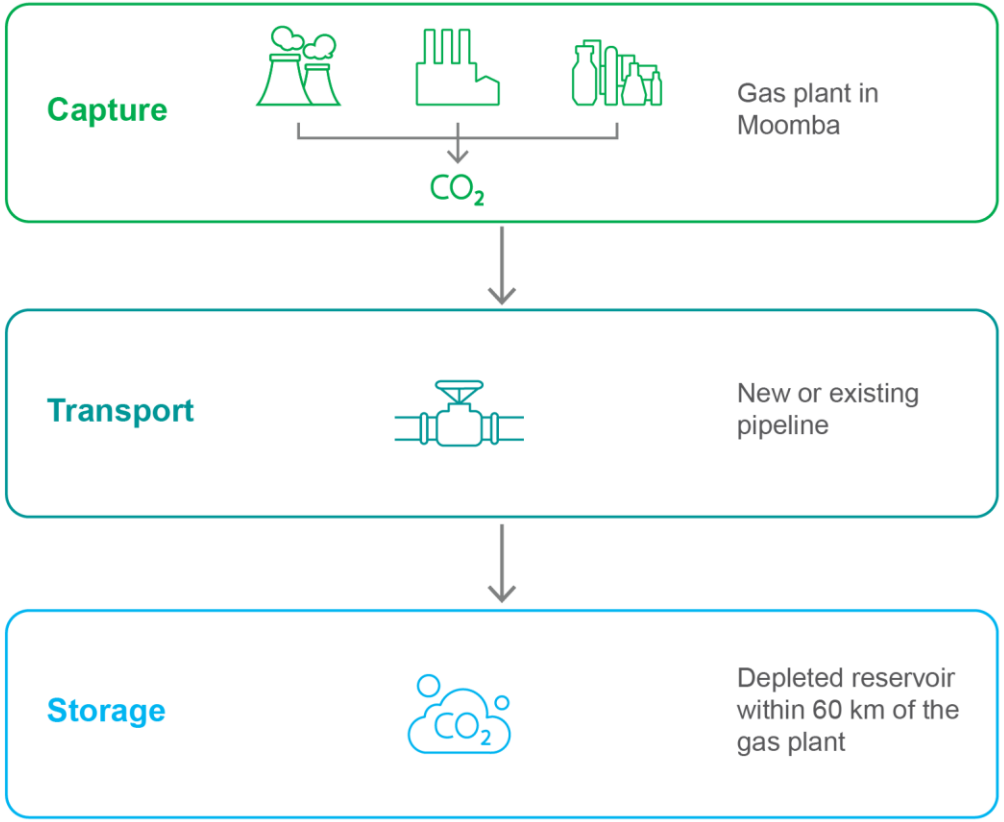
Timeline of key events in the Porthos CCS project



Note: CEF = Connecting Europe Facility
Source: IHS Markit

Moomba Santos—Australia CO_2 capture and storage with estimated storage of 1.7 $MMtCO_2$/year

Moomba Santos CCS project in Australia



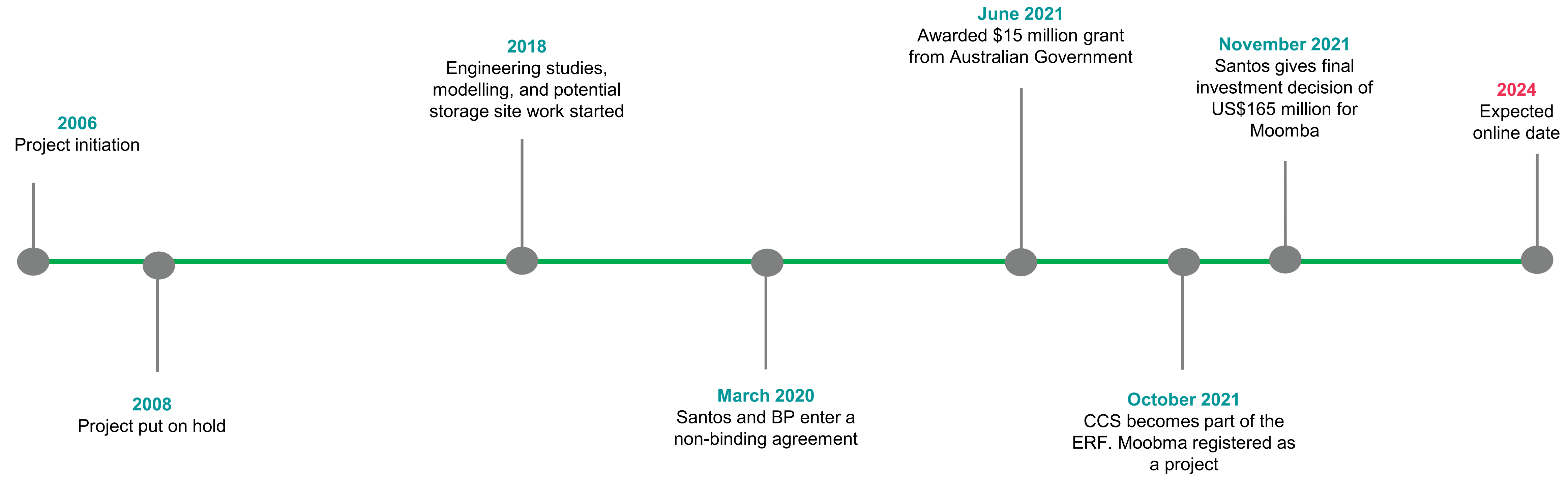
Source: IHS Markit © 2022 IHS Markit: 2005418

- **Santos is the primary creator for the entire project, backed by joint venture partners.** Santos and Beach Energy have a joint interest in Moomba—66.7% and 33.3%, respectively. BP entered into a non-binding agreement with Santos that could lead to BP investing AU$20 million in the project.
- **Santos estimates the project to cost US$165 million.** Project will receive tradeable carbon credits through the Emissions Reduction Fund.
  - Credits can be sold to the government or on the secondary market.
  - Will qualify for credits for 25 years.
- **Santos's 2020 estimate for CCS cost was AU$30/metric ton of CO_2.***
- **Long-Term Emissions Reduction Plan to achieve net zero by 2050 adopted in 2021.**
  - Technology-led approach intended to drive down costs of emission reduction and low emission technology for large scale deployment.
  - Government's role is to invest in infrastructure; ensure transparency and knowledge sharing; and provide incentives to deploy emerging technology
  - No mandated targets and no carbon taxes.
- **Emissions Reduction Fund introduced in 2015.**
  - Provides incentives for organizations and individuals to adopt new practices and technology to reduce emissions and store carbon
  - Participants can earn carbon credits which can be sold to the government or in the secondary market

Source: *https://www.petroleum.sa.gov.au/media/shared/pdf/petroleum/roundtable/roundtable_meetings/roundtable-meeting-2020/Winterfield-Christian-Moomba-CCS-Project-2020-Roundtable-for-Oil-and-Gas-Final.pdf

Moomba CCS recently given final investment decision after receiving government funding and ability to generate carbon credits

Timeline of key events in the Moomba CCS project



Note: ERF = Emissions Reduction Fund
Source: IHS Markit

Carbon capture and storage in the oil sands

What are the unique opportunities and challenges for CCS in the oil sands including geography, coordination of new projects, and capture issue based on streams?

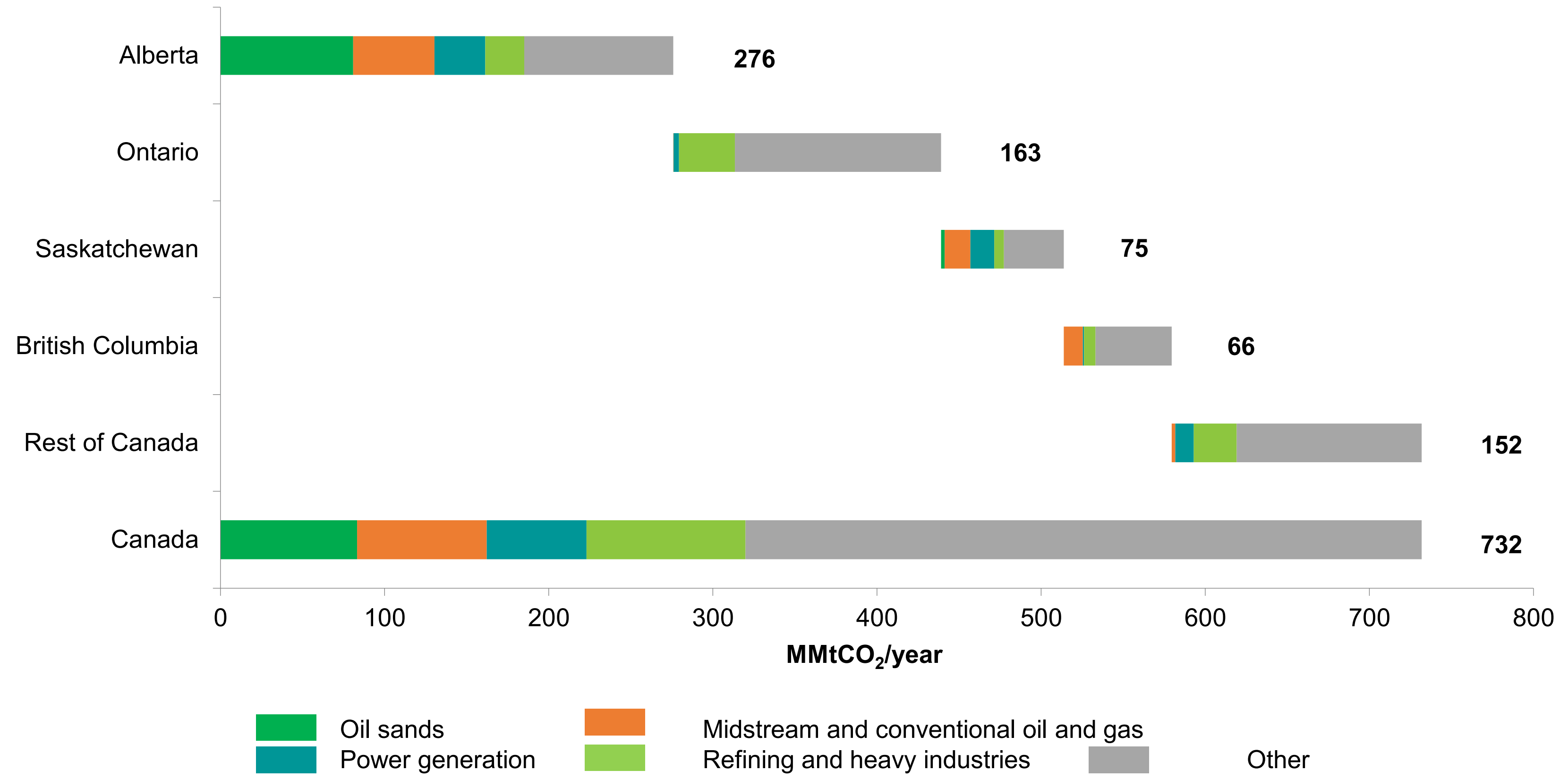
Eleonor Kramarz, Executive Director, eleonor.kramarz@ihsmarkit.com

Key messages

- Alberta is a hard place to decarbonize while preserving economic benefits, and while low-cost opportunities exist, their impact will be limited.
- Alberta’s heavy industries competes with numerous countries with less stringent environmental and climate policy regimes.
- Decarbonization of Alberta heavy industries can protect the economics benefits (nearly C$100 billion in GDP), and attract new development by enabling decarbonization while remaining competitive globally.
- Greenfield projects can achieve reductions at a much lower cost.
- A CCS and hydrogen hub approach will be a key enabler to a lower emission economy.
- Given the capital-intensive and cross-sector nature of CCS, the proper policies are key to reduce investment risk and, in turn, cost of capital.
- A long-term collaborative framework is key to advance CCS and support the viability of the industrial sector (including oil and gas).

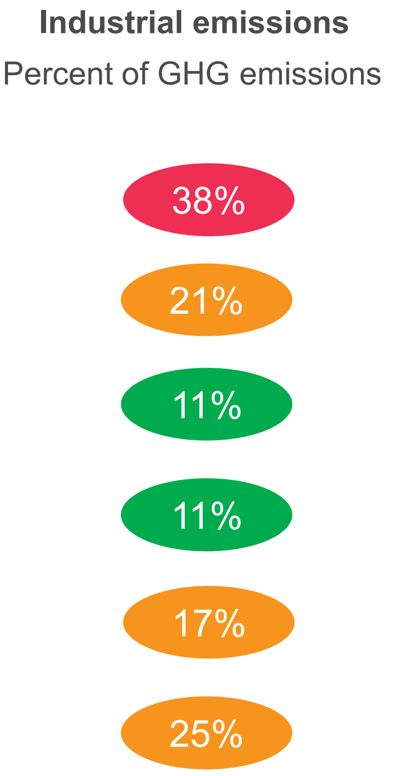
Alberta’s large share of industrial emissions complicates decarbonization

Canadian GHG emissions by province*



Note: *For year 2019
Source: Canada National Inventory Report

Percentage of industrial emissions



Source: IHS Markit

Demand for heat in oil sands, refining, and other heavy industries leaves fewer options outside of CCS and H_2 for large scale decarbonization

GHG intervention options to address brownfield infrastructure

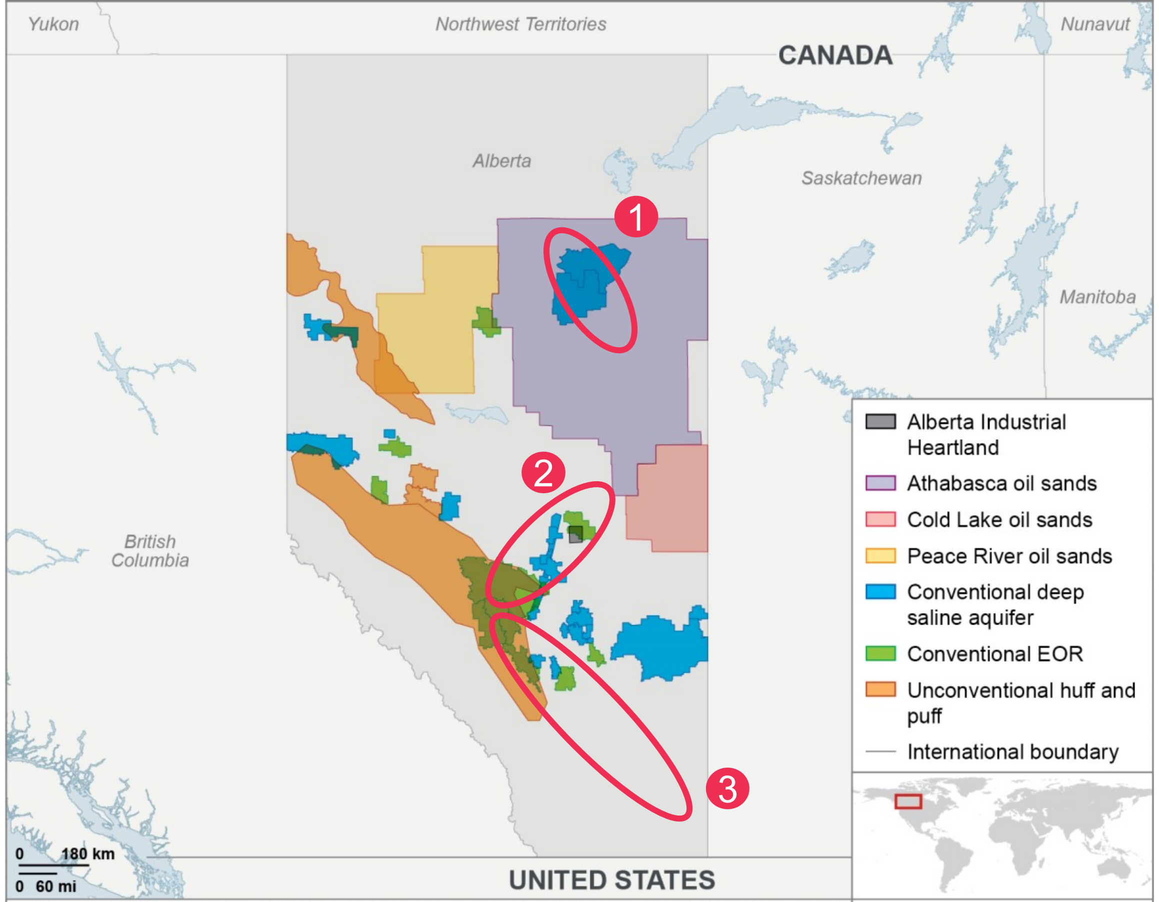
Industrial GHG emissions in Alberta[1]	$MMtCO_2$/year	Selected GHG intervention options	Commentary
Oil sands	81	Digital and physical energy efficiency, steam displacement (e.g., solvent), power switching, cogen conversion, CCS, improved tailing technology, H2 and RNG[1]	Existing trends from IHS Markit research shows avoided emission of ~10MT from baseline by 2030[4]; deep decarbonization is difficult without CCS due to significant heat requirement across oil sands operations
Other E&P and Midstream[2]	52	General efficiency improvements , NGL extraction, flaring reduction, methane (fugitive, venting) reduction, fuel switching, renewables	Alberta has committed to a 45% methane reduction target by 2025[5], representing ~5% of midstream's carbon footprint; electrification and fuel switching can help address significant portion of CO_2 emissions
Power generation	33	Fuel switching (natural gas or renewables + storage), end use energy efficiency, generation efficiency improvements, waste-to-gas, CCS	~31% of power sector generation (est. 23.8 TWh in 2020) from to coal will retire or convert to natural gas by 2023[6], with further decarbonization driven by additions of renewable power
Refining[3] and heavy industries	25	General plant energy efficiency gains, feedstock and fuel switching, renewables, CCS, SMR[8] with CCS, use of green hydrogen	Canada's CFS[7] will indirectly affect co-processing related heavy industry segments by driving demand for co-processing (soy, canola); CCS will play a key role in decarbonization due to high heat requirements within the industry

Note: 1. Renewable natural gas, 2. Includes natural gas production and processing, 3. Includes oil processing, 4. IHS Markit (2018) "Greenhouse gas intensity of oil sands production: Today and in the Future." 5. Reducing methane emissions | Alberta.ca, 6. Alberta set to retire coal power by 2023, ahead of 2030 provincial deadline - JWN Energy, 7. Clean Fuel Standard - Canada.ca, 8. Steam methane reforming

Source: Canada National Inventory data (year 2018)

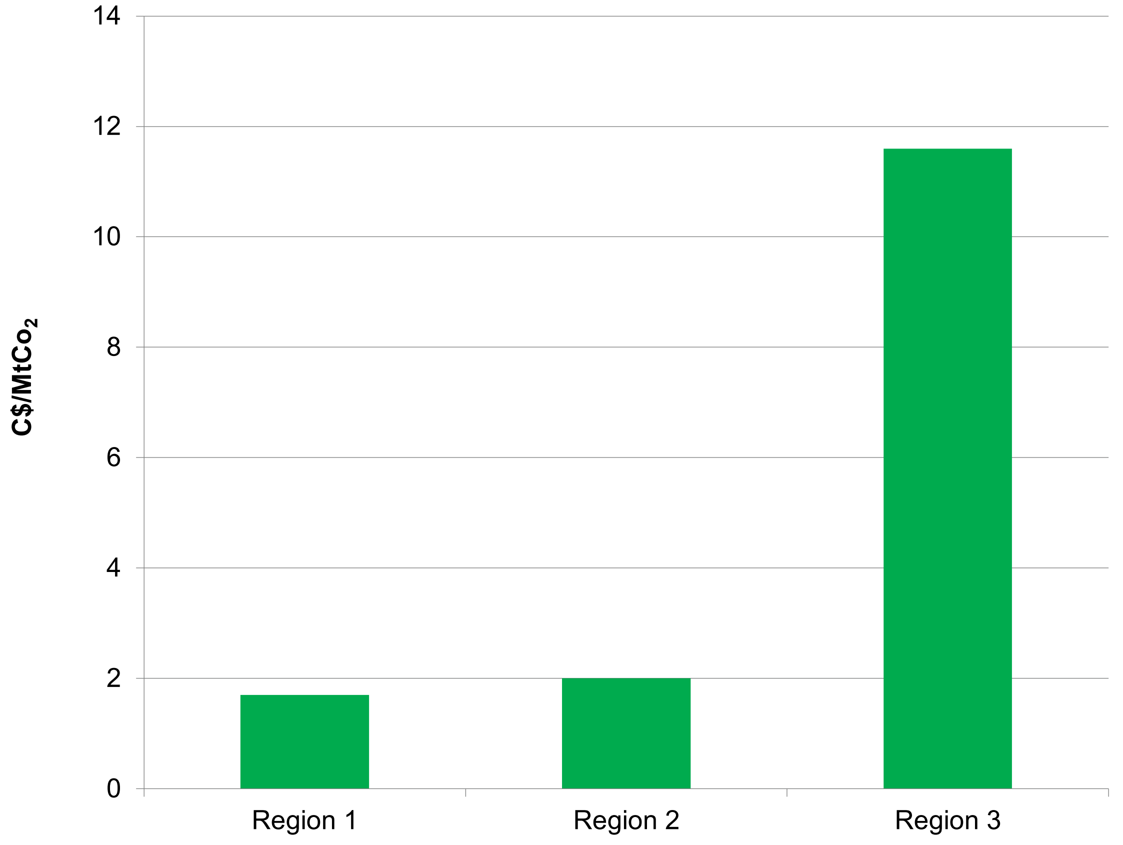
There are significant cost efficiencies from a hub-based approach to development of new CO_2 pipelines, but this requires coordination

Alberta GHG emissions



Source: IHS Markit: 2006084

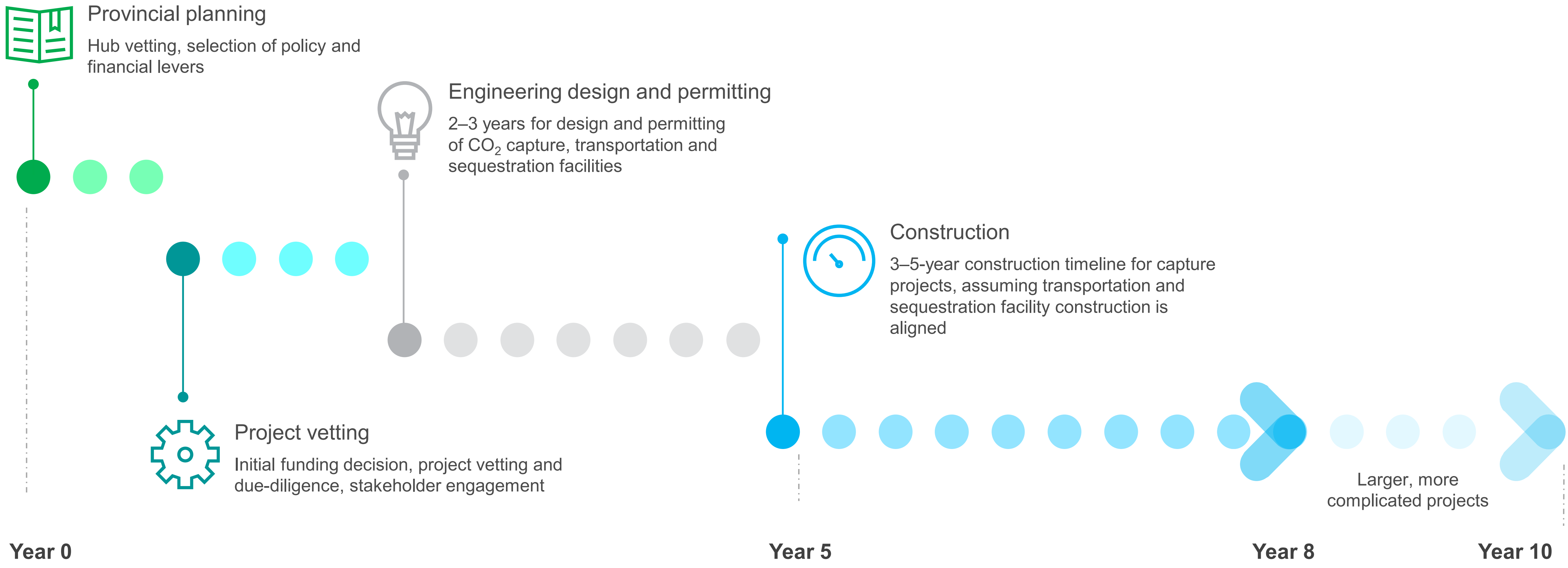
Transportation cost per region



Source: IHS Markit

CCS projects can take nearly 10 years to bring online from conception to completion; Canada must act now if its decarbonization goals are to be met

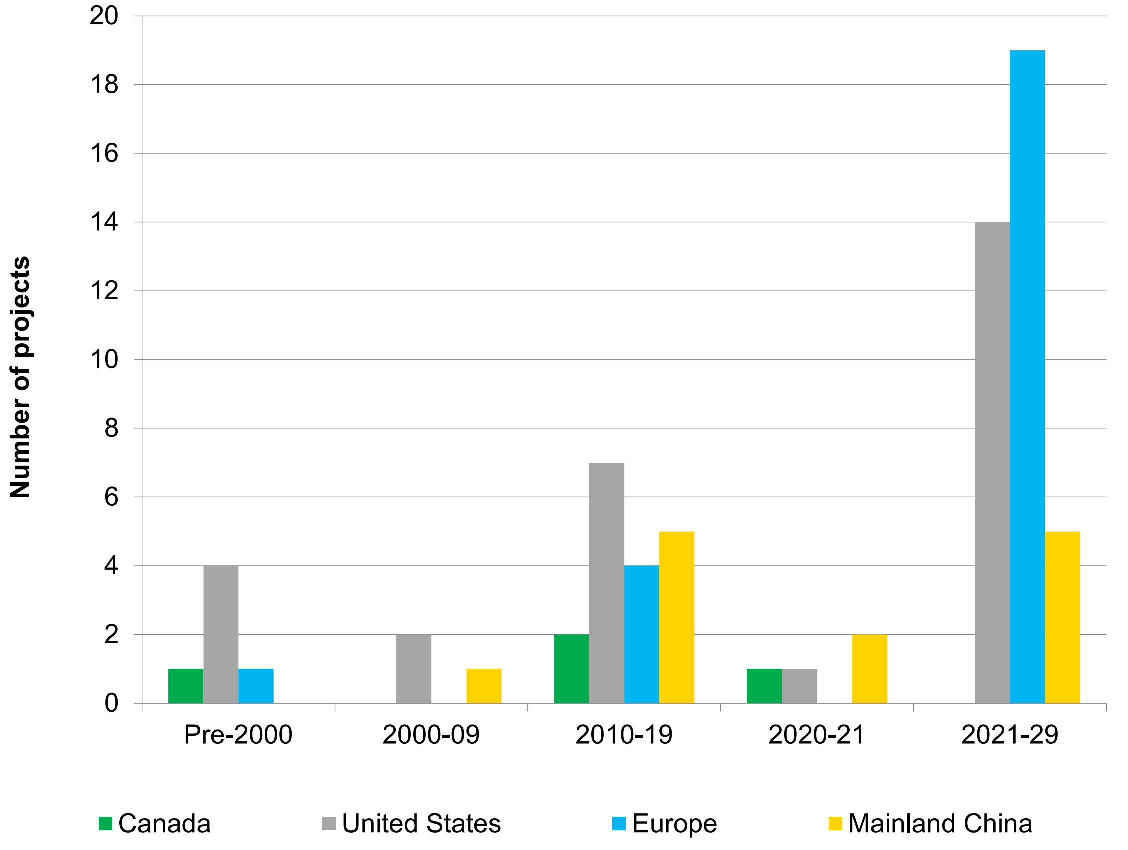
High-level development timeline—CCS project example



Source: Clean Air Task Force; CCS Knowledge Centre

Other nations have begun to overtake Canada’s early leadership in CCS

CCS/CCUS projects by completion or expected completion date



Note: Does not include pilot projects.
Source: IHS Markit

- The Canadian government, as well as provincial governments in Alberta and Saskatchewan, have provided grant funding for major operating CCS/CCUS projects
- The United States has been leading in terms of CCS projects, in large part thanks to an established tax credit for CCS (45Q)
- Norway, the United Kingdom, and the Netherlands have provided state support to CCS projects.
  - Norway is a regional leader in terms of CCS deployment, with a US$1.8 billion investment in Northern Lights CCS Project
  - In the United Kingdom, the government has made available US$190 million for CCS research programs and pilot projects
    - However, development lags due to frequent policy shifts, contract cancellations, and potential UK exit of ETS (post-Brexit)
  - Netherlands follows next with Porthos and Athos full-scale CCS projects and SOEs3 have played a major role
- CCS will be needed to support mainland China’s recent commitment to a carbon-neutral future by 2060 and it’s actively developing CCS capacity with seven of eight CCS projects being in construction or planning phase.

Scaled CCS projects deployment will incentivize breakthroughs that will lower future costs and encourage technology breakthroughs

CCS/CCUS technology development activity and cost reduction opportunities

	CO_2 capture				CO_2 transport	CO_2 sequestration and utilization	
	Absorption	Adsorption	Membrane	Cryogenic	Hub development	Storing CO_2 in products	Use of CO_2 as feedstock
Key technologies and reduction drivers	Reduce regeneration energy load	Increase of capture capacity	Increase of separation efficiency	Reduction of cooling load	Leveraging economies of scale via common infrastructure, government guarantees, and minimizing the time between infrastructure construction and full utilization.	Improvement of chemical processes	Reduction of processes' energy intensity
Example activities	New solvent chemistries New regeneration methods	New sorbent materials More efficient reactor designs	New membrane materials Optimize membrane unit configurations	Synergies with other processes or technologies (e.g., renewables) Process intensification		Replacing carbon-intensive products with low carbon alternatives	Use of CO_2 as the feedstock for production of hydrocarbons and petrochemicals

Source: IHS Markit

Unaddressed economic and non-economic barriers can stall deployment of CCS and H_2 projects

Framework for barriers for emission reduction

Economic

Financial and commercial: Barriers to financing or commercializing an emission reduction pathway. For example: capex constraints, contractual terms, low commodity prices, lack of financing partners, risk perception

Fiscal regime and regulatory: A government-imposed policy barrier to achieving emission reductions. Barriers could include the following: O&G fiscal terms, environmental policy, domestic power tariffs, etc.

Technology: A technological barrier to emission reduction (i.e., technology availability, technology maturity)

Non-economic

Institutional capacity: The ability of government to develop and implement policy and regulation (i.e., ability to enforce regulation, ability to uphold contracts, ability to prevent corruption)

Competing corporate incentives: Misalignment within companies (e.g., corporate management and business unit decision-making) or between companies (e.g., transport and storage guarantees; competitive behavior prohibiting sharing that would be beneficial to NPV and emissions reduction)

Source: IHS Markit

Special thanks

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- Clean Energy Technology
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