CHAPTER 6

ACCELERATING CCUS

A diverse commercial CCUS industry has begun to emerge in the PCOR Partnership region. Using a variety of business models, the active commercial CCUS projects are integrating private investment with federal and state incentives such as the 45Q tax and LCFS programs. Further CCUS deployment in the PCOR Partnership region will build on the current commercial activity and be accelerated by facilitating development of projects currently in the planning stages, supporting regional infrastructure, and investigating and addressing remaining barriers to widespread CCUS adoption.

CHALLENGES TO CCUS DEPLOYMENT

To accelerate commercial deployment of CCUS across the PCOR Partnership region, CCUS must be widely accepted as a suite of trusted, economical, and conventional technologies that are part of the overall carbon management solution. For this to happen, several challenges need to be addressed.

REGULATIONS AND PERMITTING – Although much has happened in the regulatory world of CCUS (e.g., states getting primacy, states establishing pore space ownership rulings, etc.), regulatory and permitting uncertainties (i.e., compliance risks) remain a challenge to accelerating CCUS deployment. Ongoing efforts to permit CCUS projects in states with and without Class VI primacy will clarify the permitting process and establish the needed pathways to receive all necessary project approvals.

LONG-TERM LIABILITY – The project operator usually has primary responsibility for the CO_2 storage project during the injection phase. However, monitoring and remediation responsibilities may vary in the postinjection (postclosure) period (many decades). The uncertainty in the scale and duration of postinjection responsibility may make some CCUS project developers wary.

ECONOMICS – For companies to deploy CCUS technologies, they will bear costs associated with carbon capture, transportation, and storage. Companies need to understand the existing regulatory environment and tax and other incentive programs well enough to see prospective CCUS deployment as being profitable over the long term, thus justifying the investment and acceptance of any risk.

TECHNOLOGY PROOF OF CONCEPT – Although several commercial-scale CCUS projects are in place, operational experience with CCUS technologies in real-world conditions is still greatly needed. Each large-scale carbon capture project that is successful leads to the next level of understanding and improvements in capture, transport and storage technology, and permitting.

INFRASTRUCTURE DEVELOPMENT – Most of the large-scale CO_2 sources in the PCOR Partnership region are not near large CO_2 storage opportunities. Increasing the adoption of CCUS will entail cost-efficient means of moving captured CO_2 to areas with ideal geologic storage opportunities. Large-scale deployment of CCUS will require a marked increase in commitment by both government and industry to plan and build the needed CO_2 transportation infrastructure.

RAMPING UP CCUS DEPLOYMENT

Looking ahead, the PCOR Partnership plans to support CCUS deployment across the region through the following activities:

1. Build upon assessments of regional storage data to verify the ability of target formations to store CO_2.

2. Facilitate the development of the infrastructure required to transport CO_2 from the source to the injection site.

3. Facilitate the development of the rapidly evolving North American regulatory and permitting framework for CO_2 storage.

4. Identify opportunities for CCUS, and support development of projects by PCOR Partnership partners.

5. Continue collaboration with the other RCSP Program partnerships.

6. Provide outreach and education for CO_2 storage stakeholders and the general public.

Through these efforts, the PCOR Partnership will help CCUS projects overcome key challenges, including cost-effective capture of CO_2, through successful integration with fossil fuel conversion systems. Advances in CCUS technology and project deployment will allow continued access to safe, reliable, and affordable energy.

REGULATION

CCUS policy is taking a prominent position in the climate management debate occurring at national, regional, and local levels, and the legal framework for the geologic storage of CO_2 continues to evolve.

In areas where extensive oil and gas production activities have taken place (in particular, EOR or acid gas injection), the regulatory framework is well established for these types of injection activities. In other jurisdictions, less of the regulatory framework may be in place for geologic storage of CO_2. Government organizations—which vary by jurisdiction—may have oversight for various aspects of the CCUS project, including the permitting, construction, health and safety, liability, protection of water supplies, and monitoring. EPA has promulgated rules for various aspects of carbon management and reporting; many states are moving forward with their own rules and regulations to accommodate CCUS projects.

Because of the evolving nature of regulatory frameworks at various levels of government, this atlas provides general overviews of select rules and policies currently under debate; this atlas can be considered up to date as of June 2021, unless otherwise noted.

To facilitate the exchange of information, ideas, and experiences among oil and gas regulatory officials, the PCOR Partnership hosts Regulatory Roundup Meetings. The meetings inform regional regulatory officials about the current status and evolving nature of regulations that affect CO_2 capture, compression, transport, injection for CO_2 storage, or CO_2 EOR. These meetings allow for improved coordination of regulatory strategies that will ultimately enhance opportunities for CO_2 storage and CO_2 EOR in the region.

PRIMACY

EPA creates minimum regulations, and the Safe Drinking Water Act (SDWA) establishes a process for U.S. states to apply to EPA for the authority to regulate underground injection. This is known as primary enforcement authority, or “primacy.” When a state demonstrates to EPA that it has established an appropriate level of statutory authority and administrative regulations, EPA grants the state primacy. Under the UIC (underground injection control) Program, primacy is distinguished by individual injection well classifications.

In the PCOR Partnership region, North Dakota and Wyoming both have received Class VI primacy. If state primacy has not been established, the EPA regional office enforces the federal UIC Program regulations.

UNDERGROUND INJECTION CONTROL PROGRAM

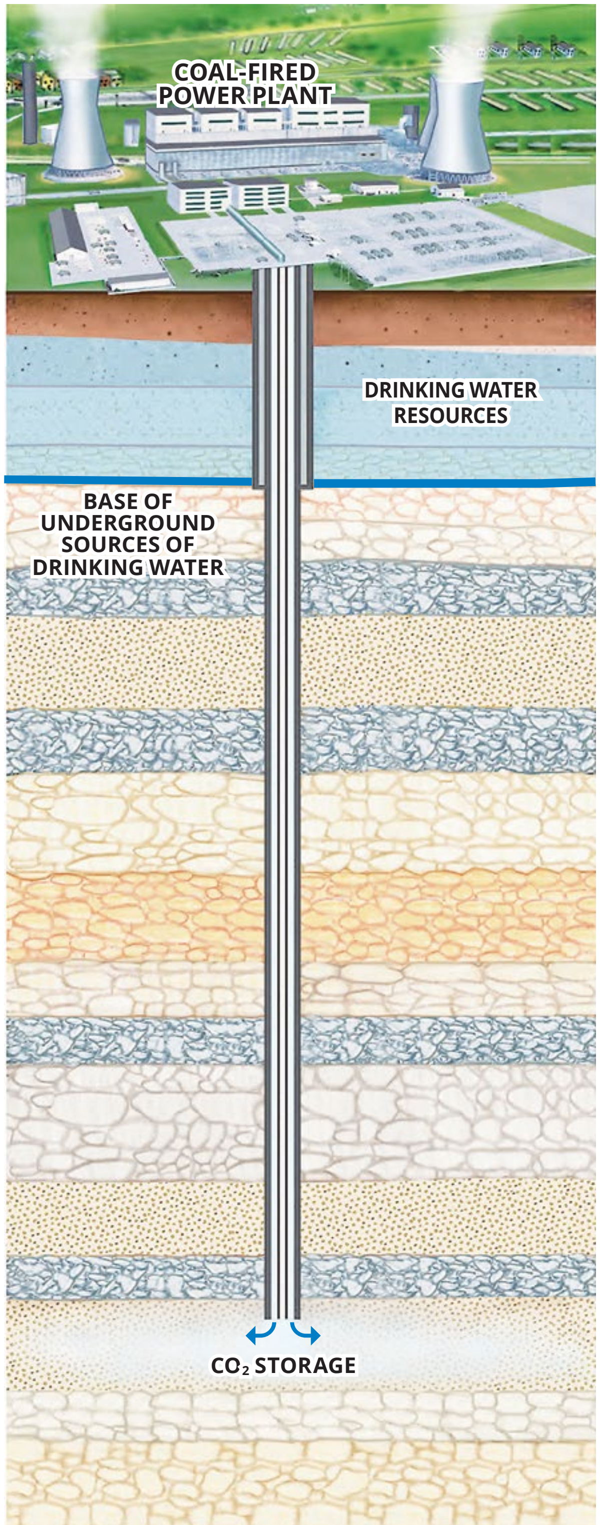
Regulations for CO_2 injection are established under the SDWA UIC Program. The UIC Program is a U.S. federal regulatory program administered by EPA and designed to protect USDWs.

In December 2010, EPA published the federal requirements for Class VI wells, which are wells used to inject CO_2 for the sole purpose of geologic storage. Class VI wells have specific criteria in place to protect USDWs. These criteria include requirements for extensive site characterization, well construction, well operation, comprehensive monitoring, financial responsibility, and reporting. EPA acknowledges that CO_2 EOR does store CO_2 while producing oil during EOR operations and that CO_2 injection under Class II rules can recognize the incidentally stored volume.

Class II wells are used only to inject fluids associated with oil and natural gas production. A Class II well can either be used for disposal purposes to inject waste fluids associated with oil and gas production or to enhance oil and gas recovery. Injection of CO_2 for EOR is regulated and permitted as a Class II injection well.

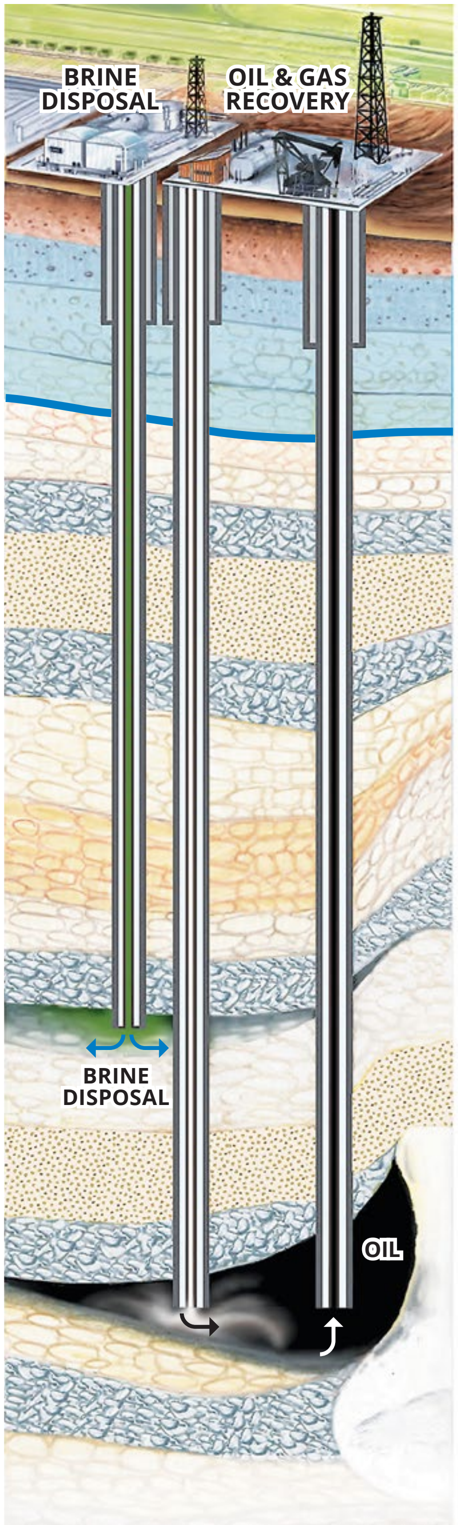
CLASS VI WELLS

Inject CO_2 for Long-Term Storage to Reduce Emissions to Atmosphere

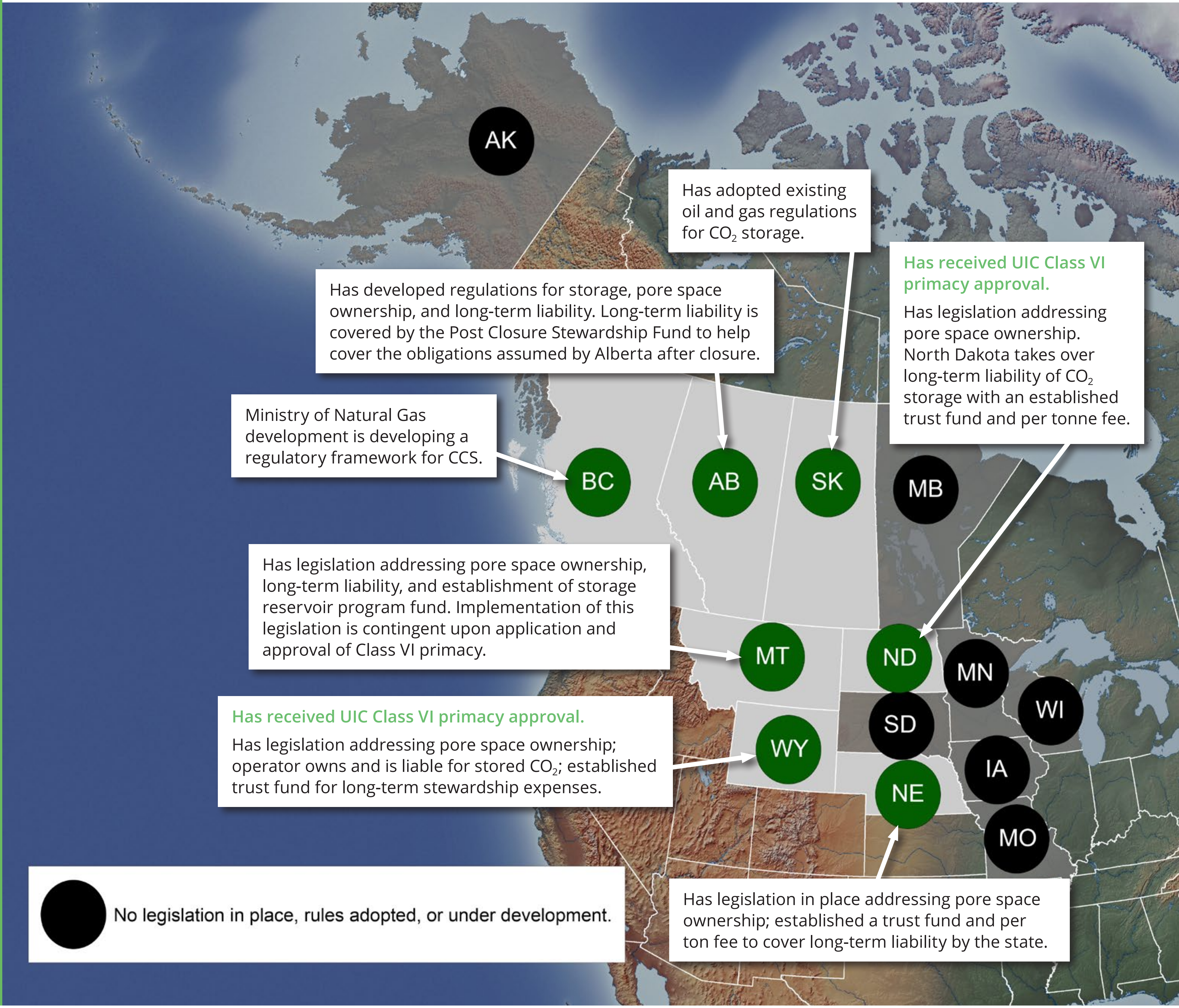


CLASS II WELLS

Inject Oil and Gas Production Fluids



REGULATORY STATUS



PORE SPACE

Pore space can be defined as “the free space between the mineral grains of a geologic formation” or “a cavity or void, whether natural or artificially created, in a subsurface sedimentary stratum.” In either case, the cavity or space is filled with some type of fluid prior to injection: typically oil and brine in an oil field or just brine in a DSF. During CO_2 injection, the injected CO_2 displaces most of the fluid originally in the pore spaces. When developing CO_2 storage projects, project developers need to ensure they have rights to the necessary pore space in a prospective storage formation.

In many countries, subsurface pore space is owned by the federal government. In the United States, only a handful of states have clarified pore space ownership: North Dakota, Wyoming, Nebraska, and Montana. To access the pore space needed to store CO_2, the CO_2 storage operator must pursue pore space access agreements with the parties that own the pore space. These agreements involve negotiations surrounding the value of the pore space. This value likely translates into payment terms of $/tonne/unit of land. Forced unitization (or amalgamation) of pore space is permitted in some states. In this case, if some percentage of owners agree (e.g., 60%–80%), the remaining owners can be required to participate with equitable compensation. This approach is very similar to the unitization process used in the oil and gas industry. Until there is a broader adoption of defined pore space management policy, pore space access will remain an obstacle to widespread CCUS implementation.

LONG-TERM LIABILITY

Long-term liability is broadly recognized as a significant challenge to widespread deployment of CCUS. During and immediately after the active injection phase, it is generally understood that the injection operator carries the liability for items such as personal injury, subsurface trespass, mitigation of leaks, etc. The main challenge is determining the appropriate policy framework to manage CCUS sites after closure. The time frame for geologic storage site management could extend for many decades beyond site closure. Without a clear understanding of if and how the long-term liability can be transferred to local or federal government, investment risk to initiate a CO_2 storage project will remain high. North Dakota, Montana, Nebraska, and Alberta have established mechanisms to transfer long-term liability to the state/province. These policies are the foundation for expanding this concept to additional states and provinces.

45Q TAX CREDIT

First enacted in October of 2008, Section 45Q of the U.S. tax code provides a performance-based tax credit for carbon capture projects and is intended to promote investment in CCUS implementation. To boost response to the 45Q tax credit program and broaden eligibility to other industries, the 2018 Bipartisan Budget Act reformed the tax credit program. The revised 45Q reduced the cost and risk to private capital of investing in the deployment of carbon capture technology across a range of industries.

Tax credit can be claimed when an eligible project has:

- Securely stored the captured CO_2 in geologic formations, such as oil fields and saline formations.
- Beneficially used captured CO_2 or its precursor carbon monoxide (CO) as a feedstock to produce fuels, chemicals, and products such as concrete in a way that results in emission reductions as defined by federal requirements.

Generally, the 45Q tax credit is claimed by the taxpayer that:

- Owns the carbon capture equipment.
- Physically or contractually ensures the capture and disposal, injection, or utilization of the carbon dioxide.

The owner of the carbon capture equipment does not need to own the industrial facility where the equipment is located to qualify for 45Q tax credits. The tax credits may also be transferred from the owner of the carbon capture equipment to another party that disposes of, injects, or uses the carbon dioxide.

	2008–2018	2018–Today
Constraint	Ends after collective 75 million tonnes claimed	Commence construction by January 1, 2026
Duration to Claim Credit	No limit	12 years
Minimum Capture Target (tonnes)	500,000	Power: 500,000 Industrial: 100,000 Direct air capture: 100,000 Small power/industrial: 25,000
Credit Value ($/tonne)	Saline storage: $20 Via EOR: $10	Saline storage: up to $50 Via EOR and other utilization: up to $35
Eligibility	Power, industrial	Power, industrial, direct air capture

In additional to federal tax incentives, states have taken the initiative to incentivize CCUS projects. For example, North Dakota eliminates sales tax on all capture-related equipment, CO_2 sold for EOR, pipeline construction, and CO_2 EOR infrastructure. In addition, North Dakota reduces the coal conversion tax when CO_2 is captured, allows for a 10-year property tax exemption on pipeline equipment, and eliminates oil and gas extraction tax for 20 years during tertiary CO_2 EOR. Wyoming has established tax incentives to spur CO_2 utilization. The state eliminates tax on the sale of CO_2 used in tertiary CO_2 EOR and allows for a severance tax credit when oil is produced from CO_2 injection. Montana offers a reduced market value property tax rate for carbon sequestration equipment. A notable law in Montana requires that all new coal plants capture and sequester at least 50% of their CO_2 emissions.

State	2008–2018
North Dakota	Sales and use tax exemption Property tax exemption Gross receipts tax reduction
Wyoming	Sales tax exemption Severance tax credit
Montana	Reduced property tax

North Dakota, Wyoming, and Montana offer a variety of tax incentives for projects involving CCUS.[56]

45Q Globally, the most progressive CCUS-specific incentive.[57]

Recent Actions

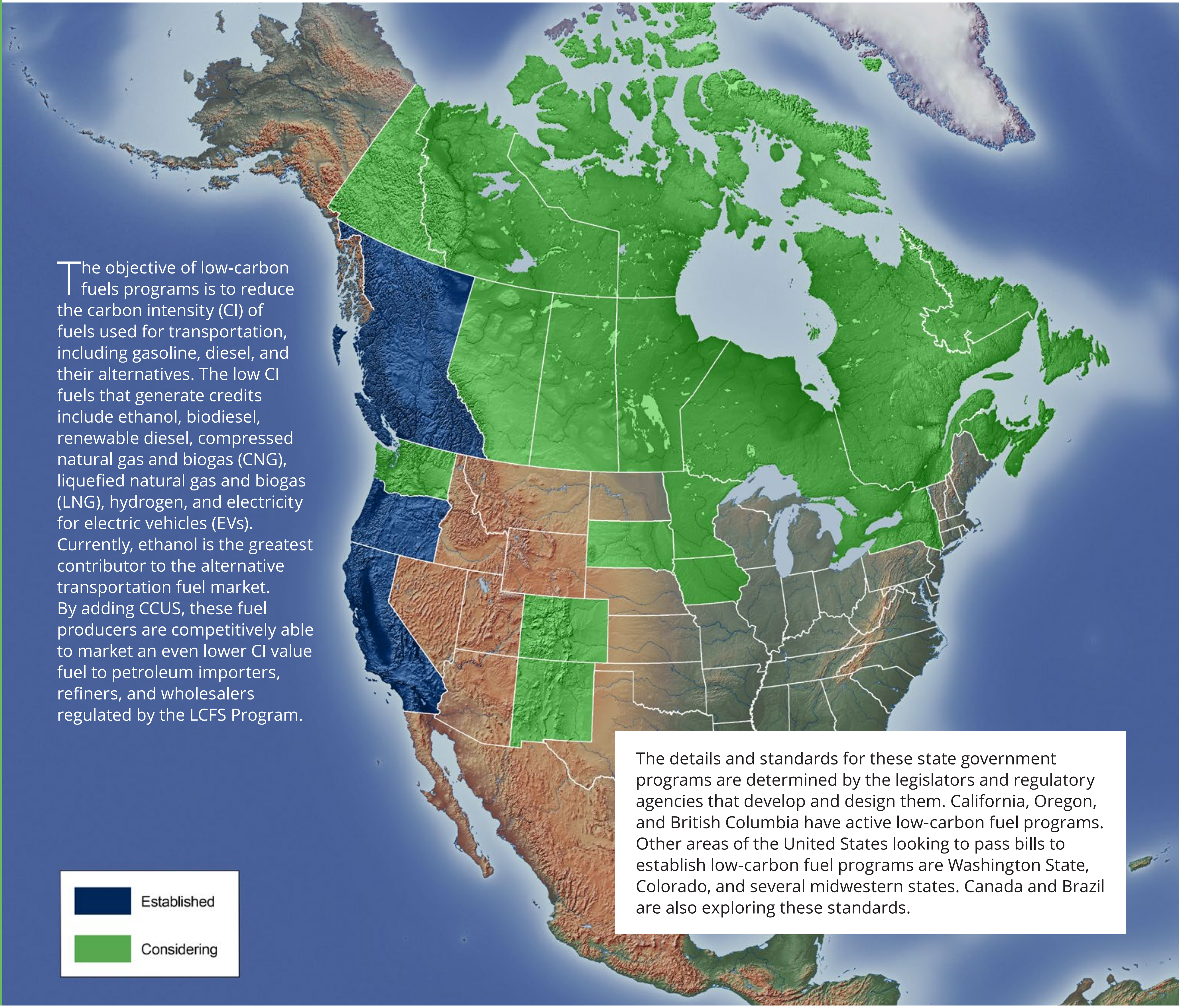
February 2020 Treasury Department provides clarification on “beginning of construction” and revenue procedure.

May 2020 Internal Revenue Service proposes regulation for 45Q. Also provides clarification on “secure geologic storage,” transfer of credit, recapture of credit, and LCA.

December 2020 Congress approves 2-year extension of 45Q tax credit. Construction must start by January 1, 2026.

January 2021 Treasury Department releases final 45Q tax credit regulation.

LOW-CARBON FUEL MARKETS



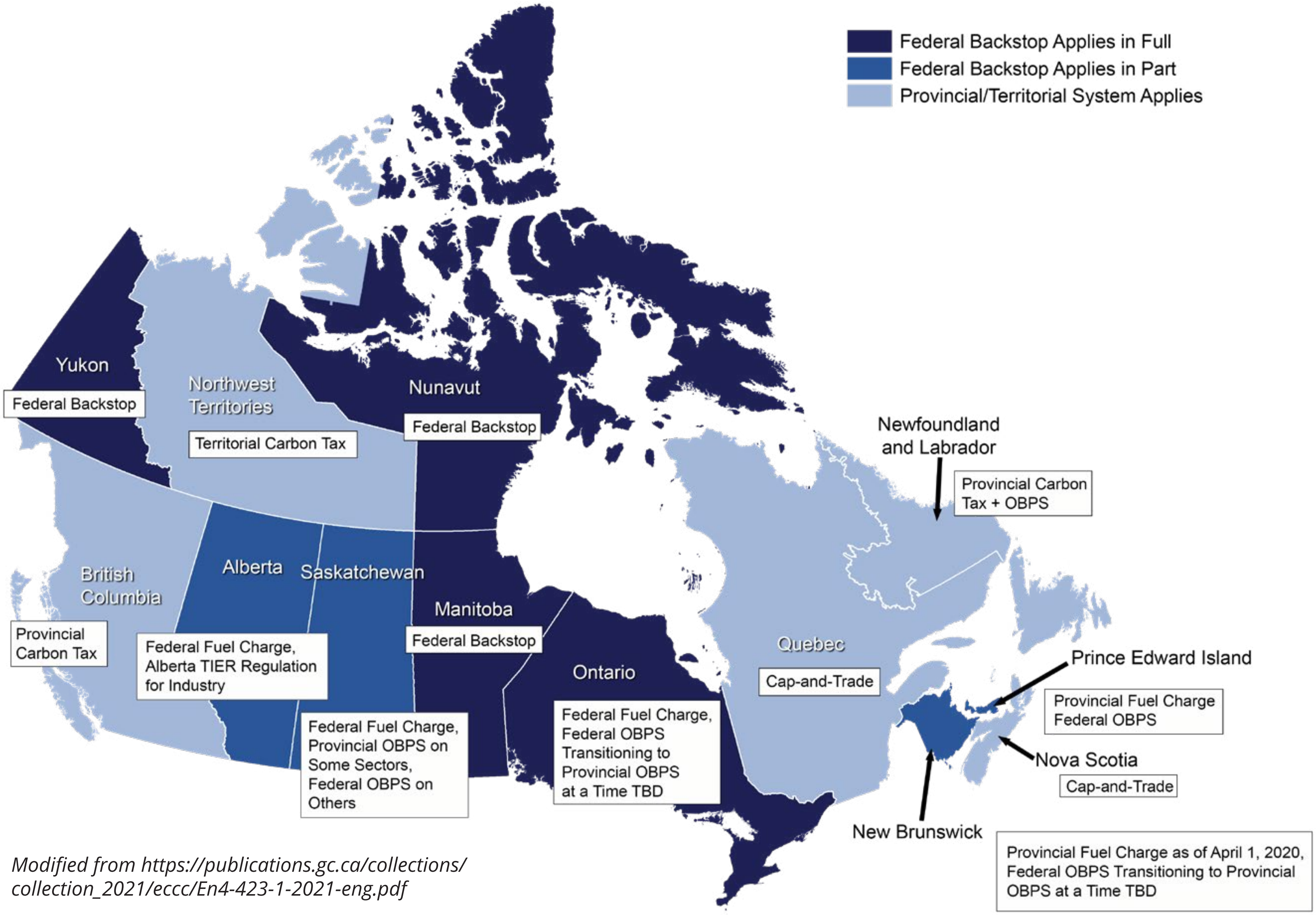
The objective of low-carbon fuels programs is to reduce the carbon intensity (CI) of fuels used for transportation, including gasoline, diesel, and their alternatives. The low CI fuels that generate credits include ethanol, biodiesel, renewable diesel, compressed natural gas and biogas (CNG), liquefied natural gas and biogas (LNG), hydrogen, and electricity for electric vehicles (EVs). Currently, ethanol is the greatest contributor to the alternative transportation fuel market. By adding CCUS, these fuel producers are competitively able to market an even lower CI value fuel to petroleum importers, refiners, and wholesalers regulated by the LCFS Program.

The details and standards for these state government programs are determined by the legislators and regulatory agencies that develop and design them. California, Oregon, and British Columbia have active low-carbon fuel programs. Other areas of the United States looking to pass bills to establish low-carbon fuel programs are Washington State, Colorado, and several midwestern states. Canada and Brazil are also exploring these standards.

CANADIAN INCENTIVES

In its 2021 budget, the Canadian federal government proposed to introduce an investment tax credit for capital invested in CCUS projects, with the goal of reducing CO_2 emissions by at least 15 Mt annually. The investment tax credit, the Output-Based Pricing System (OBPS), will be available to multiple industrial sectors, including cement, refining, power generation, hydrogen generation, and direct air capture. The tax credit is not intended for CO_2 EOR projects. The proposed legislation would come into effect in 2022.[58,59]

In October 2016, the Canadian Prime Minister announced the Pan-Canadian Approach to Pricing Carbon Pollution, which gave provinces and territories the flexibility to develop their own carbon pollution pricing system along with guidance to ensure the systems are stringent, fair, and efficient. The Canadian federal government also committed to implementing a federal carbon pollution pricing system in provinces and territories that request it or do not have a carbon pollution pricing system that meets the federal benchmark, a "federal backstop." As of 2021, the federal carbon price was Can$30/tonne and will increase to Can$170/tonne by 2030. All direct proceeds from carbon pollution pricing under the Canadian federal system will be returned to the jurisdiction in which they were generated.



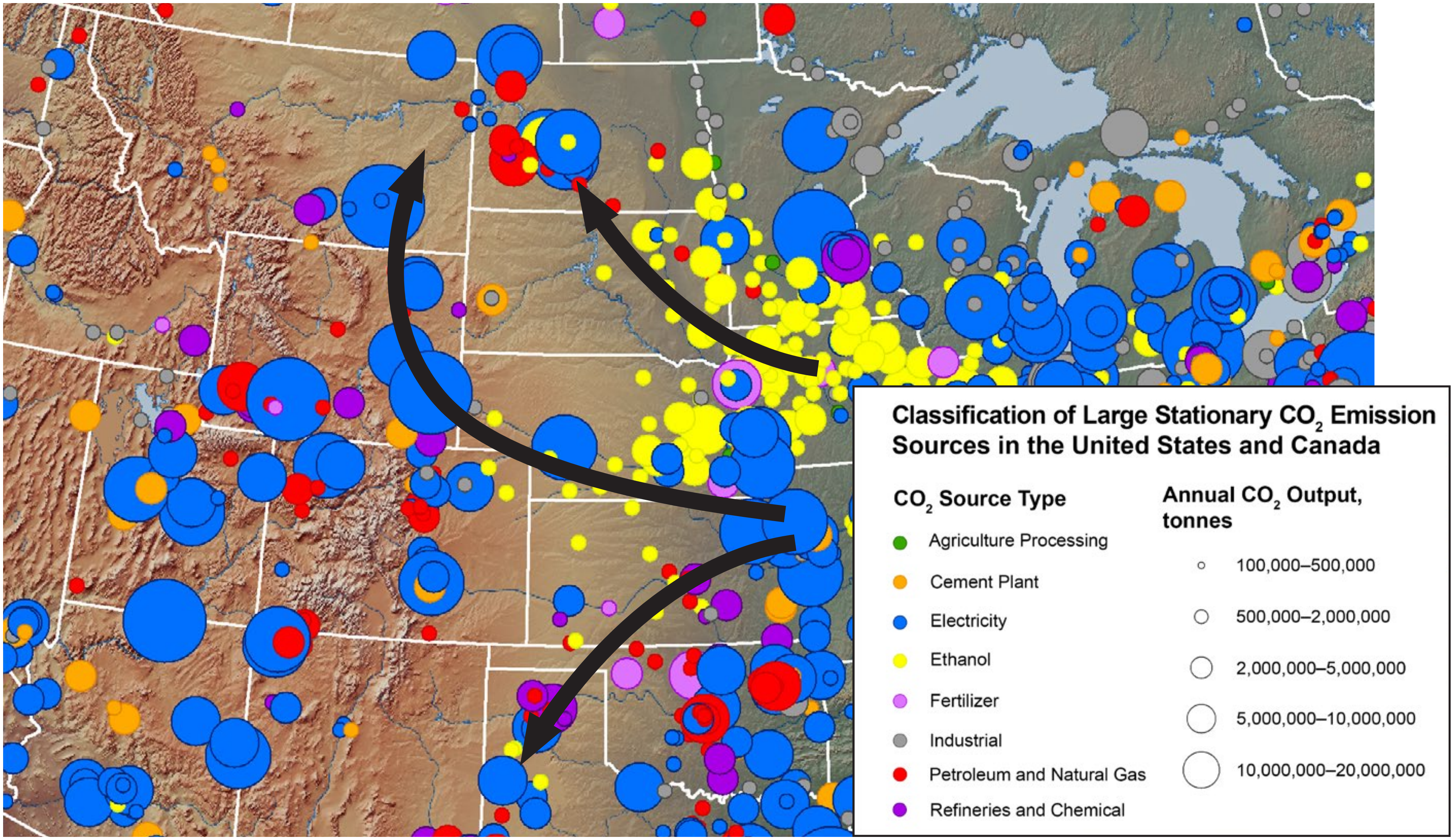
Modified from https://publications.gc.ca/collections/collection_2021/eccc/En4-423-1-2021-eng.pdf

INFRASTRUCTURE

The United States currently has the world's most extensive CO_2 pipeline network; however, more infrastructure is needed to enable widespread deployment of CCUS in the United States. For example, most of the large-scale CO_2 sources in the PCOR Partnership region are not near large CO_2 storage opportunities. Increasing the adoption of CCUS in the PCOR Partnership region will require cost-efficient means of moving captured CO_2 to areas with ideal geologic storage opportunities. Without the transport piece of the puzzle, there is little incentive to pursue the capture piece.

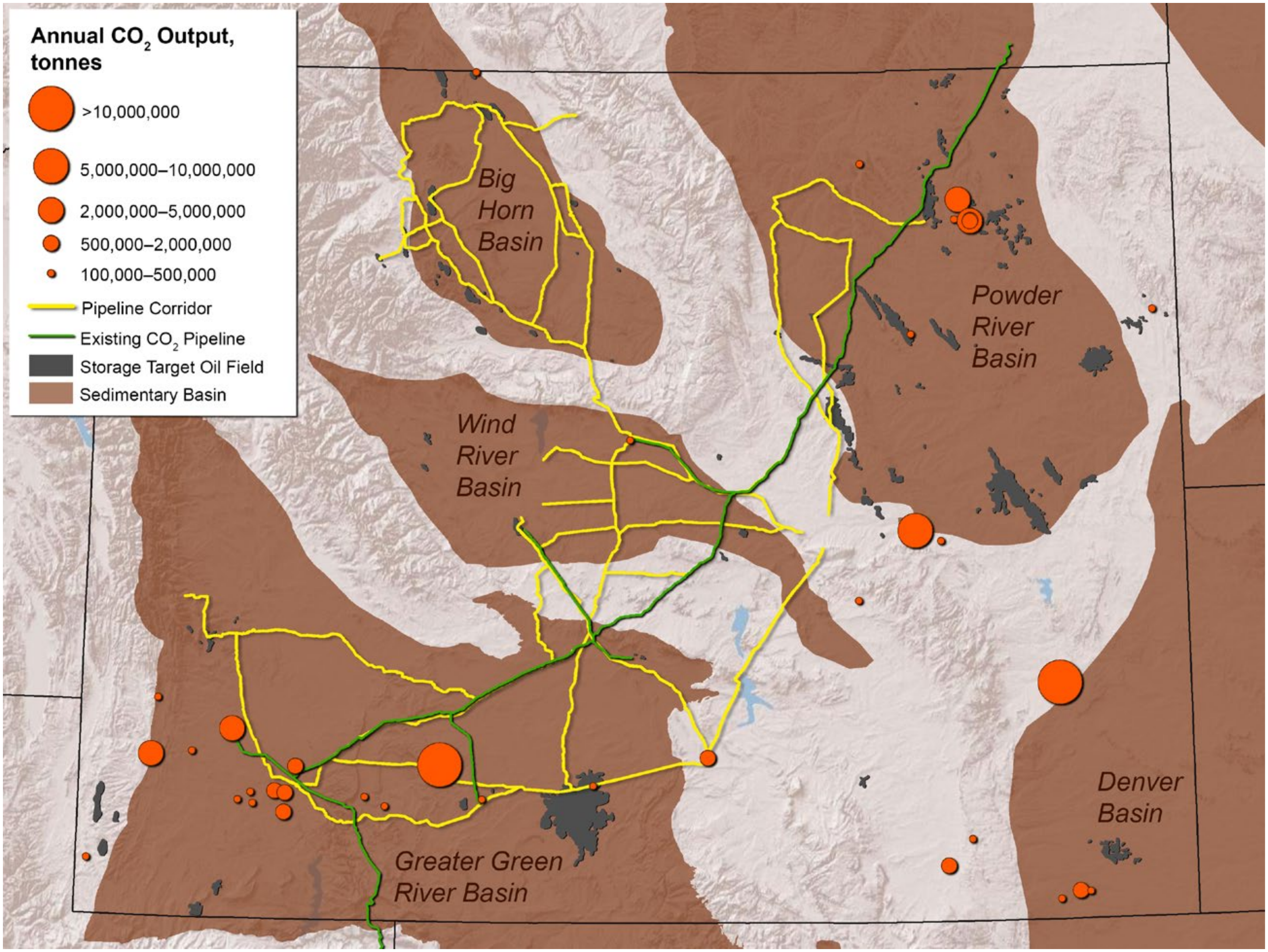
Instead of constructing many new point-to-point pipelines, a more strategic approach using prescribed trunk lines and connector pipelines would be economically advantageous for efficiently enabling widespread commercial CCUS deployment. For example, the ACTL, which had strong Canadian government infrastructure support, was designed for future expansion of CCUS. The 240-km pipeline has nearly 90% of its capacity available to accommodate future CO_2 sources. Two newly planned projects in the PCOR Partnership region involve the development of industrial CCUS hubs with shared CO_2 transport and storage infrastructure.[60,61] The development of additional shared infrastructure such as pipelines can be a strong incentive to trigger new investments.

Hypothetical CO_2 Truck Line Routes



WYOMING PIPELINE CORRIDOR INITIATIVE

A notable example of facilitating infrastructure development in the PCOR Partnership region is the Wyoming Pipeline Corridor Initiative (WPCI). WPCI was formed to promote the development of a network of CO_2 pipelines throughout Wyoming for transportation of CO_2 from emission sources (such as power plants) to suitable storage locations or for other uses (such as EOR). Under the leadership of Wyoming's Governor's Office and in collaboration with researchers, industries, and other state agencies, WPCI proposes pipeline routes that would cover almost 2000 miles and cross federal, state, and private lands in central and eastern Wyoming. More than half of the proposed corridors are through Bureau of Land Management (BLM) land, and in January 2021, BLM approved the WPCI proposal to designate over 1000 miles to the pipeline network. This approval is expected to accelerate the development of pipeline projects by reducing the time and cost of permitting.



THE BUSINESS CASE FOR CCUS

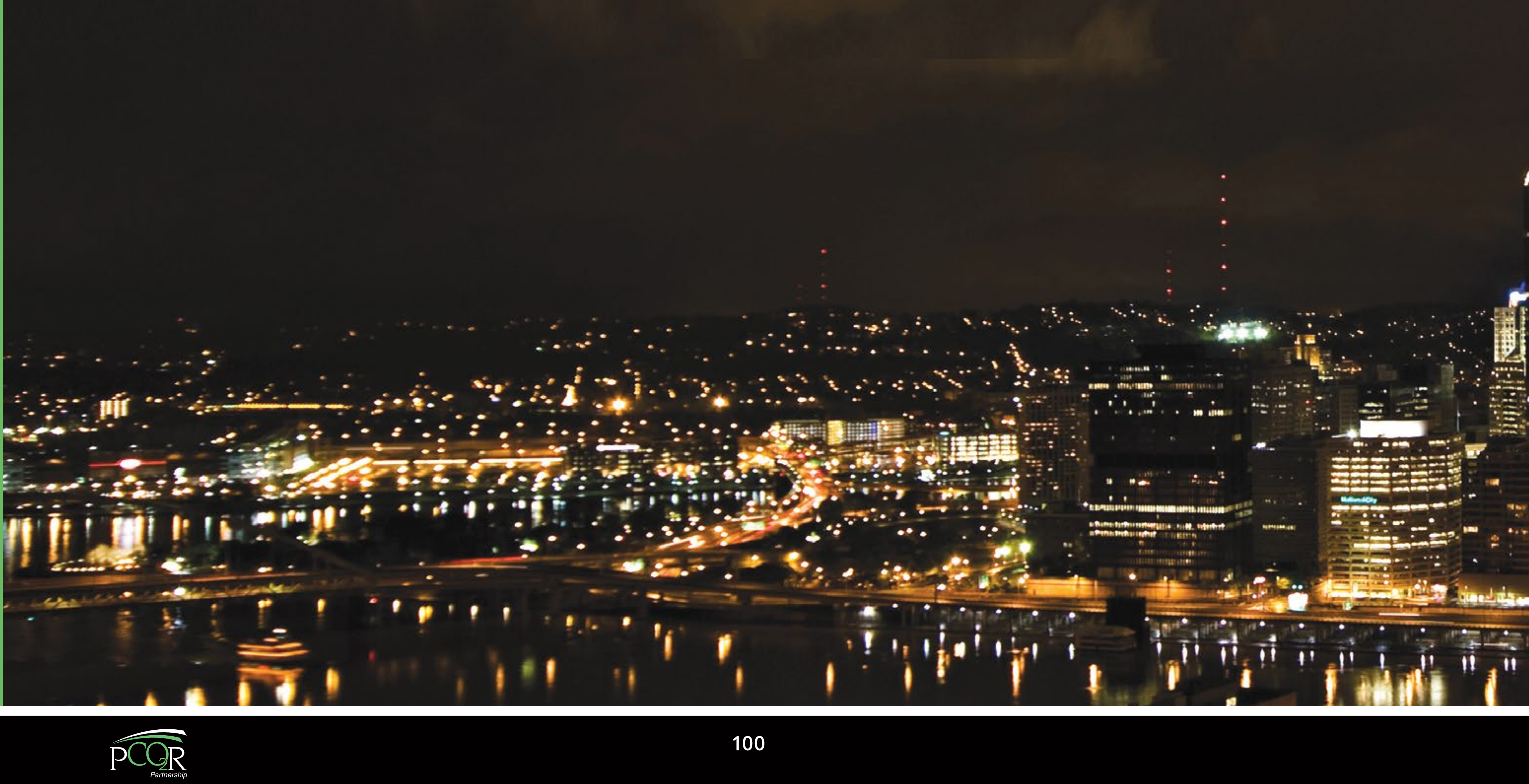
Whether from a capture-ready nearly pure CO_2 source associated with an ethanol plant or from the retrofit of an 800-MW coal-fired power plant, implementing CCUS is an expensive endeavor. For an industry to move forward with a CCUS project, an appropriate business model must be adopted.

Selling captured CO_2 as a commodity is the easiest business model if the buyer and seller can reach an agreement on the CO_2 sale price and a long-term contract. This type of arrangement defines a traditional CO_2 EOR situation.

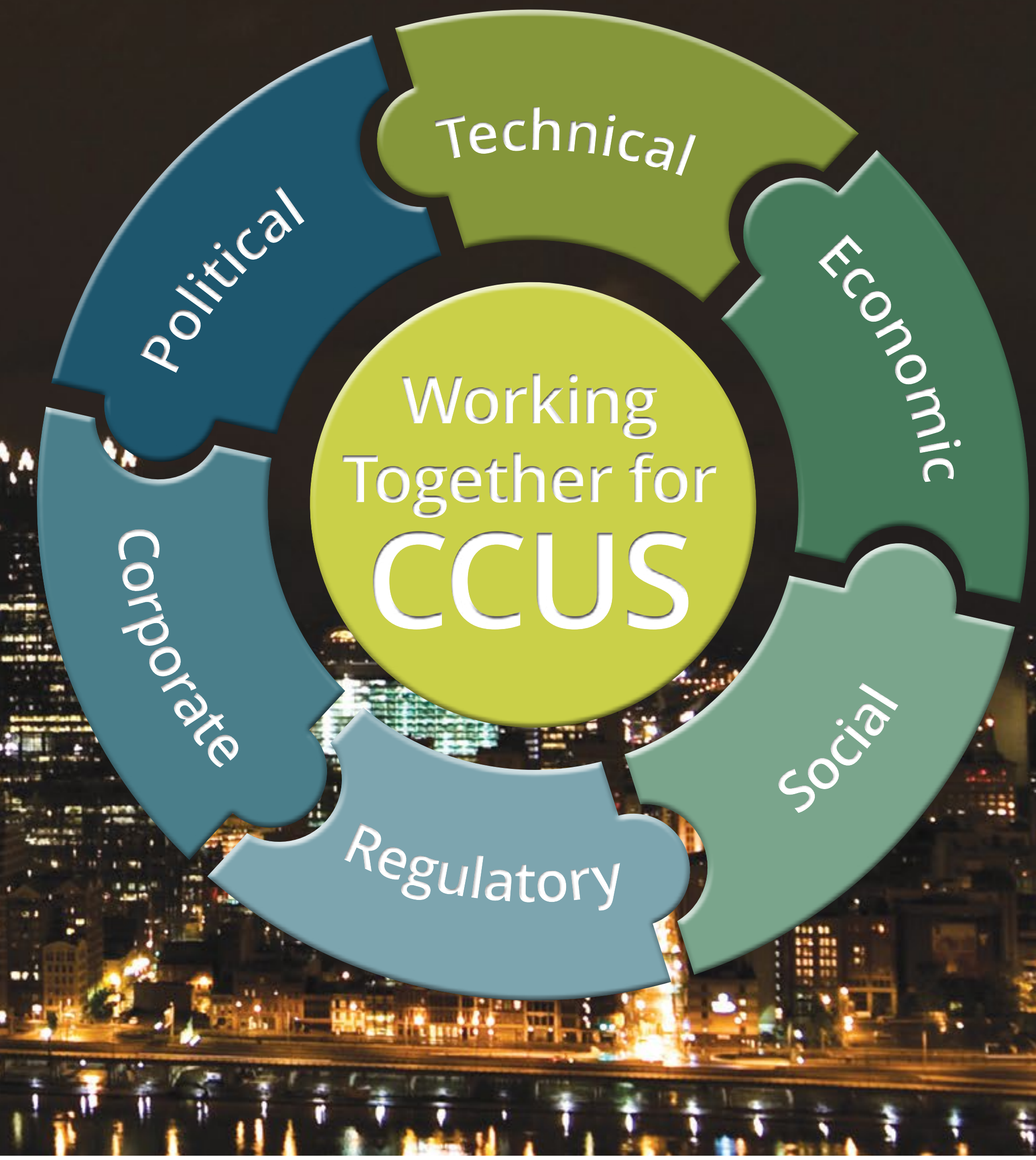
Without market price for the CO_2 and an amicable buyer–seller relationship, alternative business cases are required. To incentivize CCUS where a market does not exist, the U.S. government has established a tax credit program for storing CO_2. The value of these tax credits provides the business case to move forward with CCUS projects to offset the cost of implementation. Canada has recently proposed an investment tax credit for capital invested in CCUS projects, with the goal of reducing emissions by at least 15 Mt of CO_2 annually.

Some CCUS projects, like those associated with ethanol plants, can bolster their business case by capitalizing on increased commodity values (more $ per gallon of ethanol). Leveraging carbon markets, like the LCFS established in California, can provide direct financial gain to an ethanol company implementing CCUS. The projects may be able to stack the financial benefits of increased commodity prices and the tax credits gained from the U.S. government. This combination is the driver for recently announced large-scale gathering and transport of CO_2 from ethanol plants in the United States.

The Canadian federal government has put a tax on CO_2 emissions (currently Can$30/tonne). Under this situation, there may be financial benefit to capture and store the CO_2 rather than pay the tax. This potential financial benefit would be the business case for CCUS.



CCUS can play a vital role in reducing atmospheric CO_2 levels while simultaneously preserving the option of using abundant and low-cost domestic fossil energy resources. However, the scale of CCUS deployment needed to result in significant reductions will require thousands of CCUS deployments around the world over the next 3–4 decades. The expansion of a new technology at that rate is challenging but achievable, particularly when the technology becomes routine and impediments are mitigated. Research, development, and demonstration (RD&D) programs such as those currently conducted by DOE's RCSP Program are critical for demonstrating CO_2 storage in diverse geologic settings and will establish the basis for CCUS's widespread global deployment.



ENVIRONMENTAL, SOCIAL, AND CORPORATE GOVERNANCE AND CCUS

Environmental, social, and corporate governance (ESG) are intangible factors relating to the sustainability and ethical impact of investments. Approach, assessment, and reporting of ESG factors are growing considerations for investors, shareholders, and the public who seek greater levels of transparency to evaluate risk exposure. An increasingly central aspect of many ESG assessment and rating schemes is a corporation's exposure to climate change-related risks.

Despite broad awareness of the potential for CCUS within the investment and rating communities, substantial uncertainty remains regarding its more widespread deployment. As such, CCUS is undervalued in its potential for improving a company's ESG performance.[62] Perhaps as CCUS matures, it will have a more positive impact upon ESG ratings. In the near term, ESG factors can play a contributing role in the development of commercial CCUS projects that are founded on more robust business cases.

ENGAGING THE PUBLIC

Public awareness and support are critical to the development of new energy technologies and are widely viewed as vital for CCUS projects. CCUS remains an unfamiliar technology to many members of the public, and local opposition to specific project proposals can be significant in some cases. However, enhanced and coordinated public outreach is improving awareness of the role of CCUS as one option to reduce GHG emissions.

Developing public support for CCUS is an essential component of any potential CCUS project. To that end, the PCOR Partnership is working to increase CCUS knowledge among the general public, regulatory agencies, policy makers, and industry.

Educational Workshops

Media Relations

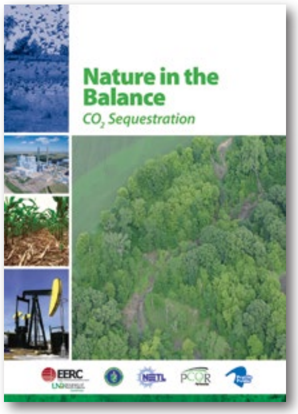
Landowner/ Stakeholder Relations

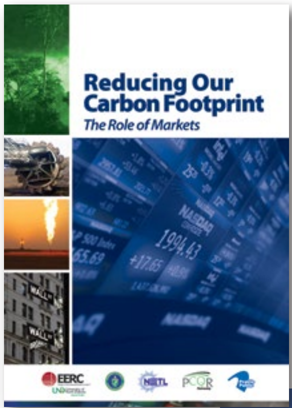
TAKE IT ON THE ROAD

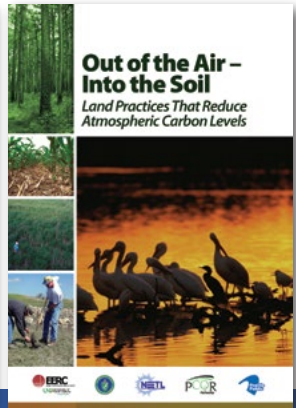
Engaging the public, policy makers, and industry on CCUS remains an essential component of PCOR Partnership activities. This is done through presentations and participation at meetings and public and industry events throughout the region.

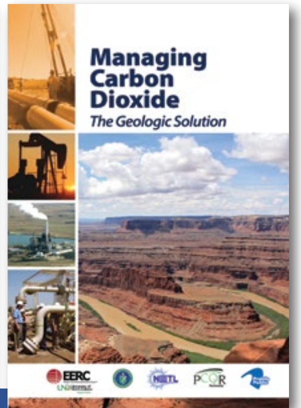
TAKE IT TO PRIME TIME

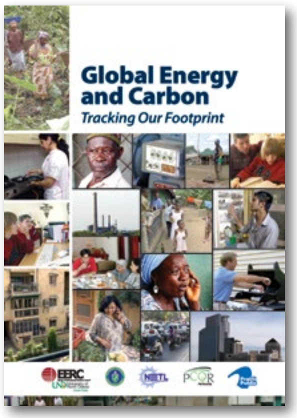
The PCOR Partnership continues its long-standing collaboration with Prairie Public Broadcasting to provide educational activities and documentary productions.



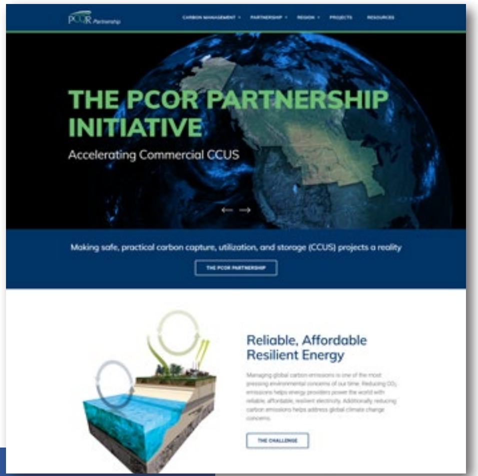




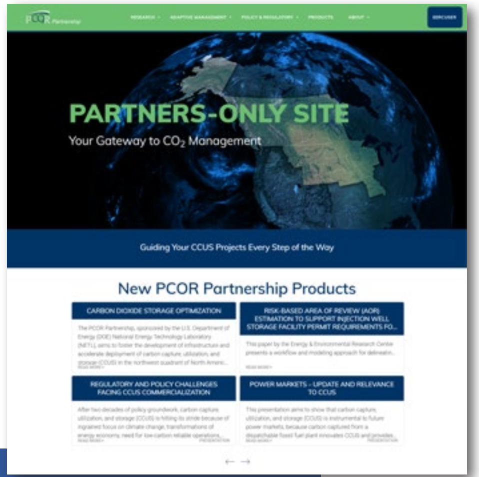




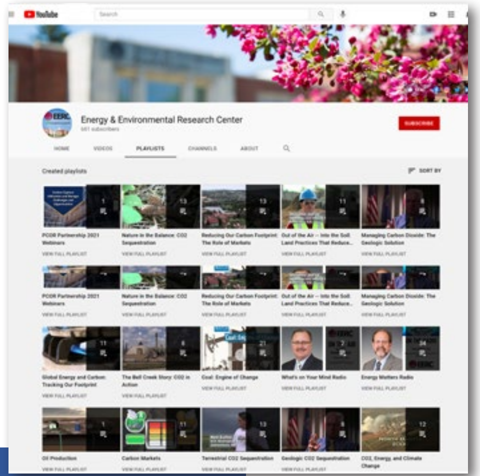
Award-Winning Documentaries



Public Web Site



Partners-Only Web Site



Video Clip Library

TAKE IT ONLINE

Separate public and partners-only websites provide information in terms and context tailored to meet the needs of the distinct demographics.

TAKE IT WITH YOU

Fact sheets, scientific presentations, posters, and reports inform technical audiences, while products such as documentaries, presentations, the regional atlas, and nontechnical posters tell the story of CCUS for a general audience.

NOMENCLATURE

ACTL	Alberta Carbon Trunk Line
bbl	barrel
BLM	Bureau of Land Management
CCUS	carbon capture, utilization, and storage
CH_4	methane
CI	carbon intensity
CO	carbon monoxide
CO_2	carbon dioxide
CNG	compressed natural gas
CO_2eq	CO_2 equivalent
DAC	direct air capture
DMR	Department of Mineral Resources
Denbury	Denbury Resources Inc.
DOE	U.S. Department of Energy
DSF	deep saline formation
ECBM	enhanced coalbed methane
EERC	Energy & Environmental Research Center
EOR	enhanced oil recovery
EPA	U.S. Environmental Protection Agency
ESG	environmental, social, and corporate governance
EU	European Union
EV	electric vehicle
FEED	front-end engineering and design
GHG	greenhouse gas
Gt	gigatonnes or billion tonnes
H_2O	water
IEA	International Energy Agency
InSAR	interferometric synthetic aperture radar
ITC	Integrated Test Center
LCA	life cycle analysis
LCFS	low-carbon fuel standard
LNG	liquefied natural gas
mg/L	milligram per liter
MRV	monitoring, reporting, and verification
Mt	million tonne
MVA	monitoring, verification, and accounting
MWh	megawatt · hour
NDC	nationally determined contribution
NDIC	North Dakota Industrial Commission
NWR	North West Redwater Partnership
NETL	National Energy Technology Laboratory
N_2O	nitrous oxide
O_3	ozone
OBPS	output-based pricing system
PCOR	Plains CO_2 Reduction (Partnership)
PCO_2C	Partnership for CO_2 Capture
PDM	permanent downhole monitoring
psi	pound per square inch
PTRC	Petroleum Technology Research Centre
RCSP	Regional Carbon Sequestration Partnership
R&D	research and development
RD&D	research, development, and demonstration
RTE	Red Trail Energy, LLC
SDWA	Safe Drinking Water Act
SER	School of Energy Resources
stb	stock tank barrel
TDS	total dissolved solids
UIC	underground injection control
UNFCCC	United Nations Framework Convention on Climate Change
USDW	underground sources of drinking water
UWY	University of Wyoming
VSP	vertical seismic profile
WPCI	Wyoming Pipeline Corridor Initiative

CCUS UNITS AND CONVERSION FACTORS

Prefixes

T	tera	10^{12}	trillion
G	giga	10^{9}	billion
M	mega	10^{6}	million
k	kilo	10^{3}	thousand
m	milli	10^{-3}	one-thousandth
μ	micro	10^{-6}	one-millionth
n	nano	10^{-9}	one-billionth

Conversion of Mass to Volume of CO_2 (all at 1 atm)

Standard Temperature	Short Ton	Tonne (metric ton)
0°C/32°F (scientific)	16.31 Mcf	17.98 Mcf
60°F (oil and gas industry)	17.24 Mcf	19.01 Mcf
20°C/68°F (utilities)	17.51 Mcf	19.30 Mcf

Mcf = 1000 ft^3

Volume

barrel of oil	X	42.00	=	U.S. gallon
	X	34.97	=	imperial gallon
	X	0.1590	=	cubic meter
U.S. gallon	X	0.0238	=	barrel
	X	3.785	=	liter
	X	0.8327	=	imperial gallon
imperial gallon	X	1.201	=	U.S. gallon

Weight

short ton	X	2000	=	pound
	X	0.9072	=	metric ton
metric ton (tonne)	X	1000	=	kilogram
	X	1.102	=	short ton

Length/Area

mile	X	1.609	=	kilometer
kilometer	X	0.6214	=	mile
hectare	X	2.471	=	acre
	X	0.0039	=	square mile
acre	X	0.4049	=	hectare
square mile	X	640.0	=	acre
	X	259.0	=	hectare
	X	2.590	=	square kilometer

Note: Most data in this atlas are described in metric units. However, some imperial units are used according to original data sources or industry standard (e.g., barrels of oil).

REFERENCES

1. https://earthobservatory.nasa.gov/features/EnergyBalance (accessed 2021).
2. www.epa.gov/ghgemissions/overview-greenhouse-gases (accessed 2021).
3. Schmidt, G.A., Ruedy, R., Miller, R.L., and Lacis, A.A., 2010, The attribution of the present-day total greenhouse effect: Journal of Geophysical Research, v. 115, D20106. doi:10.1029/2010JD014287. https://pubs.giss.nasa.gov/abs/sc05400j.html (accessed 2021).
4. Friedlingstein, P., O'Sullivan, M., Jones, M.W., Andrew, R.M., Hauck, J., Olsen, A., Peters, G.P., Peters, W., Pongratz, J., Sitch, S., Le Quéré, C., Canadell, J.G., Ciais, P., Jackson, R.B., Alin, S., Aragão, L.E.O.C., Arneth, A., Arora, V., Bates, N.R., Becker, M., Benoit-Cattin, A., Bittig, H.C., Bopp, L., Bultan, S., Chandra, N., Chevallier, F., Chini, L.P., Evans, W., Florentie, L., Forster, P.M., Gasser, T., Gehlen, M., Gilfillan, D., Gkritzalis, T., Gregor, L., Gruber, N., Harris, I., Hartung, K., Haverd, V., Houghton, R.A., Ilyina, T., Jain, A.K., Joetzjer, E., Kadono, K., Kato, E., Kitidis, V., Korsbakken, J.I., Landschützer, P., Lefèvre, N., Lenton, A., Lienert, S., Liu, Z., Lombardozzi, D., Marland, G., Metzl, N., Munro, D.R., Nabel, J.E.M.S., Nakaoka, S.-I., Niwa, Y., O'Brien, K., Ono, T., Palmer, P.I., Pierrot, D., Poulter, B., Resplandy, L., Robertson, E., Rödenbeck, C., Schwinger, J., Séférian, R., Skjelvan, I., Smith, A.J.P., Sutton, A.J., Tanhua, T., Tans, P.P., Tian, H., Tilbrook, B., van der Werf, G., Vuichard, N., Walker, A.P., Wanninkhof, R., Watson, A.J., Willis, D., Wiltshire, A.J., Yuan, W., Yue, X., and Zaehle, S., 2020, Global carbon budget 2020: Earth System Science Data, v. 12, no. 4, p. 3269–3340, https://doi.org/10.5194/essd-12-3269-2020 (accessed January 15, 2021).
5. National Oceanic and Atmospheric Administration National Centers for Environmental Information, 2021, State of the climate—global analysis for annual 2020: www.ncdc.noaa.gov/sotc/global/202013 (accessed 2021).
6. http://data.giss.nasa.gov/gistemp (accessed 2021).
7. http://earthobservatory.nasa.gov/Features/Arrhenius (accessed 2021).
8. https://climatewatchdata.org/ghg-emissions (accessed 2021).
9. https://ourworldindata.org/co2-emissions (accessed 2021).
10. www.iea.org/articles/global-energy-review-co2-emissions-in-2020 (accessed 2021).
11. www.census.gov/data-tools/demo/idb/#/country (accessed 2021).
12. https://ourworldindata.org/co2-emissions? (accessed 2021).
13. www.climatewatchdata.org/ghg-emissions?source=CAIT (accessed 2021).
14. https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement/key-aspects-of-the-paris-agreement (accessed 2021).
15. www.canada.ca/en/environment-climate-change/services/climate-change/greenhouse-gas-emissions/inventory.html (accessed 2021).
16. www.epa.gov/ghgreporting/ghg-reporting-program-data-sets (accessed 2021).
17. www.globalccsinstitute.com/resources/global-status-report/ (accessed 2021).
18. www.eia.gov/electricity/data/browser/ (accessed 2021).
19. www.powerplantccs.com/ccs/cap/con/of/of.html (accessed 2021).
20. https://archive.ipcc.ch/report/srccs/ (accessed 2021).
21. https://dualchallenge.npc.org/documents/CCUS-Chap_6-072020.pdf (accessed 2021).
22. Noothout, P., Wiersma, F., Hurtado, O., Macdonald, D., Kemper, J., and van Alphen, K., 2014, CO_2 pipeline infrastructure—lessons learnt: Energy Procedia, v. 63, p. 2481–2492.
23. Oil fields outside of the PCOR Partnership region were provided by NATCARB.
24. www.eoriwyoming.org/downloads/2019-US-CO2-EOR-Survey-ARI.pdf (accessed 2021).
25. Azzolina, N.A., Peck, W.D., Hamling, J.A., Gorecki, C.D., Ayash, S.C., Doll, T.E., Nakles, D.V., and Melzer, L.S., 2016, How green is my oil? A detailed look at greenhouse gas accounting for CO_2 enhanced oil recovery (CO_2 EOR) sites: International Journal of Greenhouse Gas Control, v. 51, p. 369–379.
26. Brandt, A.R., Masnadi, M.S., Englander, J.G., Koomey, J., and Gordon, D., 2018, Climate-wise choices in a world of oil abundance. Environmental Research Letters. 13 044027 (https://iopscience.iop.org/article/10.1088/1748-9326/aaae76/pdf).
27. Extent of sedimentary basins provided by NATCARB.
28. www.lakesuperiorstreams.org (accessed 2021).
29. http://waterquality.montana.edu (accessed 2021).
30. http://water.epa.gov/drink/contaminants/secondarystandards.cfm (accessed 2021).
31. www.pacificro.com/watercla.htm (accessed 2021).
32. http://geology.utah.gov/online_html/pi/pi-39/pi39pg9.htm (accessed 2021).
33. www.extremescience.com/dead-sea.htm (accessed 2021).
34. https://netl.doe.gov/coal/carbon-storage (accessed 2021).
35. https://ethanolrfa.org/biorefinery-locations/ (accessed 2021).
36. https://ricanada.org/industry-map/ (accessed 2021).
37. CANatural Resources Canada. https://publications.gc.ca/site/eng/9.506002/publication.html (accessed June 2021).
38. U.S. Energy Information Administration, www.eia.gov/environment/emissions/state/excel/transportation.xlsx (accessed June 2021).
39. Azzolina, N.A., Nakles, D.V., Ayash, S.C., Wildgust, N., Peck, W.D., and Gorecki, C.D., 2017, PCOR Partnership best practices manual for subsurface technical risk assessment of geologic CO_2 storage projects: Plains CO_2 Reduction (PCOR) Partnership Phase III Task 9 Deliverable D103 for U.S. Department of Energy National Energy Technology Laboratory Cooperative Agreement No. DE-FC26-05NT42592, EERC Publication 2017-EERC-10-21, Grand Forks, North Dakota, Energy & Environmental Research Center, August.
40. International Organization for Standardization, 2009, Risk management—principles and guidelines: ISO 31000:2009(E).
41. International Organization for Standardization, 2017, Carbon dioxide capture, transportation, and geological storage—geological storage: ISO 27914:2017.
42. International Organization for Standardization, 2019, Carbon dioxide capture, transportation, and geological storage—carbon dioxide storage using enhanced oil recovery (CO2-EOR): ISO 27916:2019.
43. Quintessa, 2014, Generic CO_2 FEP database, Version 2.0: Quintessa Limited, Henley-on-Thames, United Kingdom. Open access online database https://www.quintessa.org/co2fepdb/ (accessed 2021).

44. www.basinelectric.com/_files/pdf/financials/Annual-Report-2020-WEB.pdf (accessed 2021).

45. www.wcap.ca/sustainability/co2-sequestration (accessed 2021).

46. www.cbc.ca/news/canada/saskatchewan/cenovus-selling-majority-stake-in-weyburn-oil-project-1.4400817 (accessed 2021).

47. www.wcap.ca/application/files/6215/9191/1116/Whitecap-2020-ESG-Report_Final-002.pdf (accessed 2021).

48. www.pipelinenews.ca/news/local-news/weyburn-unit-up-for-sale-midale-unit-sold-1.20684078 (accessed 2021).

49. https://cardinalenergy.ca/wp-content/uploads/2021/03/March-9-2021-2020-ESG-Report-Final.pdf (accessed 2021).

50. www.saskpower.com/about-us/our-company/blog/2021/bd3-status-update-may-2021 (accessed 2021).

51. Petroleum Technology Research Centre, http://aquistore.ca (accessed 2021).

52. https://ptrc.ca/res/doc/RChalaturnyk-Webinar-April14-2021.pdf (accessed 2021).

53. Rostron, B., White, D., Hawkes, C., and Chalaturnyk, R., 2014, Characterization of the Aquistore CO_2 project storage site, Saskatchewan, Canada: Energy Procedia, v. 63, p. 2977–2984.

54. www.shell.ca/en_ca/media/news-and-media-releases/news-releases-2020/quest-ccs-facility-captures-and-stores-five-million-tonnes.html (accessed 2021).

55. https://actl.ca/ (accessed 2021).

56. www.fticonsulting.com/-/media/files/us-files/insights/reports/2020/sep/carbon-capture-utilization-storage.pdf (accessed 2021).

57. Global CCS Institute (www.globalccsinstitute.com/wp-content/uploads/2020/04/45Q_Brief_in_template_LLB.pdf) (accessed 2021).

58. https://ccsknowledge.com/news/canadas-budget-2021-carbon-capture-and-storage (accessed 2021).

59. www.budget.gc.ca/2021/report-rapport/p2-en.html#chap5 (accessed 2021).

60. www.navigatorco2.com/project-overview (accessed 2021).

61. www.summitcarbonsolutions.com (accessed 2021).

62. www.globalccsinstitute.com/wp-content/uploads/2020/10/ESG-Report-2020-LR_Digital.pdf (accessed 2021).

PHOTO AND IMAGE CREDITS

Except for those noted below, all photos and images were created by the EERC or obtained from royalty-free stock.

Preface (Pages ii–iii). Denbury Resources Inc.

Page 4. Modified from Global Carbon Cycle: U.S. Department of Energy Genomic Science Program, http://genomicscience.energy.gov (accessed 2016).

Page 5. Image of Svante Arrhenius: www.nndb.com/people/875/000092599.

Page 5. Map of average surface temperature trends: NOAA (see Reference 5).

Page 6. Industrial: Gas Technology Institute; agriculture-related processing: Lincolnland Agri-Energy; petroleum and natural gas: https://bloximages.chicago2.vip.townnews.com/bismarcktribune.com/content/tncms/assets/v3/editorial/e/29/e29d6a78-d716-5103-8094-d15a33d6c32a/5f5948317c8ab.image.jpg.

Page 7. Horia Varlan.

Page 14. Electric utility: Basin Electric Power Cooperative.

Page 22. Carbon Engineering.

Page 23. PTRC.

Pages 24–25. Denbury Resources Inc.

Page 28. Adapted from the Cooperative Research Centre for Greenhouse Gas Technologies.

Page 29. CO_2-trapping contributions. Adapted from IPCC, 2005, Carbon dioxide capture and storage: Metz, B., Davidson, O., de Coninck, H., Loos, M., and Meyer, L., eds., United Kingdom, Cambridge University Press, 431 p.

Page 29. Structural and stratigraphic trapping. Modified from https://co2crc.com.au/resources/images/ (accessed 2021).

Page 32. Paul Lowry.

Page 48. Prairie pothole region: Ducks Unlimited.

Pages 64–65. John Oleksik.

Page 74. Basin Electric Power Cooperative.

Page 75. PTRC.

Page 76. SaskPower.

Page 77. PTRC.

Page 78. Shell Quest. www.multivu.com/players/English/7680751-shell-quest-carbon-capture-storage/ (accessed 2021).

Page 79. Alberta trunk line. www.actl.ca (accessed 2021).

Page 80. University of Wyoming.

Page 91. EPA. www.epa.gov/uic/underground-injection-control-well-classes (accessed 2021).

Page 99. University of Wyoming.

Back Cover: North America *in* Colton's Atlas Of The World, Illustrating Physical And Political Geography. By George W. Colton., 1856.

FOR MORE INFORMATION

The public PCOR Partnership Web site contains a wealth of information related to CCS geared toward various audiences. Visit us at **undeerc.org/pcor**.

To learn more about the PCOR Partnership and its activities, contact:

Kevin Connors
PCOR Partnership Program Manager
701.777.5236
kconnors@undeerc.org

To obtain educational materials or schedule a presentation, contact:

Nikki Massmann
Director of Communications and Information Services
701.777.5428
nmassmann@undeerc.org

Energy & Environmental Research Center (EERC)
University of North Dakota
15 North 23rd Street, Stop 9018
Grand Forks, ND 58202-9018
701.777.5000
undeerc.org


LONGITUDE FROM GREENWICH
OCEAN
PARRY ISLANDS
RUSSIAN AMERICA
WEST GEORGIA
BRITISH POSSESSIONS
NEW CALEDONIA
MACKENZIE RIVER
GREAT SLAVE LAKE
ATHABASCA
SASKATCHAWAN
SWAN RIVER
CUMBERLAND
YORK
ALBANY
Victoriana
Cockburn Land
Cumberland Island
BAFFIN BAY
HUDSON'S BAY
Boothia Gulf
Magnetic Pole
North Devon
Melville Sd.
Fox Channel
Bristol Bay
PACIFIC OCEAN
WASHINGTON
OREGON
NEBRASKA
MINNESOTA
IOWA
ILLINOIS
OHIO
UNITED STATES
UTAH
CALIFORNIA
NEW MEXICO
KANZAS
INDIAN TERRITORY
ARKANSAS
TEXAS
TENNESSEE
GEORGIA
FLORIDA
NORTH CAROLINA
VIRGINIA
MEXICO
GULF OF MEXICO
Lake Superior
Great Salt L.
Fillmore City
San Francisco
Sacramento City
Santa Fe
Austin
Chihuahua
Cape Sable
Key West
Henderson I.
Cooper I.
Guadalupe I.