Please fill in the name of the event you are preparing this manuscript for.	SPE Western Regional Meeting, 22—25 May 2023, Anchorage, Alaska, USA
Please fill in your 6-digit SPE manuscript number.	213051
Please fill in your manuscript title.	Alaska CCUS Workgroup and a Roadmap to Commercial Deployment

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Abstract

A group of Alaskans formed a Workgroup in July 2022 to accelerate commercial carbon capture, use, and storage (CCUS) projects in the State of Alaska (State). The Workgroup's mission is to attract new investments and create options that enable continued operation of carbon intensive activities vital to the State's economy including power generation, refineries, and oil and gas production.

To meet the dual challenge of increasing global energy demand and a growing population, there is a need to provide affordable and reliable energy while addressing the risks of climate change. Policies are being created and refined to incentivize carbon dioxide removal from the atmosphere including capture at the point of generation and direct air capture. Since 2008, US Federal tax credits have been established, increased, extended, and expanded for CCUS projects. Energy policy in the US and globally is evolving, moving from exclusive focus on renewable energy towards supporting low-emission energy systems, including those employing CCUS [COP 26].

This shift recognizes utility-scale renewable energy generation generally depends on fossil fuel for back-up power. The intermittent nature of renewable power generation gives rise to energy generation gaps. Coal, natural gas, and oil generation fill these gaps to provide stability to an energy system, and CCUS is increasingly viewed as a critical part of a complete clean energy portfolio. Costs to establish clean energy security would be more than twice as expensive without CCUS [IPCC].

Interest in CCUS is growing rapidly. As of 2020, 21 large-scale CCUS facilities operate globally [IEA CCUS], with 80% of capacity based in the USA. Operations began as far back as 1972 for enhanced oil recovery and more recently for geologic sequestration. As of 2022, over 190 CCUS facilities are in the project pipeline globally. Assuming one million tonnes carbon dioxide captured per year per project, over 2,500 facilities are needed by 2040 to reach the objective of 2.52 gigatonnes captured per year [IEA 2020].

This paper addresses three important topics:

1. The importance, value, and cost of CCUS. Costs increase rapidly as the carbon dioxide (CO_2) concentration decreases within the capture inlet gas stream. Herein, costs are compared with the

value of capture especially 45Q tax credits. Other revenue and value drivers are also discussed. Costs typical of the contiguous 48 states of the US were used in this screening.

2. The Alaska CCUS Workgroup's mission, leadership, and participating organizations are discussed. Results, future plans, and approaches to ensure participant value are shared for four focus areas:
    - Develop a State legal and regulatory framework,
    - Track and respond to government funding opportunities,
    - Perform public education and outreach, and
    - Develop a roadmap to accelerate commercial CCUS deployment in Alaska.
3. The North Slope, Interior, and Cook Inlet regions are reviewed for CO_2 storage potential, stationary emission sources, seismic hazards, and expected capture costs. Potential Alaska CCUS projects are discussed, and additional work is proposed to advance commercial deployment.

Key observations, findings, and recommendations are provided.

CCUS Importance, Value, and Cost for Affordable, Reliable, Clean Energy

As global economies and populations continue to grow and prosper, the world faces the dual challenge of providing affordable, reliable energy while addressing the risks of climate change. The world gross domestic product (GDP) is expected to double in the next twenty years. With increasing GDP, energy consumption will increase. Widespread CCUS deployment is essential to meeting this dual challenge at the lowest cost [NPC Roadmap 2019].

In its Fifth Assessment Report, the Intergovernmental Panel on Climate Change (IPCC) concluded that the costs for achieving atmospheric CO_2 levels consistent with holding average global temperatures to an increase of 2°C—referred to as a "2°C world"—will be more than twice as expensive without CCUS [IPCC]. As the International Energy Agency (IEA) explained in 2017, "Our analysis consistently shows that CCUS is a critical part of a complete clean energy technology portfolio that provides a sustainable path for mitigating greenhouse gas emissions while ensuring energy security" [IEA 2017]. As of 2022, there are 30 CCUS facilities operating, with 190 new facilities in the project pipeline globally. To reach the Paris 2ºC target, more than 2,500 facilities need to be operating by 2040 with a capacity of 1.5 Mtpa (million metric tonnes per annum) each [Global CCS Institute].

Emissions Reduction

Carbon capture technology dramatically reduces emissions, as shown in Figure 1. Second-generation CCS on abated coal emits less than 100 tonnes per gigawatt hour (t/GWh), lower than wind with natural gas peakers (250 t/GWh) and natural gas (400 t/GWh). CCS technology will evolve towards reduced cost, lower emissions, and improved efficiency. The Shand CCS Feasibility Study on the Boundary Dam 3 CCS Facility details significant cost reductions between first-generation and second-generation CCS [CCSKnowledge.com].

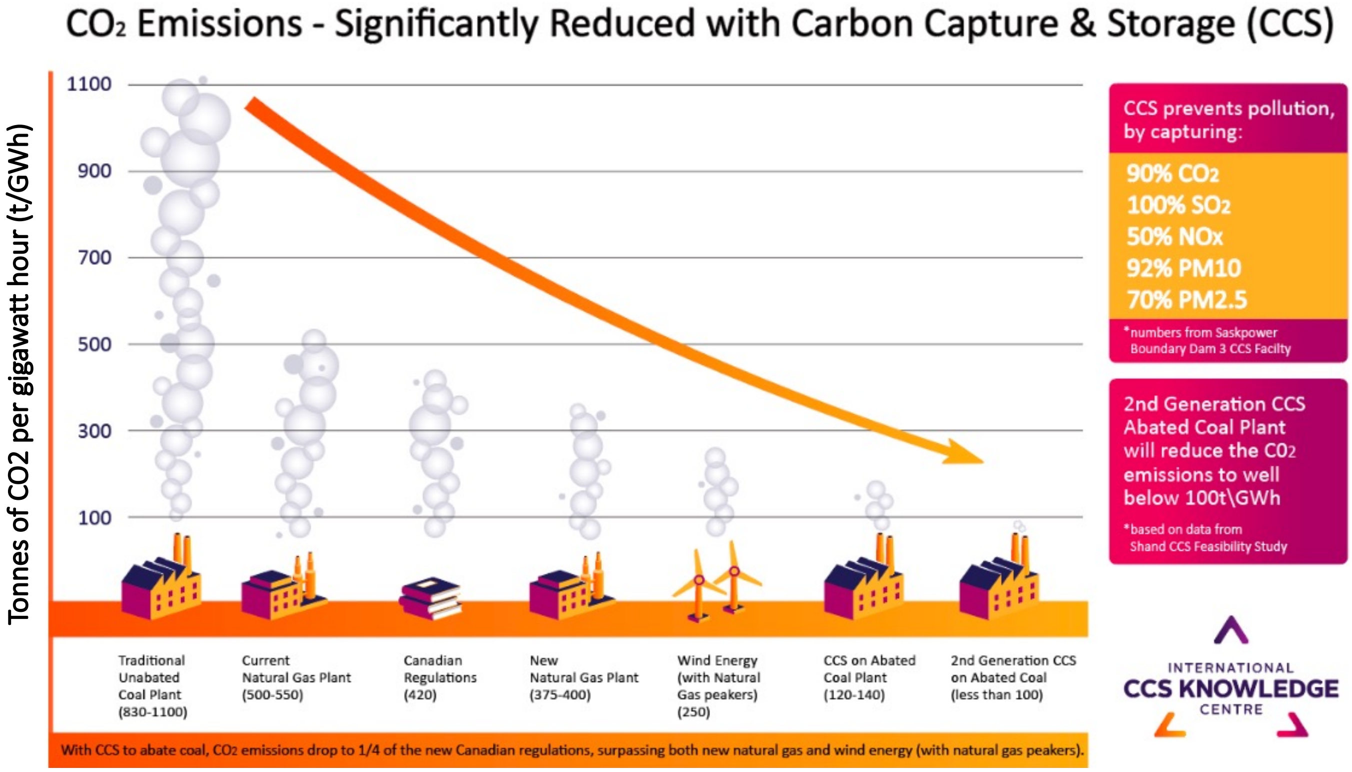

Figure 1: CO_2 Emissions Significantly Reduced with Carbon Capture and Storage (CCS) [International CCS Knowledge Centre].

Policies regulating and managing carbon will evolve, but their trajectory appears clear: to reduce carbon dioxide emissions. Various mechanisms are being tested and refined at global, national, and subnational levels including carbon cap and trade systems, carbon taxes charging emitters per tonne of carbon dioxide emitted, and carbon tax credits. There is also an emerging and growing market for carbon offsets, for example by harnessing nature-based mechanisms for carbon removal. Standards are also being developed so that CCS can quality to generate Verified Carbon Units (VCUs) under the Verified Carbon Standard (VCS) protocol [Verra].

At the United Nations (UN) Conference of Parties 26th meeting in Glasgow in 2021 (COP 26), the COP moved away from focusing exclusively on renewable energy, recognizing utility-scale renewable energy generation generally depends on fossil fuel for back-up power. When the wind is not blowing and the sun is not shining, wind and solar may not be sufficient to meet municipal, regional, and industrial power demands. Coal, natural gas, and oil generation often fill this gap to provide a reliable energy supply system. COP 26 recognizes carbon capture in support of renewable energy, with COP references to low-emission energy systems including the utilization of CCUS [COP 26]. Climate change discussions continued at COP 27, where UN Secretary-General António Guterres said more needs to be done to drastically reduce emissions now. "The world still needs a giant leap on climate ambition. [COP 27]"

The IEA concluded that adding CCUS to *existing* and *future* coal, natural gas, and oil generation delivers greater CO_2 reduction at a lower cost relative to replacing fossil fueled generation with intermittent renewable generation. Further investment in CCUS will drive technology and cost improvements so existing plants can be economically retrofitted and new plants can be built with CCUS around the world.

At the moment, the majority of global carbon prices take the form of cap-and-trade programs, the largest of which can be found in the European Union and in the state of California. Carbon taxes are growing in popularity however, and are now in place in the United Kingdom, several Canadian provinces, Sweden, and more [RFF 2019].

Even with rapid expansion of renewable energy, new fossil fueled generation with CCUS is needed to provide affordable, reliable, clean power for a growing global economy. For example, in 2021, world coal output expanded by 5.7% to just above the 2019 pre-pandemic level following the rebound in global demand [Enerdata]. As the year 2023 begins, the United States is the world's largest oil producer, the world's largest natural gas producer, the world's largest LNG exporter, and the fourth largest coal producer [Bloomberg]. The US clearly can play a role in developing CCUS projects and technologies.

Federal 45Q Tax Credits for Carbon Storage—History and Expectations

US tax policies incentivizing R&D and commercial projects drives CCUS technology development, ultimately providing low-cost solutions so existing fossil fueled plants can be economically retrofitted and new fossil fueled plants can be built with CCUS technology. In the United States, federal tax credits were first introduced in 2008 in Section 45Q of the US Internal Revenue Code which provides a tax credit for CO_2 storage. Subsequent legislation increased the tax credit and broadened its applicability.

The Bipartisan Budget Act (BBA) of 2018 made the credits more valuable, increasing the tax credit from $20 to $50 per metric tonne for dedicated secure geologic storage and from $10 to $35 per tonne for CO_2 stored during enhanced oil recovery (EOR) for projects that begin construction by January 2026.

The Inflation Reduction Act (IRA) in 2022 again expanded and extended the 45Q tax credit, currently $85 per metric tonne of dedicated CO_2 storage and $60 per tonne of CO_2 stored during EOR. The credit also addresses biologic sequestration and direct air capture (DAC) projects. The 45Q tax credit for DAC projects, recognizing their higher cost of capture, stands at $180/tonne of CO_2 stored in dedicated geologic storage. The 45Q credit values noted here are maximum values, reflecting a 5X multiplier times the base value. This multiplier depends on Department of Labor qualifiers such as local prevailing wage and apprenticeship requirements. The multiplier is variable and not guaranteed [Petrotek]. The 2022 changes include a seven-year extension to qualify for the tax credit, meaning projects have until January 2033 to begin construction. The credit is currently available to qualified facilities for 12 years after they begin using carbon capture equipment [IEA 4986].

The authors' long-term expectation is that 45Q tax credits will continue beyond their current 12-year availability or that they will be replaced by policy that similarly incentivizes CCUS financially.

This expectation is consistent with the history of federal wind tax credits which began in 1992 and have been renewed numerous times since [IER], and consistent with the recommendations in *A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage.* This Roadmap, issued by the National Petroleum Council (NPC), outlines a pathway through three phases: activation, expansion, and at-scale deployment of CCUS. The 2019 NPC study "recommended expanding current policies to a level of ~$90 per tonne to provide incentive for further economic investment during the expansion phase…. Achieving CCUS deployment at scale (i.e., additional 350 to 400 Mtpa) within the next 25 years will require substantially increased support driven by national policies…. Congressional action should be taken to bring cumulative value of economic policies to about $110 per tonne" [NPC Roadmap 2019].

The United States appears to be moving from the Activation phase into the Expansion phase. Academia, government, and industry are responding by expanding R&D, creating and clarifying the legal and regulatory CCUS framework, and initiating new CCUS projects.

The expectation for 45Q tax credits is they will continue to exist at current or increasing levels or will evolve into a different mechanism to financially inducing industry to reduce or eliminate carbon emissions. The 45Q tax credit amounts do not reflect the wide variety of capture costs for different carbon dioxide sources. Policy may evolve to address this gap. How will future policy decisions unfold? If US policymakers follow the NPC roadmap into the At Scale phase, "actions will be taken to increase the cumulative value of economic policies to about $110 per tonne".

Carbon Capture Value Drivers Beyond 45Q Tax Credits

Specific projects may have revenue streams or value other than 45Q tax credits for their economics. Examples include:

- CO_2 sale for EOR or to an agricultural greenhouse.

- US ethanol production is incentivized by the California Low Carbon Fuel Standard (LCFS) program that requires a reduction in the carbon intensity (CI) of transportation fuels that are sold, supplied, or offered for sale in the state through 2030, with a credit market price per tonne of CO_2 that has ranged from $60 to $200 [Neste].
- Coal-fired carbon capture in Section 48 of the US Federal tax code provides a 30% investment tax credit targeted at incentivizing CCUS on coal-fired power generation.
- Reducing a product's carbon intensity increases its value in markets where CI-type taxes are in place. Examples include oil to Washington State's refineries [WA CFS] and California fuels [CA LCFS] using their respective GREET models.
- In Asia, Malaysia leads the way in progressing carbon tax plans and CCS tax incentives [Energyvoice].
- Waste heat sale to agricultural greenhouses or local home or business heating.

More generally, corporations with aggressive environmental, social, and governance (ESG) goals may look at other factors outside of 45Q credit revenue. While wanting the most efficient use of Project dollars spent, they see meeting ESG goals as a corporate priority and not a strictly economic equation. Some 400 large US-based companies have committed to net-zero targets of their own, many of which have set ambitious emissions reductions targets for 2030 or sooner [McKinsey].

CCUS projects not only provide 45Q credit revenue, but also provide ancillary benefits including:

- Ease in obtaining an air permit, often the hardest and most time-consuming permit to obtain. Projects reducing emissions may allow development expansion within existing permit levels.
- Reduction of local government or NGO pressure by addressing operations-related emissions.
- Corporations with aggressive carbon intensity reduction goals are more likely to fund lower CI projects, especially important given pressures to defund Arctic oil and gas development.
- Carbon capture equipment can supplement, enhance, or replace other emissions controls.

Carbon Capture, Transport, and Storage Cost

CCUS consists of an integrated carbon capture, transport, use (optional), and storage system. Carbon capture and storage (CCS) refers to the cases where little to none of the captured CO_2 is utilized and is instead injected solely into dedicated geologic storage. Figure 2 shows a generalized CCUS schematic. *Capture* consists of separation of CO_2 from other gases, for example from flue gas from industrial processes or directly from the air. CO_2 is dehydrated and compressed so that it behaves like a liquid, making it ready for transport. *Transport* typically involves pipelines, and can also include rail, trucks, or marine vessels. *Use* can include supplying a local greenhouse with CO_2 to enhance plant growth, but use typically employs a small portion of the CO_2 captured from an industrial process. The exception is enhanced oil recovery (EOR), which can use and permanently store large volumes of CO_2 while increasing oil production from an oilfield. *Dedicated storage* is injection of CO_2 directly into carefully selected subsurface geologic formations for safe, secure, and permanent storage. Injection depths are typically 3,000 to 10,000 feet subsurface into formations such as saline aquifers, depleted oil and natural gas reservoirs, and un-mineable coal seams.

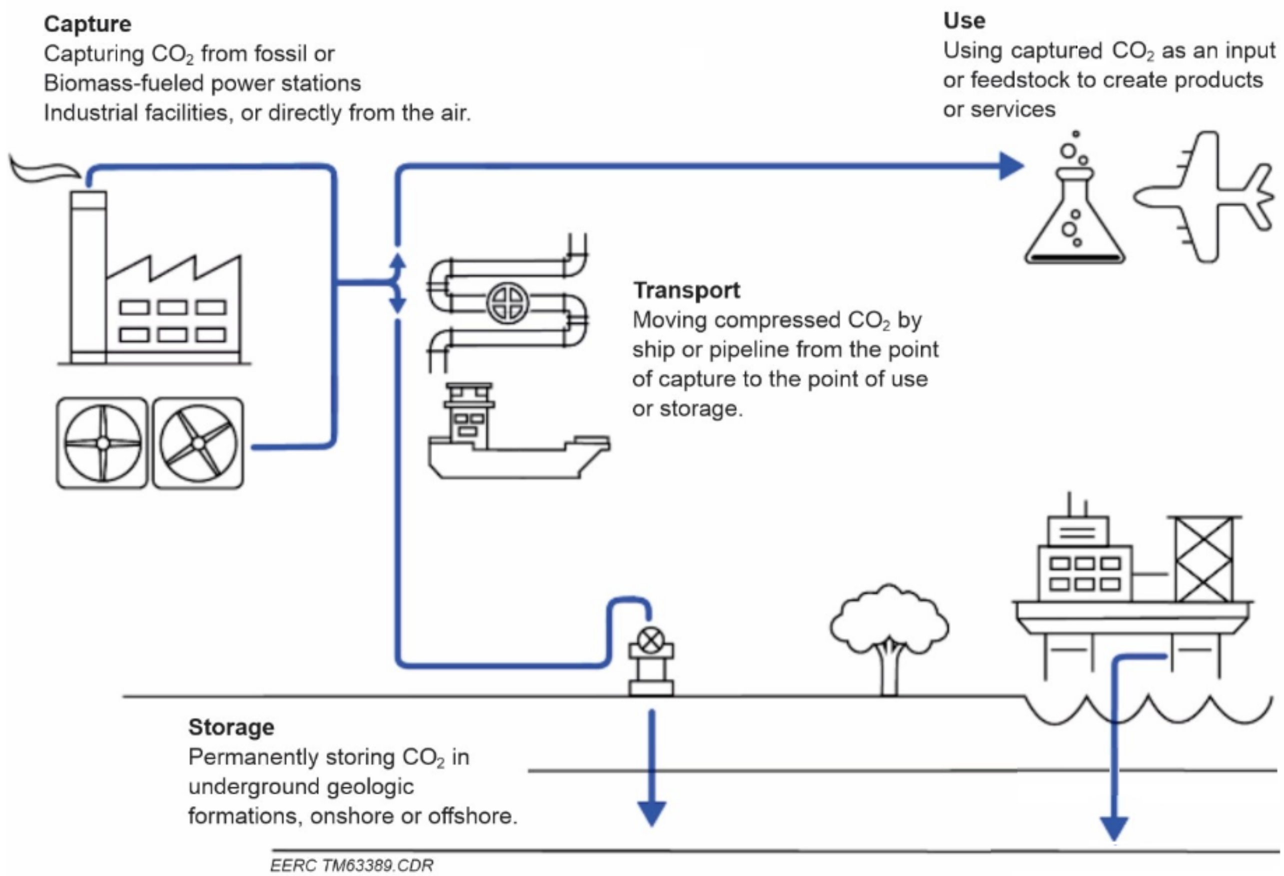

Figure 2: Generalized CCUS schematic (Modified from International Energy Agency, 2022).

CCUS or CCS can be added to existing equipment such as power generation stations and industrial processes. This helps to keep the overall cost of energy down while the overall global demand for power and energy grows, since existing power generation can be retrofit with CCS at a fraction of total power system replacement cost. CCS therefore plays an important part to ensure affordable, reliable energy infrastructure alongside growing renewables including wind and solar.

While technologies are available for CCUS systems, especially for coal-fired power generation, additional research and development is needed to lower implementation costs, improve efficiency, and create new technologies for cost effective CCUS. Notably, no commercial natural gas-fired flue gas carbon capture projects are operating in the world, and none are under construction [Global CCS Institute]. Federal R&D funding is available to institutions investigating new CCUS technologies.

Carbon capture can occur pre-, during, or post-combustion using various technologies [Wilcox, p. 17]. Discussing these technologies is beyond the scope of this paper. Interested parties are directed to the NPC Roadmap, the Global CCS Institute, the textbook Carbon Capture by Wilcox, and other information sources. Related newsfeeds have fascinating titles such as, “In silico discovery of metal-organic frameworks for precombustion CO_2 capture using a genetic algorithm” [Science Advances].

The cost per tonne of carbon capture is briefly discussed here, as it relates to available 45Q tax credits, i.e., \$85/tonne for non-EOR storage and \$180/tonne for direct air capture project storage in dedicated geologic saline formations or depleted oil and gas fields.

CCS costs are illustrated in Figure 3 for various sources, including capture, transport, and storage costs.

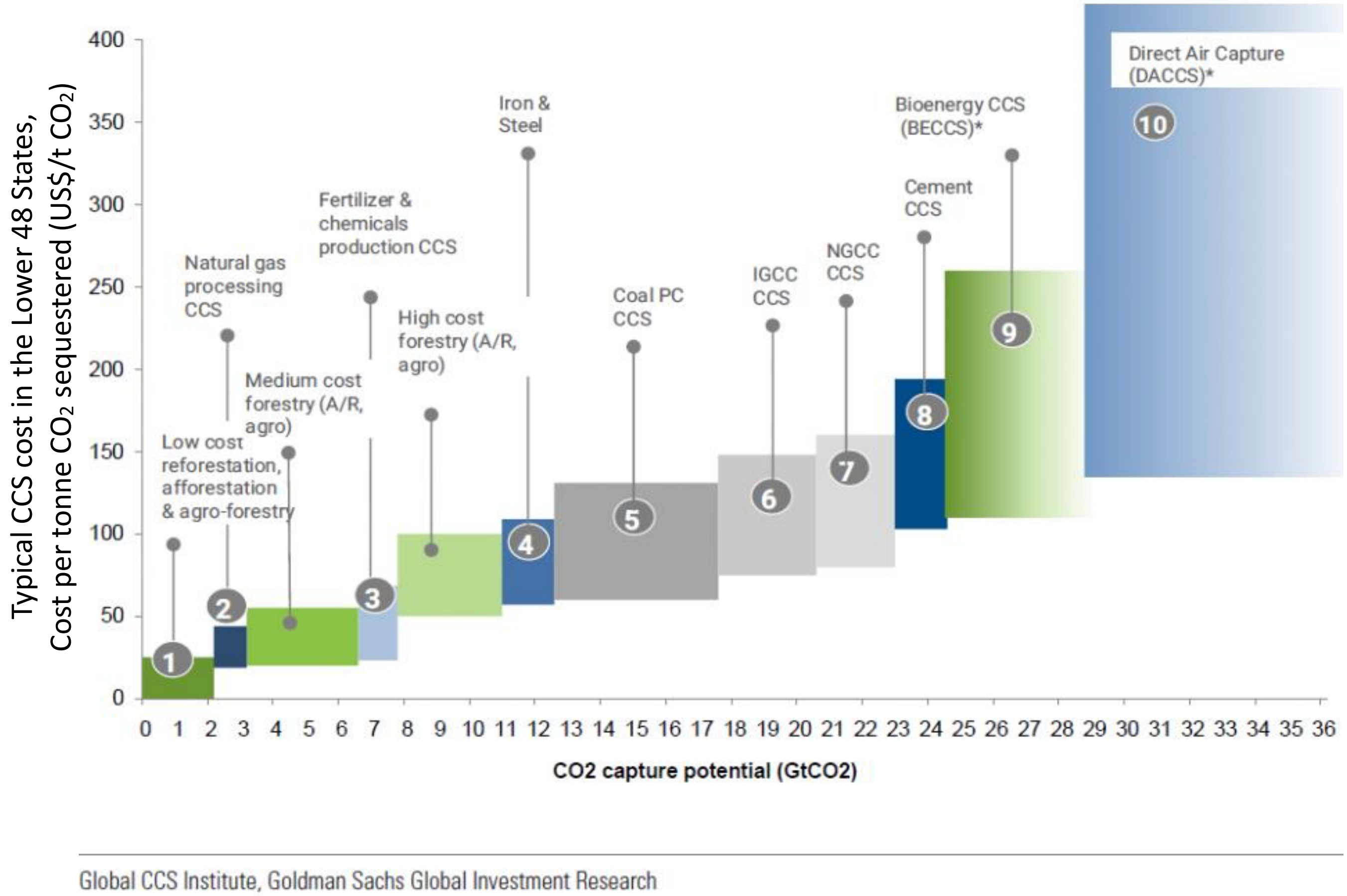

Figure 3: Cost per tonne CO_2 sequestered vs. CO_2 capture potential

For point-source carbon capture projects, the most significant capture cost driver is the partial pressure of CO_2 from the source. CO_2 partial pressure is equal to the total gas pressure from the source times the concentration of carbon dioxide. Higher CO_2 partial pressure systems, such as natural gas processing (#2 in Figure 3) and chemicals processing (#3) have lower carbon capture cost. Direct air capture (#10) has the highest carbon capture cost due to the source being low (atmospheric) pressure, 14.7 psia, and extremely low concentration, 0.04%—0.06% CO_2.

Put in terms of chemistry and physics, the minimum thermodynamic work for CO_2 separation increases as the CO_2 mole fraction decreases. This is especially true at low CO_2 concentrations (below ~5% as in natural gas combined cycle flue gas (NGCC, #7)) and ultra-low concentrations (0.04% as in direct atmosphere capture (DAC, #10)). In addition, second law separation efficiency also decreases with decreasing mole fraction, compounding the work required. Thus, the work and cost of separation increases dramatically for low and ultra-low CO_2 concentrations [Wilcox, p. 22].

In Figure 3, natural gas processing CO_2 capture (#2), for example preparing for natural gas liquefaction in an LNG plant, is differentiated from and is much lower cost than natural gas carbon capture (#7). Carbon capture for coal (#5) and coal integrated gasification combined cycle (#6) may be attractive with current 45Q credit amounts. NGCC (#7) is challenged economically and may only be attractive at the low end of the cost range shown in Figure 3. Technology improvements may lower capture costs in the future.

CCUS Technology Readiness

CCUS employs mature technologies already in deployment, technology readiness level (TRL) 7—9, and extends into fundamental research, TRL 1, as shown in Figure 4.

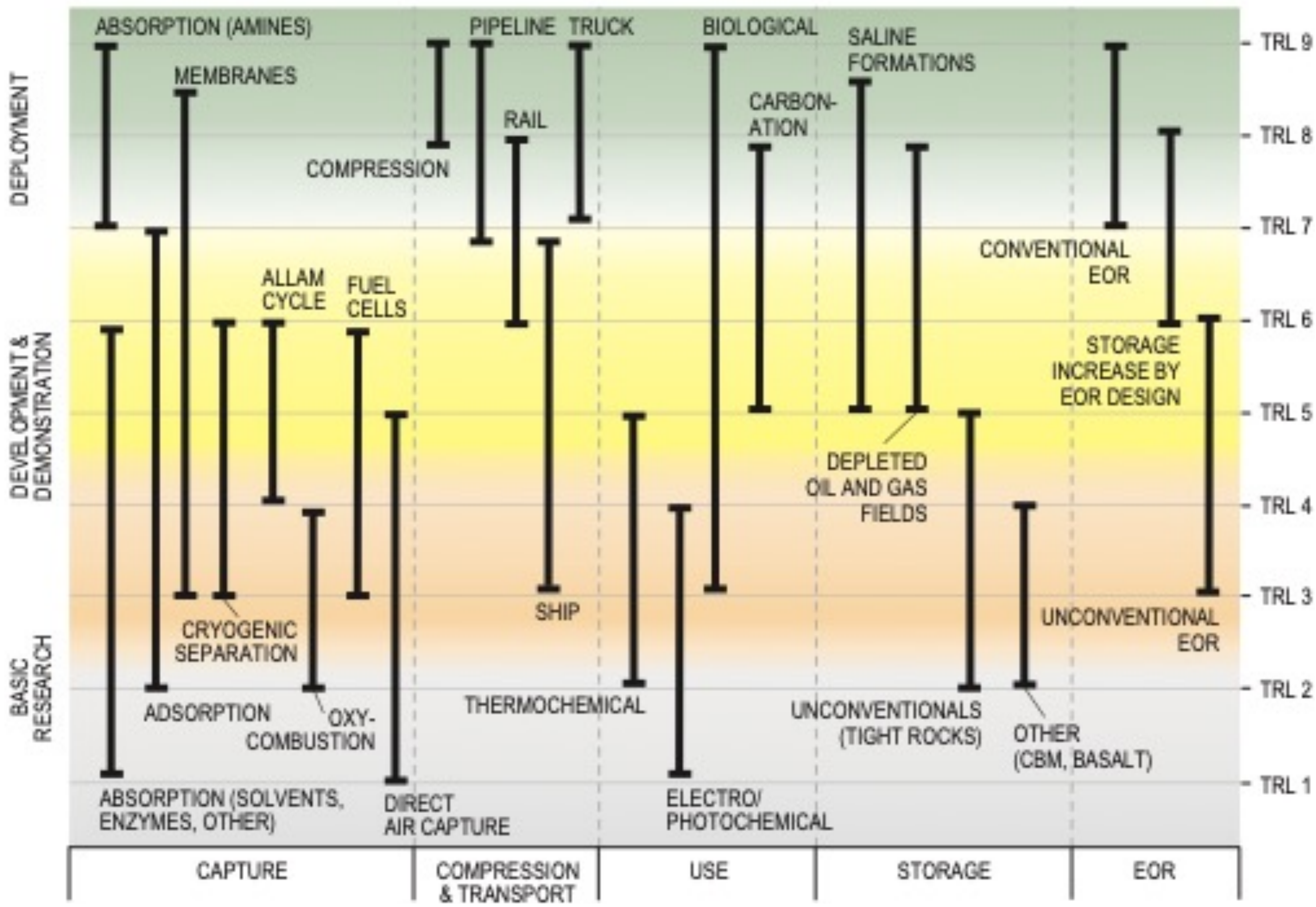

Figure 4: Technology Readiness Level (TRL) Ranges for CCUS Technologies, [NPC Roadmap, p. 32, 2019]

Selecting deployment technology, TRL 7—9, minimizes risk and increases confidence but may incur higher cost or lower efficiency than a potentially better alternative. “Never use serial number 1” is an adage oft heard in the oil and gas industry. However, the IEA states two-thirds of cumulative carbon emissions reductions through 2070 will employ technology presently in prototype or demonstration stage now [IEA 2020].

A project selecting the most mature CCUS technologies would employ amine capture, pipeline transport, saline formation storage, and may use CO_2 for conventional EOR where available.

CCUS Alaska Workgroup

A diverse group of Alaskans began collaborating Winter 2021/2022 at the request of the Governor and prepared a unified State response to a Department of Energy information request about carbon sequestration opportunities. Recognizing the value of continuing dialog, in July 2022 they launched a new Workgroup to accelerate commercial carbon capture, use, and storage (CCUS) projects within the state.

The workgroup mission, leadership, participation, and four initial focus areas are discussed below.

The Workgroup’s mission is to attract new investments and to create options enabling continued operation of power generation, industrial processes, and oil and gas production, all of which are carbon intensive activities vital to the State’s economy.

Workgroup leadership includes academic, state, and corporate industry representation from the University of Alaska Fairbanks Institute of Northern Engineering (UAF-INE), Alaska Department of Natural Resources, and Arctic Slope Regional Corporation, respectively. For financial, technical, commercial, and public outreach resources, UAF-INE joined the Plains CO_2 Reduction (PCOR) Partnership in 2019 at the encouragement of US Senator Lisa Murkowski.

In-person and online workgroup participation is augmented by crowd-sourced hybrid meeting interactions which provide detailed poll results, Q&As, and surveys to engage participants and promote the value of stakeholder input. The group has found Slido is an effective tool for this application.

Of the 177 contacted to date regarding the workgroup, 137 indicated that they wished to be informed about or participate in the workgroup. Sixty attended the kickoff meeting, 96 have attended at least one meeting since, and 25 to 50 typically attend any particular meeting. Attendance is half online using Zoom and half in person. Meetings are held at the BP Energy Center which was donated to The Alaska Community Foundation in 2020. As shown by Figure 5, workgroup participation is half from industry, a quarter from State agencies, 12% University, and 14% Public, NGO, and Federal:

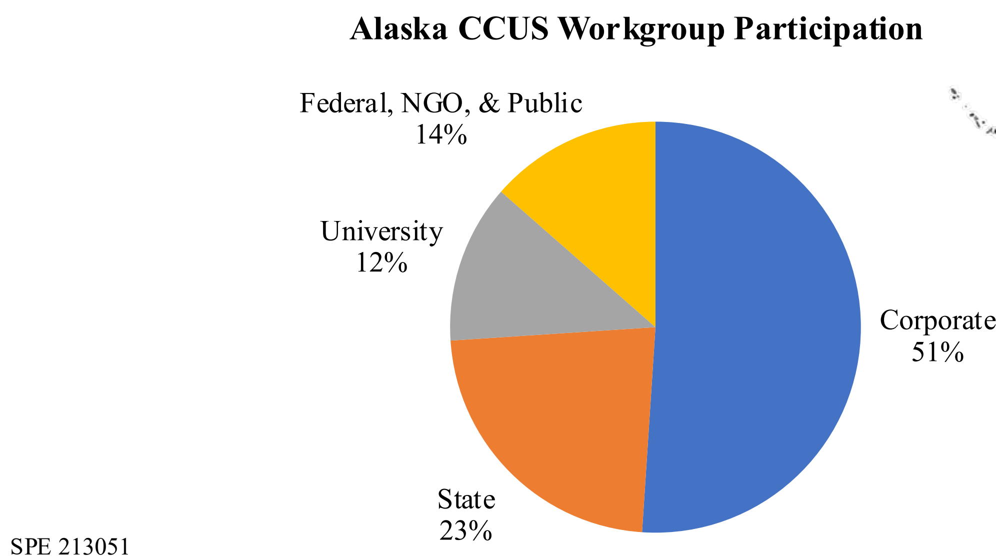

Figure 5: Workgroup Participation as of January 2023

Workgroup Subcommittees

The Workgroup has four subcommittees. The leadership team meets weekly to coordinate efforts:

- Develop a State legal and regulatory framework,
- Track and respond to government funding opportunities,
- Perform public education and outreach, and
- Develop a roadmap to accelerate commercial CCUS deployment in Alaska.

This structure was developed independently by Workgroup leadership, but was found to align with the national *Roadmap to At-Scale Deployment of CCUS* [NPC Roadmap]. The NPC Roadmap, developed by a diverse team of over 300 experts representing a wide range of industries, spans four similar avenues: regulatory framework, financial incentives, stakeholder engagement, and technology and capability.

The Workgroup subcommittees are discussed below with results to date, future plans, and methods employed to ensure workgroup participant value.

Develop a State Legal and Regulatory Framework

The Alaska Department of Natural Resources (DNR) is using results from Workgroup sessions to inform a future CCUS regulatory framework for Alaska. Fifteen other states have enacted omnibus CCUS legislation, useful templates for Alaska. The key is to ensure the frameworks are appropriate for Alaska and take into account stakeholders' values and needs, the conditions under which a CCUS project may advance, and the unique position of the State of Alaska as both a landowner and regulator. To accomplish this, the Workgroup was utilized in a four-step process to solicit recommendations for legislation: 1) Conduct 2) Identify 3) Review and 4) Convene.

DNR *conducted* a review of other state's legislation to identify the core elements of a framework to enable and regulate the CCUS industry from exploration to post-closure. This peer state review was supplemented with an evaluation of other sovereigns, such as Norway and Australia, who hold a similar position as landowner, to address topics that may not be considered in other state legislation. The results of this review demonstrated myriad approaches within legislation to address core elements.

DNR *identified* issues with the broadest menu of policy options and likely to benefit from feedback of a larger stakeholder body. At the Workgroup kick-off meeting, DNR identified five elements and used Slido to poll attendees on the sixth element the group should address. With consensus reached, the six elements for the Workgroup to evaluate were:

- licensing of public lands,
- amalgamation of property rights,
- Class VI well primacy,
- long-term liability,
- the relationship of CCUS with other mineral interests, and
- fiscal issues.

In August 2022, the Regulatory Committee held three background information meetings to *review* the six core elements with Workgroup members. At these reviews, DNR presented an explanation of each topic, discussed the options other states or sovereigns used to address it, identified any parallel programs in existence within the state, and provided context on whether the Alaska Constitution or jurisprudence of the State had any considerations for members to understand when weighing policy options. At each hour and a half long meeting, two topics were addressed, Slido polls were used throughout to garner feedback, and all meetings were recorded for absentee participants to catch up on presentations.

The Regulatory Committee then *convened* a full one-day policy symposium to discuss recommendations on legislation. The symposium structure maximized small group discussion and provided an opportunity for larger group review of results from break-out sessions. Each topic received forty-five to an hour and fifteen minutes depending upon topic complexity. The topic was introduced briefly and a one to three questions were presented to the room. Following this, participants broke into small groups of approximately five people to discuss, either in person or in an online breakout room, and input their consensus response into Slido by the secretary of the group. After small group discussions, the whole group was brought back together to review other team responses and offer comments or feedback. Slido's Q&A feature was also used for participants to offer further comments if they did not believe the consensus response captured their views completely.

The DNR then drafted a stakeholder whitepaper summarizing these inputs as findings. This whitepaper was reviewed for accuracy by participants, finalized, and transmitted to the Governor's Legislative Office for consideration in legislation creation. This whitepaper is available on the UAF-INE carbon website [UAF-INE]. On 1/27/2023, the Governor introduced Senate Bill 49 and corresponding House Bill 50 to the State Legislature for consideration, revision, and, if successful, passage into law [SB49]. As introduced, the bills materially incorporate Workgroup Committee findings and demonstrate the important role a diverse Workgroup can play in standing-up a new industry like CCUS.

Track and Respond to Government Funding Opportunities

Recognizing that opportunities were on the horizon, a Workgroup subcommittee was formed to track federal Funding Opportunity Announcements (FOAs), inform Workgroup participants of those opportunities, and form teams to respond to the FOAs when they are available. Prior to Workgroup formation, some Workgroup participants responded to a Request for Information on CCUS-related Federal opportunities in early 2022, laying the groundwork for growing interest in Alaska CCUS.

At the initial Workgroup meeting, funding mechanisms available through or expanded by the Bipartisan Infrastructure Law were reviewed. Upon passage of the Inflation Reduction Act of 2022, the

Workgroup subcommittee also summarized the expanded 45Q tax credit. As CCUS-related FOAs are released, the Workgroup subcommittee continues to provide updates to make sure entities in the State are aware of these opportunities.

Perform Public Education and Outreach

The Workgroup recognized early in the process that public education and outreach would be pivotal to eventual success of any CCS project in Alaska. Even pilot demonstration projects will need to include communication strategies to increase public awareness and to limit misinformation. Gaining public acceptance to store large quantities of carbon in the subsurface and/or transport carbon faces particular opportunities and challenges.

It is critically important to communicate the benefits and risks of carbon storage and sequestration and to address stakeholder concerns. Alaska-based corporations, nonprofits, state agencies, and the University are working together, with the assistance the American Petroleum Institute (API), to conduct initial public outreach by hosting public education sessions to share best practices and explain advantages associated with implementing CCUS to lower energy carbon intensity. Conversations have begun on the potential use of polling to gauge Alaskans' understanding of CCUS and related energy issues. Results will be used to guide public outreach endeavors.

With the introduction of legislation in the State of Alaska, it is anticipated that outreach and education efforts will coincide with legislative hearings.

Develop a Roadmap to Accelerate Commercial CCUS Deployment in Alaska

The Roadmap subcommittee addresses geological, geophysical, and engineering (GG&E) considerations, including technical and economic, for CCUS project feasibility. The Roadmap workgroup has analyzed data for possible first-mover CCUS projects in Alaska and is proposing solutions to address identified barriers to project progression. This paper documents initial steps along this path. Considerations discussed in the "CCUS Importance, Value, and Cost" section apply as Alaska faces the dual challenge of balancing and expanding affordable, reliable, clean energy while minimizing CO_2 emissions.

Alaska's vast geologic storage potential is discussed, with further GG&E work identified to define actual storage capacity. Possible CCUS projects are considered, as well as regional fuel cost considerations that may affect economics and project selection within Alaska.

Alaska CCUS Projects Roadmap

Alaska CO_2 Stationary Sources and Storage Potential

Alaska's major stationary sources of CO_2 are shown in Figure 6 left along with the deep sedimentary basin saline formations available for geologic storage of CO_2. Sedimentary basin storage potential is shown in Figure 6 right from high to low or none. Unmineable coal seam CO_2 storage potential was also evaluated, shown in Figure 7. These figures are from a 2010 statewide screening that informs current thinking [Shellenbaum and Clough 2010]. High sedimentary basin carbon storage potential is present in the North Slope and the Cook Inlet Basins.

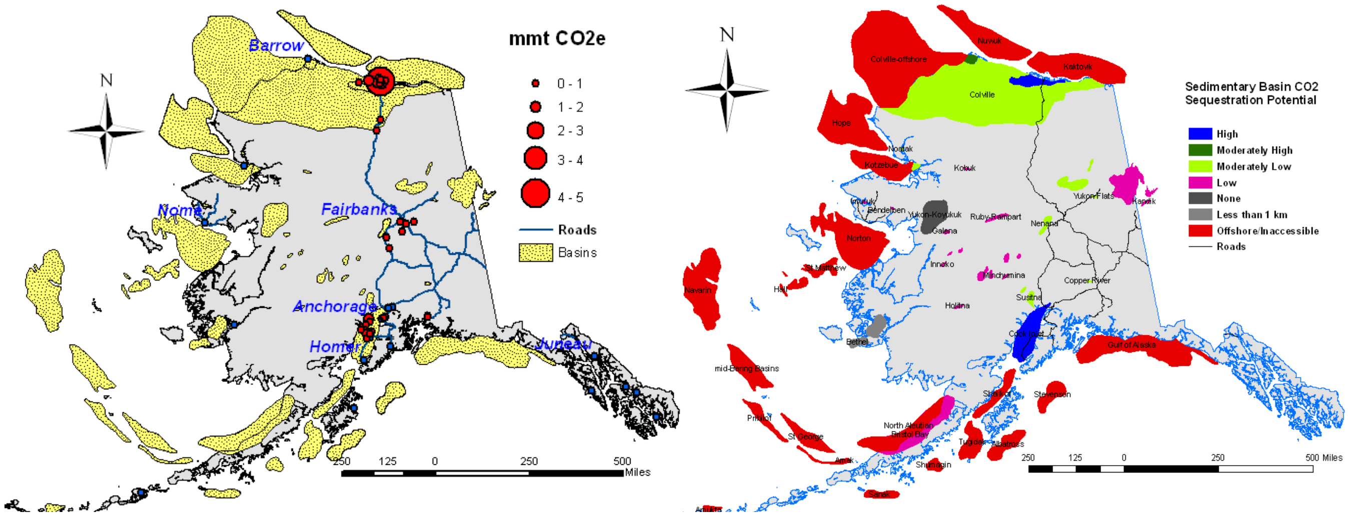

Figure 6 Left: CO_2 Stationary Sources (red) & Deep Sedimentary Basins (yellow). Right: Sedimentary Basin Sequestration Potential [Shellenbaum and Clough, 2010]

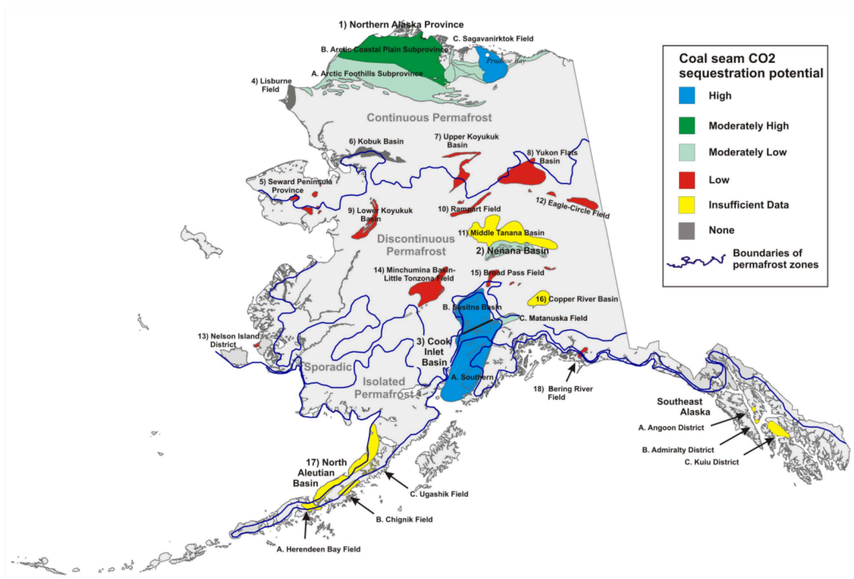

Figure 7: Coal Seam Sequestration Potential [Shellenbaum and Clough, 2010]

From Figure 4, CO_2 storage options include saline aquifers, depleted oil and gas fields, unconventionals (tight rocks), and unmineable coal beds, with the TRL highest for the first two. In the PCOR region, preference has generally been for saline aquifers, in part to avoid entanglement with oil and gas operations.

Geologic appraisal has been subsidized in other regions by the federal government in order to enhance CCS projects, verifying storage security and capacity [Peck et. al., 2020, and in preparation]. Geologic uncertainties include local depth, thickness, and quality; seal continuity and capacity of overlying strata; and the impact of seismic events. Appraisal, including exploration wells and seismic surveys, provides valuable pore space information addressing these uncertainties.

The Carbon Storage Assurance Facility Enterprise (CarbonSAFE) initiative is a system to develop a CCS storage complex from feasibility stage through project construction. Example assessments from Phases I, II, and III are available online and serve as a framework for new site assessment [CarbonSAFE].

The North Slope has abundant data available for formation characterization, gathered to explore for and assess hydrocarbons rather than for storage space evaluation. This data could be gathered and re-purposed for CO_2 storage assessment.

In Southcentral, the Hemlock Formation in Cook Inlet basin shown in blue in Figure 6 right, is considered one of the most prospective CO_2 storage locations in Alaska [Pantaleone and Bhattacharya, UAA Geoscience, 2020]. Specific reservoirs within the Cook Inlet basin and Hemlock Formation have been characterized, but outside of the explored oil and gas reservoirs there is significant uncertainty in the distribution of formation and reservoir properties [Ellett and others, 2022].

These studies, based firmly in geophysics and petrophysics, integrate some lithologies and other rock properties from core, but an improved depositional model is needed to better predict subsurface reservoir unit connectivity. Previous sedimentologic interpretations included a fluvial depositional system, yet there is evidence that the Hemlock Formation may be fluvial megafan or a combination of fluvial and fluvial megafan facies. The distinction is important for understanding reservoir communication. A detailed depositional model using integrated sedimentologic core descriptions, well-log correlation, and analog models should be incorporated to determine subsurface reservoir communication pathways. Petrographic study of potential reservoir rocks and overburden would be useful given dissolution can be an issue in carbon sequestration, and characterization of fracture networks based on high-resolution seismic would be useful to characterize potential reservoir pathways. Reservoir communication is of first-order importance for injection (and production) projects. The size, distribution, and connection within the reservoir ultimately affects the storage volume of captured CO_2 and the development strategy, including reservoir CO_2 plume modeling [Aschoff].

The Interior lacks detailed subsurface data due to the absence of oil development. It has coal seam CO_2 sequestration potential, which has lower technology readiness, and further work including fundamental subsurface and outcrop data gathering is needed to assess and verify storage capacity.

After reviewing prior work, the Roadmap subcommittee requested a seismic hazards screening for carbon sequestration in Alaska from the DNR Engineering Geology Section. Statewide and regional (North Slope, Southcentral, and Interior) features were reviewed including mapped active faults and fault-cored folds, modern seismicity, anticipated peak ground acceleration (from USGS Probabilistic Seismic Hazard Analysis, 2007), and potential for fault surface ruptures. The North Slope is least seismically active. Southcentral, while seismically active, does not currently have faulting that extends from formation depths to surface and is considered amenable for carbon storage, as evidenced by sizeable oil and gas accumulations. The Interior target, within the Northern Foothills Fold and Thrust Belt, has greater potential for surface rupturing faults than the North Slope or Southcentral [Salisbury 2022]. Local, site-specific analysis will be needed for any potential storage project.

The Alaska DNR is seeking funding from DOE-FOA-2799-AOI-2 to develop a database system to collect and share subsurface pore space characterization data. If awarded, that project begins 4Q2023.

Alaska Geologic Storage Appraisal Project Proposal

An appraisal project should be kicked-off to deepen understanding of Alaska's geologic storage potential. A CarbonSAFE Phase II Study, or perhaps three Studies for Alaska's key basins, should likely be performed. Six Phase II storage complex assessments have been performed in other states, funded by DOE plus other entities.

A Phase II Storage Complex Feasibility Study:

> "focuses on one or more specific reservoirs within the defined storage complex, encompassing:
>
> - Data collection.
> - Geologic analysis.
> - Identification of contractual and regulatory requirements and plans to satisfy them.
> - Subsurface modeling to support geologic characterization, risk assessment, and monitoring.
> - Public outreach.
>
> Projects in this phase drill at least one characterization well and acquire geologic data from seismic surveys, core logs, and well tests. These projects evaluate initial reservoir characteristics to determine if the reservoir is suitable for 50+ million tonnes geologic storage, address technical and non-technical challenges that may arise, develop a risk assessment and CO_2 management strategy

for the project; and assist with the validation of National Risk Assessment Partnership (NRAP) tools and other United States Department of Energy (DOE) tools" [CarbonSAFE Phase II].

Potential Alaska CCUS Projects

A unified State response to a DOE Request For Information on carbon sequestration outlines how Alaska meets all DOE criteria established for the Infrastructure Investment and Jobs Act (IIJA), making Alaska uniquely suited for carbon sequestration projects and be a carbon hub site [AK RFI Response]:

- A robust and competitive carbon intensive industrial base.
- High potential for carbon sequestration, including through mineral carbonization or utilization.
- Fossil-energy producing region with high levels of coal, oil, or natural gas resources.
- Considerable carbon sequestration scalability.
- Opportunities for skilled training and long-term employment in an economically disadvantaged region.
- A geographically diverse location from the contiguous United States.
- Climatic conditions that provide unique commercialization advantages.

Considering stationary emission sources for point source capture (Figure 6 left), these can include:

- North Slope: natural gas fired equipment, collectively emits over half of Alaska's stationary CO_2
- Interior: Coal-fired power plants
- Southcentral: Natural gas-fired power plants, refinery, and, in light of natural gas supply shortfall, potential coal-fired power plants

The Alaska RFI response outlines several potential projects which could make Alaska a regional carbon hub with the potential to import CO_2 for storage from the US West Coast or the Asia-Pacific.

Potential CCS projects include Direct Air Capture (DAC). Operating costs are lower where fuel prices are low, such as on the North Slope, and low air temperatures can improve process efficiency.

Alaska has the potential to accept imported CO_2 captured in other states or countries. Alaska has far more sequestration potential than emissions, naturally positioning the state as an importer. Japan and Singapore are considering CO_2 capture with export, as they have emissions but no meaningful way of geologic sequestering. Other potential sources of exported CO_2 are closer, including California.

Another project under initial evaluation would export clean electrical power to Alaska and Western US Interconnections. This project would generate power on the North Slope with an integrated natural gas combined cycle (NGCC) power plant with comprehensive carbon capture technology, which would sequester the carbon in the basin, then deliver this clean power to the Alaska and Western Interconnections via an Ultra High Voltage, Direct Current transmission line. Scoping economics indicate this NGCC CCUS plant could deliver clean power at current wholesale electricity prices at massive scale.

Another potential project is a regional hydrogen hub. The Alaska H2Hub concept would generate commercial-scale, low carbon intensity hydrogen to be used in Alaska, the Western U.S. including Hawaii, and exported to Asia markets. The primary Alaska H2Hub hydrogen production would be liquid ammonia (NH_3). North Slope natural gas shipped via the Alaska LNG Project pipeline to the Cook Inlet would be reformed with atmospheric nitrogen to produce ammonia. Carbon capture and sequestration would sequester 1.6 Mtpa of carbon dioxide (CO_2) in the Cook Inlet Basin [AGDC H2Hub Concept Paper].

Coal- and Natural Gas-Fired Carbon Capture and Transport Cost in Alaska

Our analysis suggests that Alaska's most economically attractive carbon capture opportunities benefit from low-cost fuel, specifically coal-fired plants and natural-gas fired plants located on the North Slope. The least attractive carbon capture opportunities are the natural gas fired plants located in Southcentral Alaska due to high fuel cost and limited natural gas supply. Only 45Q tax credit incentives are considered in this analysis. Other incentives such as grant money, R&D funding, property tax breaks, etc., were not considered. Specific projects may have other benefits that make for compelling economics, but these are not considered here.

Coal- and natural gas-fired plant capture costs are $56 and $71/tonne, respectively, in one study using current technology and lower 48 fuel prices [NETL p. 17], excluding transport and storage. Coal- and natural-gas fired power generation, items #5 and #7 respectively in Figure 3, show carbon *total* sequestration cost ranges from ~ $50 to $160 per tonne including all CCS costs.

For today's Southcentral Alaska natural gas prices, the authors' preliminary estimate for natural gas-fired carbon capture cost is $93 per tonne, excluding transport and storage. The primary reason for higher carbon capture costs for Southcentral is the higher price paid for natural gas.

Carbon capture costs are compared in Table 1 for coal, natural gas at lower 48 prices, and natural gas on Alaska's North Slope and Southcentral, excluding transport and storage cost. Future Southcentral costs are also estimated for imported LNG, as LNG import is being considered to meet the expected demand/supply gap [AK Public Media]. Natural-gas carbon capture is attractive for the North Slope but is not attractive in Southcentral Alaska with current technology, costs, and 45Q tax credits. Fuel price per million British thermal units (MMBtu) are indicative estimates.

Table 1: Carbon Capture Cost Comparison, Natural Gas- and Coal-Fired Power Generation

Fuel	**Fuel Price**, $/MMBtu	**Capture Cost**, $/tonne
Coal	3	56[1]
Natural Gas, US Average Price	5	71[1]
Natural Gas, AK Central North Slope	1.15[2]	65
Natural Gas, AK Southcentral, Current Day	10—12	93—99
Natural Gas, AK Southcentral, Imported LNG	15—20—25[3]	109—124—140

[1]NETL. This excludes 30% investment tax credit for eligible coal-fired CCUS projects which would lower coal capture cost.
[2]AGDC 2022. Central North Slope-based price, i.e., at Prudhoe Bay, excluding transportation cost.
[3]Long term price-range delivered Southcentral Alaska excluding regasification cost, authors' estimate.

Considering emissions, coal-fired power generation with CCS delivers electricity with half or less of the CO_2 emissions of natural gas when the natural gas plant does not have CCS. Meanwhile the cost of coal-fired electricity with CCS is expected to be lower or cost competitive with natural gas generation without CCS, which would be an important factor in areas with already high electricity costs, such as is the case in Southcentral and the Interior. Costs and emissions are discussed below.

Natural Gas-Fired Carbon Capture – North Slope vs Southcentral Alaska

Natural gas-fired carbon capture costs are higher since its ~4% CO_2 flue gas concentration is much lower than ~14% CO_2 flue gas concentration from a coal-fired plant. In part this is because higher amine regeneration temperatures are required, which consumes more fuel.

With an $85/tonne 45Q tax credit available to cover capture, transport, and storage, natural gas-fired carbon capture is more attractive on the North Slope than in Southcentral due the North Slope's much lower natural gas price. Southcentral Alaska natural gas costs $10 to $12 per MCF, while on the North Slope the cost is $1.15 per MCF, a tenfold difference [YCHART, AGDC]. Another obstacle for Southcentral is the natural gas fuel price may increase significantly if LNG imports are required to meet local demand [ADN Nov-2022].

At today's 45Q tax credit level and using screening-level capture costs, North Slope natural gas carbon capture is substantially more economically attractive than Southcentral natural gas carbon capture, advantaged by lower fuel prices. Natural gas CCS operating costs increase significantly with higher natural gas fuel prices. As Table 1 shows, capture costs range from $65 to $140 per tonne for natural gas prices from $1 to $25 per MMBtu, excluding transport and storage costs. These calculations, consistent with the NETL cost model, illustrate the importance of fuel gas price in carbon capture. However, new technology may make these type projects more attractive.

Coal-Fired Carbon Capture

Coal-fired plant carbon capture has the advantages of higher flue gas CO_2 concentration and lower fuel price per unit of heat, and both lower capture costs. United States' electricity producers paid $4.98 per MMBtu for natural gas in 2021. Meanwhile, coal power plant operators nationally paid an average of $1.98 per MMBtu. Natural gas prices are typically 2.5 times higher than coal per unit of heat [Statista]. Alaska has abundant coal reserves, but limited, high-cost natural gas except on the North Slope.

Another advantage for coal-fired carbon capture is Section 48 of the US Federal tax code. It provides a 30% investment tax credit targeted at incentivizing CCUS on coal-fired power generation. This tax credit is not available to other forms of fossil-based plants.

Coal remains the world's leading power-generation fuel. Efforts should continue as a priority to advance coal-fired plant carbon capture technology, for retrofitting existing plants and designing new plants with carbon capture incorporated in initial design. In 2020, more than 35% of the world's power came from coal according to the BP Statistical Review of World Energy. Roughly 25% came from natural gas, 16% from hydro dams, 10% from nuclear and 12% from renewables like solar and wind. There are 6,559 coal-fired plants operating globally. There are 365 new coal-fired plants currently under construction, and another 576 units announced, pre-permit, or fully permitted [GEM 2023].

In China alone, more than 1,000 coal plants are in operation, with almost 240 planned or already under construction. [Reuters COP26] In 2022, China approved more than three times as much new coal-fired power generation capacity than in 2021 according to Peking University, with more than 65 million kilowatts of coal-fired generating capacity winning government clearance [CX Daily]. Several pilot- or demonstration-scale CCUS projects have been achieved in different industry sectors in China; however, large-scale deployments are lagging other nations, especially in the coal power sector [ACS].

Emissions From Coal- and Natural Gas-Fired Plants With and Without Carbon Capture

A coal-fired plant *with* CCS typically has one-half or lower carbon intensity, measured in tonnes carbon per MWh net electricity, of a natural gas plant *without* CCS. As shown in Table 2, national lab analysis shows the carbon intensity for a coal-fired plant with CCS is just 28% of a natural gas plant without CCS [NETL p. 15], 0.10 and 0.36 t/MWh-net, respectively, consistent with Figure 1 data. Specific plant carbon intensities vary depending on many factors including capture technology and process efficiency.

Table 2: Carbon Intensity Emissions, Natural Gas- and Coal-Fired Power Generation

	Natural Gas		Coal	
	Without CCS	With CCS	Without CCS	With CCS
Carbon Intensity, metric tonnes/MWh-net	0.36	0.04	0.77	0.10

For natural gas turbines, carbon capture reduces carbon emissions by 90%, from 0.36 to 0.04 t/MWh-net. This opportunity is particularly relevant for Alaska's North Slope with abundant, low-cost natural gas fuel and substantial industrial-scale emissions.

Transportation and Storage Cost Assumptions for Alaska

For the purposes of this study, the authors are assuming transportation and storage costs to be no more than $20/tonne. This in part is based on the difference between current tax credit level and current capture costs, and is a placeholder until further, site-specific costs are analyzed. UAF-INE is performing a transportation network source/sink cost analysis for Alaska and a $20/tonne upper limit is consistent with their methodology.

Observations for Potential CCUS Projects in Alaska

Several observations can be made, informed by geological, geophysical, engineering, and economic considerations. They are grouped by region below:

For the North Slope:

- The North Slope contains high sequestration formation potential and extensive subsurface well and geophysical data from commercial oil and gas development. This data, primarily gathered to appraise hydrocarbons, can to some extent be repurposed to delineate geologic CO_2 storage potential.
- The North Slope emits half of the State's stationary CO_2 emissions from natural-gas fired equipment, making it the largest opportunity for industrial scale capture and storage.
- The North Slope contains abundant, developed natural gas resources. Low-cost fuel improves natural gas carbon capture costs as discussed and may make CCS projects economically attractive.
- Carbon capture would make CO_2 available for EOR use which could enhance project value.

For the Interior:

- The Interior has six coal-fired plants which may be attractive for deploying capture technology, but the Interior has moderately low saline sequestration potential based on initial screening.
- The Interior has un-minable coal seam CO_2 sequestration potential, which has a lower technology readiness level than other storage targets.
- The Interior, within the Northern Foothills Fold and Thrust Belt, has greater potential for surface rupturing faults than the North Slope or Southcentral [Salisbury 2022].
- The Interior lacks detailed subsurface data. Further work, especially fundamental geological and geophysical data gathering, is needed to assess and verify secure geologic storage capacity.

For Southcentral:

- Southcentral contains high sequestration formation potential and extensive subsurface well and geophysical data primarily gathered to appraise hydrocarbons for oil and gas development.
- Carbon capture would make CO_2 available for EOR or enhanced gas recovery use which could enhance project value.
- Southcentral has high natural gas prices compared to the national average, resulting in carbon capture costs that exceed the potential financial benefits of the 45Q tax credit.
- Southcentral has an imminent gas supply shortfall. The Cook Inlet proved gas supply is forecast to fully meet demand until 2026—2027 [AK DNR 2022, p. 17], after which a shortfall is expected.
- Southcentral has abundant coal available as a low-cost fuel, which when coupled with CCUS can provide clean, reliable, affordable energy at one-half or lower emissions than natural gas.

Screening Findings and Recommendations

Technology breakthroughs and market pressures can lower CCUS costs, so these statements should be periodically revisited. Only 45Q tax credit revenue has been considered in this economic screening. Other revenue, such as financial grants, loan guarantees, offsets, or other funding are not considered. Particular projects may have specific advantages that may improve economics, including ESG considerations. Given this is a screening study, Screening Findings are provided rather than Conclusions.

Screening Findings:

1. For Southcentral and the Interior, natural gas plant carbon capture appears unattractive economically in this screening due to regionally high natural gas prices, current 45Q tax credits, and using project costs typical of the lower 48 states. Capture costs alone, excluding transport and storage, exceed the current 45Q tax credit amount.
2. Carbon capture on the North Slope and Cook Inlet could enhance oil recovery and oil production revenue by making CO_2 available for EOR use, which may increase CCS project value. CO_2, a well-known EOR injection fluid, can also enhance gas field recovery.
3. Coal-fired plants with CCS produce electricity at one-half or lower carbon intensity of a natural gas-fired plant without CCS. Coal-fired CCS tends to be attractive economically using 45Q tax credits and lower 48 capture costs, and may achieve carbon neutrality with beneficial use such as food growing operations.
4. In-state carbon capture could enhance food security by making CO_2 and heat available for local greenhouse use.
5. Transportation and storage costs are assumed to be no more than $20/tonne for this study. This is based in part on the difference between current 45Q tax credits and estimated capture costs and is a placeholder until further, site-specific costs are analyzed.

Screening Recommendations:

1. A legal and regulatory framework for CCUS should be established for the State. The Legislature should consider passage of the recently introduced Carbon Storage bill into law.
2. The State should seek Class VI injection well Primacy from the US Environmental Protection Agency (EPA), clarify departmental roles and responsibilities to facilitate timely project evaluations, appropriate necessary funding and staff, and set and publish internal targets for the time required for project reviews and approvals. Recently introduced legislation allows the Alaska Oil and Gas Conservation Commission (AOGCC) to seek Primacy ("may" not "shall"), and AOGCC has notified the EPA in a letter of intent that it will seek offered funding to assess the work required to establish State Primacy for Alaska.
3. Subsurface data should be organized and made publicly available so project teams can evaluate local and regional storage options. The Alaska DNR applied for DOE-FOA-2799 AOI-2 funding to progress this work.
4. An appraisal project should be kicked-off to deepen understanding of Alaska's geologic storage potential. A CarbonSAFE Phase II Study, or perhaps three considering Alaska's key basins, would focus on one or more specific reservoirs within the defined storage complex, drill at least one characterization well and acquire and integrate geologic data from seismic surveys, core logs, and well tests. Six Phase II Studies have been completed in the US, funded by DOE plus other entities.
5. Pipeline analysis should be performed to evaluate economic advantages for carbon capture CO_2 pipeline networks from sources to a CO_2 hub storage site.
6. Coal-fired power generation CCS projects appear prospective economically, when screened using current 45Q tax credits and lower 48 state's typical capture costs, and should be evaluated for existing and new plants. US tax code Section 48 provides an additional 30% investment tax credit for coal-fired power generation CCS projects which was not considered in this screening.
7. For the North Slope, with the State's largest stationary emissions sources, CCS represents an opportunity to reduce CO_2 emissions by 90% from its natural gas-fired equipment. North Slope natural gas CCS, advantaged by low-cost fuel, assuming capture costs typical for lower 48 states, appears economically attractive in this preliminary screening and should be evaluated further.
8. DAC may also be attractive on the North Slope given abundant, low-cost natural gas fuel and colder temperatures that increase operating efficiency. Further evaluation and DAC pilot projects should be considered.

Disclaimer

Opinions and views expressed are solely those of the authors and do not reflect the organizations with which they are affiliated. Forward-looking statements are to some degree speculative and uncertain.

Acknowledgments

The authors recognize and thank:

- Senator Lisa Murkowski for encouraging UAF-INE to join the PCOR partnership in 2019.
- Governor Mike Dunleavy for leadership and vision establishing carbon storage in Alaska.
- Former DNR Commissioners Corri Feigi and Akis Gialopsos for supporting the Workgroup.
- Ryan Fitzpatrick, Aaron O'Quinn, and Sean Clifton of the DNR for their efforts to stand-up the regulatory committee and advance CCUS legislation in the State.
- Barrett Salisbury for the Alaska seismic hazards screening, and Marwan Wartes for his support. Both are with DNR's Energy Resources Section, Division of Geological and Geophysical Surveys.
- Nick Fulford, Gaffney, Cline and Associates, for a CCUS technology review including Figure 3.
- Jennifer Aschoff, Tyler Burton, Abhijit Dandekar, Corri Feigi, Nick Fulford, Lisa Novak, Travis Peltier, Anthony Pennino, Robert Power, and Rawdon Seager for reviewing this paper.
- The PCOR Partnership for financial and technical support of UAF-INE's CCUS work, including the Workgroup.
- Arctic Slope Regional Corporation for supporting the Workgroup.
- Workgroup participants for their efforts, ideas, and recommendations for further work and topics.

Those wishing to join the Workgroup should contact an author.

Nomenclature (shown in parentheses)

45Q – Section 45Q of US Internal Revenue Code provides tax credits for CO_2 storage.
48 – Section 48 of US Internal Revenue Code provides a 30% investment tax credit for CCUS on coal-fired power generation.
AGDC – Alaska Gasline Development Corporation.
AOGCC – Alaska Oil and Gas Conservation Commission
API – American Petroleum Institute.
BBA – US Federal Law, the Bipartisan Budget Act of 2018.
BE – bioenergy.
CI – Carbon Intensity, grams of CO_2 equivalent per Megajoule of energy, or metric tonnes/MWh-net electrical energy,
CCS – Carbon Capture and Storage.
CCUS – Carbon Capture, Use, and Storage.
CO_2 – Carbon Dioxide.
COP 26 – United Nations Conference of Parties 26th meeting in Glasgow in 2021.
DAC – Direct Air Capture.
DNR – Alaska Department of Natural Resources
DOE – US Department of Energy
EERC – The Energy and Environmental Research Center at the University of North Dakota.
EOR – enhanced oil recovery; CO_2 EOR dates from 1972 with the Val Verde pipeline to West Texas Permian Basin oil field.
EPA – The US Environmental Protection Agency
ESG – Environmental, Social, and Governance.
FOA – Funding Opportunity Announcement, typically issued by a US government agency, e.g., the US Department of Energy.
GDP – gross domestic product.
GG&E – geological, geophysical, and engineering.
IEA – International Energy Agency.
IGCC – Integrated Gas Combined Cycle.
IPCC – Intergovernmental Panel on Climate Change
IRA – US Federal Law, Inflation Reduction Act of 2022.
MCF—thousand cubic feet, a standard unit measure of natural gas.
MMBtu – Million British thermal units. Natural gas has 1.037 MMBtu per thousand cubic feet (MCF) typically.

Mtpa – million tonnes per annum.
NGCC – natural gas combined cycle.
NGO – Non-Government Organization.
NH_3 – ammonia.
NPC – National Petroleum Council. The NPC is a federal advisory committee to the US Secretary of Energy.
PC – Pulverized Coal.
PCOR – Plains CO_2 Reduction Partnership, sponsored by EERC of UND, one of four US regional CO_2 reduction partnerships.
REC – Renewable Energy Credits.
t or Tonne – metric tonne – 1000 kilograms; a metric tonne is a common unit for measuring carbon dioxide.
TRL – Technology Readiness Level, a scale where 1 is fundamental physics and basic research and 9 is deployed technology.
UAA – University of Alaska Anchorage
UAF-INE – University of Alaska Fairbanks Institute of Northern Engineering.
UND – University of North Dakota.
US or USA – United States of America.
UN – United Nations
VCUs – Verified Carbon Units
VCS – Verified Carbon Standard

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