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Carbon Capture, Utilization & Storage

Market Overview and Project Considerations

October 2021

Carbon Capture, Storage and Utilization (“CCUS”) is a game-changer in terms of reducing anthropogenic carbon emissions, which is critical to reaching net zero emission targets. CCUS improves the carbon footprint of existing emitters, reduces historical emissions through direct air capture, and enables the production of low-carbon hydrogen. Despite these attributes, historical CCUS development has been slow – but that’s changing. Recognizing the importance of CCUS in achieving net zero emissions, policymakers are actively developing the regulatory and pricing frameworks needed for widespread CCUS deployment. It is now industry’s turn to get smart and leverage new policy into action. In this report, we examine the current state of the global CCUS market and its role in achieving net zero emissions, as well as key drivers underpinning a successful CCUS project with a focus on capture costs, geological, and regulatory considerations.

This report addresses the following:

- Achieving net zero with CCUS in a global context
- Current state of CCUS globally
- Breakdown of CCUS project economic drivers
- Capture cost supply curve and recent project capture costs
- Geological factors in CCUS
- Regulatory considerations and carbon pricing mechanisms

CCUS in a Global Context

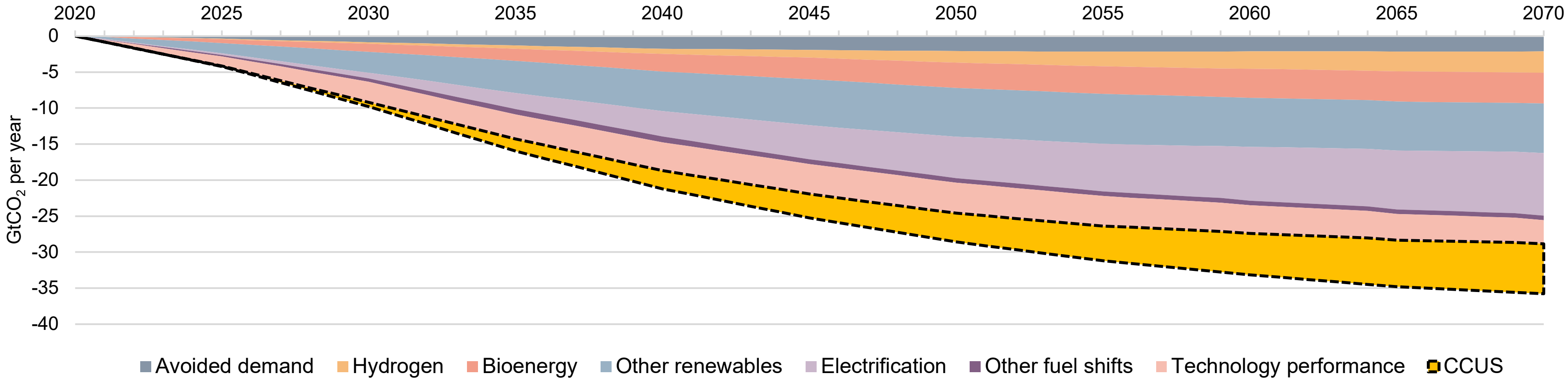
Achieving Net Zero Emissions, and Where We Are Today

Achieving Net Zero with CCUS

CCUS a critical catalyst for net zero global energy system

- Over the past several years, governments and industries around the world have charted a new course – one aimed at achieving net zero emissions before the year 2100. The consensus view is that net zero will be achieved mostly through electrification, renewable technologies, and increasing efficiencies of existing energy systems. However, there are several key elements critical to achieving net zero emissions that rely on CCUS:
  - reducing emissions from existing energy systems, particularly in hard to abate sectors;
  - producing clean hydrogen
  - balancing unavoidable emissions by removing carbon directly from the atmosphere.
- In the EIA's Sustainable Development Scenario, CCUS-related emission reduction accounts for 20% of total CO_2 emission reduction by 2070, which is the year the Scenario has global energy systems achieving net zero.

Annual Energy Sector CO_2 Emissions Reductions – IEA Sustainable Development Scenario



Source: IEA, Sproule Analysis

Current State of CCUS

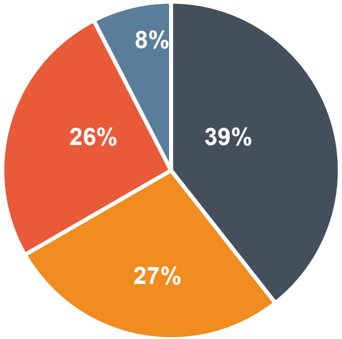
Existing CCUS deployment lags other clean technologies

- There are currently 33 existing commercial CCUS facilities globally – 12 in the United States, 4 in Canada, 3 in Norway, with the remaining projects in Brazil, Saudi Arabia, UAE, China, and Australia. Of the existing commercial projects, 27 use and store CO_2 via Enhanced Oil Recovery (“EOR”).
- Considering the widespread potential of CCUS technology applications, the current low number of projects and concentration in EOR schemes demonstrates that existing CCUS deployment lags other clean technologies, but there is significant potential for growth.

But momentum is growing

- A recent surge in CCUS investment is being spurred by strengthening national climate commitments and evolving carbon pricing mechanisms. There are over 100 commercial projects currently proposal, being developed or under construction, with 10 of these linked to Enhanced Oil Recovery projects. Many of these projects are being designed around CCUS industrial hubs and shared transportation networks, like the Alberta Carbon Trunk Line in Canada.

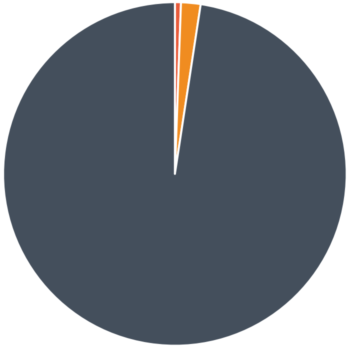
2019 Global Energy-Related CO_2 Emissions



34 $GtCO_2$

■ Power Plants ■ Industrial Plants ■ Transport ■ Buildings

CCUS Capacity – Existing vs Required ($GtCO_2$ per year)



■ Existing CCUS Capacity - 0.04 GtCO2/yr

■ Capacity Under Development - 0.13 GtCO2/yr

■ Capacity Required to Achieve Net Zero by 2070 (IEA SDS) - 6.9 GtCO2/yr

Source: IEA, Sproule Analysis

Key Factors Driving Successful CCUS Projects

Economics, Geology, and Regulation

What Drives CCUS Economics?

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Carbon Capture Cost

- CO_2 capture is the single largest contributor to CCUS associated costs and is inversely proportional to the concentration and pressure of the CO_2 emission stream. Overall challenges include energy penalty, cost, technology maturity and scale-up, and need for further R&D.

Compression and Dehydration

- Compression and dehydration costs will vary depending on dryness (or wetness) of CO_2, as well as depth of the reservoir.
- Dry, high purity CO_2 is more common in blue hydrogen production processes.

Transportation

- Distance between emission sources and storage sites as well as greenfield vs brownfield infrastructure development drive transportation costs. Significant economies of scale can be achieved through the development of CCUS hubs.

Injection and Geological Attributes

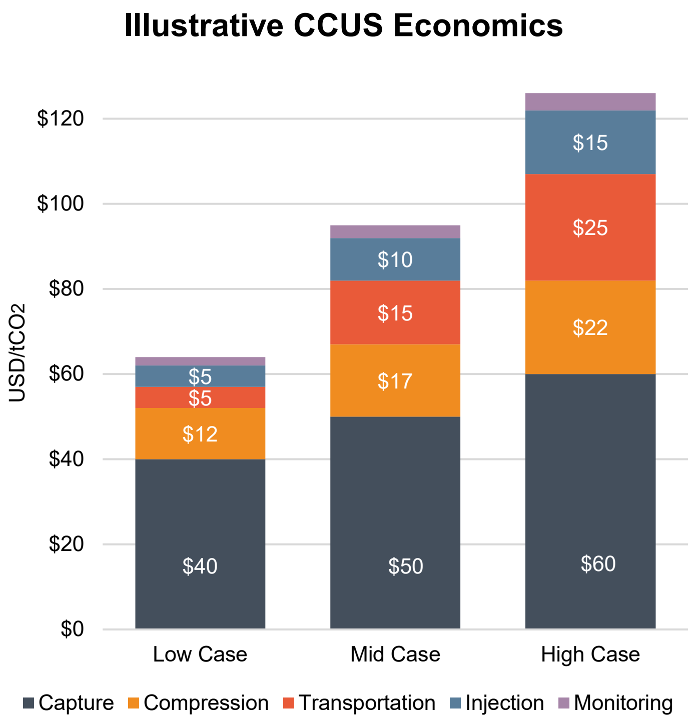
- Number of injection wells, depth of the reservoir, location of reservoir (onshore/offshore), size of reservoir, injection rates, all contribute to injection costs.

CO2 Monitoring

- Monitoring costs depend largely on the regulatory requirements governing a specific project.
- Typically, higher well penetrations, number of injectors and larger CO_2 plume sizes will increase monitoring costs.

Carbon Pricing and Other Incentives

- The economics need to make sense. Near-term, policy initiatives providing support to project developers will accelerate development. Long-term, widespread CCUS deployment depends on an effective carbon pricing framework.

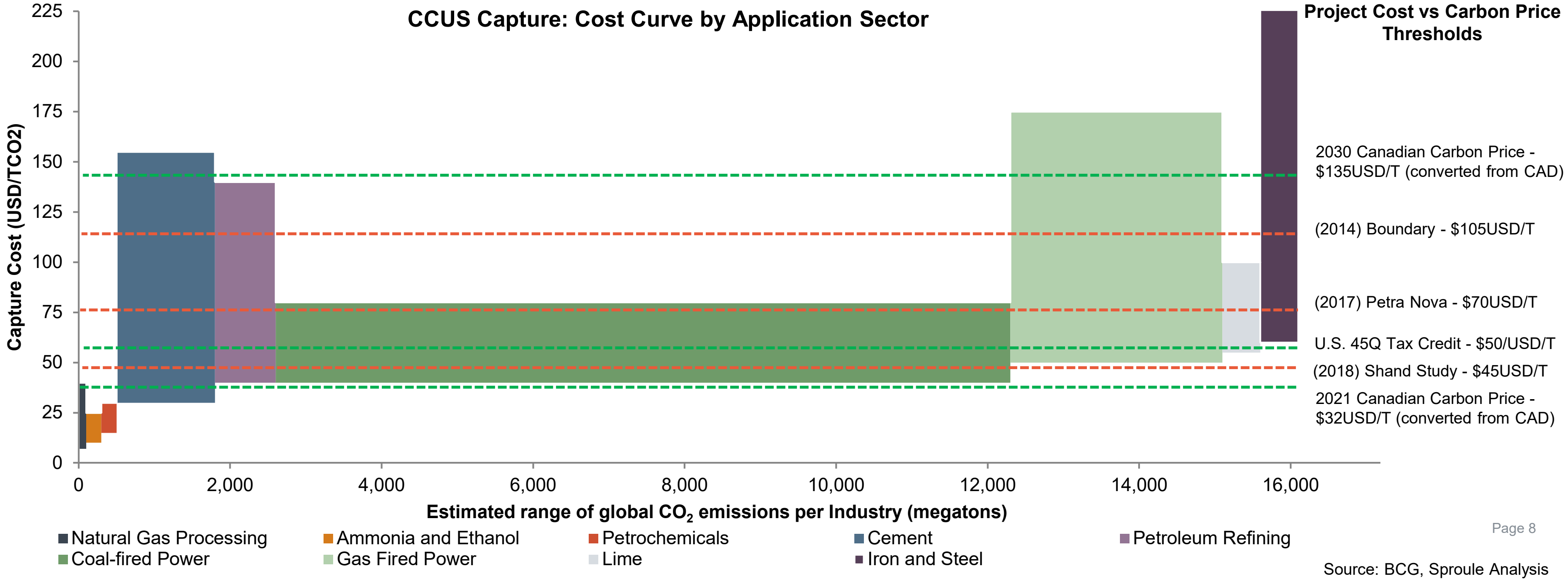


Source: GCCS, National Petroleum Council, Sproule Analysis

CCUS Capture: Cost Curve by Application Sector

Highgrading projects to concentrated CO_2 emission sources will support near term development

- Capture costs are currently the largest single contributor to overall CCUS project costs and vary widely depending on concentration of the CO_2 stream and maturity of the capture technology. Natural gas processing, Ammonia and Ethanol, and Petrochemicals offer the lowest capture costs due to their highly concentrated CO_2 stream. CO_2 capture from power plant flue gas streams, on the other hand, is expensive due to lower concentrations and high capital costs of retrofitting existing infrastructure. Capture costs in hard to abate sectors like petroleum refining and cement manufacturing are highly variable due to the wide CO_2 concentration variance in flue gas streams
- Costs are decreasing as technologies mature. Scale of projects is also critical to cost efficiency, as is greenfield vs brownfield expansions where CO_2 from various point sources share existing infrastructure.



Source: BCG, Sproule Analysis

CCUS Cluster-Hub Model

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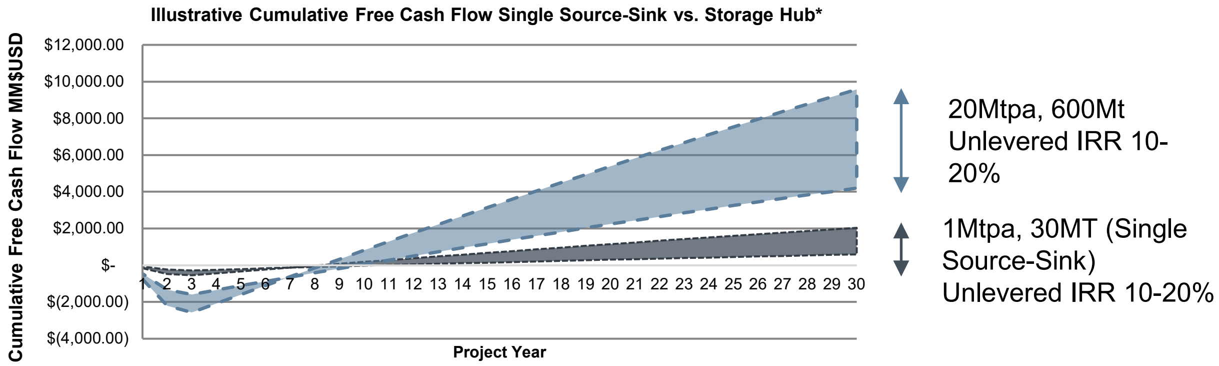
- The Carbon Capture, Storage and Utilization (CCUS) Cluster-Hub model aggregates and connects multiple CO_2 emission sources to single or multiple storage locations (sinks) using shared infrastructure. This model targets cost savings through economies of scale to promote and accelerate development of CCUS projects. Cluster-Hub is the business model of choice for governments and regulators looking to maximize the use of pore space, maximize efficiency of government grants, strengthen risk management practices, and generate direct revenue through revenue sharing or fee per tonne models. The CCUS business model is being implemented in Canada, U.S., Europe, and other countries. CCUS Cluster-Hub projects require a large capital commitment, often with government support through grants or private-public partnerships.
- Cluster-Hub projects provide an opportunity for attractive, stable lower risk returns for investors from transportation and storage fees. Projects can be underpinned and de-risked through multiple source emissions and sinks and simultaneous partnerships targeting anchor emitters near favorable geological storage to avoid large infrastructure costs. Co-locating high-purity, low capture cost, emission sources with high-quality, lower risk, geological storage opportunities is optimal for CCUS projects.
- Capital costs can range from tens to hundreds of millions of dollars depending on distance between source and sink, volume of CO_2 being transported, and storage site characteristics such as a depth and quality of the target saline aquifer among other considerations. Cost reductions through economies of scale are driven by operational, transportation, monitoring and post injection site closure cost efficiencies.
- Illustrative Cluster-Hub example below demonstrates the cumulative free cash flow profile and cost of a 1Mtpa versus a 20Mtpa Cluster-Hub, transportation and sequestration, highlighting the impact of economies of scale on the project economics.
- Based on this model, assuming a capture cost of $50/T, a carbon tax, and resulting offset or tax credit, of $90/T is required for smaller CCUS projects to be viable. The carbon tax or subsidy threshold will drop with increasing purity of source CO_2 and closer proximity to storage.



USD/TCO2	1Mtpa		20Mtpa
Total Capex	$10/T		$2/T
Total Opex	$18/T		$3/T
Equity Return	$9-20/T		$4-10/T
Total Transportation & Storage Cost	**$37-48/T**	**vs.**	**$9-15/T**

* 30 year project, 200 km pipeline, no carbon subsidies or offset credits included, fixed IRR range of between 10% and 20%, assuming CCS will be a regulated business

Geological Factors for Carbon Storage

Detailed subsurface analysis is critical to address the key issues of injectivity, storage resource, and containment risks

- Finding the right reservoir to inject CO_2 requires detailed subsurface analysis given the numerous variables that make a reservoir suitable for CO_2 sequestration: reservoir pressure and temperature, porosity, permeability, seal thickness and continuity, geomechanical properties of pressurization and faulting, wellbore leakage pathways – all key factors for CO_2 sequestration suitability.
- Knowledge of geothermal and hydrogeological regimes is critical to evaluating the presence of supercritical dense phase CO_2 and CO_2 storage capacity in aquifers. The aquifer needs to be sufficiently deep, typically >800m, to allow pressures and temperatures necessary for CO_2 to exist as a super critical fluid (i.e., 31.1ºC and 7.8 MPa).
- CO_2 sequestration modelling is required to evaluate, predict and monitor the underground behavior of CO_2 during and post injection, and to optimize the injection strategy – mobility of CO_2 in the reservoir is highly dependent on structure and horizontal and vertical permeability.
- Many requirements of suitable geological storage are similar to what is needed for the occurrence of subsurface hydrocarbon accumulations. Learnings from the characterization of hydrocarbon reservoirs provides insight into geological formations suitable for sequestering CO_2.
- Depleted oil and natural gas reservoirs have lowest technical risk since reservoirs are well characterized, have demonstrated their ability to contain buoyant fluids, and have lower development cost through leveraging existing infrastructure.
- Deep saline aquifers offer the largest storage potential, with the highest risk due to the least amount of data, new wells and infrastructure are often required, making their development more capitally expensive.

Source: 2017 PCOR Partnership Atlas

Regulatory Considerations

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Regulatory clarity and certainty critical to successful CCUS strategy

- A clear and well-structured CCUS regulatory framework is critical for widespread CCUS development, but due to the limited number of existing projects to date, most jurisdictions are in early stages of regulation development. Resource-rich countries that have a history of resource development, such as Canada, U.S., Australia, and Norway are more advanced in CCUS project development and regulation, likely resulting from analogous resource development regulations and greater societal acceptance of similar projects.
- In addition to promoting CCUS technology and project development and meeting needs of project proponents, policy and regulations equally need to address risk and liability issues to ensure the safe long-term storage of CO_2.
- For project proponents, navigating early-stage regulatory frameworks can prove problematic considering the variety of upstream, midstream, and downstream aspects of CCUS projects as well as significant differences between regulatory regimes across regions.
- Regulatory clarity and certainty, long-term liability, and pore space rights are commonly highlighted as the largest barriers to commercial-scale deployment of CCUS.

Implications

- Permitting and approval processes can be lengthy, complicated, and onerous, with multiple levels of government regulatory oversight. Clarification of regulatory responsibilities and greater alignment between various regulatory bodies would help further streamline CCUS applications and permitting.
- Regulatory and statutory assurances should be framed to improve the long-term risk mitigation and storage costs associated with CCUS. Many risks associated with CO_2 storage could have lower probabilities of occurrence and be mitigated; liability protections must not be prohibitively expensive.
- Opportunity for value creation through effective pore space management, leasing pore space and fee for storage models.
- CCUS Regulations need to be aligned with climate policy and commitments. CO_2 subsidies, tax or offset credits must be compatible with regulations.
- Legal and regulatory framework fundamental to the advancement of CCUS projects. Future regulations for CCUS should be comprehensive, transparent and build on frameworks developed by countries with more advanced CCUS regulatory environments.

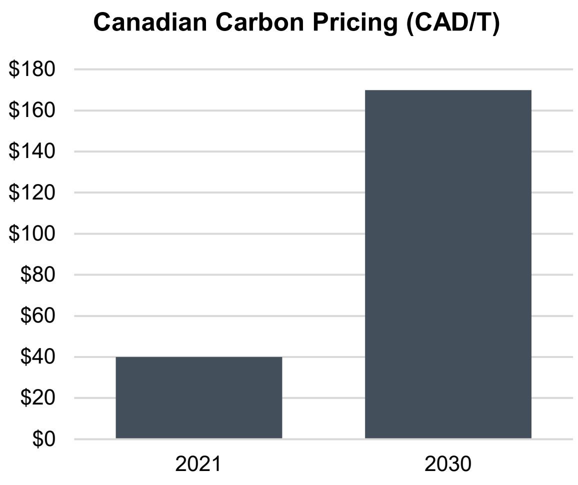
Regulatory Considerations over CCUS Lifecycle

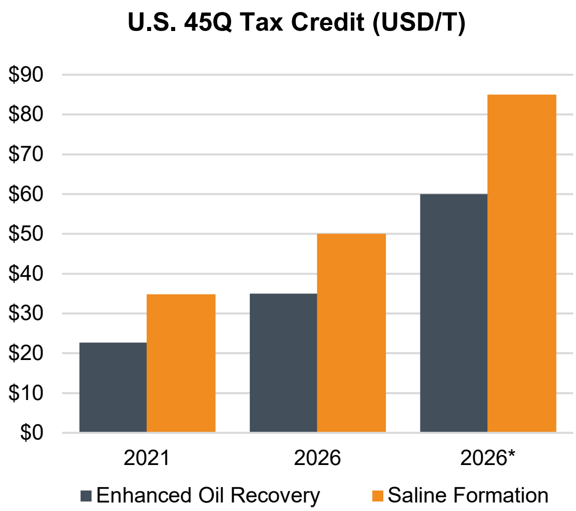
Design, Application & Approvals	Operations		Closure & Post-Closure	Other
Pre-injection	Transport	Sequestration		
Regulatory roles and responsibilities of government and agencies	CO_2 Pipeline Construction Guideline Regulations	Measurement, Monitoring, And Verification – Requirements, planning, & reporting	Shut-down and/or closure planning	Compatibility to emissions reduction targets
Environmental impact, and mitigation and risk assessments	Open access consideration and service rate regulations	Lease applications and terms of pore space ownership	Post injection stewardship and liability for CCUS site	Interaction with mineral rights and other resource development (hydrocarbon, coal, geothermal, lithium)
Permitting processes (Drilling, CO_2 Injection)	Pipeline Integrity Regulations	Carbon storage tenure regulation	Surface reclamation	
Stakeholder and public consultations	Definition of CO_2 and CO_2 purity for transport	Leakage provisions	Post-closure Stewardship Funds	

Carbon Pricing and Other Incentives

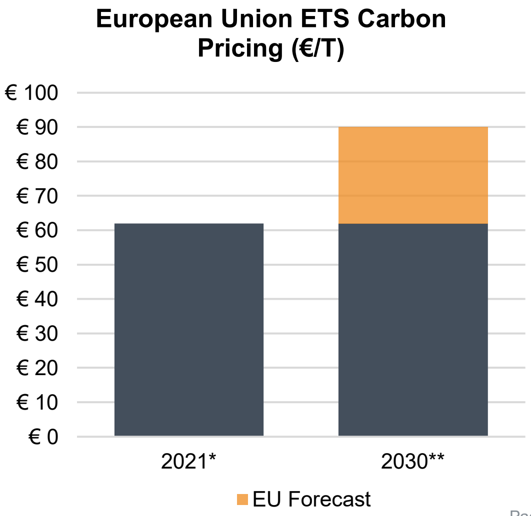
Carbon prices, tax incentives, and government support are all key to advancing CCUS development

- To date, virtually all major non-EOR related CCUS projects have relied on significant government support, whether through funding or tax incentives, in order to make the projects economically viable. This is due to the significant risks associated with many “first-of-their-kind” projects, and sub-breakeven carbon pricing.
- Widespread CCUS deployment will not occur unless carbon prices are sufficient to make projects economically competitive, and we are seeing significant progress in legislating carbon pricing schedules that are sufficient to drive CCUS project development.
- In Canada, prices are proposed to increase 4.25x between now and 2030, from $40 CAD/T to $170 CAD/T. This is critical when you consider that at $170 CAD/T, major CCUS projects like Boundary Dam in Saskatchewan would be economically viable without government support.
- In Norway, the carbon prices are increasing from $70 USD/T today to $237 USD/T by 2030. We are also seeing the Norwegian government step in to fund major CCUS projects, like the $2.6 billion USD Longship project 70% funded by government.
- In the U.S., the 45Q tax credit has accelerated CCUS development, offering $50 USD/T for captured and permanently stored CO_2. U.S. legislation has been proposed to raise the value of 45Q tax credit from $50 to $85/T for CO_2 captured and stored in saline geologic formations.





*Proposed CCUS Tax Credit/Direct Pay Amendments



*EU ETS Futures Price Sept. 28, 2021
**Estimated EU ETS Price

Challenges and Opportunities in the CCUS Market

Challenges

- The capital-intensive nature of CCUS projects has limited the deployment of CCUS outside of Enhanced Oil Recovery applications.
- Grants, incentives, and reliable/sufficient carbon pricing mechanisms are needed to stimulate the level of CCUS investment and project development needed to meet national and global emission reduction targets.
- CCUS regulatory frameworks are not mature, and in many jurisdictions are still being developed. Widespread CCUS project development is unlikely until both government and industry has clarity on the regulations governing CCUS projects.
- Global storage resource is not a constraint - CO_2 storage resource is massive. Global prospective CO_2 storage resource is estimated between 10^4 –10^5 Gt of CO_2. The challenges are more surrounding financial incentives and business drivers and supportive regulatory regimes.

Capital Costs | **Carbon Pricing** | **Emissions and Storage** | **Policy and Regulatory**

Opportunities

- Meeting global net zero targets requires global CCUS capacity to increase roughly 175x, offering tremendous growth and revenue generation over the energy transition time horizon.
- Learnings from existing projects will continue to advance and push new projects further down the cost curve. Decreased project costs combined with evolving carbon pricing regimes will continue to increase the economic competitiveness of CCUS projects.
- For jurisdictions with significant upstream and midstream oil and gas expertise, existing oil and gas extraction, processing, transport, and injection capabilities will support cost-leading CCUS development.
- More and more CCUS supportive policy is emerging, creating new CO_2 value drivers for CCUS projects globally. These include CCUS-specific language in climate policy and incorporation of CCUS in national emissions targets, hydrogen strategies, direct CCUS grants, low carbon fuel standards, carbon pricing and tax, direct pay, and offsets credits systems.
- Now more than ever, governments, retail, and institutional investors are supporting green technology and energy transition initiatives like CCUS.

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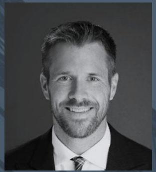

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About Sproule

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