Carbon Capture, Utilization, and Storage

Handbook for Policymakers

Opening Letter From Secretary Raimondo

Climate change is a profound and global challenge. The United States has risen to meet this challenge. In Executive Order 14008, the Administration recognized that now is the moment to act to avoid the worst impacts of the climate crisis as well as to seize the opportunity that tackling climate change presents. The U.S. Department of Commerce is part of this whole-of-government effort to meet the climate moment and ensure a just and rapid transition to a lower carbon, sustainable, and prosperous future.

In addition to full-scale mitigation efforts, the Administration has indicated that meeting global climate ambitions will require responsible deployment of carbon capture, utilization, and storage (CCUS) and carbon dioxide removal (CDR) technologies. CCUS has a critical role to play in industrial sectors where emissions are challenging to address. Likewise, CDR can help with removing carbon dioxide from ambient air. The U.S. and its partners are working now to help countries adopt CCUS policies, mobilize climate financing, take up CCUS technologies and practices, and reform laws and regulations to attract responsible CCUS investment.

At the U.S. Department of Commerce, the Office of the General Counsel's Commercial Law Development Program (CLDP) has assisted countries to update their commercial laws and regulations for over 30 years. Now, with funding and support from the U.S. Department of State's Bureau of Energy Resources (ENR), CLDP has organized a free, accessible, fit-for-purpose guide for policymakers and regulators on how to catalyze investment into capturing carbon dioxide emissions for use or permanent storage.

In developing the handbook, CLDP convened a group of experts on CCUS from the US Government, multilateral institutions, non-governmental organizations, industry, and academia. These authors and many other supporters of the handbook collectively volunteered innumerable hours. The result is a guide that legislators, ministry officials, and regulators worldwide can use right now to draft, adopt, and enforce new legislation that will accelerate the deployment of CCUS.

This handbook also expands the scope of a series developed by CLDP. This series began with our *Understanding Power* guides sponsored by Power Africa: an open-source and plain-language knowledge library of handbooks that explain a range of essential topics in power project contracts, financing, and procurement. In partnership with ENR, the series continued with new decarbonization guides. The first of these new decarbonization guides was on methane abatement from oil and gas. These handbooks further U.S. Departments of Commerce and State climate and cleantech trade objectives in addition to supporting global climate goals.

I am grateful to CLDP and the authors, sponsors, and supporters for developing this important contribution to our collective effort to seize the opportunity. Working together, we can address the climate crisis, develop creative solutions, and rise to the challenge.

Gina M. Raimondo
U.S. Secretary of Commerce

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A Guide to This Book

Who Is This Book for?

The international community has committed to rapidly reducing carbon dioxide (CO_2) emissions from the petroleum, power, manufacturing, and other emissions-intensive sectors to meet climate change objectives and enhance economic and energy security. Many countries, however, still seek to understand how to achieve these objectives, particularly through the use and deployment of Carbon Capture, Utilization, and Storage (CCUS). This handbook introduces government officials to a range of options for CCUS and guides the design and implementation of legal and regulatory frameworks that will catalyze sustainable private investment into CCUS projects, building on lessons learned from regulatory schemes in various countries. Policymakers and regulators from emerging economies, including those in Asia,[1] considering or actively pursuing any part of the CCUS value chain can benefit from this handbook.

What Is the Scope of This Book?

This handbook provides information to support policymakers in developing and implementing effective CCUS policies and regulations. It describes technologies, policy and legal/regulatory frameworks, and engagement across the CCUS value chain. This handbook covers some of the specific CCUS technologies in depth and focuses on salient points on other topics. This handbook is not intended to advocate for a particular suite of CCUS policies but provides an overview of options.

Who Wrote This Book?

The authors are diverse energy sector practitioners, including government officials, engineers, public policy experts, lawyers, and academics. This handbook seeks to capture their collective practical experience and current knowledge. However, it does not represent the policy positions of the organizations, institutions, countries, and/or companies with which the individual authors are or have been affiliated. For such views, please refer to the publications and websites of the respective organizations, institutions, countries, and/or companies.

Addressing the climate crisis is a critical issue in many countries. Many experts and organizations indicate that a key process in mitigating CO_2 emissions and their related greenhouse gas effects is through the use of CCUS. The authors hope this handbook will advance the development and implementation of CCUS policies and regulations and contribute to lowering global carbon dioxide emissions from hard-to-abate sectors.

How Was This Book Developed?

The handbook was produced using the Book Sprints (www.booksprints.net) method, which allows for the drafting, editing, and publishing of a complete product in just five days.

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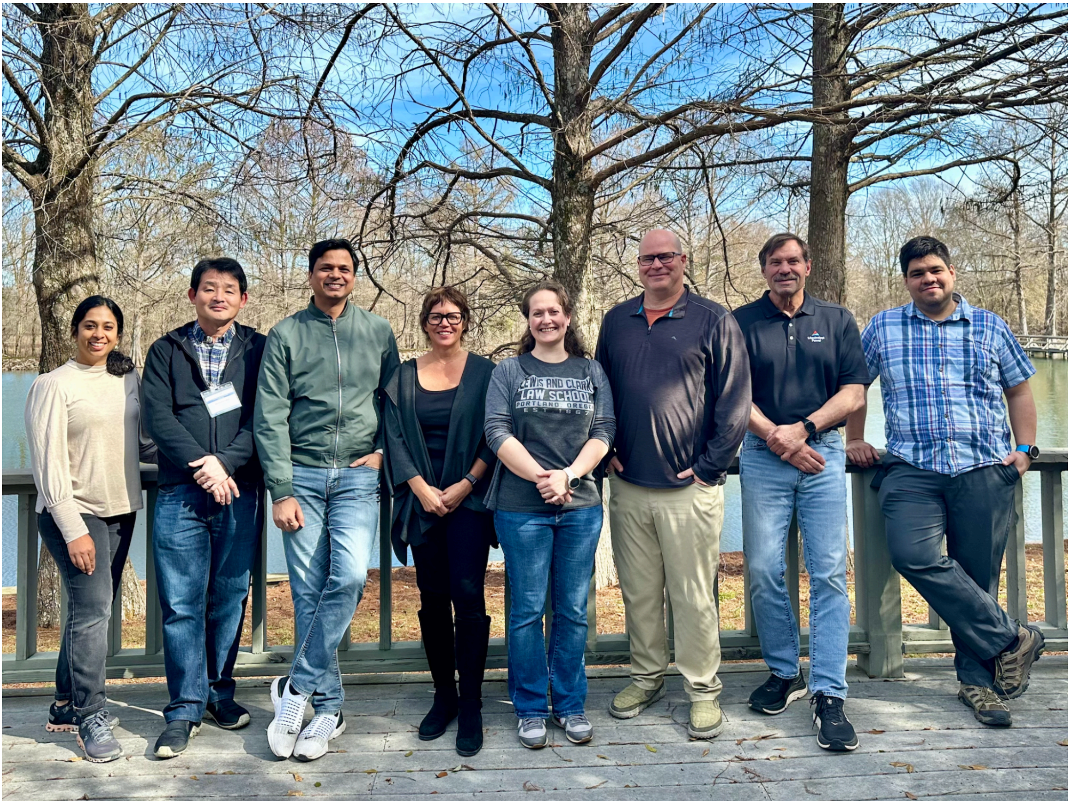
How May I Use This Book?

In the tradition of open-source knowledge sharing, this handbook is intended to reflect the vibrant nature of the Book Sprints process and serve as a reference and a jumping-off point for further discussion and scholarship. It is issued under the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License (CC BY NO SA). In selecting this publication license, anyone is welcome to copy, excerpt, rework, translate, and re-use the text for any non-commercial purpose without seeking permission from the authors, so long as the resulting work is also issued under a Creative Commons License. The handbook is initially published in English. Translations may soon follow. It is available in electronic format at *https://cldp.doc.gov/resources* and in print format. In addition, the handbook can be used as an online interactive resource. Many of the contributing authors are also committed to working within their institutions to adapt this resource for use as the basis for training courses and technical assistance initiatives.

Sincerely,
The Contributing Authors



Authors during their Book Sprint.
From left to right: Priya, Atsumasa, Vikram, Pamela, Ingvild, George, Richard, and José

Vikram Vishal, Ph.D.
National Centre of Excellence in CCU
Indian Institute of Technology, Bombay
UrjanovaC Private Limited
(India)

Atsumasa Sakai
Asian Development Bank
(Philippines)

Priya Prasad
Commercial Law Development Program
U.S. Department of Commerce
(United States)

José Benítez Torres
Office of Fossil Energy and Carbon Management
U.S. Department of Energy
(United States)

Ingvild Ombudstvedt
IOM Law
(Norway)

Richard Esposito, Ph.D.
Southern Company
U.S. National Carbon Capture Center
(United States)

George Koperna
Advanced Resources International, Inc.
(United States)

Pamela Tomski
ENTECH Strategies, LLC
Research Experience in Carbon Sequestration (RECS)
(United States)

Executive Summary

Capturing carbon dioxide (CO_2) emissions will be a vital tool to curbing climate change. Countries are therefore seeking to rapidly accelerate investment into CCUS: Carbon Capture, Utilization, and Storage. CCUS has been successfully demonstrated at a commercial scale. The challenge now is to catalyze sufficient investment into CCUS, in particular into those industries where emissions are hard to reduce. Emerging economies are especially poised to take advantage of CCUS investment, benefitting from comparative lower cost and cross-border investment.

This Handbook is a guide for policymakers on how to adopt those policies, laws, and regulations that will successfully attract responsible private investment into CCUS projects. We define a country's suite of policies, laws, and regulations governing investment into a project as a "framework". Carbon dioxide has been commercially stored for nearly 30 years. Many countries already have longstanding and time-tested policies, laws, and regulations that govern oil and gas, and often will look to their oil and gas sector as the source for guidance on policies, laws, and regulations that govern CCUS. But CCUS has its own considerations around value creation, technology, community engagement, capacity building, risks, and financial penalties and incentives. This creates a challenge for policymakers responsible for creating an investment framework for CCUS, and threatens to slow the necessary investment. Companies prepared to spend significant capital on a CCUS project will look at a country's policies, laws, and regulations – its domestic CCUS framework – and will choose to invest in a country that has a reliable CCUS framework over one that does not.

To begin with, CCUS is a suite of different interlinked components: capture, transportation, utilization, storage. Each of these components requires its own infrastructure and therefore its own governance considerations. Carbon capture components include capture equipment at industrial facilities, power plants, and removal facilities. After capture, CO_2 often must be moved to where it will be used or stored. CO_2 can be transported by pipelines, rail, ships/barges, and trucks to the storage and/or utilization facilities. Utilization means using the captured CO_2 that results in a net reduction of CO_2 emissions. Facilities will permanently store the captured CO_2 in geologic formations. Chapter 2 provides a detailed explanation of CCUS.

For policymakers to be prepared to create a CCUS framework, this guide recommends that policymakers first have in place processes for stakeholder engagement and capacity building. These are the subjects of Chapters 3 and 4. For a CCUS framework to be durable – and for individual CCUS projects to be constructed on time and on budget – policymakers must have stakeholder engagement "baked in" to the framework development process. As Chapter 3 explains, one of the most significant risks to new CCUS projects is a lack of coordination among the key actors in CCUS: the policymakers, regulators, project developers and the public/local communities. Another risk is the lack of capacity among the key actors in CCUS. Chapter 4 details how policymakers can put in place the capacity for each of these key actors: the policymaker's capacity to adopt a durable CCUS framework, the regulator's capacity to implement CCUS rules, a project developer's capacity to construct CCUS projects in compliance with those rules, and the country's local workforce capacity to meet the needs of CCUS projects.

With stakeholder engagement and capacity building processes in place, a government is ready to adopt a CCUS framework. Chapter 5 sets out a six-step process for putting in place a CCUS framework that will meet the expectations of the private and public sectors and catalyze investment into new capture, transportation, utilization, and storage infrastructure. The first step starts with adopting a clear-stated policy (or strategy) that declares the country's interest in responsible CCUS investment and how it will proceed to adopt a framework for investment. This sets the stage for policymakers to determine where laws and regulations need to be adopted or amended to attract the developers and financing for new CCUS projects.

In adopting and amending these laws and regulations, policymakers are not on their own. Chapter 6 explains how policymakers can begin by first understanding their obligations under international law, and the existing body of international standards for CCUS. There are a number of existing international conventions that obligate countries on how they must govern CCUS investment both domestically and across borders. In addition, the International Organization for Standardization (ISO) has standards that relate to CCUS and these can be a useful source of regulatory guidance for a CCUS framework that catalyzes responsible investment.

To truly scale up CCUS investment to meet the climate challenge will require financing. It is therefore essential for policymakers to understand the economics of CCUS projects, and how governments should position themselves to attract responsible lending. Chapter 7 explains how CCUS projects are made "bankable": determined to be worth the risk of the loans provided by financial institutions. Countries need to develop a CCUS legal and regulatory framework for the safe and secure deployment of CCUS technologies. A CCUS framework will determine whether a CCUS project is bankable, because it is the country's domestic policies, laws, and regulations that will determine the legal risks to the project developers and lenders.

CCUS is rapidly becoming a destination for huge investment sums. New institutions, associations, and resources are emerging for policymakers and other key actors, to help CCUS reach its full potential. This guide closes with a set of additional resources for policymakers, and a reminder that much remains to be done.

1. Why Carbon?

Key Takeaways

- Carbon capture, utilization, and storage (CCUS) is expected to play a critical role in managing climate change.
- Scaling up CCUS also has important economic growth benefits: CCUS has the potential to create jobs, catalyze innovation, drive trade, monetize low-carbon product manufacturing, and sustain existing industries with decarbonization.
- Companies are ready to invest, as CCUS has, for decades, demonstrated commercial success. The earliest commercial CCUS project that did not include enhanced oil recovery was in 1996, and since then CCUS projects have expanded significantly. For example, in China alone, three projects became operational just in 2023.
- For many countries, therefore, the challenge is putting in place the policy, law, and regulations that will invite responsible investment into CCUS.

CO_2 and Its Contribution to Climate Change

Carbon dioxide (CO_2) is a greenhouse gas (GHG) and a major contributor to climate change. CO_2 is part of the natural carbon cycle. Human activities, including the increased use of fossil fuels, are contributing to an unprecedented volume of CO_2 in the atmosphere (illustrated below in Figure 1.1), which the natural carbon cycle cannot absorb. Because CO_2 acts as a heat-trapping mechanism that causes global warming, the additional CO_2 acts to increase global temperature. As a result, significant reductions and removals of CO_2 emissions are required to minimize global temperature increases and meet climate goals to limit global temperature rise to 1.5°C.[1]

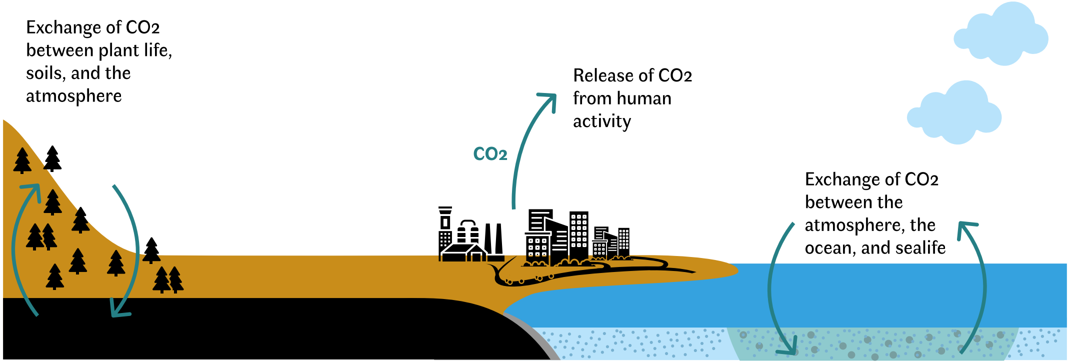


Figure 1.1: Carbon dioxide sources in the atmosphere.

Global Energy Demands and Drivers for Climate Mitigation

In the coming decades, developments in emerging economies will dramatically grow per capita energy consumption. For instance, in 2022, countries in Asia emitted more than ~58 percent of the world's CO_2.[2] As countries in the region develop, CO_2 emissions may also grow.

Addressing climate change requires major transitions in the energy use sectors, including climate mitigation, which involves reducing the flow of heat-trapping greenhouse gases (including CO_2) into the atmosphere. There are several drivers for climate change mitigation. An overarching goal is the need to reduce or eliminate regional climate impacts (e.g., record high/low temperatures and weather patterns). Others include:

- International and domestic policies to achieve net zero emissions per the Paris Agreement[3] climate goals.
- The European Union's Carbon Border Adjustment Mechanism imposes a CO_2 tariff on imports of certain goods from countries outside of a carbon pricing scheme.[4]

- Available incentive schemes, such as carbon markets and leveraged tax credits.
- The general public's insistence on transparency and accountability for emissions reduction and reporting.

Emerging economies, including a number of countries in Asia, have taken steps to address climate change. The case study below highlights steps taken in India.

India's Panchamrit Agenda Around Climate Mitigation[5]

India, which ratified the Paris Agreement in 2016, subsequently announced its Panchamrit, Five Point Agenda, to address climate change. Reducing CO_2 emissions is a key part of the agenda. Announced during the COP26 climate summit in 2021, the plan includes steps for the country to:

- Reach 500 Gigawatts of non-fossil energy capacity by 2030
- Fulfill 50 percent of its energy requirements through renewable energy by 2030
- Reduce total projected carbon emissions by one billion tonnes by 2030
- Reduce the carbon intensity of the economy by 45 percent by 2030 vs. 2005 levels
- Achieve net-zero emissions by 2070

Climate Change Mitigation Approaches

No single mitigation approach will address the climate challenge. Each has strengths and limitations relating to cost, reliability, accessibility, scale, and environmental performance. Experts widely agree that a portfolio of different mitigation options offers the least expensive, most economically sustainable path to achieving climate mitigation goals.[6]

While each country will differ in its mitigation approach, a portfolio of solutions is needed. Some solutions include reductions in fossil fuel emissions, energy efficiency improvements, expanding the use of renewable sources of energy, and the development and use of alternative fuels — such as hydrogen. In addition to these mitigation strategies, there is carbon capture, utilization, and storage (CCUS).

What is CCUS?

As illustrated below (Figure 1.2), CCUS can include (1) capturing CO_2 from point sources or directly from the atmosphere, (2) transporting the captured CO_2 for either (3a) geological storage or (3b) utilization. CCUS can contribute to substantial CO_2 emissions reductions while lowering overall mitigation costs. The CCUS value chain is unique in that the technologies themselves are not necessarily new, but the combination of existing technologies are linked together in a unique way to meet the emissions reduction objective.

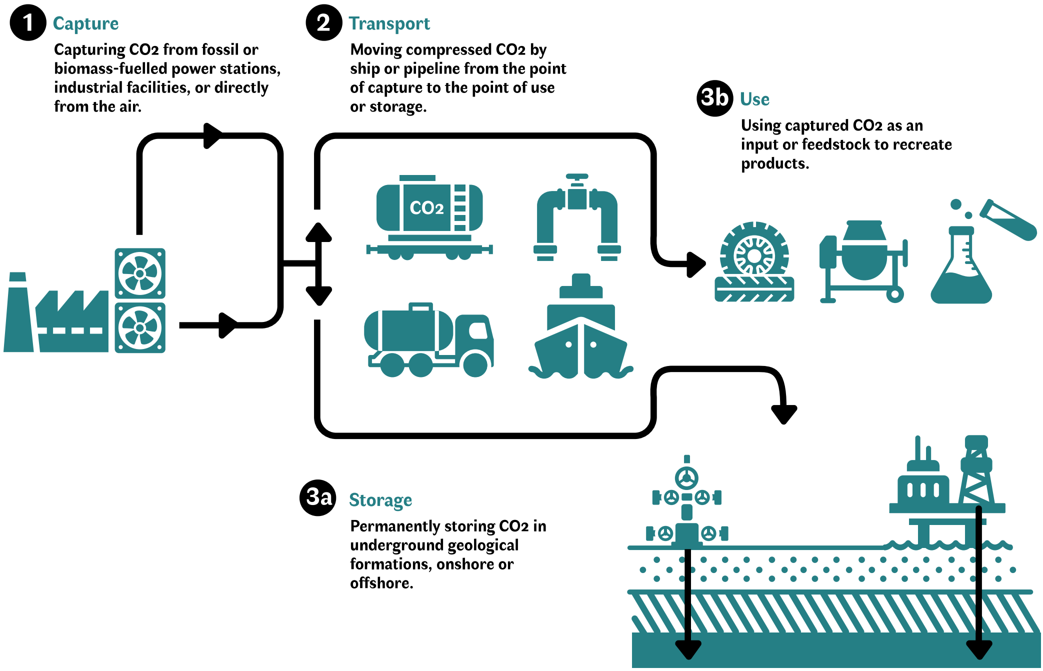


Figure 1.2: Flow diagram of carbon capture, transport, utilization, and storage.

CCUS deployment is needed this decade to keep within reach of the Paris Agreement's target to limit global temperature rise to 1.5°C by 2030.[7] It is a key mitigation option that can achieve reductions in CO_2 emissions from fossil fuel power plants and large industrial facilities while enabling countries to meet climate goals under the Paris Agreement. While cost estimates vary, there is no question that meeting climate goals will cost significantly more without CCUS (in some cases 138 percent more expensive) than with CCUS.[8] Developing a CCUS industry also has the potential to create jobs, catalyze innovation, drive trade, monetize low-carbon product manufacturing, and sustain existing industries with decarbonization.[9]

CCUS Technology is Commercially Ready

Carbon capture and storage has been successfully deployed since 1996,[10] with a much longer history of commercially deploying the component technologies at scale including capture in various industries and enhanced oil recovery. There is tremendous global momentum and activity that provides confidence in successful CCUS deployment. As of January 2024, there are over 500 CCUS projects globally at various stages of development and operation.[11] While the oil and gas industry has been the traditional leader in CCUS deployment, several other industries are also engaged in project activity, such as electricity, cement, fertilizer, steel, and ethanol producers.

Asia Has Substantial CCUS Opportunities

The Asian region has substantial opportunities for CCUS deployment. More than half of global CCUS by 2050 could take place in the Asia-Pacific region.[12] A pan-Asia CCUS network could include a cluster of more than 20 carbon capture and underground storage hubs.[13]

This potential is more than just theoretical. There are a number of projects and activities that provide confidence in the region's ability to deploy CCUS. For example, in China, three projects became operational in 2023 (Asia's largest coal-power plant CCUS facility, the first offshore CO_2 storage facility, and carbon capture at an oil refinery).[14] Japan has announced seven CCUS networks that will capture CO_2 in Japan for storage.[15]

Foundation of Regional Collaboration on CCUS

Asia has created a foundation for regional collaboration on CCUS. The capacity and potential for CCUS deployment in Asia-Pacific drive coordination and collaboration across the region. Countries are inviting their neighbors to tour facilities and attend technical and policy dialogues to share their learnings. Apart from projects, there has also been a growth in regulations and policy developments in the region. This, in turn, can encourage the international industry to deploy CCUS in the region.[16]

Beyond the Asia-Pacific region, coalitions and consortia are emerging globally to bring together stakeholders to advance CCUS frameworks. As will be described in Chapter 6: Resources and Responsibilities for Frameworks, one such resource is the International Organization for Standardization's (ISO) committee on CCUS, which has almost 50 countries convening together to develop standards and technical reports across the full CCUS value chain. Coordination is particularly critical when transporting and storing CO_2 across international borders.

2. What is Carbon Capture, Transport, Utilization, and Storage?

Key Takeaways

- Carbon dioxide and other greenhouse gases are typically emitted at the site where they are produced. CCUS takes the CO_2 before it is released (or, in the case of Direct Air Capture, from the atmosphere) and then transports it to a place where it can be used or stored underground permanently.
- Simply put, therefore, CCUS is a set of four interdependent components: capture, transport, utilization, and storage. Each of these requires its own consideration by policymakers and regulators.
- As a starting point, it is essential for policymakers and regulators to understand the evolving options and technology behind each of these four components, such as the options of pore space for safe and secure long-term storage of CO_2.
- Although the "U" in CCUS stands for Utilization, it is estimated that while captured CO_2 will find means to be converted and/or utilized, most CO_2 will need to be injected underground for permanent storage.
- There are a number of cross-cutting considerations as well. For example, technical requirements for CCUS projects will need to integrate safety provisions throughout the entire value chain.

Introduction

CCUS is composed of four interdependent components, as shown in the prior chapter, and reproduced below as Figure 2.1. It starts with the **capturing (1)** of CO_2, which can be at industrial facilities, power plants, and negative emission facilities (e.g., direct air capture or biomass combustion facilities). The CO_2 can then be **transported (2)** to its final **use** or **storage** location. Available modes of transporting (2) CO_2 include pipelines, rail, ships, and trucks. Where appropriate, capture and storage or utilization sites can be co-located to minimize transport infrastructure requirements.

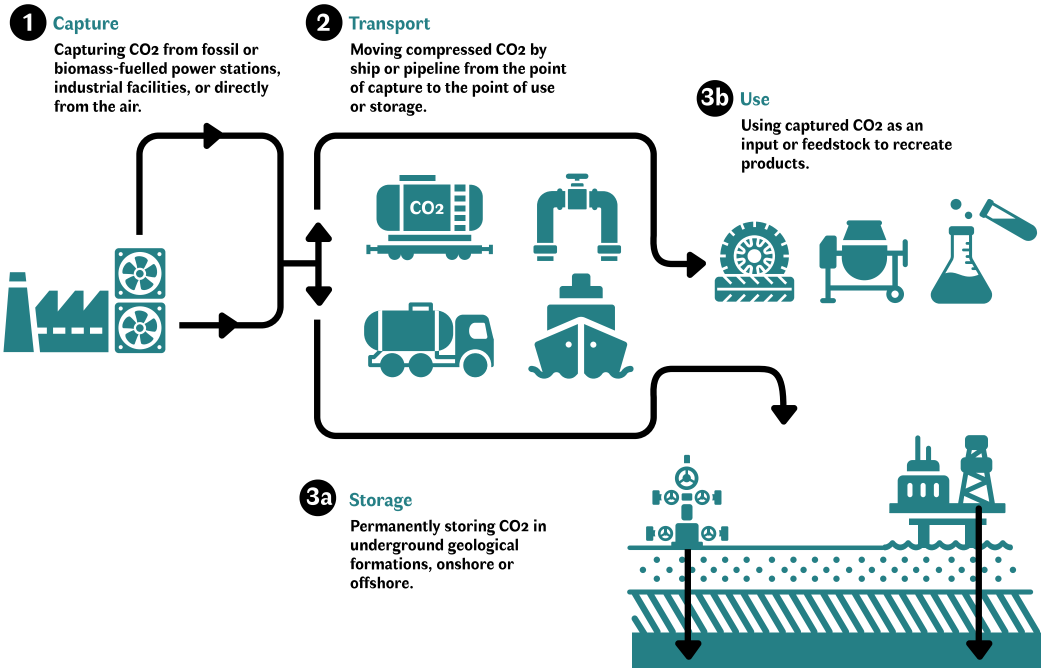
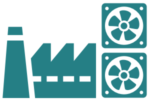


Figure 2.1: CCUS components.

For geologic storage (3a), the goal is safe long-term storage. Storage can consist of one or more types of geological storage sites. For utilization (3b), the goal is to beneficially use the CO_2 to create products, thereby reducing the amount of CO_2 emitted into the atmosphere. A special case is the use of CO_2 for enhanced oil recovery (EOR), which acts to generate additional oil production.

Capture



CO_2 capture can be performed using a number of commercial technologies. CO_2 can be captured from point sources or the atmosphere. The choice of capture technology deployed is typically based on selection criteria that can span facility type, geographic location, and cost. At a very high level, facility types are often subdivided into low and high CO_2 concentration sources, in terms of emissions purity before capture.

Table 2.1. Key capture considerations.

Selection Criteria	Emissions volume, CO_2 concentration, remaining asset life, flue gas pressure and temperature, proximity to storage, available space for capture equipment, and water supply (for cooling).
Safety/Integrity	Minimize non-CO_2 emissions, material degradation, waste disposal, process design, retrofit vs. new build.

High-concentration Capture

CO_2 capture from high-concentration sources may require very little processing before being transported. An example of this is the emissions from ethanol production facilities that produce CO_2 essentially as a pure byproduct of the fermentation process. Some oxygen removal may be undertaken prior to compressing the CO_2 for transmission.

Other processes considered to be high-concentration emissions sources include oil refining, hydrogen production from natural gas (methane reformation), ammonia production (methane reformation), and natural gas processing applications.

Low-concentration Capture

Flue gas emissions from an electric power station are an excellent example of a low-concentration emission source. The volume of flue gas is very large, and the total quantity of CO_2 in the emissions stream may be lower than 10 percent depending on the source. Other low-concentration sources can come from processes such as cement calcination, steelmaking, pulp and paper production, and chemical manufacturing.

Low-concentration capture systems include chemical solvents (often based on amines), cryogenic separation, membranes, and sorbents. These types of systems generally need to be designed for the specific host application. Energy and cooling needs for such a system could leverage existing infrastructure at the host facility (e.g., steam extraction, cooling water use, waste heat recovery).

The scaling up of low-concentration capture technologies is typically done in stages — from testbed, demonstration/pilot, to commercial deployment. An example of a low-concentration source CCUS R&D demonstration/pilot project is Alabama Power's Plant Barry facility, described below. There are also examples outside of the U.S. for commercial CCS deployment. For instance, in 2014 the SaskPower Boundary Dam in Canada became the first power station in the world to successfully use CCS technology.

Scale Up of Alabama Power's Plant Barry 25 Megawatt Capture Project

In 2009, a 25 Megawatt CCUS Demonstration Project at Alabama Power Company's Plant Barry in the U.S. was the world's largest carbon capture on a pulverized coal power plant. CO_2 was captured from the flue gas using Mitsubishi Heavy Industries' advanced amine solvent capture technology. The CO_2 was compressed on-site and transported 12 miles to the geologic storage site. A total of 114 kt of CO_2 was captured, transported, stored, and monitored throughout the pilot project.

The test data collected and lessons learned from this project provided an excellent test foundation for the scale-up of this technology from the 25 Megawatt slip stream capture at Plant Barry near Mobile, Alabama to the 240 Megawatt capture system at NRG's W.A. Parish Generating Station near Houston, Texas. NRG's project continues to operate today.

Carbon Dioxide Removal (CDR)

Carbon dioxide removal (CDR) is a process through which CO_2 is removed from the atmosphere and permanently stored. Two CDR processes linked to CCUS, due to similarities in technology, are described below.

Direct Air Capture

Direct air capture (DAC) is a type of CDR that involves the use of processes to remove CO_2 from the air. This generally involves the use of solvent-based or sorbent-based technologies. Given the dilute concentration of CO_2 in the air, large volumes of air need to be processed for every unit of CO_2 captured. This makes the process energy intensive and generally more expensive than industrial capture systems.

An emerging type of CDR is direct capture of CO_2 from seawater. The concentration of CO_2 in seawater is higher than that in air, as a result a number of pilot projects are being pursued to remove CO_2 from seawater.

Biomass CCS

Biomass CCS involves the conversion of feedstocks directly into energy or a chemical product, with the removal of the carbon produced by the process. Direct energy conversion includes combustion for power generation and/or steam production with point source capture in the flue stream. Chemical conversion takes place by gasifying the biomass into syngas and further processing the syngas into hydrogen and CO_2.

Transportation

After capture, CO_2 can be transported via pipelines, rail, trucks, and ships. Pipelines have been the most widely used transportation mode for moving large volumes of CO_2. Rail, truck, and shipping transportation options require the development of onloading and offloading facilities to handle transportation.

Table 2.2: Key transportation considerations.

Selection Criteria	Volume, CO_2 purity, distance, geography, cost, and land use limitations.
Safety/Integrity	Land use limitations, pressure and temperature requirements, impurities, and distance.

Pipeline

Pipeline transportation is used onshore and offshore. Onshore, CO_2 is generally transported in carbon steel pipelines buried underground. Offshore, pipelines will generally be laid on top of the seabed. To be transported via pipeline, CO_2 needs to be compressed. This process is energy intensive and can lead to associated emissions of CO_2 if the power for the compressors is not from low carbon sources. CO_2 pipelines have been operating in the U.S. for more than 50 years, with over 5,000 miles of pipelines currently in operation.[1]

Rail

Rail transportation of CO_2 mainly occurs by using pressurized tank cars that transport liquid CO_2. To transport via rail, the operator must develop the appropriate infrastructure to liquefy, store, onload, and offload the CO_2 onto the tank cars. At the storage site, the appropriate equipment for offloading, tank storage, and re-compression is needed to handle the CO_2. Transportation of CO_2 via rail must also consider boiling off of some of the CO_2, known as boil-off losses, incurred during transport.

Ship/Barge

Transporting CO_2 via shipping[2] requires onloading and offloading facilities at the waterfront to facilitate transport. Ship transportation has been considered a viable option for offshore projects aiming to store either small volumes or volumes from multiple sources, and a viable option for the cross-border transport of CO_2 (currently being considered in feasibility and pilot studies in Northern Europe and Southeast Asia). In Japan, a vessel with a capacity of 1,450 m^3 was constructed in 2023[3] to transport liquefied CO_2 for large-scale demonstrations at Tomakomai.[4]

Truck

Trucking of CO_2 is widely used for relatively short-haul small volume transport. Typically, low-volume cryogenic tankers or pressurized vessels are used to move the CO_2. This technology also requires onloading and offloading facilities to transfer the CO_2 to and from the trucks.

Storage

After transport, CO_2 can be stored geologically in deep saline reservoirs, depleted oil and gas reservoirs, and other formations, as shown in the figure below (Figure 2.3). Storage via utilization (1) can occur in the subsurface during enhanced oil recovery (EOR) and enhanced gas recovery (EGR) and (2) can also be used to create products such as building materials, carbon black, carbon fiber, or plastics.

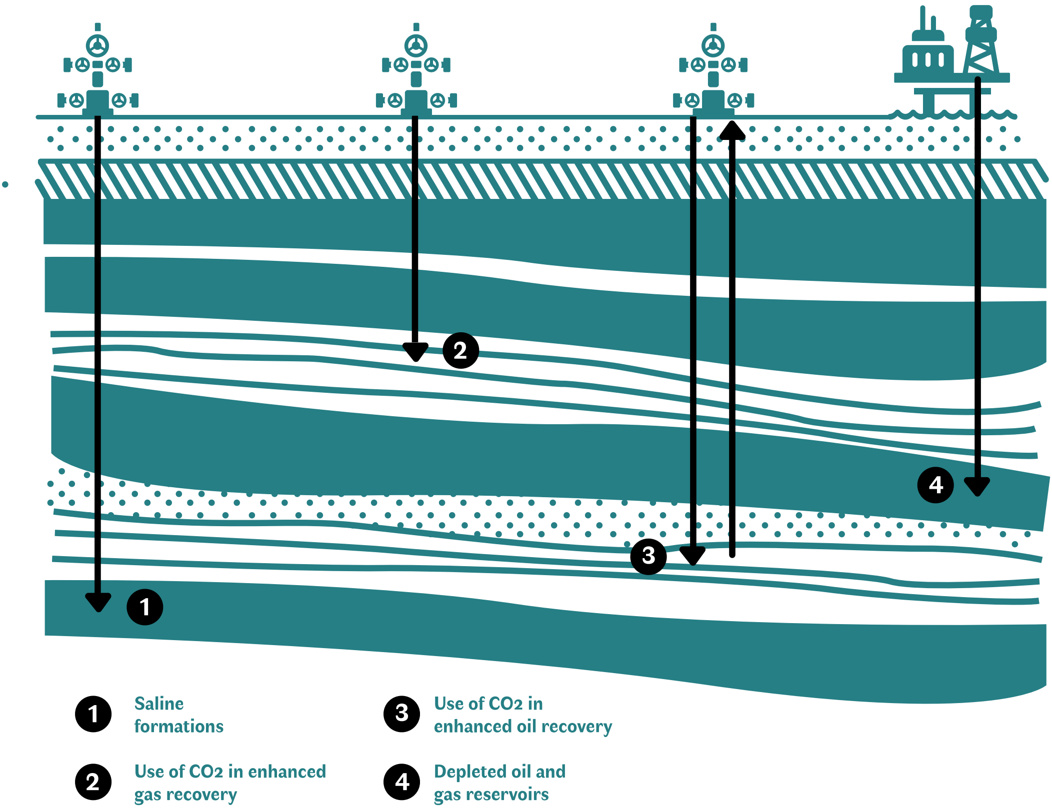


Figure 2.3: CO_2 geologic storage site options.

While multiple pathways exist for the utilization of captured CO_2, large-scale mitigation of captured CO_2 needs to be done through storage.[5]

Table 2.3: Key Storage Considerations.

Selection Criteria	CO_2 volume, depth, pressure, temperature, available pore volume, injectivity, geologic boundary conditions, geologic complexity, degree of cap rock confinement, rock mechanics, topography, land use limitations, legacy wells, legacy infrastructure availability, and cost.
Safety/Integrity	Pressure and temperature requirements, containment, induced seismicity that is unacceptable, land use limitations, legacy wells, protecting natural resources, and safety equipment.

Saline Formation Storage

Saline formations are porous sedimentary strata that exist within onshore and offshore basins and are commonly made up of sandstones and carbonates that contain brine within their pore spaces. These formations present some of the largest opportunities for storing commercial volumes of CO_2. Suitable properties for storage in saline formations include depth, stratigraphic containment, porosity, and permeability. Containment of injected CO_2 within overlying impermeable layers is required to ensure safe long-term storage and long-term stability of injected CO_2.

Depleted Oil/Gas Reservoirs

Oil and gas reservoirs that are nearing or are at the end of their productive lives may be potential candidates for storing CO_2. These reservoirs are similar to saline formations as indicated above, but have oil and gas trapped in them — either in sedimentary layers or structural traps. With the addition of CO_2, reservoir pressure can be restored to near-original conditions through a monitored wellfield.

Mafic Igneous Rocks

Mafic rocks, such as basalts and peridotite, contain minerals that react with CO_2 to form stable mineral carbonates (in situ mineralization). This process may be important in locations where this rock type is the available storage resource.

Utilization

After transport, CO_2 can be utilized to assist in the extraction of hydrocarbons or product creation. Utilization can contribute to the development of CCS infrastructure, particularly for EOR or EGR. CO_2 can also be used to create products such as building materials, carbon black, carbon fiber, or plastics.

Enhanced Oil Recovery

EOR is a mature oil production technology that has been used since the 1970s.[6] CO_2 at reservoir pressure is a dense-phase gas with liquid-like properties that can mix with oil. This mixing lowers the viscosity of the hydrocarbons and allows for further recovery of oil from the reservoir. Typically, CO_2 is injected into the reservoir, but a closed-loop system is employed to remove produced CO_2 from the production stream, compress it, and mix it back with new CO_2 that may be sourced from a capture source.

Enhanced Gas Recovery

EGR is a hydrocarbon production technique that can be used in either natural gas reservoirs or coal seams. EGR works by directly replacing natural gas. The technology application works best when in situ conditions minimize CO_2 diffusion and premature breakthroughs in the reservoir. A special case of EGR is enhanced coalbed methane recovery. This process works by using CO_2 to replace methane within the coal.

CO_2 Conversion Into Products

Excluding fuel creation, which leads to the direct release of the utilized CO_2, there are multiple CO_2 utilization options for products that could be considered as long-term storage. Conversion of CO_2 into products for purposes of utilization should consider the total effect of the process with respect to the atmosphere, also referred to as a life cycle assessment.

The case study below highlights a product selection process at an Indian cement facility to identify viable options and market conditions for commercial deployment.

Assessing Products from Captured CO_2 in India's Cement Industry[7]

In 2021, the Asian Development Bank (ADB) supported a cement study in India to assess the feasibility of products converted from captured CO_2. The study evaluated six products: urea, soda ash, mineralization, methanol, algae for feed, and algae for oil. The evaluation shortlisted urea and mineralization as top-ranking options. The CO_2 capture plant may adopt post-combustion technology with a capacity of 500kt of CO_2 per year. This amount of captured CO_2 can be converted into 680kt of urea. The financial analysis indicated a low return on investment under the standard conditions assumed. To improve commercial viability, the study concluded that the following are critical:

- → The steep increase in urea prices in the Indian market.
- → Availability of low operational costs for onsite electricity and steam.
- → A specific price level of carbon credits to fill the financial viability gap.

Crosscutting Considerations

Safety

Technical requirements for CCUS projects will need to integrate safety provisions throughout the entire value chain. Safety considerations for CCUS projects should include:

- → Protection from major CO_2 releases (asphyxiation, impact from CO_2 impurities, impact on marine ecosystems), including provisions for emergency response and engineered safety systems.
- → Monitoring incremental air emissions of hazardous air pollutants (amine degradation products, ammonia, particulate matter).
- → Assessing storage integrity. The primary subsurface leakage pathway for displaced CO_2 is via legacy well penetrations completed through the confining system. For example, to protect drinking water sources, well penetrations should maintain integrity to ensure there are no fugitive pathways for CO_2 movement into them. In addition, geologic features such as faults should be reviewed.

Risk Analysis and Management

Risks to a CCUS project success may include financial, operational, storage, health/safety, public perception. Regulatory entities will need to consider the development and deployment of risk analysis and mitigation systems. In the case of operational, health, and safety risks, mitigation systems, these can include supervisory control and data acquisition (SCADA) systems that provide automated system control and alarm systems to protect various components of CCUS. In addition, regular risk management and mitigation workshops should be conducted to identify, track, and close risks.

Quality Specifications

CO_2 produced from different capture sources may have a different composition of impurities. Transportation and storage options will require some of these impurities to be removed as a measure to protect the transport or storage infrastructure from damage (e.g., corrosion and public risk). Several countries are also developing regulatory requirements to limit impurities in CO_2 streams. All these requirements will need to be considered by capture and transportation operators to ensure compliance. Some capture operations might require additional processing equipment.

Integrated Infrastructure

As the CCUS infrastructure is built, it will be important to integrate all necessary components for the CCUS project. For instance, the operating requirements based on the CO_2 source for capture may require transport and storage system considerations.

3. CCUS Project Engagement

Key Takeaways

- → CCUS projects need engagement to be successful. Engagement is communication by policymakers, regulators, project developers, and the public across the life of a project.
- → Policymakers and regulators need to be prepared to engage at the outset with public stakeholders — including local communities — to avoid delays and cancelations.
- → A critical first step is understanding the key players, their respective activities, and the appropriate level of engagement: stakeholder mapping and planning.
- → Even communities that are familiar with oil and gas projects, or other extraction projects, may be skeptical with CCUS projects. The Barendrecht Project in the Netherlands shows the risks of failing to engage with the community on a CCUS project.

Introduction

Engagement is the process of involving policymakers, regulators, project developers, and the public in communication across the life of a project. Community engagement is not a new concept for the energy industry, but has changed significantly in the last decade to be more inclusive, responsive, and robust. Large infrastructure projects, including wind turbines and railway lines, have provided experience about the importance of getting public engagement right, early in a project.[1] The risk of failing to meaningfully engage with the local community and the larger public can be project delays, or even cancelations. More positively, key elements of engagement that set strategy/guidance, oversight, decision-making, and sharing information are shown below. The intersection of policy and laws/regulations to drive impact with communications to the public about a project can make up the elements of engagement. This chapter will describe these elements and several more in further detail.

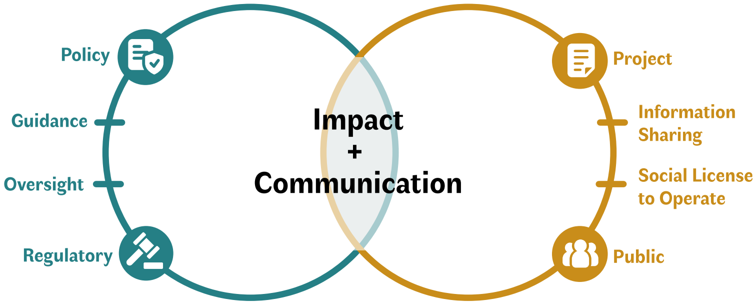


Figure 3.1: CCUS engagement elements.

Unfamiliarity or a lack of awareness of carbon capture, utilization, and storage (CCUS) as a climate mitigation technology may be problematic for the success and deployment of projects. At a simplified level, insufficient information about project development, technologies, background, or the decision-making process can lead to a lack of acceptance or support amongst surrounding communities. For several projects, this can result in project cancelation. Thus, communication and engagement are key elements of deploying CCUS projects.

Importance of Engagement and Core Principles

Effective engagement is critical to establishing open lines of communication, informing stakeholders about potential risks and benefits, addressing questions, concerns, and perceived risks, exchanging ideas, cultivating knowledge, and building trusted relationships and long-term engagement. It can also raise awareness, increase support, build influence, support policy and regulatory development, improve decision-making processes, and proactively mitigate potential opposition. It should be noted that the method and level of public engagement will evolve over the life of any given CCUS project.

A non-exhaustive list of key principles for CCUS engagement, based on the contributor's experience in these projects, is described below.

Transparency. Share factual information, developments, community impacts, and potential risks and benefits in a clear, open, and direct manner; provide a public record summarizing events.

Diversity, Inclusion, and Accessibility. Be inclusive and engage people with different types of views and lived experiences. Ensure that opportunities to participate offer full accessibility. Make reasonable accommodations for those with special needs.

Understanding Communities. Project developers might recognize issues facing communities, and as a project develops they will become part of the community. Different communities engage with information and communicate differently. This may require diverse communication and engagement strategies within a project.

Engage Early and Often. Identify the level of need and the appropriate frequency/forum for engagement.

Decision-making. Include the community in the decision process and vet the project with technical peers at symposia, and technical events.

Guidelines for Engagement. Establish guidelines to support the respectful exchange of views that builds toward shared understanding.

Two-way Exchange. Facilitate two-way exchange of information, encourage active listening, and acknowledge and incorporate new perspectives and ideas.

Collaboration and Partnerships Actively build collaboration and partnerships among diverse groups and individuals to advance shared goals.

Connect with the Big Picture. Clearly communicate the 'Why CCUS' and connect activities to the big picture.

Community Benefits. Under the local context by working with the on-the-ground residents to determine the direct value to a community that results from project developments. Look beyond property owners to other members in the community, including how the CCUS project can provide opportunities for the underserved — minority-owned businesses, women-owned businesses, and veteran-owned businesses.

Measure/Survey Impacts. Include measurable success metrics to understand how engagement activities impact stakeholders over time (see the case study on the Houston CCS Alliance below). Evaluate to understand what is working and what is not, and revise accordingly.

Flexibility. Be flexible and acknowledge, adapt, and incorporate feedback as practically realizable.

Language. Identify the major languages in the relevant communities and develop materials and host meetings in these languages as needed.

Clarity. Use clearly understandable graphics, including unexaggerated depth scales to relay distance.

Capacity Building. Explain workforce development and project engagement with academia (e.g., the establishment of internship programs).

Houston CCS Alliance's Engagement Efforts

Figure 3.2: Based on an analysis of data from the U.S. Department of Energy (2018) and NYC Mayor's Office of Sustainability. (Graphic courtesy of Houston CCS Alliance)

The Houston area has one of the most concentrated sources of CO_2 emissions in the United States and is located near prolific underground geological storage formations, making it ideal for the development of large-scale CCS projects. In 2021, eleven of the largest industrial CO_2 emitters in Houston, Texas, formed the Houston CCS Alliance to better address the need for enhanced public engagement and more thoroughly educate communities on the local benefits carbon capture and storage can bring to the Texas Gulf Coast region.

Member companies have worked together to host more than 30 public discussions on CCS, develop bilingual community printed resources and educational videos, sponsor important local events, and organize impactful volunteer activities to improve public resources. These efforts have resulted in more than 20 supportive statements from elected officials and organizations, positive media coverage in local markets, two resolutions from local governments recognizing the Houston CCS Alliance, and most recently, an award from a Harris County Commissioner honoring the Alliance for helping communities thrive. The Alliance continues to engage communities to this day.

Key Players

The key players for engagement fall into four primary spheres: policymakers, regulators, project developers, and the public. The table below (Table 3.1) summarizes the key roles and nature of engagement for each.

Policymakers. Various government agencies can be involved in developing CCUS policies which may require a multi-stakeholder engagement process. One mechanism is an interagency working group to coordinate and align policy developments, share information, incorporate recommendations from all relevant line ministries, develop legal frameworks, and/or delegate the framework development to respective governmental agencies, and identify drivers such as penalties/mandates including the setting of overarching national emission reduction targets as applicable. Another mechanism is to develop the core datasets, such as by governmental science agencies and state-owned laboratories, that support policy decisions. This could include an assessment of CCUS potential in a particular jurisdiction and/or a roadmap to support emissions reductions, as described in Chapter 5: Roadmap for Developing Legal and Regulatory Frameworks. Particularly in emerging economies, the policymakers have a critical role in identifying the lead agency, not only for the design and implementation of legislation/regulation, but also for coordinating stakeholders and the preparatory phase that supports the regulatory process.

Regulators. Regulators develop the rules, oversee their implementation (such as through reviewing permit applications), and enforce them. Regulators are often required for leading public engagement on proposed rules and projects. Through public comment and meetings, regulators may gather comments and concerns from the local community. Often, regulators will respond to public comments but project developers may respond as well. Public participation/consultation at key stages of the project — site selection, operations, and decommissioning — is typically encouraged.

Project Developers. Building on a business case, project developers guide the project along its path to completion. Often, project development teams within a company conduct extensive internal and external engagement to ensure CCUS is supported across business units and within leadership. Once a project location has been identified, project developers can conduct a responsible stakeholder and community engagement mapping exercise to develop and implement an engagement plan.

Communities. The core of CCUS engagement is the community affected by the project. The community includes local leaders, elected officials, landowners, NGOs, and the general public. It is important to take note of and understand issues with disadvantaged and/or marginalized populations, including the status of demographic diversities of different types that will be significantly affected by a CCUS project. There are also significant considerations from a legal standpoint regarding the issue of 'standing' for determining who may be involved in formally challenging any decisions around projects.

Key players come together across a number of activities to engage. The nature of these activities are shown below.

Table 3.1: Activities and Nature of Engagement for Key Players.

	Activities	Nature of Engagement
Policymakers	→ Develop CCUS policies, support innovation and public-private partnerships → Conduct multi-stakeholder engagement → Engage in interagency coordination	→ Determine levels of engagement → Institutionalize processes through task forces
Regulators	→ Rule-making → Review permit applications → Project developer oversight and implementation of engagement → Enforcement	→ Establish engagement processes → Seek updates from project developers → Evaluate impacts → Improve levels of participation

Project Developers	→ Implement projects → Conduct stakeholder mapping and assessment → Engage in two-way dialogue → Develop equitable relationships and build trust	→ Implement engagement processes → Consult and negotiate → Discuss benefits, risks, and mitigation
Community	→ Participate in dialogues → Seek information → Share concerns and ensure resolution → Influence policy-makers and project developers	→ Regular and continued dialogue with project developers → Communicate with regulators → Comment on environ-mental impact assessments

These groups interact throughout a CCUS project to exchange plans, challenges, experiences, and know-how for informed decision-making. The interaction among these four groups is critical for safe and successful CCUS projects.

As shown in the figure below (Figure 3.3), engagement should be an ongoing process with key players throughout the project's lifetime. Engagement starts even before site selection and is maintained through development, operations, closure, and then post-closure. The authors recognize that not all engagement will follow a natural curve as shown in the figure, as an event during operations may result in a spike in engagement, or after development the level of engagement may decrease due to competing issues that stakeholders may face. Nevertheless, building relationships takes time, effort, transparency, and planning.

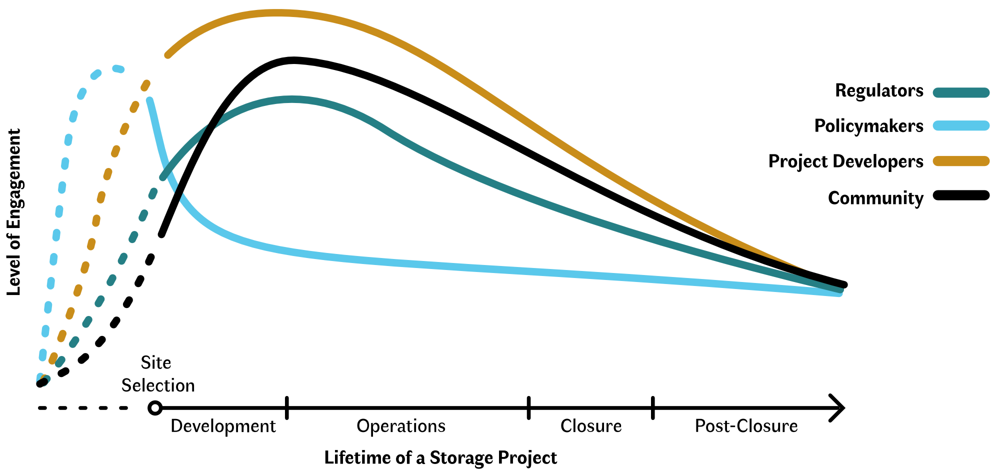


Figure 3.3: Level of engagement of key players throughout the project lifetime.

Engagement Processes: Community Focus

The core principles and key players for a CCUS project have been addressed. This section describes the process of engagement with a focus on communities. First, consider understanding who your constituents are through mapping and surveys. Next, tailor the outreach technique(s) based on the type of message and community make-up.

Understanding the Constituents

There are many approaches and alternatives for engagement. These processes are dependent on developing a good understanding of matters important to the local communities and affected stakeholders. Thoughtful approaches can be developed by using targeted surveys that map or assess the community's feelings toward certain actions or themes. These techniques can rapidly assess larger segments of the community. Community participatory processes, where community members identify the engagement methods and topics that are most important to them, can also be a helpful technique to understanding constituents.

Direct engagement with stakeholders can also be conducted using face-to-face meetings whereby those possible actions and themes are aired to the community for feedback. Outreach events generally consist of public gatherings, which may include a large number of constituents and a mix of presentations, questions and answers, public comments, and one-on-one communication with those stakeholders.

Typically, there is no singular means of determining how stakeholders feel regarding certain issues. It is a leading practice to engage with them frequently and in a variety of manners to ensure a reasonable cross-section of views is received.

The following table (Table 3.2) summarizes some engagement methods along with general advantages and disadvantages. In all cases, when applying core engagement principles, these activities are critical to building trust.

Table 3.2: Outreach methods and potential advantages and disadvantages.

Outreach Method	What is it?	Advantages	Disadvantages
Surveys	A set of questions to gauge how the community feels about activities or issues	Can reach a large number in the community	No direct interaction and often low percentage return; may only reach a subset of the community
Public Gathering	An event where information is presented, representatives answer questions from the community, and they receive comments	Messages can have a broad reach across the community at once. Ability to understand key questions and concerns, and incorporate feedback	Conversation can be driven by a small number of people
Targeted Outreach	An event where representatives present details from the project. This may include site tours and Q&A	Improved exchange of two-way communication	Often a smaller sampling of the community, perhaps community leaders
Public Office/Booth	A fixed location where the public can freely learn about the project and engage representatives	Drives one-on-one communication and information sharing	There is a lot of engagement to reach fewer in the community
Technical Outreach	Presentations at meetings, symposiums, and forums	Technical vetting of the project by peers	Engagement with a small technical subset of the community

Newspapers/ Local News	Outreach through media outlets	Reach local communities and may involve third-party involvement (journalists) in the communication	There is no direct interaction; not all people may have access to the news and may involve third-party involvement (journalists) in the communication
Websites	A project website containing information about the project, technologies, risks, and decision processes	Can reach a large number in the community; a dynamic platform with options to update as the project develops; may be translated into several languages	No direct interaction
Flyers/Ads	Targeted information hung or handed out in public places	Reach local communities	No direct interaction

Often, more than one of these processes needs to be used in combination to ensure an appropriate level of engagement. See the case study on the Houston CCS Alliance, above.

Engagement Techniques

There are a variety of ways in which to share and exchange information with stakeholders. When approaching community engagement, it can be helpful to first meet with key leaders to begin to understand important issues that may require additional attention before engaging directly with the community.

Stakeholder mapping can be an important tool to support effective engagement activities (see Resources for Engagement section in Chapter 9: Additional Resources). It provides a framework to identify, assess, and visually map potential individuals and groups to engage, identify key roles, consider potential common ground and obstacles, determine the potential frequency and priority of engagement, and develop key messages.

Local partners and facilitators may help identify these groups of individuals. Neutral experts (e.g., academics) may be brought in to share their unbiased opinions regarding the soundness of such projects within the community. NGOs may also play an important role, representing interests such as the environment or community health and safety.

There are also a number of one-way communication techniques. The use of websites or social media to engage stakeholders is a growing facet of outreach. Media interviews (whether it be print, radio, podcasts, or television) may also be used for widespread community messaging.

However, leading practices indicate that two-way communication methods — those in which both parties can take in and disseminate information — are superior. The challenge with this engagement technique is to ensure that project messaging reaches many in the community.

This likely requires project developers to have a direct presence within the community and become a part of it. This helps to build trust and allows for more frequent and continuous engagement. A variety of ways can be used to develop this sense of community, but there is no substitute for a direct presence within the community. Some successful project developers open an outreach office within the community to allow for day-to-day engagement.

The example below describes how a poor community engagement plan can lead to the cancelation of a CCUS project.

Barendrecht Project in the Netherlands Canceled due to Insufficient Community Engagement

Lack of public acceptance can be a root cause of project cancelations. One example is the Barendrecht project in the Netherlands. The project was planning to separate and capture CO_2 emissions from an oil refinery before injecting and storing about 10 Mt of CO_2 over 25 years in a depleted gas field under the town of Barendrecht. The community was concerned about the damage to homes and the potential drops in property value due to the proximity to a storage site. There was also a strong sentiment that the community had not been kept informed of project developments and was given very little to no ownership in the decision-making process. Further, there were disagreements between the local and national regulators regarding the public engagement process and perceived risks of the project. Ultimately, the project was canceled.[2]

The project developers engaged with the communities and invested time and resources into community engagement. However, engagement began too late in the process. Because the project was conceived as exclusively commercial,[3] there was little community involvement in the early scoping or decision-making processes. Following the cancelation of the project, the project developers had little doubt regarding the lessons learned in relation to community engagement. They stated that "[the] most important lesson learned from the Barendrecht project is that it is important to create mutual trust between stakeholders and commitment to each other and to the project. This can be done by including all stakeholders in the project process at an early stage and communicating about the project and its process to the community".[4]

Engagement includes bringing the skills, knowledge, resources, and networks necessary to advance the CCUS industry, as detailed in Chapter 4: Capacity Building.

4. Capacity Building

Key Takeaways

- Countries will need to ensure that all key actors – policymakers, regulators, project developers, and communities – have capacity. Capacity building is the process of developing and improving the local skills, knowledge, resources, and networks needed to advance the CCUS industry.
- An emerging CCUS industry can create sustainable jobs, but a CCUS workforce needs a broad range of science, engineering, legal, and other skills.
- Capacity-building activities include establishing CCUS testing and training centers, supporting RD&D activities, fostering internships, and facilitating career networks.
- Case studies from the U.S. and Norway show the importance and potential of capacity building facilities.

Introduction

Capacity building for CCUS aims to equip organizations and individuals with the skills, knowledge, resources, and networks necessary to perform and advance the CCUS industry. It should also aim to support the growth of strong networks and recruit the talent needed to catalyze this emerging industry. Capacity building can be done through a number of approaches including knowledge transfer, training, workforce development, internships, and research.

Because CCUS technology is generally not well known, engagement in capacity-building activities could benefit just about anyone working directly or tangentially in the field. Capacity development in countries with early mover projects and frameworks often focuses activities around demonstration projects leading to commercial projects. In emerging countries, the exchange of knowledge from early moving projects allows them to learn from what has been done elsewhere. This chapter addresses workforce needs, challenges, development, academic research, and research/development/deployment (RD&D).

CCUS Workforce Needs

While a number of skills needed for CCUS are transferable from other industries, CCUS includes specific considerations needed for retraining of the existing workforce or the next generation of CCUS workers. The emerging CCUS industry has the potential to create many quality jobs and be an important part of a more sustainable global energy sector. Workers are needed throughout the CCUS project lifetime from capture (which will require more trainer personnel and more equipment), site screening, selection, and characterization to site design and approval, construction, operations, post-injection monitoring, and site closure (see Table 4.1 below).

In addition to project-specific workforce needs, policymakers, regulators, community leaders, and elected officials who want to understand how to maximize the CCUS opportunity must also build some level of CCUS capacity and knowledge. Academic research can support topical mastery and the inclusion of CCUS topics in academic curricula which builds interest and capability in CCUS.

Table 4.1: Workforce needs for CCUS projects.

Crosscutting	Project managers; health, safety, and environmental professionals; hydrologists; electrical engineers; civil engineers; economists; lawyers; electricians; welders; pipefitters; truckers; heavy equipment operators; site security; financial analysts; accountants; compliance officers; and community relations specialists.
Capture	Chemical engineers; mechanical engineers; air emission modelers; and process engineers.
Transportation	Rail engineers; rail conductors; dispatchers; pilots; captains; longshoremen; merchant mariners; pipeline construction and maintenance personnel.
Utilization	Chemists; sales and marketing; and materials engineers.
Storage	Geologists; geophysicists; petrophysicists; geomechanics; petroleum engineers; seismologists; hydrogeologists, geochemists, oil and gas service professionals; drillers and drill crews; well-completion engineers; and drill engineers.

CCUS Workforce Challenges

A range of technical and non-technical roles are required for CCUS. On the technical side, the oil and gas workforce has many foundational skills to conduct CO_2 transport and storage operations, and the chemical and gas processing industries have experience related to CO_2 capture. As described in Chapter 2: What is Carbon Capture, Transport, Utilization, and Storage?, the requirements for CCUS go well beyond the current industry. Therefore, it is important to catalyze a CCUS industry that has strong workforce pipelines to universities, community colleges, vocational institutes, and specialty training programs. Building strong networks is also important to ensure collaboration across complex projects that cut across the CCUS value chain.

Develop a CCUS Workforce

The following briefly describes several approaches to developing CCUS capacity and an eventual CCUS workforce, including embedding capacity building into project outreach, building strong networks, establishing CCUS testing and training centers, and supporting academic research.

Embed Capacity Building into Project Outreach

Real-world CCUS projects can provide focal points for capacity building. Industry-government partnerships can support the development of know-how and leading practices through the successful implementation of CCUS projects, starting with small-scale field demonstrations and scaling up. All field demonstrations should include education and outreach activities and be a focal point for capacity building.

Build Strong Networks

There are many aspects across the CCUS value chain that must be integrated for successful project deployment. It is important to build strong networks that support collaboration and communication across all roles required for a CCUS project, and the industry more broadly.

Establish CCUS Testing and Training Centers

Technology test centers offer the opportunity to test and advance CCUS technologies (especially for capture) by providing a platform for cost-effective testing and development, and catalyzing larger-scale deployments. They also enable the hands-on capacity building and training of a future workforce and provide a venue for engagement between technology developers and a wide range of stakeholders, including industry, policymakers, regulators, government officials, and the public. An example of a training center, as described below, is India's National Centre of Excellence in Carbon Capture and Utilization (NCoE-CCU).

India's National Centre of Excellence in Carbon Capture and Utilization

Figure 4.1: Inauguration of the NCoE-CCU. (Courtesy of Vikram Vishal)

In 2021, the Government of India's Ministry of Science and Technology established the first National Centre of Excellence (NCoE) at the Indian Institute of Technology, Bombay. The NCoE acts as a multi-disciplinary, long-term research, design development, collaborative, and capacity-building hub for state-of-the-art research and application-oriented initiatives in the field of carbon capture and utilization. NCoE is mandated to define milestones, and spearhead science and technology initiatives for industry-oriented CCUS innovation in India while developing novel methodologies for improving technology readiness levels in CCUS. NCoE is working on the conversion of captured CO_2 to chemicals, CO_2 transport, compression, and utilization, as well as enhanced oil and gas recovery as co-benefit pathways. NCoE has developed novel, low-cost sustainable, and scalable methods for the capture of CO_2 using an aqueous-based capture system and the conversion of carbonate salts and carbon monoxide, among others. The NCoE serves as an advisor and knowledge partner to multiple ministries within the Indian government while providing access to its R&D facilities to others domestically. On a regular basis, NCoE organizes capacity-building programs, such as short courses for industry and others.

Support Academic Research

While the CCUS industry is still in an early stage, sustained government support for graduate school CCUS research is foundational to CCUS capacity building and workforce development. In addition to government-backed support for CCUS workforce development, major geosciences and engineering societies are conducting CCUS capacity-building activities (such as CCUS-focused workshops or technical sessions at major international meetings). See Engagement section in Chapter 9: Additional Resources for more information.

Develop Focused Training Experiences and Career Networks

Focused training and education can be an excellent means of targeted learning. The IEAGHG International Interdisciplinary CCS Summer School, running since 2007 with over 700 alumni from 60 countries, provides young scientists and researchers seeking a greater understanding of CCS a weeklong immersive educational opportunity.[1] The following case study describes an international capacity-building program for graduate students and early career professionals in the U.S.

Research Experience in Carbon Sequestration (RECS): A Capacity Building Model to Develop CCUS Leadership, a Talent Pipeline, and a Career Network

Figure 4.2: RECS participants visited the Citronelle Project in Alabama, United States where CO_2 from Alabama Power-Plant Barry was transported via pipeline and injected at a depth of 3-3.4km. (Courtesy of Pamela Tomski)

In 2004, the U.S. Department of Energy's Office of Fossil Energy and Carbon Management provided support to launch the Research Experience in Carbon Sequestration (RECS) program with the vision to build a world-class CCUS workforce and create a community of young professionals to help lead the emerging CCUS industry and clean energy transition. RECS is widely recognized as the premier CCUS education and training experience, as well as a career network for graduate students and early career professionals in the U.S. RECS offers an annual intensive 8-day program that combines classroom instruction, group exercises, CCUS site visits, communications training, and hands-on CCUS field activities. These activities cover a wide range of topics, including science, technology, policy, engagement, and business aspects associated with CCUS deployment. RECS also provides networking, stakeholder engagement, and team-building opportunities to improve engagement skills and foster interdisciplinary knowledge and collaboration.

A core RECS principle is to focus learning activities at CCUS sites and build an understanding of the project lifecycle and commercial deployment considerations. RECS participants gain invaluable hands-on experience and exposure to real-world CCUS projects, reinforcing their understanding of the challenges and opportunities in the field, and equipping participants with the skills and networks needed to navigate the complex CCUS landscape and advance CCUS deployment.

RECS is a catalyst for building CCUS leadership and professional growth, and RECS alumni are at the forefront of advancing CCUS in the U.S. and globally. RECS facilitates networking and collaboration among more than 700 RECS alumni who are actively engaged in all facets of CCUS, from government and industry to NGOs and academic research. Alumni contribute to the CCUS workforce via different roles, including project management, various technical and engineering roles, business development, policy and regulatory aspects, and advancing innovation and entrepreneurship through their own start-up companies.

RECS serves as a successful model for other countries and jurisdictions to consider. Programs such as RECS can play a significant role in helping to build a skilled and diverse CCUS workforce, create and nurture effective CCUS networks, build capacity, and develop CCUS leaders who will drive deployment and create a sustainable future.

Research, Development, and Deployment

Investment in research, development, and deployment (RD&D) directly supports decarbonization strategies, reduces costs, increases efficiency, lowers risk, and reduces environmental impacts for CCUS. RD&D activities can also assist with speeding up the integration of CCUS components and are important for capacity building.

RD&D programs should leverage public-private partnerships to further development and deployment activities. Added attention is needed in the following RD&D areas for the commercial development of CCUS with new solutions that are affordable, scalable, and sustainable. Recommendations for effective CCUS RD&D include:

- ➔ **Supporting Technologies at All Stages of Development.** Commercial success requires assisting technologies through all stages of development and building on each experience toward increasingly larger scale and more efficient projects. CCUS RD&D should support technology from first-of-a-kind to next-of-a-kind so that the private sector can leverage cost reductions from experiential learning to widely deploy CCUS on a commercial scale.
- ➔ **Continuing and Enhancing Early-stage Research.** For emerging economies interested in accelerating CCUS adoption (such as Vietnam, Thailand, Indonesia, Malaysia) research that supports technological breakthroughs is important for mitigating against technology lock-in and creating new opportunities for CCUS deployment.

- **Broadening Research Scope and Application.** CCUS can be applied effectively across many different sources of CO_2. RD&D should not be confined to just one topic but instead should embrace the full range of potential applications to encourage widespread deployment of the technology and integration with broader economic activities. For emerging economies focused more on one part of the CCUS value chain, an RD&D effort on that topic may be more realistic.
    - **RD&D for Carbon Capture.** Expanded capture research is essential to reduce cost and improve performance as carbon capture is applied to fossil power generation and manufacturing industries. Although first-generation capture technologies are widely and commercially available, RD&D could optimize and lower costs of existing commercial technologies, and help develop second-generation technologies with improved economic and technical performance.
    - **RD&D for Utilization Pathways.** While enhanced oil recovery (EOR) remains a viable and economic option for long-term CO_2 storage, many large CO_2-emitting sources are not located near suitable EOR fields. EOR revenues are also strongly dependent on oil prices and might be subject to decline as the world transitions to other energy sources. For these reasons, RD&D in storage and non-EOR utilization options is imperative for developing new CO_2 utilization markets and opportunities. Further RD&D opportunities exist for carbon use and reuse with laboratory-supported research by providing technological mechanisms for utilizing CO_2, and have the potential to provide economic benefits by creating new export products.
    - **RD&D for Transport.** Transport of CO_2 is a fairly mature activity but it can nonetheless benefit from the undertaking of RD&D activities. RD&D activities can focus on improving safety, lowering costs, discovering new routes,

and optimizing modes. Research into new materials is also an area of opportunity that can result in significant cost reductions and increased transportation safety.

- **RD&D for Storage.** Undertaking subsurface injection of CO_2 requires a detailed understanding of the storage processes and local geologic conditions. Advancement in research is needed to improve upon commercial site characterization techniques, advanced computational tools for handling large volumes of data, and improved monitoring systems.
- **RD&D for Crosscutting Issues.** RD&D expenditures in basic science can catalyze innovations and breakthroughs in CCUS technologies. Support for market and integrated analysis can assist countries in understanding how CCUS and other strategies can contribute to decarbonization goals and determine cost-efficient solution pathways.

The following case studies for the National Carbon Capture Center (NCCC) in the United States and Test Center Mongstad (TCM) in Norway show the value of research/test centers in developing CCUS technologies.

National Carbon Capture Center (NCCC) in Alabama

Figure 4.3: National Carbon Capture Center. (Courtesy of Southern Company)

The U.S. Department of Energy/National Energy Technology Laboratory (NETL) and Southern Company operate the NCCC, a neutral research facility working to advance technologies to reduce greenhouse gas emissions from fossil-based power plants and industrial processes, and to promote carbon conversion and carbon removal innovations, such as direct air capture (DAC). Located in Wilsonville, Alabama, the Center offers a unique test bed for third-party evaluations of cost-effective CO_2 capture, CO_2 conversion, and DAC technologies — bridging the gap between laboratory research and large-scale demonstrations and deployment. In 2023 alone, more than 50 stakeholder organizations visited and toured the NCCC.

The NCCC offers benefits to technology developers by providing them with testing opportunities in the real-world operating conditions of an industrial site, thereby accelerating the commercialization of low-cost carbon capture and conversion processes, as well as emerging DAC technologies. Through the testing of more than 75 technologies, for innovators in the U.S. and six other countries, the Center has directly participated in the reduction of the projected cost of CO_2 capture from fossil generation by more than 40 percent. The NCCC supports the evaluation of advanced technologies from domestic and international developers. These evaluations are critical in identifying and resolving environmental, health and safety, operational, component, and system development issues, as well as achieving scale-ups and process enhancements in collaboration with technology developers. DOE-sponsored projects, as well as projects from industry, universities, and other collaborative institutions, provide a full spectrum of technologies for testing at the Center.

Performance data generated in testing at the NCCC has validated laboratory data, allowing for engineering scale-up and, in turn, driving breakthroughs in carbon management solutions. The NCCC also offers assistance in finding domestic and international partners for scale-up. The NCCC operation has provided more than 150,000 hours of testing enzymes, membranes, sorbents, solvents, hybrids, and associated systems for post-combustion carbon capture, as well as CO_2 conversion technologies and DAC technologies.

The NCCC has completed three carbon conversion tests to date, including a demonstration of a Southern Research thermochemical process to produce ethylene by using CO_2 from coal-fired flue gas and ethane, and a demonstration of the

CarbonBuilt Reversa™ CO_2 mineralization process, which uses CO_2 in flue gas and coal combustion residuals to produce low-carbon concrete. In addition, the NCCC completed tests in 2023 with Helios-NRG LLC on the first algae conversion technology — a novel, multi-stage continuous algae-based system to capture CO_2 from power plant flue gas. In 2023, the NCCC also completed its first DAC onsite test, in collaboration with the Southern States Energy Board and Aircapture, and is performing additional testing.

Norway's CO_2 Technology Center Mongstad (TCM)

Figure 4.4: CO_2 Technology Center Mongstad, Norway.
(Courtesy of Technology Center Mongstad, tcmda.com)

TCM is co-owned by the Norwegian State and industry (Equinor, Shell, and TotalEnergies). Since 2012 it has been available to national and international researchers and technology developers wanting to test and verify CO_2 capture technologies, component testing, and problem-solving. TCM also offers advisory services on capture and advises on aspects such as solvent degradation, corrosion, emission issues, and waste handling, all important aspects of the capture process.

One of the most important contributions of test centers like TCM is testing out and verifying technologies before commercialization. To date, 23 test campaigns have been conducted at TCM. For instance, capture technology used for Norway's demonstration project Longship was first tested at TCM.[2]

An often underestimated benefit of TCM and other test centers is the capacity-building effect following the existence and operation of the facility. TCM has produced a large number of publications and publicly available reports, to the benefit of industry, regulators, and academia.[3] TCM provides ample opportunity to build capacity for researchers in Norway and abroad. There are agreements ensuring collaboration with research institutes, through the sharing of information,[4] and allowing the researchers to test technologies at the test center.[5] TCM further initiated and takes part in the International Test Center Network, which aims to share knowledge that may be vital to refine and commercialize CCS globally.[6] There are test members from China, Japan, and South Korea in this network,[7] enabling the Asian region to benefit from over 10 years of TCM operations, as well as the knowledge and expertise from other test centers from Europe, the U.S., Canada, and Australia.

Policymakers and Regulators

The resources described above are not only limited to use domestically, but can also be used to build relevant expertise within governments (such as with policymakers and regulators). Bilateral and multilateral exchange initiatives exist across the U.S. and other governments that provide opportunities for technical assistance and cooperation.

Knowledge sharing across early movers is not only important for CCUS technical developments but also for developing legal and regulatory frameworks, as described in Chapter 5: Roadmap for Developing Legal and Regulatory Frameworks.

5. Roadmap for Developing Legal and Regulatory Frameworks

Key Takeaways

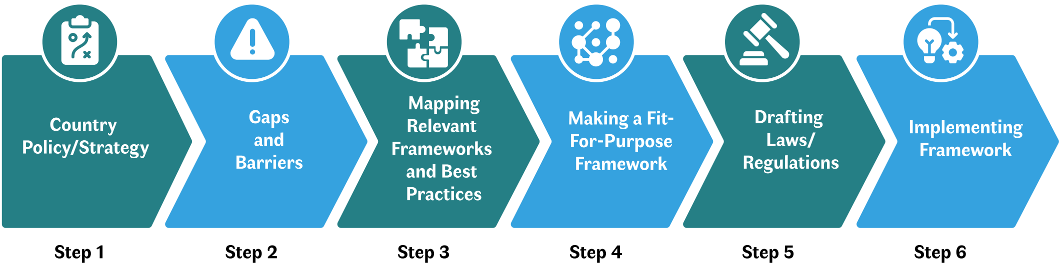
- To build a thriving and safe CCUS industry, countries need to develop frameworks. A CCUS framework consists of policies, laws, acts, regulations, and related instruments that set the terms for the key actors to build CCUS projects.
- To create a successful framework, this Handbook proposes a six-step process, starting with assessing a country's existing policies so as to establish a country policy (or strategy) for CCUS.
- The fourth step in this six-step process is creating the framework. Countries can decide if they want to adopt all new legislation to create a standalone CCUS framework; or to adapt existing legislation to an existing framework (such as oil and gas). Countries can also leverage external standards and sources or not. There is no one "right" way.
- While there is no one right way, a successful CCUS framework must address all parts of CCUS to ensure that regulatory activities by different governmental players are coordinated.
- Japan and Norway offer examples of how CCUS projects can proceed even without a fully developed CCUS framework in place.

Introduction

A CCUS framework is a set of policies, laws, acts, regulations, and a suite of legal instruments that provide structure to support the development of the CCUS industry and protection of the environment. Frameworks are needed by both the public and private sectors to help ensure the predictability, operability, accountability, transparency, and bankability of CCUS projects.

A Roadmap to Developing a Framework

There are many ways to establish a CCUS framework. One approach can include a combination of the following six steps as illustrated below:[1] Assess and revise a country's national policy or strategy; identify gaps and barriers in existing frameworks; map relevant frameworks and best practices using available resources; develop a fit-for-purpose framework; draft laws and regulations; and implement the framework.



Step 1: Country Policy/Strategy

It is important for CCUS to be included in national policy and strategy documents. This sets the direction for the development of CCUS frameworks. Also, in many countries, government approval is needed before laws can be made and enacted. Therefore, a national-level policy (or a 'strategy document') that includes CCUS and identifies the lead ministry/agency is important to support legal and regulatory developments. A stakeholder engagement strategy for developing and sharing the policy or strategy is recommended.

The first step in establishing a CCUS framework is to assess existing country policies and strategies to determine if CCUS is included. Because CCUS is a climate mitigation technology, CCUS may be included as part of the emissions mitigation strategy as part of a country's climate goal. For instance, the Government of Malaysia has identified CCUS as a key initiative within its Energy Transition Levers.[2] In India, NITI Aayog, a Government of India policy think tank, has issued a strategic report that outlines broad-level policy interventions needed across various sectors for CCUS deployment.[3]

When developing a country policy/strategy, considerations include identifying relevant industries, determining the role of the State, addressing ownership/liability/access, gathering resources, and determining financial options.

- ➔ **Relevant Industry.** Power, oil and gas, chemical manufacturers, cement, and steel producers. A phased approach towards framework development can often help focus efforts and accelerate the timeline to later scale up to an industry-agnostic law/regulation.
- ➔ **Role of the State.** To regulate or delegate authority to sub-national governments.
- ➔ **Ownership, Liability, Access.** For transport and storage, including the role of private contracts. Consider whether the State will assume responsibility for long-term stewardship of storage and how will land (surface/subsurface) rights and access be determined.
- ➔ **Resources.** Domestic and international. Chapter 6: Resources and Responsibilities for Frameworks discusses this in further detail.

→ **Financial Incentives/Mandates.** To help spur CCUS deployment. Chapter 7 discusses this in further detail.

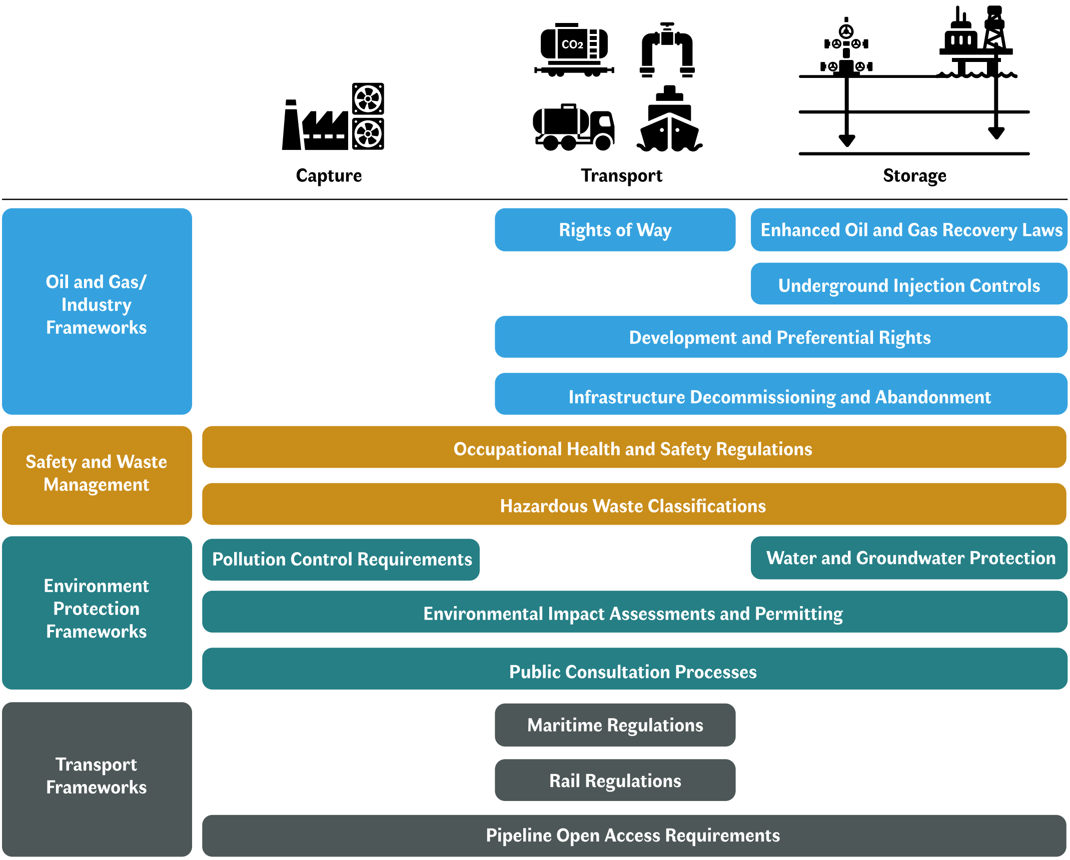


Figure 5.2: Examples of existing regulations that may be relevant for CCUS activities. (Adapted and expanded from IEA 2022: CCUS Legal and Regulatory Handbook, p.24)

Step 2: Gaps and Barriers

Step 2 involves conducting a gap and barrier analysis of existing CCUS-related legal and regulatory instruments to determine whether existing frameworks (such as those used for CO_2 EOR) can be repurposed to support CCUS activities or whether a new regulatory framework is necessary. A World Bank study found that many countries already have a large number of legal instruments needed to support a CCUS framework such as Environmental Impact Assessments, a legal classification for CO_2, permitting criteria for pipelines, emissions and waste handling, etc.[4]

These instruments could potentially comprise parts of a CCUS framework. For instance, the Government of Norway found its existing Petroleum Act and Regulation to be flexible enough to incorporate CO_2 capture, transport, and storage from natural gas production offshore without any amendments. In Japan, national regulators found that some gaps in the framework could be addressed to accommodate new activities. The previous figure (Figure 5.2) illustrates examples of regulations that may be relevant to a CCUS framework.

Step 3: Resources for Developing Frameworks

Step 3 involves mapping relevant legal/regulatory frameworks and identifying best practices. Several publicly available resources can be utilized during the mapping exercise, as described in Chapter 6: Resources and Responsibilities for Frameworks.

Step 4: Making a Fit-for-purpose Framework

Step 4 involves making a fit-for-purpose CCUS framework, using resources described in Step 3. A fit-for-purpose framework can be developed as a new stand-alone CCUS framework or as an amendment to an existing framework. If there is no existing framework, external resources could be leveraged to develop a suitably tailored framework.

Step 5: Drafting Laws and Regulations

Based on the results from the Gap Analysis (Step 2), it may be possible to apply or amend an existing law by clarifying the applicability to CCUS projects. Sometimes, a more rigorous process may be required to draft new laws/regulations.

Step 6: Implementing the Framework

The final stage is implementing the framework. Several activities and considerations are involved in this phase including:

- Identify agencies for compliance and enforcement of the laws/regulations
- Develop tools for permitting, monitoring, reporting, and verification
- Offer online resources and templates for applications and reporting requirements
- Develop and make available resources such as a geological atlas, licensing data
- Provide capacity-building and training for regulators, industry, and others parties

→ Pilot test the framework, such as through a demonstration project coupled with an engagement plan

Finally, while these activities are listed in Step 6, they can be critical in aiding the successful deployment of CCUS projects. For instance, the success of the rapidly growing number of carbon capture projects hinges on the ability to timely obtain a permit. Permitting delays pose significant project risk because of the uncertainty in the timing of receiving project approval, thereby jeopardizing project financing and overall deployment. Establishing a clear permitting timeline will increase the efficiency of the process and provide greater certainty to project developers.

Chapter 6: Resources and Responsibilities for Frameworks provides resources available, from the use of standards, early movers, and international conventions, that may be leveraged when developing a domestic legal and regulatory framework.

6. Resources and Responsibilities for Frameworks

Key Takeaways

- When creating a framework for CCUS, policymakers can draw upon a number of resources including international standards such as those developed by the International Organization for Standardization (ISO), as well as existing CCUS legislation from the US, EU, and others.
- In addition, when creating a framework, policymakers should look to existing international conventions. These conventions may not only obligate the country to regulate CCUS projects in a certain way, they may also be a source of guidance.
- Project Greensand is an example of how two countries are using international standards and international conventions in a CCUS project.

Introduction

There are several publicly available resources, including international standards and early mover frameworks, that can be leveraged to help establish CCUS frameworks. Some of these resources are presented in this chapter.

- International standards, particularly those from ISO/TC 265 Carbon Dioxide Capture, Transportation, and Geological Storage, can help develop country-specific CCUS frameworks.
- Early mover frameworks may offer guidance for regulatory framework development, including the IEA's Legal and Regulatory Framework for CCUS.[1]
- Regulatory models also exist for cross-border CO_2 transport and storage.
- International conventions may also be required, based on the nature of the CCUS project.

International Standards

International standards, particularly those developed by ISO/TC 265 Carbon Dioxide Capture, Transportation, and Geological Storage, can help develop country-specific CCUS frameworks.

The standards are developed through member consensus under the International Organization for Standardization (ISO). ISO membership is composed of countries and liaisons represented by international subject-matter experts who convene under technical committees to formulate a specification/guideline/definition based on leading practices. Members then vote on the standards through ballots and if approved, a standard is typically reviewed and updated every five years. Standards are voluntary and cannot be used in place of existing regulations or laws. However, standards may be referenced, incorporated, or adopted into a regulation. When jurisdictions adopt a standard, it can help harmonize regulations and laws across jurisdictions.

ISO/TC 265 was established in 2011 and is currently active. Several working groups cover CO_2 capture, pipeline transportation, geological storage, cross-cutting issues, enhanced oil recovery, and shipping. Issues relating to quantification and verification are split among the respective working groups. As of the date of the publication of this handbook, in ISO/TC 265, there are 28 participating member countries, 16 observing member countries, and several liaisons.[2] Once ISO/TC 265 promulgates a standard, any country's national standards body can adopt the standard in whole or in part (see case study on ISA 27914 below). Such adoption does not imply that the standard has been included in the legal framework. Implementation rests with the regulators.

ISO 27914

ISO 27914 was developed in 2017 and covers CO_2 geological storage. This standard is currently being revised under ISO/TC 265 to add a quantification and verification portion for storage without hydrocarbon production and incorporate experiences made since publication. The revision process is expected to be completed in 2025.

ISO 27914 has been adopted by Japan and Canada, and referenced by Norway's regulators in its guidelines for CO_2 safety regulations. It has also been referred to and used by a number of projects, including the CO_2 storage project Greensand on the Danish Continental Shelf,[3] and in projects in the Russian geological formations within the Yamal and Gydan license areas. Both of these license areas have been certified according to ISO 27914, confirming compliance with 27914 e.g., the site selection process and storage capacity estimations.[4]

The example below describes how Indonesia's Carbon Capture and Storage Center has leveraged international resources to advance CCUS domestically, including by joining ISO/TC 265 as a voting member.

Indonesia Carbon Capture and Storage Center leverages international resources to advance CCUS

Figure 6.1: Indonesian Carbon Capture and Storage Center Leadership (Courtesy of the Center)

In 2023, the Indonesia CCS Center (the Center) was inaugurated, led by a team of experts encompassing engineering, science, policy, and business. Several members were seconded from key institutions within Indonesia, including the national oil company Pertamina and the Ministry for Maritime Affairs and Investment. The Center's establishment was driven by the imperative to serve as a dedicated resource to accelerate CCUS technology development in Indonesia through research, innovation, and advocacy. The Center has facilitated several government-to-government discussions on CCUS cross-border cooperation, participated in numerous international speaking engagements, hosted the country's first international CCUS forum, and supported participation by the country's national standards body as a voting member of ISO/TC 265. The Center is actively engaged in developing a CCUS regulatory framework and supporting domestic and regional business-to-business initiatives.

Early Mover Frameworks

Frameworks developed by those overseeing legacy CCUS projects (early movers) may guide the construction of emerging laws and regulations. Examples of early mover frameworks include:

- The EU published its comprehensive framework for CO_2 storage in 2009 through Directive 2009/31/EC on the geological storage of carbon dioxide (EU CCS Directive).
- The International Energy Agency (IEA) published a model regulatory framework for CCS, leveraging frameworks from Australia, Europe, and the U.S.[5]
- The U.S.'s Underground Injection Control Class VI program is discussed in the case study below.

U.S. UIC Class VI 'Primacy'

The primary regulatory instrument for underground CO_2 storage in the U.S. is the Underground Injection Control (UIC) Class VI program (under the Safe Water Drinking Act). The goal of the UIC program is to protect underground sources of drinking water from injection activities. The Class VI program provides requirements for CO_2 injection for permanent geological sequestration. This regulation is currently managed at the federal level except for three states (North Dakota, Wyoming, and Louisiana) that have received EPA approval to administer a Class VI program (referred to as approval for 'primacy'). The EPA has a number of guidance documents related to UIC Class VI that may be helpful for CCUS framework development in other jurisdictions.[6]

Liability and stewardship for the CO_2 storage site are important issues to consider when enacting a legal framework for CCUS. IEA's Model Framework provides some guidance on this topic.

IEA Model Framework: Long-Term Liability and Stewardship

The IEA Model Framework is an example of an early mover framework. There are several issues linked to liability, including allocation of risk and liability during the transportation phase from the capture point to the storage site. A particularly complex issue that has been the subject of much debate is long-term liability.

The IEA Model Framework observed that the issue of long-term liability is generally addressed in one of three ways: a provision is made for transfer of responsibility to the relevant authority, long-term liability explicitly rests with the operator, or long-term liability is not explicitly addressed.[7] Where liability is not explicitly addressed, it will be assumed that the operator retains liability for a storage site in perpetuity.[8] The Class VI rule requires post-injection site care for a default of 50 years, during which the operator must conduct monitoring of the CO_2 plume to ensure things are going as planned. The operator must maintain financial responsibility during this time. Some states have developed long-term liability frameworks that would take effect after the post-injection site care period (such as the state of Louisiana).

In the 30 countries having transposed the EU CCS Directive, the situation is different. In the CCS Directive, it is prescribed that the operator is strictly liable for the storage site up to a point of transfer, which will happen no sooner than 20 years after injection stops and the site is closed. The timeframe for transfer may be shorter than the prescribed 20-year period within the CCS Directive, where the competent authority is satisfied that the core transfer condition is met at an earlier date. Such transfer implies the regulator is taking on the liability and stewardship of the storage site. However, it is dependent on the operator demonstrating that the "stored CO_2 will be completely and permanently contained".[9] How such demonstration may be done is not mandated but an important aspect is to demonstrate that the storage site and the CO_2 plume are behaving and stabilizing as predicted. The regulators may use checklists in the permits, technical standards, and best practices to enable a more predictable and transparent approach to the demonstration.

International Conventions

A number of cross-border transport laws, international regulations, and treaties may be relevant to international cross-border CCUS projects and the development of national frameworks. Not all of these will be ratified or geographically relevant for the policymakers this handbook is addressing. However, they may either contain mechanisms or text that could be informative or be a potential place to start when implementing a framework for CCUS. The table below (Table 6.1) summarizes a few of the key international frameworks.

Table 6.1: International Conventions.

The United Nations Convention on the Law of the Sea (1982) (UNCLOS)	UNCLOS does not expressly regulate CCUS activities. Its provisions may have an impact if CCUS activities are deemed to constitute "pollution". Under Article 210 of UNCLOS, dumping is a form of pollution. Currently, there is no conclusive opinion on whether CO_2 transport to an offshore injection platform or the injection of CO_2 into subsea geological formations constitutes dumping and/or pollution under UNCLOS. Furthermore, Article 195 of UNCLOS requires states "not to transfer, directly or indirectly, damage or hazards from one area to another".
1996 Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972. (The London Protocol)	The London Protocol is a comprehensive international legal instrument for the protection of the marine environment. It is also the most commonly discussed international treaty in the context of cross-border CO_2 transport. While many emerging economies, particularly those in the Asia-Pacific, are not Contracting Parties to the Protocol, this does not prohibit them from importing/exporting CO_2 with a Contracting Party.[10] The London Protocol initially prohibited the export of CO_2 for offshore storage as it was regarded as disposal at sea, which is prohibited (Article 6 states, "Contracting Parties shall not allow the export of wastes or other matters to other countries for dumping or incineration at sea"). In 2009, an amendment to the London Protocol was proposed to allow the export of CO_2 for disposal if the countries concerned entered into an agreement (it need not be a contract). This amendment has not entered into force; however, parties have adopted a resolution on its provisional application. This action now supports the transfer of CO_2 across borders. An exporting country that is a Contracting Party to the London Protocol is responsible for demonstrating that the legal/regulatory frameworks of the importing country comply with the requirements of the London Protocol. Several countries with no pre-existing frameworks for CO_2 storage are considering acceding to the London Protocol and using the provisions of the protocol as building blocks for national frameworks.

	The International Maritime Organization (IMO) hosts the secretariat for the London Protocol and its parties. IMO facilitates knowledge sharing through its website by allowing access to guidance documents and resolutions,[11] and further by assisting potential new Contracting Parties directly and by facilitating contact with other Contracting Parties. This assistance may entail both advice on how to become a Contracting Party and how to implement frameworks in compliance with the Protocol. The IMO also has a number of guidance documents for sale in their database, several of which relate to CCS.[12] The London Protocol has 54 Contracting Parties, many in the Asia-Pacific region.[13]
Basel Convention (1989)	The Basel Convention provides that international trade in hazardous waste is subject to the prior consent, or refusal, of the receiving country. It is not clear whether CO_2 constitutes a hazardous waste within the scope of the Basel Convention. Without further clarification, this could further procedural challenges by imposing stricter conditions for CO_2 transport across international borders.
Convention on Environmental Impact Assessment in a Transboundary Context ("Espoo Convention")	The Espoo Convention requires parties to assess the environmental impacts of their transboundary activities during the early stages of project planning and to take all appropriate measures to mitigate significant adverse transboundary impacts. CCUS and CO_2-related activities are not expressly listed as covered activities, but a CCUS project may be subject to the convention's requirements if it is conducted within the territory of, or by, convention parties and meets the criteria under Appendix III to the convention. The Espoo Convention has 45 Contracting Parties, but currently none in the Asia-Pacific Region.[14]
Convention on Access to Information, Public Participation in Decision-Making, and Access to Justice in Environmental Matters (Aarhus Convention)	The Aarhus Convention imposes public participation requirements on member parties within the territorial scope of the convention for activities that may have a significant effect on the environment. The Aarhus Convention has 48 Contracting Parties, but currently none in the Asia-Pacific Region.[15]

The London Protocol is most commonly discussed in the context of cross-border transport of CO_2 in the Asian region. The two examples below illustrate how countries that have ratified the London Protocol (as Contracting Parties) can work together and how a country that has ratified the Protocol (as a Contracting Party) and one that has not (as a Non-Contracting Party) can work together.

Transportation of CO_2 between Two Contracting Parties to the London Protocol

Project Greensand started CO_2 injection in March 2023, marking the world's first offshore cross-border CCS project. CO_2 captured in Antwerp, Belgium, was shipped to the Nini West depleted oil field on the Danish continental shelf for injection.[16] The first phase of the project was conducted on a pilot scale. Site selection and characterization were done according to ISO 27914 on geological storage (referenced above) after which the pilot was implemented.[17] A final investment decision is still pending. Should the project move forward, a full-scale storage permit would be needed. This project could store up to 1.5 Mt CO_2 per year starting in 2025/2026, with a potential further scale-up to 8 Mt CO_2 per year in 2030.[18] Both Denmark and Belgium are Contracting Parties to the London Protocol. The Memorandum of Understanding (MoU) between Belgium and Denmark is the first arrangement pursuant to the London Protocol Article 6.2.[19] The non-legally binding MoU is high-level, identifying permitting agencies in both countries and confirming the purpose and scope, as well as confirming the intention to perform the activities pursuant to applicable laws and regulations, without going into project specifics.[20] The MoU is considered to comply with Article 6.2 requirements, and the format is chosen in a subsequent MoU between the

Netherlands and Denmark as well. Other Contracting Parties are considering more comprehensive and legally binding agreements.

Transportation between Contracting and Non-Contracting Parties to the London Protocol

Led by the Australian company Santos, Timor Gap (Timor-Leste's state-owned oil company) has signed an MoU with the Bayu-Undan joint venture.[21] The Bayu-Undan field is offshore on the Timor-Leste continental shelf, with a potential storage capacity of up to 10 MPTA. Australia is a Contracting Party to the London Protocol, whereas Timor-Leste is not. Article 6.2 is more prescriptive for cases between a Contracting and Non-Contracting Party than for arrangements or agreements between two Contracting Parties. As a Contracting Party, Australia has to ensure its agreement/arrangement with Timor-Leste contains “provisions at a minimum equivalent to those contained in this Protocol, including those relating to the issuance of permits and permit conditions for complying with the provisions of Annex 2, to ensure that the agreement or arrangement does not derogate from the obligations Contracting Parties under this Protocol to protect and serve the marine environment”. Thus, Australia would have to conduct a due diligence process of the Timor-Leste legal framework for CO_2 storage to confirm to other Contracting Parties that by exporting CO_2 to Timor-Leste, Australia still meets its obligations under the London Protocol. Currently, Timor-Leste is still developing a regulatory framework for CO_2 storage,[22] making this due diligence process challenging.

7. Project-specific Frameworks

Key Takeaways

- → At the project level, policymakers and regulators should understand the suite of contracts that a typical CCUS project requires, and how these contracts allocate risks.
- → Most if not all of these contracts will refer to the laws and regulations of a country, even if these are not CCUS-specific.
- → The bankability of CCUS projects will likely be determined by the nature of the property rights granted by a domestic framework, such as the rights to the pore space, or the rights to the carbon credits generated by the project.

Introduction

Chapter 6 described resources for developing frameworks, including standards, early mover frameworks, and international conventions. Some emerging economies are moving forward with CCUS legal and regulatory frameworks at a project-specific level. This method can generally provide a nimble approach by addressing the key issues for a CCUS framework without the lengthy cross-ministry approval process that may be needed for a new standalone CCUS law/regulation. Countries that are adopting project-specific regulations can still work on amending existing laws/regulations in parallel and using the project-specific regulation as a pilot.

Leveraging of frameworks may involve implementing standards, new permitting procedures, or guidelines. A non-exhaustive list of considerations for a CCUS framework is outlined below.

Key considerations for a CCUS framework

- Objective for CCUS deployment in country
- Emission reporting requirements (capture air emissions, CO_2 leakage, hazardous waste, etc.)
- Property rights, land use, and access for transportation and storage
- Storage liability
- CCUS Supply Chain Permitting
- Monitoring, verifying, quantification
- Reporting requirements and documentation retention
- CO_2 classification (waste, commodity, hazardous/toxic)
- CO_2 stream composition and characterization requirements
- Short- and long-term stewardship and liability of potential storage sites
- CO_2 ownership and private-party contracts
- Environmental Assessments
- Community engagement, including environmental justice considerations, community benefits plans
- Matching sources of CO_2 with permanent geological storage sites (also known as 'Hubs and Clusters')
- Local content requirements
- Taxes for CCUS projects (e.g., depreciation rules and tax incentives)

Norway's Sleipner and Japan's Tomakomai projects

Commercial CCUS projects have proceeded without a comprehensive legal/regulatory framework including the Tomakomai project in Japan and the Sleipner in Norway.

Figure 7.1: Tomakomai CCUS Demonstration Project. (Photo courtesy of IEA (2021), CCUS around the world in 2021, IEA, Paris https://www.iea.org/reports/ccus-around-the-world-in-2021, License: CC BY 4.0)

Asia: Tomakomai, an offshore CCUS demonstration project led by Japan CCS Co. Ltd., was commissioned in 2012 by the Ministry of Economy, Trade, and Industry (METI), and in 2018 by the New Energy and Industrial Technology Development Organization.[1] Because Japan did not have a CCUS-specific law when Tomakomai was launched, existing laws and regulations governing the operation were applied or amended. For example, the Act on Prevention of Marine Pollution and Maritime Disaster was amended to regulate offshore CO_2 storage in line with the 2006 amendment to the London Protocol.[2] The Act required a permit to be issued from the Minister of Environment for CO_2 storage under the seabed, and the permit application required a project plan, monitoring plan, and an environmental impact assessment report.[3] Furthermore, the Mining Act and Mining Safety Act were applied to ensure safety standards for CO_2 injection and storage operations.[4] METI also developed a guideline, 'Safe Operations of a CCS Demonstration Project',[5] and a 'Reservoir Management Standards Manual During CO_2 injection' was prepared and applied. This manual took into account international CCUS regulations, technical standards, and guidelines.[6] Provisions for long-term liability, site closure, and the transfer of such liability have not yet been established in Japan but are being developed as part of the government's ongoing regulatory program. The country continues to work towards a more comprehensive CCUS framework.

Figure 7.2: Sleipner Project. (Photo courtesy of Gullfaks B. Av Ole Jørgen Bratland. CC BY SA 3.0. https://snl.no/Equinor)

Europe. In Norway's Sleipner project, CO_2 has been injected offshore in a subsea saline formation for more than 25 years.[7] The Sleipner project separates CO_2 from natural gas produced at an offshore platform. The CO_2 is then injected and stored in the adjacent offshore Utsira formation beneath the sea floor.[8] This project was initiated in 1996, long before Norway implemented a dedicated CCUS regulatory framework in 2014.[9] The project commenced under the existing oil and gas framework; however, CCUS activities were addressed under the Plan for Development and Operation before gas operations started. After the new framework was passed, the project sponsors applied for, and were granted, an updated permit.[10] The project successfully transitioned project operations under the new framework.[11]

The above case studies set forth how existing, non-CCUS frameworks were employed to conduct CCUS projects in Japan and Norway.

When starting the process of drafting a CCUS legal/regulatory framework, include health and safety, environmental, and industry experts with experience in both technology and legal frameworks. While there are different ways to approach legislative drafting, there are generally five key components:

- Legalize (achieve the intended legal effect)
- Formalize (choose the right legislative vehicle)
- Integrate (relate new law to existing law)
- Organize (arrange the legislative text appropriately)
- Clarify (achieve clarity of expression)[12]

A draft regulation or law must be fit-for-purpose, understandable, and enforceable in the jurisdiction where it applies. The drafting process can be prescriptive (sets requirements or standards the operator must meet) or performance-based (provides criteria that the operator must meet). There are many helpful resources available to help with the drafting process such as international standards, existing frameworks, etc. which are shared in more detail in Chapter 6: Resources and Responsibilities for Frameworks.

The development of frameworks should be an iterative process that includes information and lessons learned from real-life projects. Using resources, model frameworks, best practices, and lessons learned from other countries may accelerate the drafting process and mapping of issues and potential solutions to both technical and commercial challenges in the CCUS industry. However, all countries have their own unique characteristics and challenges; therefore, pilot testing any framework is an important part of implementation.

Demonstration projects will test the flexibility and appropriateness of legal instruments and permitting regimes and help determine any regulatory gaps.[13] A demonstration project also enables engagement between the project developer, regulator, and other governmental officials, which can enhance collaboration and support the incorporation of lessons learned. The Norwegian Longship demonstration project is one example of a demonstration project that was used to test the new legal framework for CCUS. Longship is the first project that has been developed under the dedicated CCUS framework. A number of unforeseen challenges and issues have been identified, and to a degree, addressed as a consequence of the project.[14]

The Figure 7.1 is an illustration of the decision tree for developing a utilization or storage framework, in conjunction with Steps 1 to 6 described in Chapters 5, 6, and 7 of this Handbook.

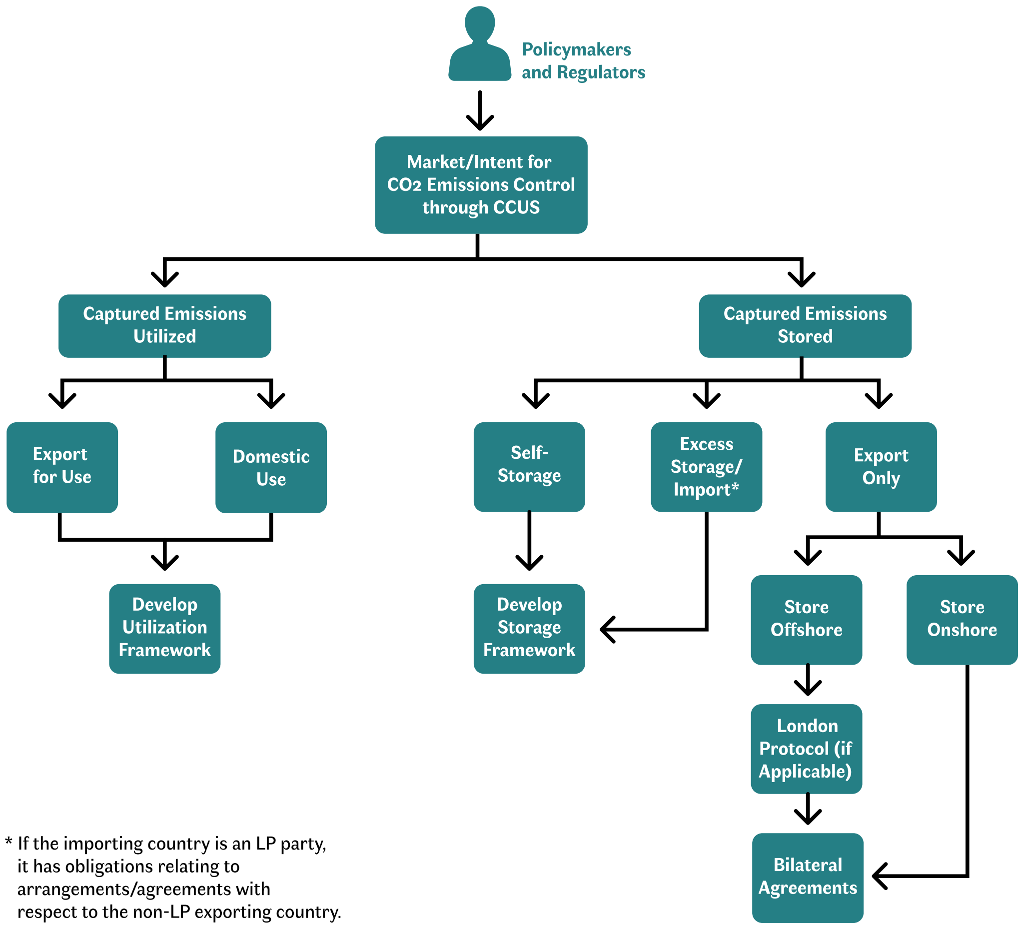


Figure 7.1: Decision path for creating a framework. (The London Protocol is discussed in Chapter 6: Resources and Responsibilities for Frameworks)

Best Practices for Project-specific Frameworks

The resources described above can support the development of international or domestic legal and regulatory frameworks. At the project level, there is also a suite of legal instruments and contracts to consider.

As shown in the figure below (Figure 7.2), there are several key players and different types of contracts that are typically necessary for a storage project. This is just one type of model for a project. Any company conducting CCUS will need to determine how vertically integrated they will be in the value chain. A project developer, separate from the emitter, may oversee some or all of the CCUS value chain, such that the capture/transport/storage (upstream/midstream/downstream) companies may be multiple or single entities. Several of the instruments are similar to contracts needed for the power sector, as illustrated in CLDP's Understanding Power Purchase Agreements Handbook.[15]

- **Permits and Related Documents.** Grants the project developer (owner/operator) the right to inject CO_2 for permanent storage. Typically, the regulator will require the developer to provide site characterization information, an environmental impact assessment, a plan for monitoring the site during injection, and a plan for stewardship of the site upon closure.
- **Transport and Storage Service Agreement.** Obligates the developer to obtain the necessary permits, including those needed for pipelines, to conduct operations at the site as a condition of the midstream company providing CO_2. This agreement may also require the developer to comply with protocols to secure incentives such as storage production tax credits or other storage incentives.

- **Offtake Agreement.** Obligates the upstream company (e.g., the entity capturing the CO_2) to provide CO_2 at specific specifications and volumes. This agreement can include a 'take or pay' clause such that the storage developer/operator will compensate the upstream company even if CO_2 transportation or storage operations are interrupted.
- **Pore Space/Land/Access Agreement.** Governs the lease/concession for the access of surface property or pore space where the storage site is to be developed. This can occur through a purchase, lease, or can be issued by the owner of the pore space via pre-planned release of storage resources or by bidding.
- **Engineering, Procurement, and Construction (EPC) Contract.** Sets the terms and conditions for storage site design, procurement of materials and equipment, and site construction. The obligations created under this agreement can also be divided among multiple contracts that include one or more of these scopes.
- **Loan Agreement.** Creates the obligation of the lenders to finance the storage project, as well as the obligations of the project developer to comply with various covenants in the loan agreement.
- **Carbon Purchase Agreement.** Governs the terms between the developer and the buyer of carbon credits generated from the storage project. The use of carbon markets is discussed further in Chapter 6: Resources and Responsibilities for Frameworks.
- **Concession Agreement.** Grants the project developer the right to develop, finance, construct, and operate the storage project. This is particularly important when the project developer is not local to the country.
- **Injection and Post-closure Stewardship Plans.** Prior to injection, the project developer may be required to show proof of financial security to the state. This interest-bearing fund can

be used by the state to cover stewardship costs after a certain number of years following site closure. In some instances, the state may allow the long-term transfer of stewardship from the developer to itself after the developer meets certain post-closure requirements.

Coupled with community engagement and legal and regulatory frameworks, financial instruments are also key to enabling a CCUS project's success.

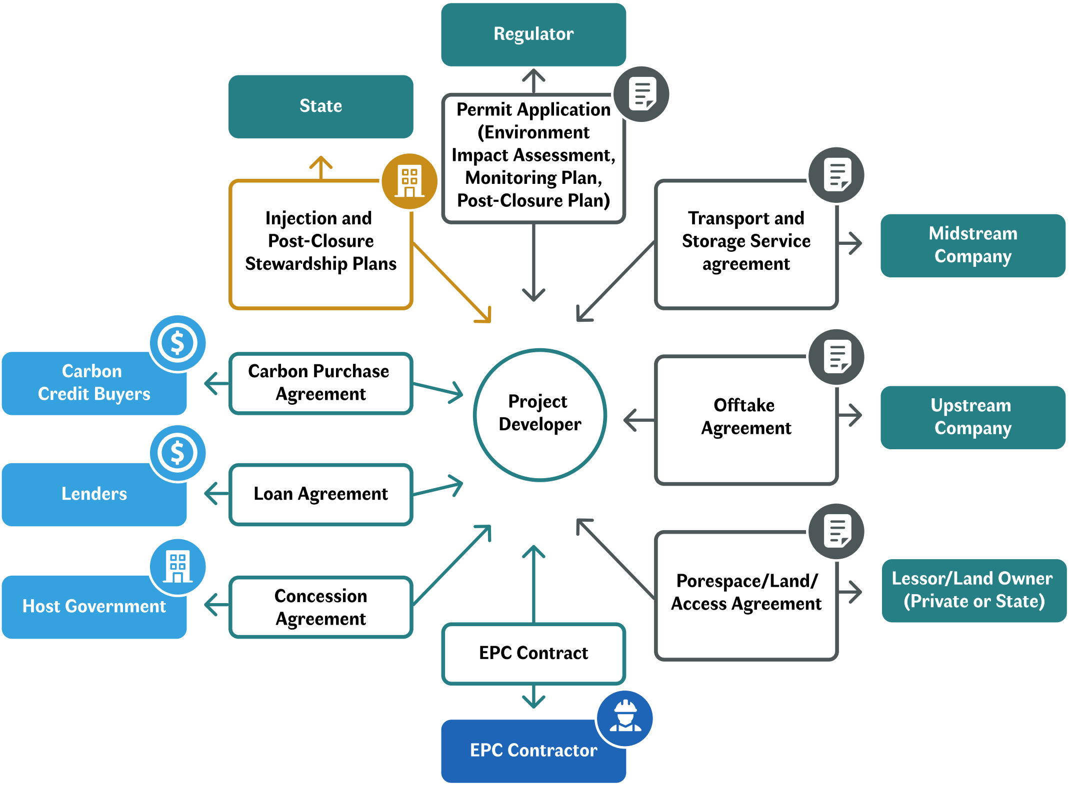


Figure 7.2: Suite of contracts for a project developer of a storage project.

8. Finance and Incentives

Key Takeaways

- Most produced carbon must be disposed of permanently. CCUS project investors and operators will be incentivized to construct and operate CCUS projects when there is an economic reason to capture, transport, and store waste carbon. Captured carbon must have a value.
- For policymakers and regulators seeking to incentivize investment into CCUS projects, there are a number of ways to create value from capture/stored carbon. These include tax credits, carbon taxes on emissions, cap-and-trade schemes for emissions, and simply regulatory requirements that limit how much carbon can be emitted (and thus spur investment into CCUS to meet such a threshold). Voluntary carbon markets may also be a source of value for CCUS projects.
- However, policymakers should be aware of the unintended consequences of their policy choices, and be prepared to adapt fiscal incentives once these consequences become clear.
- To reduce the cost of capital, CCUS project investors and operators may have access to loans and other financial instruments that are tied to climate objectives.

Introduction

This chapter discusses financial instruments and mechanisms for policymakers to consider when setting carbon capture utilization and storage (CCUS) strategies and frameworks. It also outlines a number of financial tools that could be considered by countries and project developers to advance CCUS projects, including bank loans, carbon taxes/incentives, border adjustments, and carbon markets.

When developing these instruments and mechanisms, it is important to consider the different project development stages and how incentives can help advance each stage, largely by reducing costs and risk. The following graphic shows the typical scaling up of a project from technical studies and pilots to demonstrations and full-scale commercial deployment. It also tracks these stages to different public-private partnership roles and types of incentives and funding mechanisms that could be applied at each stage. It is also possible that industry could pursue these projects without R&D support, such as by relying on the RD&D experience from other countries.

From a demonstration and commercial project perspective, financial planning for a CCUS project spans a variety of phases noted in Figure 8.1. Early in the life of a project, costs are estimated and refined for capital and operating expenditures based on a Front End Engineering Study (FEED). As the project matures, expected project costs are further refined throughout all stages of the project. Because CCUS generally does not produce direct products or create project income, some type of regulatory mandate may be necessary to enable a positive investment decision.

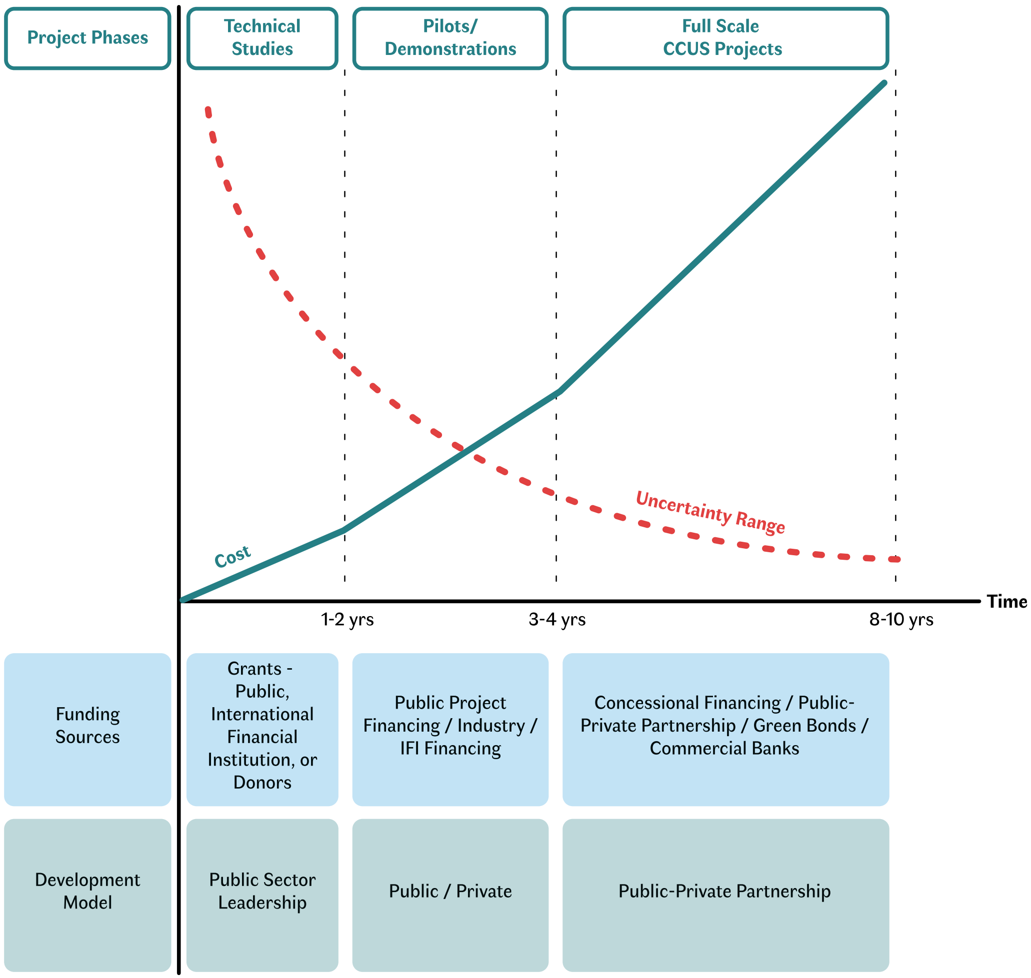


Figure 8.1: How RD&D supports early development in public-private partnerships. Harshit Agrawal, The World Bank Group, November 2023, Catalyzing CCUS Deployment in Developing Countries (PowerPoint slides).

Economics of CCUS Projects

An understanding of the economics of CCUS projects is important to help policymakers shape incentives to encourage their deployment. CCUS projects can have significant initial capital and long-term yearly operating and maintenance (O&M) costs. An understanding of these costs is critical in quantifying the level of incentives at different phases of a project to support widespread commercial development. For example, the initial capital costs and construction of a carbon capture plant can range from $50M USD to $1B USD depending on the source and volume of CO_2 required to be captured.[1] This is generally the largest lump expenditure for a CCUS project. Long-distance pipeline transport and storage operations also require significant capital expenditures. Access to a storage site close to the capture project is generally most desirable from a total project cost standpoint since transportation expenses can be reduced. Each project will have unique attributes which will make cost profiles somewhat different.

CCUS projects should be evaluated in a manner consistent with general economics and project finance principles. The goal of project analysis is to ascertain both the future revenues and total capital and O&M costs over time. Along with revenues and costs, an assessment of the risk profile for each component is also necessary to understand how potential changes in market and regulatory conditions will affect project cash flow.

The revenues for projects are in large part driven by governmental action. These actions can be in the form of mandates (e.g., carbon taxes and environmental mandates), or incentives (e.g., direct government expenditure, tax credits, and financial services). In some limited cases, the revenues from the sale of CO_2

for utilization could potentially help justify the project costs, as in the case of early CCUS via CO_2-EOR development in the United States.

Bankability and Financial De-risking CCUS

Government Actions for CCUS

There is a suite of economic approaches that governments can adopt to incentivize the reduction or removal of CO_2 emissions through CCUS. Mandates include imposing a carbon tax or mandating a regulation on an industry/power process to reduce emissions. Incentives include R&D expenditures, governmental grants or funding through cooperative agreements, direct investment and production incentives, production tax credits (PTC), and investment tax credits (ITC), and building demand for decarbonized products through regulation or incentives.

Carbon Tax

A carbon tax is a mechanism by which CO_2 emissions are taxed based on their volume, impact and/or source. An important consideration in a carbon tax policy is to include mitigation measures such as CCUS or net negative activities like CDR.

Tax levels can be set by the government and are transparent and predictable, and provide a stable price on emissions. However, this type of policy may result in an under/over estimation of market response to the tax, and the risk of carbon leakage (i.e., having operations moved out of the country or region to a jurisdiction without or with a lower tax).

In 2012, Japan implemented a carbon tax as part of overall tax reform policies.[2] Japan's tax applies to the fossil fuels sectors, however, the government has extended several exemptions and refund measures on carbon tax rates for fossil fuel products used in particular energy-intensive industries, such as agriculture, public transportation, petrochemical industries, and coal-fired power plants. Singapore has also issued a carbon tax in 2019, starting at \$5/tonne of CO_2-equivalents, with incremental increases up to \$50-85/tonne of CO_2-equivalents by 2030.[3]

Cap-and-trade

A cap-and-trade system sets a maximum amount of allowed emissions. Allowances, or authorizations for emissions, would be sold under a competitive market to the highest builder. Mitigation measures can also be part of the mandatory market system in which transactions between emitters and mitigators can take place (see case study on the European Union's Emission Trading Scheme below). A cap-and-trade system has the benefit of allowing the carbon value to vary based on the demand for emissions and the supply for mitigation. A downside of such a system is the potential for volatility in the market and thus a reduction in the certainty of risks and revenues for CCUS projects.

European Union's Emission Trading Scheme Cap-and-trade

The European Union's Emission Trading Scheme (ETS), was implemented in all 27 European Union Member States as well as the European Free Trade Association countries (Iceland, Liechtenstein, and Norway).[4] The ETS regime provides for a total cap of emissions, in which a tonne of allowed emission is expressed as an allowance. The emitters must surrender (and pay for) allowances equivalent to their emissions. If they fail to do this, they will be subject to a fine.[5] If the emitter emits less than the allowance, the ETS regime allows for emitters to trade (sell) the excess allowances to other emitters. If emitters reduce or remove emissions through CCUS, the ETS recognizes the CO_2 as not emitted. This results in the emitter not being mandated to surrender allowances for the volumes removed or reduced. The risk of the emission transfers from the emitter when the CO_2 is transferred to either a capture, transfer, or storage facility or if the CO_2 is transferred out by permanently chemically binding in a product (i.e., the CO_2 cannot enter the atmosphere under normal use of the product).[6]

The ETS does not cover all types of emissions, and several countries are implementing carbon taxes to incentivize emission reductions outside the ETS. However, the ETS does not exclude the EU Member States from implementing carbon taxes in addition to the cap-and-trade for emissions that are comprised by the ETS. In Norway, the ETS allowances are stacked on top of Norway's CO_2 tax for the offshore oil and gas sector, creating a compelling incentive to engage in CCUS rather than emitting the CO_2.[7]

Emission Regulations of Industrial Processes/Power Plants

Direct regulatory restrictions on emissions can be used alone or in combination with other mechanisms, such as cap-and-trade as described above. This would require the emitter to implement emission control measures[8] or reduce or eliminate the emission source (e.g., forced asset retirement or CCUS) and require compliance with a performance standard. Regulations of this type can be done on a mass balance basis (allowed emission mass/process fuel input), a final product performance basis (allowed emission mass/production output unit), or a gross balance basis (allowed emission mass per time period). An example of this type of regulation is the proposed U.S. rule "New Source Performance Standards for Greenhouse Gas Emissions from New, Modified, and Reconstructed Fossil Fuel-Fired Electric Generating Units".[9] The rule contains requirements for the installation of carbon capture equipment at power plants. As another example, Saudi Arabia is considering mandating all new gas plants have CCS, or be at least 'CO_2 capture-ready'.[10]

RD&D Expenditures

A potential pathway to incentivize the deployment of CCUS is for governments to undertake research, development, and deployment (RD&D) activities to advance local and global knowledge of CCUS technologies. Robust RD&D programs are currently available in the United States, Europe, Canada, Australia, and Japan to aid in the deployment of CCUS. Some of these programs are partly funded by incentives, such as taxes or surplus allowances.[11]

Deployment of new RD&D programs should be preceded by a robust identification of needs and target opportunities.

Consistent review by external experts may also be needed to ensure that funding is being used efficiently and productively. These programs are valuable in encouraging industry to undertake desired actions. Early movers can be rewarded with RD&D grants, favorable tax breaks, etc. to drive deployment. It is possible to use infrastructure from RD&D projects in future commercial deployment. An example may include the use of wells drilled for geologic site characterization studies.

Multilateral Development Banks

Multilateral Development Banks, such as the Asian Development Bank (ADB) and the World Bank Group, provide various resources to developing countries to facilitate the development of CCUS infrastructure (see the following case study on ADB's Support of the CCUS in People's Republic of China). As summarized below, the resources include grants to conduct feasibility studies and draft relevant policies, create knowledge-sharing publications, events like study tours, concessional loans, and establish special funds to mobilize carbon finance.

A key best practice to mobilize support from banks is to express clearly that a country wants a bank to engage in accelerating CCUS and request assistance from the bank throughout the project life cycle, from preparatory work to funding a demo CCUS project. Representatives from these various banks have also shared their willingness to have direct conversations with governments before a formal application is received.

ADB's Support of the CCUS in the People's Republic of China (PRC)

Since 2009, the PRC has partnered with the Asian Development Bank (ADB) to raise awareness of CCUS through knowledge products, workshops, and establishing CCUS Centers of Excellence. As a result of this support, in 2012, post-combustion capture technology on a coal-fired power plant (capture capacity of 20,000 t/a) commenced operation in Tianjin.

PRC is a CCUS leader in the Asia-Pacific region, with 21 projects, 11 of which are operational as of 2023 (according to GCCSI).[12] The key to two decades of successful deployment is largely attributed to several factors. First, the country developed (2015) an initial roadmap for CCUS Demonstration and Deployment that was later updated (2022). This encouraged a number of developments in CCUS policy, technology, and financing.

Second, the Carbon Capture and Storage Research Center in Shanghai was established (2016) to promote the CCUS innovation and industrial capacity building for the Shanghai and Yangtze River Delta. Further, the Guandong CCS Center for Excellence developed institutional capacity for researching and demonstrating technologies, policies, and financial mechanisms to commercialize CCUS. Third, the country continues to develop and improve CCUS policies and regulations, publishing "Carbon Capture and Storage — Ready Policy to Facilitate Future CCS Deployment in the People's Republic of China" (Dec 2014). Finally, the PRC continues to proactively support CCUS engagement since its 11th Five-Year Plan (2005-2010).

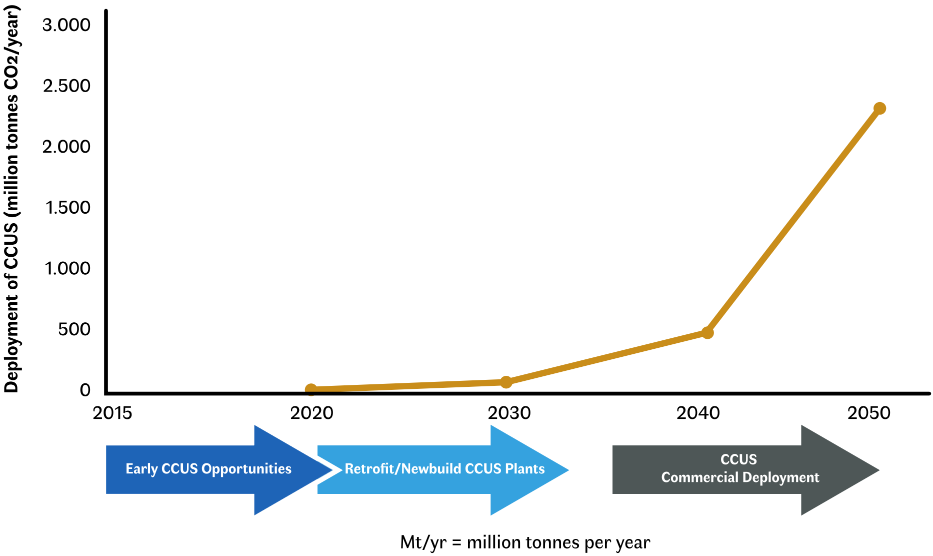


Figure 8.2: Roadmap for CCUS demonstration and deployment in PRC. (Simplified from ADB 2015: Roadmap for Carbon Capture and Storage Demonstration and Deployment in the People's Republic of China)

Direct Investment and Production Incentives

In North America, Investment Tax Credits (ITC) and Production Tax Credits (PTC) are the two primary direct incentives. ITCs are distributed based on infrastructure and construction expenditures and are generally available immediately after the equipment is put into service, independent of equipment usage. PTCs are distributed based on the production of a material (e.g., $/tonne). The credit only gets disbursed after the product is produced and conditions for their delivery are met. PTCs do not take into consideration the cost incurred in producing the unit of output being incentivized, but they are effective in ensuring meaningful utilization of the investment. In the U.S., the Section

45Q PTC has had a major impact on the announcements and development of CCUS projects (see the following case study on PTC — Section 45Q). In Canada (Alberta) a similar stimulus has been developed for CCUS project development in the form of an ITC (also described below).

In Europe, there are other direct investment and production incentives. Some of this aid comes in the form of both the direct grants, to cover capital and/or operating expenses (frequently funded by revenue from the ETS), as well as guarantees, loans, and reduced regulatory burdens. In Norway, the Longship demonstration project is the recipient of state aid worth about ⅔ of the total cost of the project, which will cover a range of costs for developing the project infrastructure, incentives for biogenic CO_2 volumes (which is currently not incentivized by a carbon tax or allowance), operation costs for a period, risks related to interface issues between stakeholders in the value chain and potential emission allowances.[13]

PTC — Section 45Q of the U.S. Inflation Reduction Act (IRA) of 2022

Tax credits under 45Q have been available since 2008. However, the value, threshold limitations, and Commence Construction Date limited widespread commercial deployment. In 2022 changes provided the needed level of incentives and an actionable time frame for deployment based on market-driven mechanisms in an ever-changing geopolitical landscape. The modifications include (1) an increase in tax credit value from $50 to $85 per tonne for geologic storage; (2) an increase in tax credit value from $35 to $60 for CO_2-EOR, (3) a tax credit value for direct air capture (DAC) at $180 per tonne for geologic storage and $130 per tonne for CO_2

utilization, including CO_2-EOR; (4) a decrease in emissions eligibility thresholds of qualifying projects, and (5) allowing for direct pay while retaining tax credit transferability for liquidity options (will allow project developers to avoid the burdensome and often costly process of raising tax equity to monetize the traditional tax credits generated under Section 45Q).[14]

From an industry perspective, one of the most significant changes included in the IRA is the extension of the Commence Construction Date to January 1, 2033. Prior to this, "construction" of a capture facility had to begin by January 1, 2026, by either beginning physical work of a significant nature or by incurring 5 percent or more of the total cost of the qualified facility.

Section 45Q provides a tax credit for CO_2 storage, whether the storage is part of a CCS value chain or for EOR/industrial applications. The IRS's guidance permits entities who operate CO_2-enhanced oil recovery projects to use ISO 27916 as a tool for quantification and verification of CO_2 stored during the CO_2-EOR project in order to obtain tax credits. The U.S. EPA requires that a monitoring, reporting, and verification (MRV) plan be submitted pursuant to Subpart RR of the Greenhouse Gas Reporting Program and has provided some guidance.[15] Generally, this includes a description of the site and its geology, the monitoring area, the monitoring plan and its frequency, and potential leakage pathways in the monitoring area. If granted, annual reporting to the U.S. EPA includes the yearly mass of CO_2 injected/produced from the storage site, surface leakage at wells and near-well equipment, the net stored value, as well as the cumulative mass stored over the life of the project.

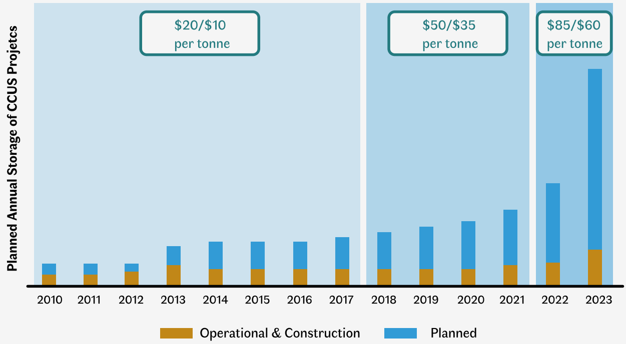


Figure 8.3: Project development based on the evolution of the Section 45Q tax credit. (Adapted from IEA CCUS Projects Tracker 2023)

ITC Example: Canada

In November 2023, the Government of Canada and the Province of Alberta announced a CCUS investment tax credit (ITC) program, aimed at incentivizing CCUS project development. The ITC will be set at 50 percent for equipment used to capture carbon and 37.5 percent for equipment used in transporting and storing carbon. In addition, the draft legislation released last August expanded the CCUS ITC to make a portion of enhanced oil recovery projects eligible for CCUS ITCs. The CCUS ITCs are available from January 1, 2022.

Loans and Financial Assurances

Apart from mandates and incentives, low-interest financial programs offered by governments can also help initiate projects. While not widely available in emerging economies, these mechanisms are more commonly seen in the U.S., such as the Department of Energy's Loan Office. The Carbon Dioxide Transportation Infrastructure Finance and Innovation Act (CIFIA) within the DOE's Loan Programs Office in collaboration with the Fossil Energy and Carbon Management, provides financial support for high-capacity, common-carrier CO_2 transport projects (e.g., pipelines, rail, shipping, and other transportation methods) as part of the CIFIA initiative, integrated into and enacted under the Infrastructure Investment and Jobs Act (IIJA).[16]

In Asia, there are climate change-relevant funds that support capital investment. Possible funds, subject to the design condition, include the ADB's Climate Action Catalyst Fund and the Japanese government's Japan Fund for the Joint Crediting Mechanism. In general, the multilateral development banks' loan interest is lower than those of commercial banks.

Markets for Low-carbon Products

Creating a market for lower-carbon products, sold as premium materials, can also accelerate CCUS adoption. These products, such as low-carbon cement, steel, and chemicals could be acquired by both the public and private sector in sizeable quantities (particularly in emerging economies where the demand for these materials continues to exist).

Unintended Consequences

Unintended consequences can create a barrier to project development or result in project cancelations. An example is capping credits that discourage or hinder additional CCUS deployment. Another case is selling carbon credits to an emitter for capture, which may discourage the emitter from making other investments in technologies that would limit its total emissions. [17]

External Drivers

A government can also be affected by forces outside of its borders. This includes cross-border carbon taxes (such as the EU's Carbon Border Adjustment Mechanism), the mandatory or voluntary reporting and disclosure of CO_2 emissions at a sectoral or industry level, and carbon markets.

Carbon Taxes Overseas

In 2023, the EU adopted a carbon tax for carbon-intensive products imported, known as the Carbon Border Adjustment Mechanism (CBAM). While not enforceable until 2026, reporting obligations have started. The primary objective is to reduce the likelihood of carbon emissions by imposing a tax based on the carbon intensity of certain imports including iron, steel, cement, fertilizers, aluminum, electricity, and hydrogen on products imported to the EU from jurisdictions without a carbon tax or allowance. Other countries that import these carbon-intensive goods from Asia-Pacific are considering adopting similar cross-border taxes. Accordingly, hard-to-abate sectors subject to CBAM are considering capturing CO_2 emissions to help reduce the emissions intensity of the good (and therefore the carbon tax that would be levied during export).

Carbon Accounting/Disclosure/Reporting

There is increasing pressure for industries and corporations to be transparent in their disclosure and reporting of GHG emissions. While several emissions-intensive industries often have domestic reporting requirements through their environmental regulations, recent demand has been by State and Federal agencies, as well as the general public, to make emissions disclosures available. In the case of publicly traded companies, shareholder proposals are increasingly demanding the reporting of direct and indirect emissions. The International Sustainability Standards Board, formed at COP26 in Glasgow, is developing sustainability-related disclosure standards.

While this trend is increasing in Western economies, international companies doing business in emerging economies (including Asia) are being asked to make a clear accounting of the emissions intensity of all products and processes they plan to import. For this reason, transparent and verifiable monitoring of CO_2 quantities along the CCUS value chain is important. The use of a third-party auditor to review the emissions quantification data provides a level of independence for the operator/developer and the public. In India, the top 1,000 publicly listed companies by market capitalization are required to make their ESG disclosures with direct and indirect emissions, under the Business Responsibility and Sustainability Reporting framework, prescribed under the Securities and Exchange Board of India (Listing Obligations and Disclosure Requirements) Regulations, 2015.

Carbon Markets

Countries in the region, such as Malaysia, Indonesia, India, Vietnam, and Thailand, have also looked to the use of carbon markets to enable CCUS projects. A carbon credit represents the quantity of emissions reduced, removed, or avoided and is typically measured in 1 tonne of CO_2 or CO_2-equivalent. There are two types of carbon market schemes — voluntary and mandatory/compliance. The EU ETS, as described above, is an example of the latter. In both schemes, buyers (e.g., individuals, companies, governments) purchase carbon credits to offset their emissions from sellers (e.g., project developers, owners, financers).

To support the integrity of a carbon market, it is critical to (1) set a conservative baseline (emissions quantity before the reduction, removal, or avoidance), (2) measure the reduction to that baseline, ensure the activity is real and additional (the activity has taken place and would not have occurred but for the credit mechanism), (3) make permanent (no future reversal of the emissions reduction, removal, avoidance activity), and (4) not double-count the activity (an emissions reduction activity should be counted only once). It is also key for emitters to prioritize emissions within their value chain — namely, direct, and where possible, indirect. Carbon credits can help the industry with residual emissions to achieve net zero targets.

Incentives and Revenues for States

Similar to other industrial projects, there are several costs associated with regulating, permitting, and overseeing CCUS activities. Countries can potentially offset these costs by embedding cost recovery mechanisms into CCUS frameworks. These mechanisms may take several forms, such as implementing a license fee, allowing the state to collect “rent” on the area permitted for the activities, compliance fees, and injection tariffs.

Countries can also require state-owned companies to participate as partners in CO_2 storage licenses. For example, Denmark's state-owned company Nordsøfonden will have 20 percent participation in all CO_2 storage licenses.[18] Therefore, the state of Denmark will assume 20 percent of the costs, risks, and revenues associated with the development and operations of storage licenses. In other regions of the world, state-owned companies (particularly the national oil companies) tend to have a more prominent role in developing the full value chain of CCUS compared to those entities in Europe. For instance, Aramco in Saudi Arabia and China National Offshore Oil Corporation in China.

9. Additional Resources

Justification for CCUS

United States Long-Term Strategy for Net Zero Emissions
www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf
This link leads to the report for the United States Long-Term Strategy for Net Zero Emission Reductions. The report can be used as an example of integrated analysis and a roadmap for achieving deep decarbonization.

IPCC Sixth Assessment Report
www.ipcc.ch/assessment-report/ar6/
This link leads to the International Panel on Climate Change Sixth Assessment Report which contains valuable information about the need to achieve GHG emission reductions. It also contains technical data necessary for countries to consider when developing their decarbonization strategies.

IEA Net Zero Roadmap
www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach
A roadmap developed by the International Energy Agency for the world to achieve decarbonization. It highlights the need for CCUS technologies to be deployed.

CCUS in China's Mitigation Strategy
www.sciencedirect.com/science/article/am/pii/S1750583617307570
An example of CCUS deployment analysis for China using the Global Change Analysis Model (GCAM). It shows how Integrated Assessment Models can be used to study the role of CCUS in deep decarbonization.

Net-zero CO_2 by 2050 Scenarios for the United States
www.sciencedirect.com/science/article/abs/pii/S2666278723000119
An example of the use of an intermodel comparison exercise can help in understanding the uncertainty of models in representing deep decarbonization scenarios. The paper also presents information about the value of CCUS as part of decarbonization strategies.

Project Status/Tracker

Clean Air Task Force U.S. Carbon Capture Project Tracker
www.catf.us/ccsmapus
Interactive Map of CCUS Projects in Development in the U.S.

IOGP Global CCUS Projects
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Global CCS Institute CCS Facilities Database
www.globalccsinstitute.com/co2re/
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IEA CCS Project Tracker
www.iea.org/data-and-statistics/data-tools/ccus-projects-explorerCCUS
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U.S. EPA Permit Well Tracker
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U.S Department of Energy Carbon Storage Atlas
https://netl.doe.gov/carbon-management/carbon-storage/atlas-data
A website maintained by the U.S. Department of Energy National Energy Technology Laboratory with GIS-based information for storage resources in the United States.

Draft 2030 Roadmap for CCUS for Upstream E&P Companies
https://mopng.gov.in/files/article/articlefiles/Draft_UFCC_Roadmap_2030_v3.pdf
A technical report by the India Ministry of Petroleum and Natural Gas explains the technical aspects of CCUS.

Feasibility of Accelerating the Deployment of CCUS in Developing APEC Economies
www.apec.org/docs/default-source/Publications/2014/3/Feasibility-of-Accelerating-the-Deployment-of-Carbon-Capture-Utilization-and-Storage-in-Developing-A/Final-EWG_24_2011-ARI-APEC-CCUS-EOR-Report.pdf
A report by the Asia Pacific Economic Cooperation about the feasibility of accelerating CCUS-EOR in selected developing APEC economies.

International CCS Knowledge Center
https://ccsknowledge.com/
The International CCS Knowledge Center, hosted by Sask Power in Canada, is an organization focused on building capacity for international CCUS framework developments. The Knowledge Center focuses on optimizing large-scale CCUS applications for steel, cement, and thermal power plants (natural gas and coal) through cost-reduction initiatives and technological advancements.

Frameworks

London Convention Protocol
www.imo.org/en/OurWork/Environment/Pages/London-Convention-Protocol.aspx
A website maintained by the International Maritime Organization (IMO) about the London Convention Protocol.

IEA CCS Model Regulatory Framework
www.iea.org/reports/carbon-capture-and-storage-model-regulatory-framework
An IEA report that contains information about the necessary components to create a model regulatory framework for the development of CCUS.

U.S. Reporting Requirements for UIC Permittees
www.law.cornell.edu/cfr/text/40/146.92
This link contains the current regulation for the reporting of CO_2 being injected into geologic reservoirs permitted under Class VI.

CCUS Policy Framework and its Deployment Mechanism in India
www.niti.gov.in/sites/default/files/2022-12/CCUS-Report.pdf
A report by the Government of India about the policy framework for CCUS.

Asia CCUS Network
www.asiaccusnetwork-eria.org/
A website for the Asia CCUS Network which provides a platform for CCUS stakeholders in the Asia region.

Engagement

WRI Guidelines for Community Engagement in Carbon Dioxide Capture, Transport, and Storage Projects
www.wri.org/research/guidelines-community-engagement-carbon-dioxide-capture-transport-and-storage-projects

A guideline report by the World Resources Institute for the development of community engagement about CCUS projects.

U.S. DOE Public Outreach and Education for Carbon Storage Projects
https://netl.doe.gov/node/5828
Manual by the U.S. Department of Energy for designing a framework for public outreach for storage projects.

Guidance for Creating Community Benefits Plans for Regional Direct Air Capture Hubs
www.energy.gov/oced/articles/community-benefits-plan-guidance
A guidance document created by the U.S. Department of Energy Office of Clean Energy Demonstrations (OCED) for the creation of community benefit plans with special emphasis on the Direct Air Capture hubs program.

List of Professional Organizations involved in CCUS Development

- American Association of Petroleum Geologists (AAPG)
- American Chemical Society
- American Geophysical Union
- American Institute of Chemical Engineers (AIChE)
- American Institute of Mining, Metallurgical, and Petroleum Engineers (AIME)
- Association for Iron and Steel Technology (AIST)
- Institute of Electrical and Electronics Engineers (IEEE)
- National Centre of Excellence in Carbon Capture and Utilization, IIT Bombay, India
- European Association of Geoscientists and Engineers (EAGE)
- Geological Society of America (GSA)

- The Society for Mining, Metallurgy, and Exploration (SME)
- Society of Petroleum Engineers (SPE)
- The Minerals, Metals, and Materials Society (TMS)

Acronyms

ADB	Asian Development Bank
BECCS	Biomass Carbon Capture and Storage
CAPEX	Capital Costs
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilization, and Storage
CDR	Carbon Dioxide Removal
CIFIA	Carbon Dioxide Transportation Infrastructure Finance and Innovation Act
CO_2	Carbon Dioxide
EOR	Enhanced Oil Recovery
DAC	Direct Air Capture
DFI	Direct Foreign Investment
EGR	Enhanced Gas Recovery
EHR	Enhanced Hydrocarbon Recovery
EOR	Enhanced Oil Recovery
EOR/EGR	Enhanced Oil/Gas Recovery
ETS	European Trading Scheme
FECM	Fossil Energy and Carbon Management
FEED	Front End Engineering Studies
FOM	Fixed Operation and Maintenance Cost
GCSSI	Global CCS Institute
GHG	Greenhouse Gas
IEA	International Energy Agency
IIJA	Infrastructure Investment and Jobs Act
IPCC	Intergovernmental Panel on Climate Change
IRA	Inflation Reduction Act
ISO	International Organization for Standardization

ISO/TC	International Organization For Standardization Technical Committee
ITC	Investment Tax Credits
LCA	Life-cycle Analysis
MoU	Memorandum of Understanding
MRV	Measurement, Reporting, and Verification
MTPA	Million Tonnes Per Annum
NCCC	National Carbon Capture Center
NGO	Non-Governmental Organization
NCoE	National Centre of Excellence
NDC	Nationally Determined Contribution
PTC	Production Tax Credits
R&D	Research and Development
RD&D	Research, Development, and Deployment
RECS	Research Experience in Carbon Sequestration
SCADA	Supervisory Control and Data Acquisition
TCM	Test Center Mongstad
UIC	Underground Injection Control
UNCLOS	United Nations Convention on the Law of the Sea
VOM	Variable Operating and Maintenance Costs

Glossary

Abandonment
Process used to permanently end the operation; used a term of art in the industry to denote cessation of well operations

Authority
Governmental entity or entities with legal power to regulate or permit activities

Barge
Floating unit carrying freight on waters under tow by a vessel

Capture plant
Process and associated equipment that separates and handles CO_2 from facility emissions

Carbon dioxide (CO_2)
A colorless, odorless gas composed of one molecule of carbon and two of oxygen; categorized as a greenhouse gas that contributes to climate change; generally produced by combustion or conversion of carbon-based products

Carbon dioxide (CO_2)-equivalent
Measure to compare emissions from various greenhouse gases based on their respective global warming potential, compared to the warming potential of CO_2

Carbon dioxide (CO_2) stream
Fluid composed mainly of carbon dioxide

Closure
Closing a storage site that is no longer in use; typically requires permission from an authority having jurisdiction

CO_2 emissions reduction
Calculated net decrease of CO_2 emissions for a given process; use of complex analysis methods like Life Cycle Assessment is needed to ascertain net reductions

Compression
The use of a device that raises the pressure of CO_2. A compressor normally uses mechanical displacement to compress the gas to higher pressures so that the gas can flow into pipelines and other facilities

Containment
Status of CO_2 being confined within the storage reservoir by an effective trap or combination of traps

Decommission
The process of taking an engineered system or component out of service, and returning the area to its previous state

Dense phase CO_2
CO_2 in its liquid or supercritical phases

Engagement
Consultation process that involves stakeholders identifying and addressing issues of common importance and sharing information

CO_2-enhanced oil recovery (CO_2-EOR)
A process designed to produce hydrocarbons CO_2 from a geologic reservoir using the injection of CO_2

Emissions
The release of chemicals from industrial processes into the environment

Flue gas
A mixture of gases produced by the combustion of fuel; flue gases can be composed of combustion by-products and other chemicals produced by secondary reactions

Formation
Rocks, sediments, or deposits

Geological storage
Long-term containment of CO_2 in the deep subsurface in pores within formations

Greenhouse gas (GHG)
Greenhouse gases are gases in the atmosphere such as carbon dioxide, methane, fluorinated gases, and nitrous oxide that can absorb infrared radiation, trapping heat in the atmosphere

Impurities
Substances that are present in very small quantities within the confines of a material; as used in this book, non-CO_2 substances that are part of the CO_2 stream that may be added from the source materials or the capture process, added as a result of comingling for transportation, or released or formed as a result of sub-surface storage and/or leakage of CO_2

Leakage
Unintended release of CO_2

Life cycle assessment (LCA)
Compilation and evaluation of the inputs, outputs, and potential environmental and health impacts of a CCUS project throughout its life cycle

Long-term liability or stewardship
Legal and financial responsibility for all aspects of a geologic storage site beyond closure for an extended period of time

Monitoring
Continuous or repeated checking, supervising, critically observing, measuring, or determining the status of a system to identify change from a baseline or variance from an expected performance level

Net zero
The overall balance between greenhouse gas emissions produced and greenhouse gas emissions taken out of the atmosphere

Operator
Person or entity that is legally responsible for the operation of the CCUS project

Onshore storage
Geologic storage under land

Offshore storage
Geologic storage under the ocean

Paris Agreement
Adopted in 2015, the Agreement is an international treaty that covers climate change mitigation, adaptation, and finance. It requires economic and social transformation based on the best available science

Point source
Source of CO_2 emissions from industrial processes and stationary combustion from industry and power plants

Post-closure period
The period that begins after the demonstration of compliance with the criteria for site closure

Post-combustion CO_2 capture
Capture of carbon dioxide from a flue gas stream produced by fossil fuel combustion

CO_2 purity
Percentage by mass of CO_2 as a component of the CO_2

Regulator
Entity or entities that have the authority to permit, approve, and/or otherwise authorize one or more CCUS projects

Risk assessment
Overall process of risk identification, risk analysis, and risk evaluation

Safe long-term
Period necessary for storage to be considered environmentally safe by the scheme under which the quantification is being implemented, and may be pursuant to a standard or agreement

Site characterization
Detailed evaluation of one or more candidate sites for CO_2 storage identified in the screening and selection stage of a CO_2 storage project to confirm and refine storage integrity, storage resource, and injectivity estimates and provide basic data for initial predictive modeling of fluid flow, geochemical reactions, geomechanical effects, risk assessment, and monitoring and validation program design

Site screening and selection
The process of assessing and prioritizing a number of geologic storage sites

Site stewardship
The job of supervising or taking care of the storage site

Social license to operate
The ongoing acceptance of a company or industry's standard business practices and operating procedures by its employees, local communities, indigenous affected groups, and the general public

Stakeholder(s)
Individuals, a group of individuals, or organizations whose interests are or could be affected by a CCUS project

Storage project
The physical and temporal extent of activities associated with a project for the geological storage of CO_2 that includes site selection and characterization, baseline data collection, permitting, design and construction of site facilities (site pipelines, compressors, etc.), well drilling, receipt of CO_2 at the storage site and CO_2 injection during the active injection phase, and site closure (including well and facilities abandonment)

Storage site
A site that comprises the storage facility and storage project wells

Supercritical CO_2
CO_2 at pressures and temperatures above the critical pressure and the critical temperature

Verification
Confirmation by examination and provision of objective evidence that specified criteria are met

Well or wellbore
Holes created into the ground in which combinations of tubing, casing, and cement are emplaced to convey fluids into or out of the subsurface

Notes

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Colophon

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Authors: Vikram Vishal, Atsumasa Sakai, Priya Prasad, José Benítez Torres, Ingvild Ombudstvedt, Richard Esposito, George Koperna, Pamela Tomski

Book Sprints facilitator: Barbara Rühling, Anna Roxas

Copy editors: Raewyn Whyte, Christine Davis

HTML book designer: Agathe Baëz

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