UNECE

TECHNOLOGY BRIEF

CARBON CAPTURE, USE AND STORAGE (CCUS)

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The project was run under the auspices of the Group of Experts on Cleaner Energy Systems with continuous support from countries and the whole UNECE Sustainable Energy Programme.

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The document does not necessarily reflect the position of reviewers and partners listed above who provided their comments and helped to develop this publication.

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KEY TAKEAWAYS

Access to energy has been recognized by the United Nations Economic Commission for Europe (UNECE) as critical for assuring quality of life. At present, 80% of the energy usage in the UNECE region is fossil-fuel based. Many countries are reliant on non-renewable sources for their energy security and economic well-being, yet there is a growing global urgency to transition to a more sustainable energy future with increased dependence on renewable energy sources, improved energy efficiency, and reduced global carbon emissions.”

Carbon capture, use and storage (CCUS) technology is an essential step towards mitigating climate change. CCUS allows UNECE member States to establish a pathway to carbon neutrality and stay within their emission targets. Political agreement is required for long-term engagement and societal commitment, recognizing the scale and cost of the industry that needs to develop in a very short time – billions of tonnes of CO_2 and trillions of US$.

We are running out of time

Structural change will be much deeper than most people expect and needs to start now. The greater the delay, the greater the change required.

Sharing good practice is needed

Inclusive multi-stakeholder initiatives can bestrengthened by public-private partnerships. Government and industry support is key.

Industry commits to wide ranging greening

The private sector should lead the structural change through design, material efficiency, sustainable energy technology interplay and requires government support.

Scale up favorable conditions

Legal, financial and regulatory frameworks must be developed with infrastructure and banking institutions. Government support can provide initial momentum that will get industry engaged.

Working together beyond borders

A sub-regional approach to share knowledge and best practices is needed to improve cost efficiencies for large infrastructure projects.

Act now, CCUS unlocks full decarbonization of energy sector

Countries need to include CCUS in long-term strategies and commence retrofitting existing infrastructure.

CAPACITY BUILDING

The UNECE has taken action to support countries in implementing CCUS technologies and attaining carbon neutrality. This action has focused on three core aims. These are to:

Raise awareness

Recognize CCUS as an essential climate mitigation option and consider it when developing national plans.

Accept technology

Develop and integrate policies to allow full use of CCUS technologies for energy and intensive industries.

Finance project

Create funding mechanism for CCUS and direct investments towards modernization of energy infrastructure.

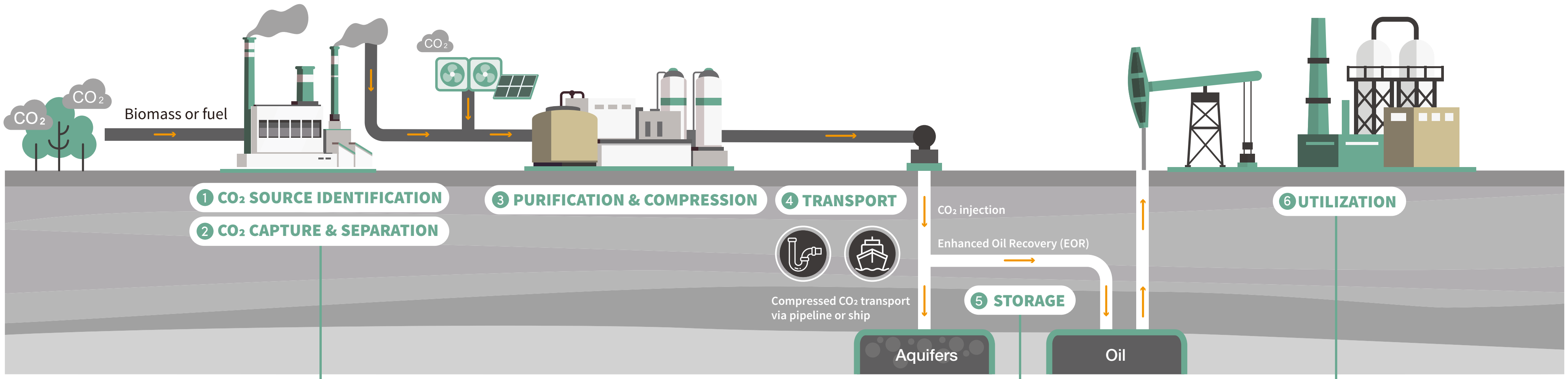
High level roundtables, policy dialogues and development of financial guidelines continue to raise awareness with stakeholders about the potential of CCUS technologies to attain carbon neutrality in the UNECE region.

UNECE convened a Task Force on Carbon Neutrality under the auspices of the Group of Experts on Cleaner Electricity Systems to understand the potential of CCUS technologies across the UNECE region.

This work has been conducted by the Task Force on Carbon Neutrality as part of implementation of the extrabudgetary project on “Enhancing the understanding of the implications and opportunities of moving to carbon neutrality in the UNECE region across the power and energy intensive industries by 2050”.

CARBON CAPTURE, USE AND STORAGE (CCUS)

CCUS is essential to unlock the full potential of decarbonization and attain carbon neutrality



① CO_2 SOURCE IDENTIFICATION

② CO_2 CAPTURE & SEPARATION

③ PURIFICATION & COMPRESSION

④ TRANSPORT

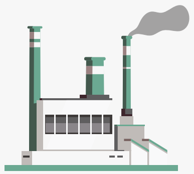
Compressed CO_2 transport via pipeline or ship

⑤ STORAGE

⑥ UTILIZATION

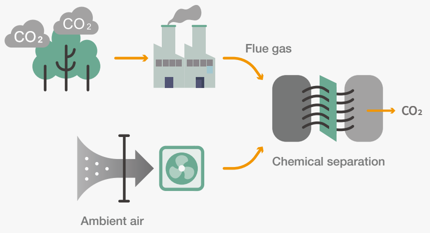
Point Sources of CO_2 in Industry

CO_2 from industries (cement, steel), hydrogen production from fossil fuels, or power generation is captured before it reaches the atmosphere and is then compressed and injected into porous rock layers.



Biomass Energy with Carbon Capture and Storage (BECCS)

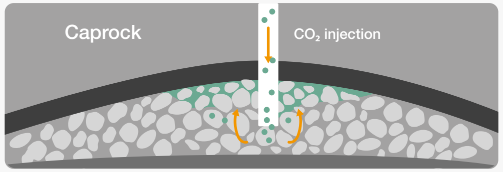
Direct Air Carbon Capture and Storage (DACCS)



Net negative emissions technologies are key to reach net-zero and then net negative emissions. In BECCS, CO_2 is taken out of the atmosphere by vegetation, then recovered from the combustion products when the biomass is burnt. In DACCS, CO_2 is captured directly from the air.

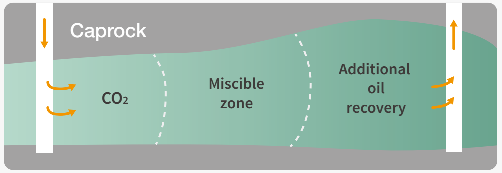
Aquifers for Sequestration of CO_2

Aquifers are geological formations containing brine in porous rock at depths over 1km. CO_2 can be pumped down into the rock for sequestration.



Enhanced Oil Recovery (EOR)

EOR is a family of techniques that increases the recovery of oil and gas while storing CO_2. Dependent on operational choices, the volume of CO_2 stored could exceed the CO_2 content of the produced hydrocarbons.



Solutions for Carbon Utilization

Building Materials
Aggregate, concrete

Chemicals
Methanol, ethanol

Plastics
Polymers

Mineralization
Carbonates

Carbon utilization can unlock the commerciality of CCUS projects for the industrial, steel, cement and chemical sectors. CO_2 captured can be used as a feedstock to produce a range of products, such as concrete, methanol, ethanol, carbonates, plastics etc.

Awareness

Recognise CCUS as a viable climate mitigation option and consider it when developing national plans.

Acceptance

Develop and integrate policies to allow full commercialisation of CCUS technologies.

Finance

Create a funding mechanism for CCUS and direct investments towards modernization of energy infrastructure.

1. INTRODUCTION

Energy is critical for assuring quality of life and underpins attainment of the 2030 Agenda for Sustainable Development (2030 Agenda). The role that energy plays in modern society is recognized, but there remains an important disconnect between countries' agreed energy and climate targets and what countries are doing in reality.

This brief builds on the recommendations from the Pathways to Sustainable Energy project and is the first in a series of technology briefs that directly support implementation of the Carbon Neutrality project. The underlying objectives of this brief are:

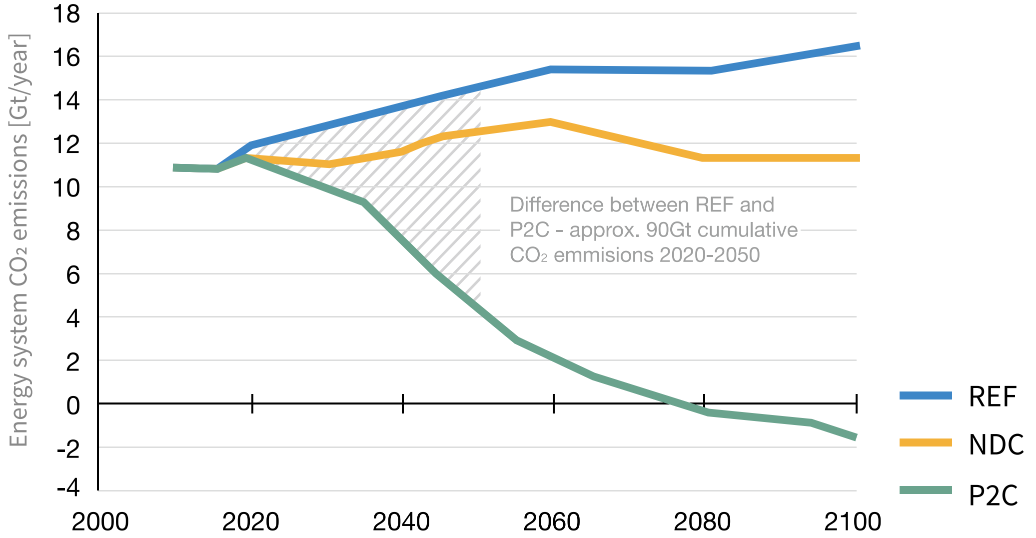
- Introduce member states to a portfolio of CCUS technologies
- Help policy makers to evaluate the benefits of the CCUS technologies
- Build capacity in economies in transition with regard to CCUS

Reality Check and Rationale for CCUS Technologies

The countries from the UNECE would need both to reduce their dependence on fossil fuels from over 80% to around 50% by 2050, and to achieve significant negative carbon emissions. The countries in the UNECE region need to cut or capture at least 90Gt of CO_2 emissions by 2050 to stay on a pathway to meet the 2°C target (see chart).

As fossil fuels are likely to continue to play an important role for UNECE member States in the short and medium term, achieving carbon neutrality will require deployment of CCUS technologies to allow reduced and negative carbon emissions to bridge the gap until innovative, next generation low-, zero-, or negative- carbon energy technologies are commercialized and to keep hard-to-abate sectors operating.

Figure 1.1 **CO_2 emissions in the UNECE region by policy scenario for the energy sector. Assuming long term economic growth and the cost projections of renewable, low carbon and fossil fuel energy technologies**



Difference between REF and P2C - approx. 90Gt cumulative CO_2 emmisions 2020-2050

The **reference scenario** is a forecast of CO_2 emissions based on maintaining economic growth. It assumes a 'Middle of the Road' scenario for socio-economic, market and energy technology developments. The model estimates energy demand and the lowest cost option to supply that energy. If constraints are placed on CO_2 emissions this changes how the model satisfies the forecast demand by shifting investments towards low carbon and renewable energy. The **NDC scenario** assumes the constraints imposed by Nationally Determined Contributions under the Paris Agreement up to 2030 and maintains them indefinitely. The **P2C scenario** constrains emissions to those consistent with less than 2 degrees Celsius global warming.

***Source**: Pathways to Sustainable Energy, UNECE 2020a*

Scope and Structure

This brief introduces a portfolio of CCUS technologies and solutions, and proposes possible policy actions to allow their faster commercialization and wider deployment across the region. It further conducts comparative analysis of the CCUS technologies based on carbon capture potential, cost, technology readiness level, commercial readiness level, social readiness level as well as environmental impact.

Figure 1.2 Carbon flows in CCUS chain

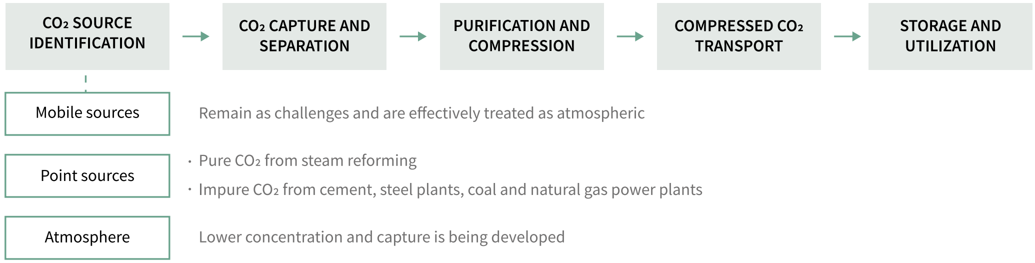
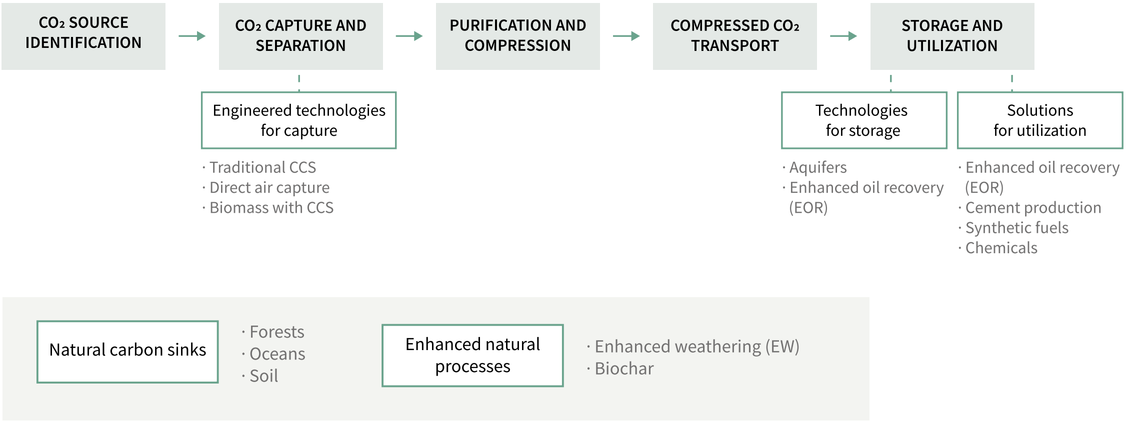


Figure 1.3 Portfolio of carbon capture and use technologies



Carbon Sequestration Technologies are the Key to Unlock the Full Decarbonization Potential

Removing carbon dioxide begins with carbon capture. CCUS is a proven technology with costs on strong downwards trajectory. The cost of CO_2 capture depends on the source of CO_2 and separation method. We can differentiate between mobile and point CO_2 sources as well as the atmosphere (see chart).

High concentration sources typically have lower costs for CCUS. The potential of CCUS as a technology solution can be assessed along the value chain. CO_2 can be captured at the source of the emissions, such as power plants, or can be directly captured from the air itself using membranes or solvents. Captured concentrated CO_2 can be transferred via pipelines to be later used as a feedstock or stored underground.

This brief reviews a portfolio of CCUS technologies as well as natural carbon sinks. The technologies are divided into engineered technologies for carbon capture – fossil fuels with CCS, direct air capture (DACCS), energy from biomass with CCS (BECCS), and technologies for carbon storage - storage into aquifers, enhanced oil recovery and technologies for use of carbon.

While some CCUS technologies might be considered mature, such as capture of CO_2 from high-purity sources or EOR as a storage option, the deployment of integrated, commercial CCS projects is still an aspiration. Large-scale capture of CO_2 is demonstrated in power generation and some industry sectors with large-scale demonstrations projects in operation or coming onstream. Still, more is needed to scale up and overcome the current lack of experience while developing and integrating capture, transport and storage infrastructure.

CCUS is also an enabler for production of low-carbon hydrogen that is expected to play a key role in attaining carbon neutrality. [note: a separate brief on hydrogen is in preparation]. This is mostly relevant in countries with low-cost natural gas resources and available CO_2 storage, and might be attractive for significant parts of UNECE membership in the east.

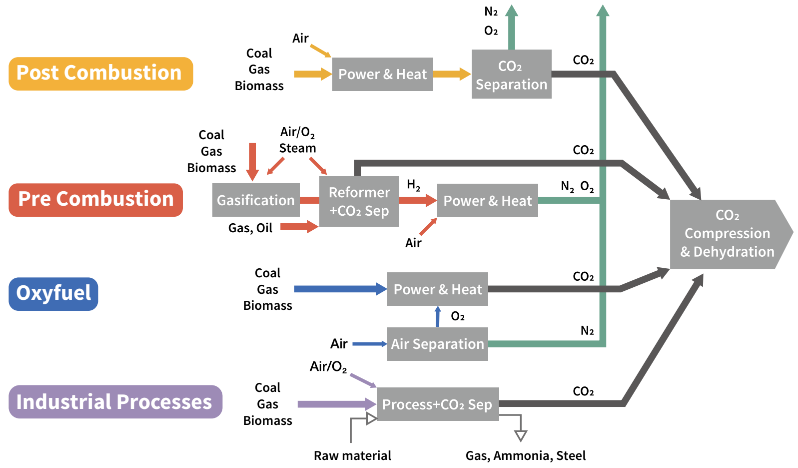
The next section of the brief gives an overview of a range of CCUS technologies. The following technology “snapshots” introduce the technology, discuss their sequestration potential, highlight where the know-how is still needed to scale it up and reach full commercialization, and propose some policy actions.

2. ENGINEERED TECHNOLOGIES FOR CAPTURE

2.1 CCUS from Point Sources

In CCS from point sources, CO_2 is captured before it reaches the atmosphere in industries such as cement and steel production, hydrogen production from fossil fuels, incineration of waste, and power generation. It is then compressed to over 100 atmospheres and injected into porous rock layers a kilometre or more underground, beneath impermeable rocks that will keep it in place for tens of thousands to millions of years. Alternatively, the CO_2 can be incorporated into products such as building materials, as long as they give the same long-term storage.

Figure 2.1 **Carbon capture options**



CO_2 can be permanently stored in aquifers or old oil and gas reservoirs.

***Source**: Adapted from IPCC Special Report on CCS, 2005*

CO_2 can be captured from point sources efficiently with a capture level of over 90% using a range of different engineering approaches. Costs will vary, in the order of 10-100 \$/tCO_2. Although more expensive than for the greenfield projects, carbon capture equipment can be retrofitted in existing fossil infrastructure to avoid stranded assets while delivering on net zero strategies.

CO_2 captured then needs to be transported to a secure storage site by pipeline or ship. Some locations will have easier access to storage than others but even long-distance pipelines can have low unit costs for large amounts of CO_2. Storage may need to be in other countries, so common standards and confidence for coordinated long-term investments are essential.

CCUS will be critical for achieving net zero emissions fast enough to avoid dangerous climate change and meeting sustainable development goals for the world's population.

All of the elements of CCUS have examples in use, but deployment and learning-by-doing are needed to refine and improve techniques and bring capture costs down. Transport and storage costs can also be cut by economies of scale for shared infrastructure; individual industries can install capture but need somewhere to send the CO_2. To achieve this CCUS needs focused support in a similar way to that provided to renewable energy, such as wind and solar PV.

Know-How Required

- **Geological**: Geological: to identify, engineer and manage secure subsurface storage.
- **Engineering**: to build equipment to capture CO_2 from a wide range of sources.
- **Infrastructure planning**: for large, transformational projects that cannot be achieved by ad hoc incremental development.

Sequestration Potential

- **Annual**: CCS 10-30 Gt CO_2/yr by 2050, limited by CO_2 transport and storage infrastructure development and support for early and rapid sector growth.
- **Total**: Essentially unlimited. CCS storage capacities potential exceed the fossil fuel storage capacities.

Appropriate Policy Action

- **Governments need to establish regulatory environment to allow CCUS technologies to be deployed** at scale and early to establish a new industry sector. CCUS potential to attain net-zero is vast.
- **Build CO_2 transport and storage infrastructure at scale to bring down costs and encourage CCUS uptake by industries.** This is something that individual businesses cannot do themselves.
- **Plan all the way to net zero.** CCUS cannot be added effectively to an energy and industry system that was really designed for only marginal CO_2 emission reductions.
- **Prepare international standards and arrangements to share CO_2 storage.** CO_2 transport and storage infrastructure needs to be as international as that for electricity, gas and oil supplies.

2.2 BECCS and DACCS

BECCS – Biomass Energy with Carbon Capture and Storage
DACCS – Direct Air Carbon Capture and Storage

Negative Emissions Technologies (NETs) return carbon from fossil fuels that has been released as CO_2 into the atmosphere back to permanent and secure storage underground.

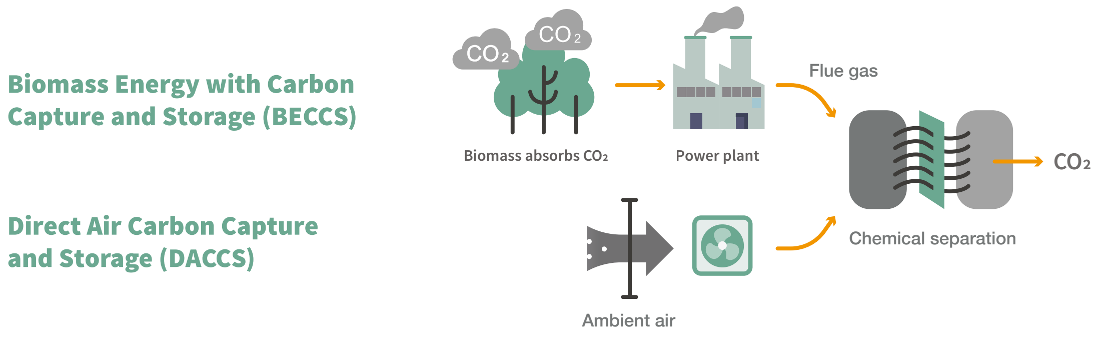
In BECCS, CO_2 is taken out of the atmosphere by vegetation, then recovered from the combustion products when the biomass is burnt. In DACCS, CO_2 is captured directly from the air. In both cases, the captured CO_2 is compressed and then injected into porous rock layers a kilometre or more underground, beneath impermeable rocks that will keep it in place for tens of thousands to millions of years.

BECCS and DACCS can in effect capture CO_2 from the air from any fuel source anywhere in the world. BECCS is expected to be cheaper, at maybe \$50-200/tCO_2 removed and stored, while DACCS might be roughly twice the cost. But DACCS is able to remove large amounts of CO_2 from the atmosphere without the demands on natural systems required by growing biomass.

Often it will be cheaper to capture, or avoid, CO_2 emissions at source, rather than capture them from the air. BECCS and DACCS can capture the same quantity of CO_2 generated by mobile, natural or infrequent emissions.

NETs will also have to be used to remove CO_2 if net zero is not achieved quickly enough to avoid dangerous climate change.

Figure 2.2 BECCS and DACCS



Net negative emissions technologies are key to reach net-zero and then net negative emissions. In BECCS, CO_2 is taken out of the atmosphere by vegetation, then recovered from the combustion products when the biomass is burnt. In DACCS, CO_2 is captured directly from the air.

Know-How required

- **Land management for BECCS**: Biomass must be resourced in a sustainable way, that ideally also enhances carbon sequestration in soils and minimises the use of industrial fertilizers
- **Engineering**: to build equipment to concentrate CO_2 from biomass combustion products or air, compress it and transport it by pipelines or ships.
- **Geological**: to identify and manage secure storage sites.

Sequestration Potential

- **Annual**: BECCS 5-20 Gt CO_2/yr by 2050, limited by biomass availability; DACCS 5-20 Gt CO_2/yr.
- **Total**: essentially unlimited, since geological storage can be anywhere in the world.

Appropriate Policy Action

- **Plan all the way to net zero**. BECCS / DACCS cannot work effectively in an energy and land use system that was designed for only marginal CO_2 emission reductions.
- **Develop technology and deploy at scale to reduce cost and set a carbon price**. DACCS can represent the carbon price needed for achieving net zero.
- **Prepare international verification and negative emission trading standards.** Verification of the effective CO_2 captured is essential whether the negative emissions are traded or used internally. (Note: especially if fertilizers are used for BECCS)
- **Ensure BECCS/DACCS are used fairly**. Avoid burden on future generations of the cost of retrospectively capturing CO_2. Recognise food-water-energy nexus approach to avoid jeopardising global food or water security to produce biomass for BECCS.

3. TECHNOLOGIES FOR STORAGE

3.1 Aquifers for Sequestration of CO_2

Aquifers are geological formations containing brine (salt water) in porous rock. Suitable aquifers are in sedimentary rock underneath a 'caprock' which is impermeable. They are vast and found all over the world at depths over 1km. It is probably the most significant CCS option available.

CO_2 can be pumped down into the rock for sequestration. At such depths CO_2 is pressured to a density of 200-800kg/m^3. In the aquifer, CO_2 displaces brine and forms a plume from the injection point that tends to move to the top of the aquifer. At the CO_2/brine interface, CO_2 will dissolve in brine (about 1-2% solubility) and some water will dissolve in CO_2 plume. These effects cause an increase in acidity affecting the normal chemical reactions and biome in the aquifer. Over tens of thousands/ millions of years the CO_2 can mineralise to rock. Comprehensive reservoir engineering are required to characterise the rock properties prior to any sequestration, to avoid costly topside infrastructure developments that will be redundant if the aquifers do not have the storage capacity.

Rate of injection and total capacity of the aquifer is determined by geology and pressure limits in the aquifer. The pressure in the aquifer must be limited to ensure that CO_2 in the plume or brine cannot escape. It depends on the rate of CO_2 injection and how quickly the brine permeates through rock. Once injection stops, the pressure decreases over centuries as the CO_2 continues to dissolve and mineralise. But there can also be dissolution of the caprock/seal dependent upon the rock properties due to the acidity. This can impact the integrity of the storage and sequestration in the reservoir.

Adverse effects can occur if CO_2 or brine leak into sources of drinking water or soils. This leakage can be from geological faults, abandoned oil or gas wells (often found in the same location), movement of brine into adjacent geological formations, closure of the injection point when the site is abandoned (acidification is a concern for the metals and concrete used). Monitoring is necessary by various seismic and other techniques during and after injection to identify if leakage may be occurring and prevent it.

Know-How Required

- **Oil & Gas Industry**: The technique is used to today at a scale of several million tonnes per year where CO_2 emissions from operations incur high cost penalties.

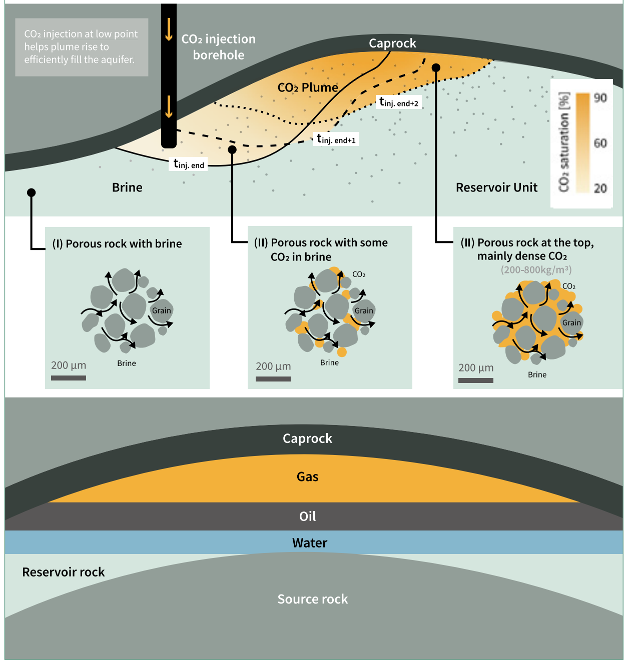
Sequestration Potential

- Estimated at "**more than a trillion tonnes CO_2**". The costs of operations at the injection head are low, <$30/te storage cost only (excluding collection, transport and pressurisation of CO_2).

Appropriate Policy Action

- **Recognise the scale and cost of the industry** that needs to develop in a very short time – billions of tonnes CO_2 and trillions of US$.
- **Harmonize national and international frameworks governing rights to sub-surface resources.** Ensure that laws do not restrict the use of aquifers and protect other users from adverse effects such as contamination of drinking water aquifers. Consider the financial and legal conditions in the event of any leakage.
- **Develop infrastructure to overcome location issues.** CO_2 sources and aquifers are not all co-located. Distribution infrastructure and DACCS will be required. Cooperation will be needed to access unused capacity across countries.
- **Cover the costs.** No revenue streams of significance are anticipated, hence a funding mechanism must be created to cover costs of storage, collection, clean up and transportation of CO_2.
- **Raise awareness to gain public acceptance.** Funds are required to complete geological investigations, scale up to 100's millions tonnes/yr and ensure the technology is safe.

Figure 3.1 Simplified view of aquifer with a plume of CO_2 injected below a caprock



Source: *Adapted from M. Hefny (et. al) 2020*

3.2 Enhanced Oil Recovery (EOR)

EOR is a family of techniques to increase the recovery of oil and gas. One EOR technique is to inject CO_2 into the well at pressure. At depths greater that 700m, CO_2 becomes supercritical and acts as a good solvent to release oil and gas from rock strata and flush them to the well head. CO_2 can also be co-injected with water. First tried in 1972, EOR is a common technique applied in mature oil & gas wells. Injected CO_2 can be used as a secondary drive mechanism to push out remaining hydrocarbons in an oil and gas reservoir. CO_2-injection technology is an EOR method that is gaining most popularity. The source of CO_2 used is based on lowest locally available cost and the majority is from natural sources.

The interest in CO_2 EOR is that once the field is exhausted, some CO_2 can be left in the reservoir, sequestrating it for centuries or millennia. The reservoir, possibly including its aquifers, may have capacity to store CO_2 created when the subsequent production is combusted. In special cases, therefore further production can be carbon neutral.

As there are many ways to produce oil and gas, CO_2 EOR must be economically competitive versus opening new wells and other EOR techniques (for example, Thermal EOR uses steam to heat the oil in the well and reduce its viscosity, Chemical EOR uses acids or alkalis to chemically release the hydrocarbons, and Polymer EOR uses polymers to increase the viscosity of water flushing out the hydrocarbon). The competitiveness of CO_2 EOR depends on suitability of the reservoir, the payback period required because of the relatively high capital costs, the local cost of CO_2 and availability of technical resources to do it.

Know-How Required

- **Oil & Gas Industry**: Integration of existing technology into the economic production of oil.
- **Other industries**: Processing concentrated sources of CO_2 so that it can be transported and used for EOR.

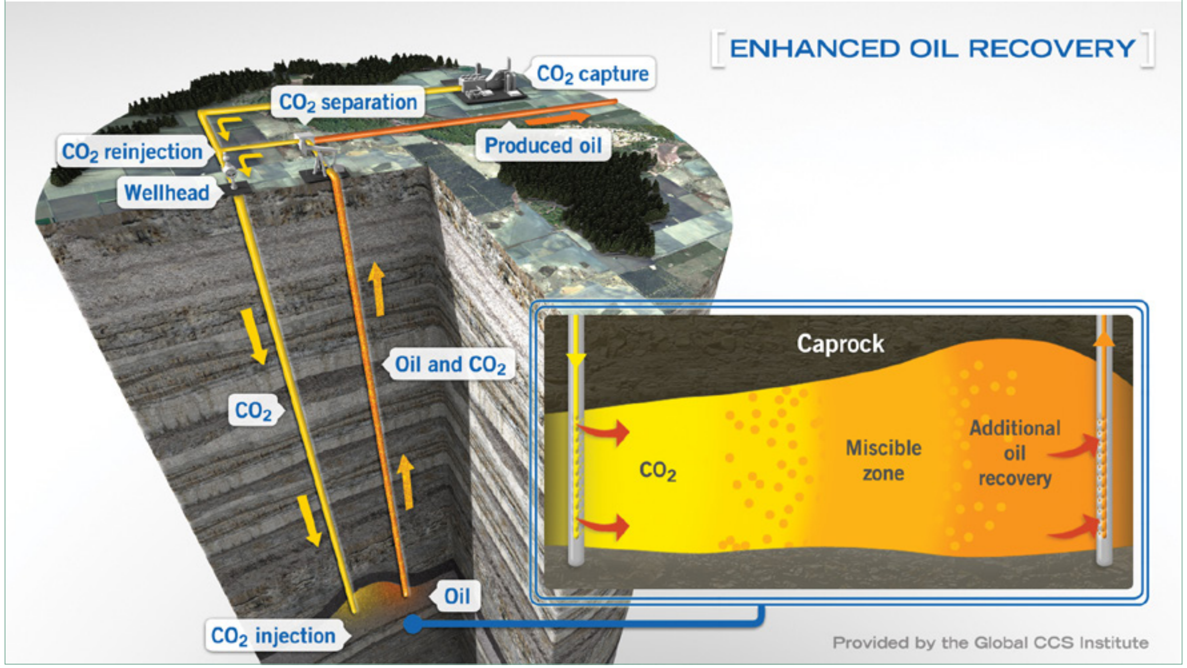
Carbon Storage Potential

- **Total**: 50 – 350 Gt (IEA 2015 estimate)
- Onshore has the largest CO_2 EOR potential globally, but some good offshore candidates exist. Based on Rystad Energy data, of all global producing fields with potential for CO_2 storage, over 80% are onshore fields.

Appropriate Policy Action

- **Strengthen the competitiveness of CO_2 EOR for the oil and gas industry.** Reduce the relative costs of CO_2 EOR in comparison to other oil recovery methods (Capex, cost of CO_2 and regulations making other production techniques relatively more expensive).
- **Encourage the oil and gas industry to use CO_2 EOR.** A system of credits based on future CO_2 sequestration once the well is closed or hydrocarbons marketed from well using CO_2 EOR. Encourage more CO_2 to be sequestrated than is required just for oil recovery.
- **Incentivise CO_2 capture from anthropogenic sources.** Encourage collaboration between industrial sources of CO_2 and users of EOR.
- **Increase the amount of CO_2 stored (EOR+).** Promote and disseminate research into techniques to increase CO_2 sequestration above that needed for EOR. Classify sources of hydrocarbons based on a net carbon emission after EOR (standardised life cycle analysis).

Figure 3.2 Enhanced oil recovery



Source: *Mai Bui (et.al) 2018*

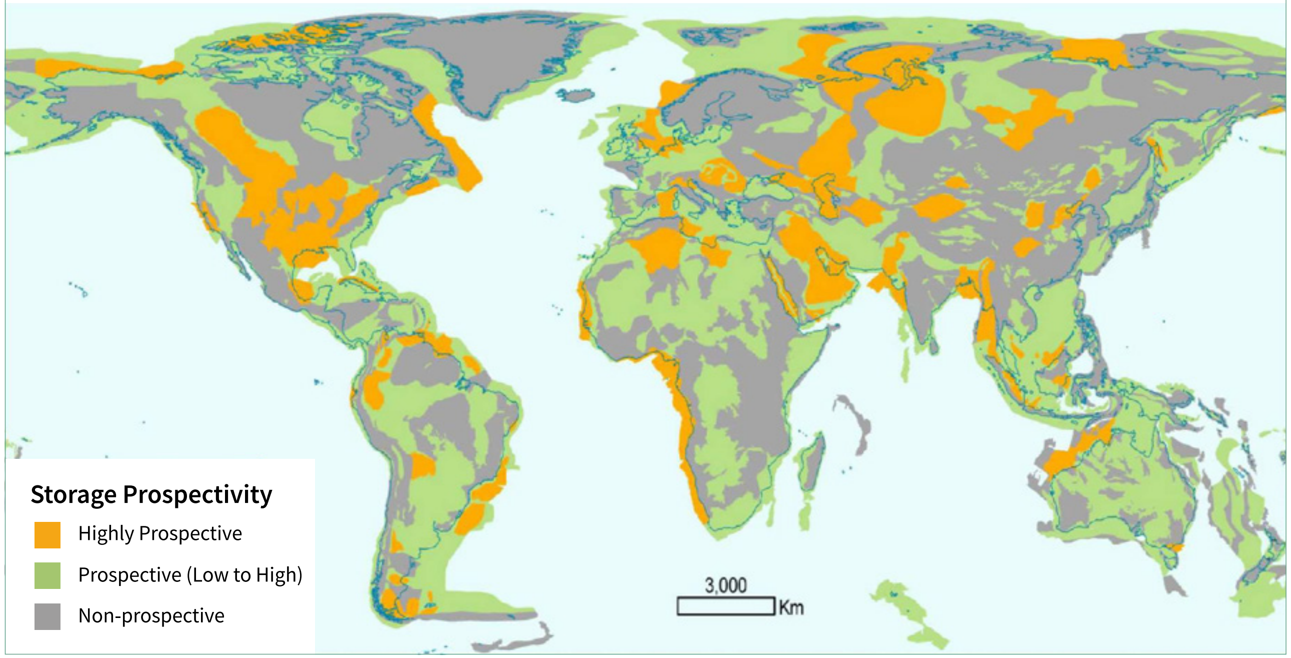
4. CARBON STORAGE READINESS

Large scale deployment of carbon capture and storage technologies will require availability of vast geological storage capacity across the whole UNECE region. Information on the geographical distribution of storage potential and its quantitative characterization is important to understand the role of CCUS in stabilizing atmospheric concentration of CO_2 and for developing effective and efficient policies for CCUS. Countries in the UNECE region have relatively high carbon storage potential (see chart).

At present, known suitable sedimentary basins in the UNECE region have been identified in North America and Western Europe, namely the UK, the Netherlands and Norway. Assessments still have not been conducted in the eastern part of UNECE region - in the Russian Federation (Volga Urals, West Siberia, Caspian subregion) nor in Kazakhstan, Azerbaijan Caspian Sea. (UNECE is also preparing a study on Geological CO_2 storage in Eastern Europe, Caucasus and Central Asia.)

Access to secure geological CO_2 storage will be an issue in some countries in the UNECE region. Geology does not recognise, nor is controlled by geopolitical boundaries. Cooperation amongst member states will provide the most effective and efficient mitigation strategies for the subsurface storage and sequestration of CO_2. There is an urgent need to cooperate on shared, regional CO_2 transport and storage infrastructure, including via CO_2 shipping, if CCUS is to be deployed at a scale capable of making a substantial contribution to attaining carbon neutrality.

Figure 4.1 **Carbon storage potential**



***Source**: Bradshaw, J. and Dance, T.(2004)*

5. SOLUTIONS FOR CARBON UTILIZATION

Carbon utilization is the use of CO_2 to create products with economic value. A widespread application in some UNECE countries is EOR (increasing the recovery factor from oil/gas).

Utilization can be subdivided in 3 main areas (Mineralization, Biological and Chemical) as observed below. It is important to note that certain carbon application options, such as the use of CO_2 in some chemicals processes, fire suppression products, etc. (see Figure 5.1.) are not equal to permanent sequestration solutions such as concrete or carbonates. Coupling with DACCS is needed to neutralise the issue of re-releasing CO_2 and to attain carbon neutrality.

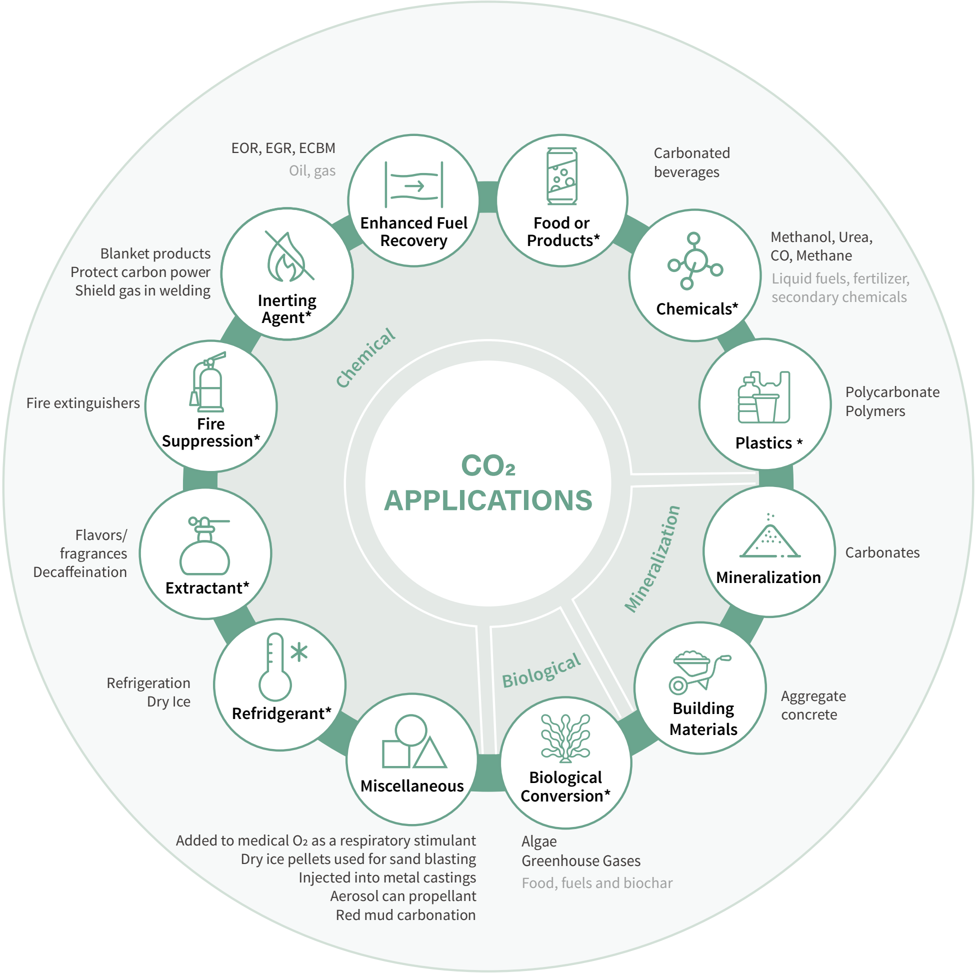
Due to its current market size, the conversion of CO_2 into products makes a small but important contribution to GHG targets for climate change. In a future hydrogen economy, carbon from CO_2 can be used to make many of the chemicals and plastics currently made using fossil fuels.

Carbon utilization can unlock the commerciality of these projects for the industrial sector, steel, cement and chemical.

Utilization Potential

- **Mineralization**: Incorporating CO_2 into concrete has the most potential to become a large market for CO_2 in the near term. Cement, one of the components of concrete, is responsible for 8% of the total GHG. This process is energy efficient using minimal external energy.
- **Chemicals**: CO_2 is currently used in small quantities to make urea fertiliser and some special polymers. In a future hydrogen economy, CO_2 could be combined with H_2 to make synthetic fuels, syngas and methanol. Syngas and methanol are basic chemical feedstock from which many chemicals and polymers can be made.
- **Biological**: CO_2 is used to promote plant growth and can be captured in soils by using biochar to increase soil quality.

Figure 5.1 **CO_2 applications**



* *Products that use carbon but do not sequestrate carbon permanently*

Source*: Mission Innovation Carbon Capture, Utilization, and Storage Workshop, September 2017*

Outlook

- **CO_2 utilization** will require large energy consumption due to the many reaction and separation steps involved. Industrial scale carbon capture will create a source of CO_2 which is required to attract industrial users into a future CCUS value chain.
- **Benefit analysis** of these new technologies could look at market, cost and carbon use potential.
- **Life cycle assessments** (use, disposal and recycling) are essential to understanding the true merits of a product including how long the CO_2 can be sequestered.

Appropriate Policy Action

- **Establish an overall policy strategy and pathway for CCUS** in industry, incorporating the necessary R&D priorities, commercialization potential, incentive policy mechanisms, and enabling legal frameworks.
- **Promote R&D programs** and initiatives that can unlock the economic potential of CO_2 utilization. Pursue large-scale demonstration for CCUS in industry in national and regional programmes.
- **Set standards to help industry develop products with CO_2** and promote use of products that sink CO_2 (e.g. concrete industry).
- **Introduce financing mechanisms**, such as tax credits, carbon prices & taxes, mandate & standards, carbon financing in development countries.

Figure 5.2 Utilization markets and potential CO_2 demand

Product	Price ($/t)	Demand (Mt/yr)	CO_2 Use (tCO_2/t)
Aggregate	10	55,000	0.25
Concrete	100	20,000	0.025
Methanol*	350	140	1.37
Ethanol	475	100	1.91
Sodium carbonate	150	60	0.42
Calcium carbonate	200	10	0.44
Polymers*	1,900	24	0.08

***Source**: BloombergNEF. March 2020*

* For chemical products, CO_2 utillization is only a net benefit if it replaces petrochemicals. Chemical products are too short lived to be considered as carbon sinks. For higher environmental impact, CO_2 must come from BECCS, DACCS or waste streams.

Emerging Uses for CO_2

Besides EOR, many products are emerging as potential sinks that could increase demand in the future.

Products indicated in the table above can use CO_2 as a feedstock to produce the material. Many start-up companies are emerging with the objective of producing more economic and environmentally friendly paths to sink CO_2 into products rather than into underground geological storage.

Aggregate and concrete produced from CO_2 have the greatest potential to sink CO_2 with a combined annual market size of about 2500bn $/yr. However, the low price of existing products make market penetration of such products challenging.

Production of methanol and ethanol also creates opportunities for sinking of CO_2 in products, but since liquid fuels are eventually burnt they are not considered as long-term CO_2 sink solutions unless combined with DACCS, BECCS and green hydrogen to create fuels that replace fossil fuels.

The rest of the products have limited potential to fully emerge as CO_2 sink solutions, as markets for these products are small compared to the market for fossil fuels and processing costs are high.

As CO_2 use increases for aggregate, concrete and chemicals production, low-cost CO_2 availability will limit its use for chemical production. Partnerships between CCUS technology providers and the chemical industry will be needed to develop new capture capacity and infrastructure.

6. COMPARATIVE ANALYSIS OF CCUS TECHNOLOGIES

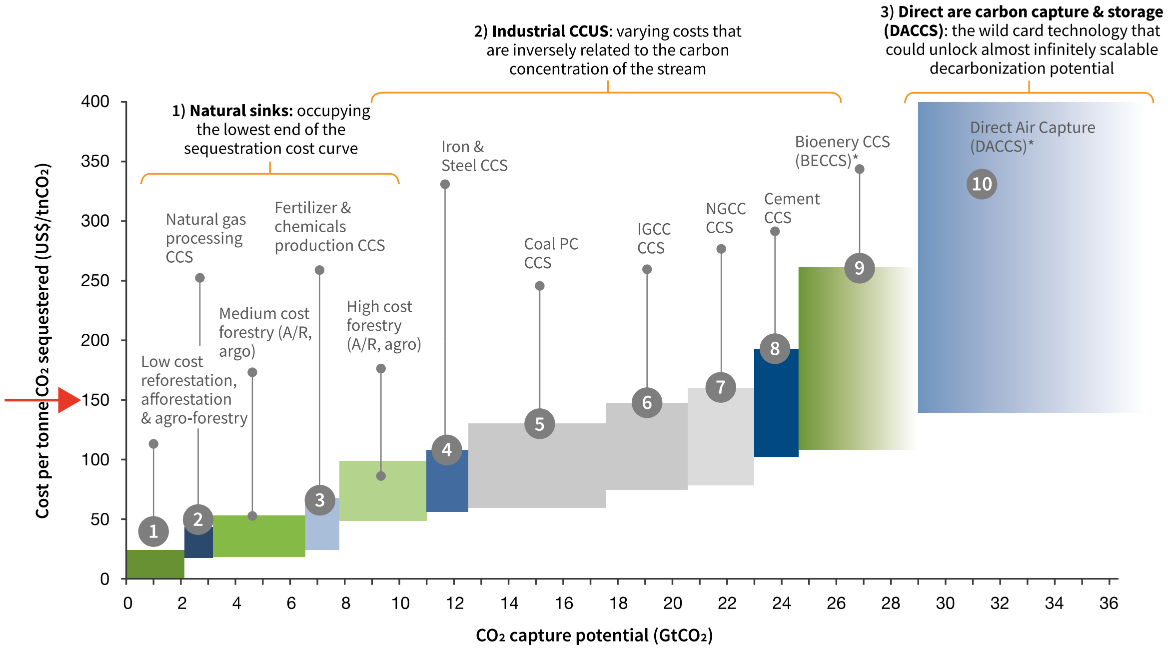
6.1 CCUS Technologies Cost Curves and Carbon Capture Potential

Cost is perceived as one of the main barriers for the development of CCUS projects. It is forecasted the cost of CCUS planned development for Europe could cost up to 50 billion euros. The speed at which CCUS costs can be reduced will drive rapid deployment of large-scale CCUS technologies.

CCUS technologies have evolved quickly over the last 5 years through testing in multiple R&D pilot projects around the world and through experience gained during deployment of large-scale projects, which has triggered further optimization of the technologies. There is quite a lot of uncertainty around the costs for the different carbon abatement technology options as observed in the figure below. The cost of natural sinks including reforestation, afforestation and agro-forestry is the lowest cost at around USD 50/ton CO_2 sequestered or below. CCUS cost of technologies that capture CO_2 from point sources for the Industrial sector vary considerably for different technologies depending on the concentration of the CO_2 with the Cement CCS and BECCS being the more expensive sources. DACCS technologies have the larger costs (more than USD 100/ton CO_2). The uncertainty in DACCS cost is the highest with some costs reported as high as USD 400/ton CO_2, however these technologies have a high potential to capture CO_2 from sources beyond the industrial sector 28 Gt CO_2 and up to 36 Gt/CO_2.

As the quantity of CO_2 to be captures is far greater than any potential market for the CO_2 (with the exception of the gasoline pool), these investments will not be paid back but should be seen as the cost to society of avoiding unacceptable climate change.

Figure 6.1 Carbon sequestration cost curve (US$/tn CO_2 eq) and the GHG emissions abatement potential (GtCO_2 eq)



*Indicates technologies still in early (pilot) stage of development

***Source**: Goldman Sachs, Equity Research 2020*

CCUS may be expensive, but it is an affordable option for an economy that aspires to be carbon neutral. Figure 6.1 gives the broad estimated costs of the main CCUS technologies. In order to appreciate how theses costs affect the cost of using fossil fuels in a transition period, the arrow indicates the cost of CCUS, $150 per tonne of CO_2, that implies a doubling of energy costs, assuming an oil price of $60/barrel and approximately 0.4 tonnes of CO_2 emitted per barrel used. Even a doubling of energy costs is still within the historical high oil price range. All the CCUS technologies are viable in this scenario.

***Source**: World Resource Institute 2016*

6.2 How Can Policy Makers Support the Private Sector to Act on Climate Change?

Technology readiness levels (TRLs) are a method for estimating the maturity of technology.

Commercial readiness levels (CRLs) are a method that assesses various indicators which influence the commercial and market conditions beyond just the technology maturity.

Social readiness levels (SRLs) are a method that assesses to what extent new ideas and innovations resonate with individuals and groups and whether they will be integrated into society and reach decisions concerning their adoption in the form of a regulatory and financial regime.

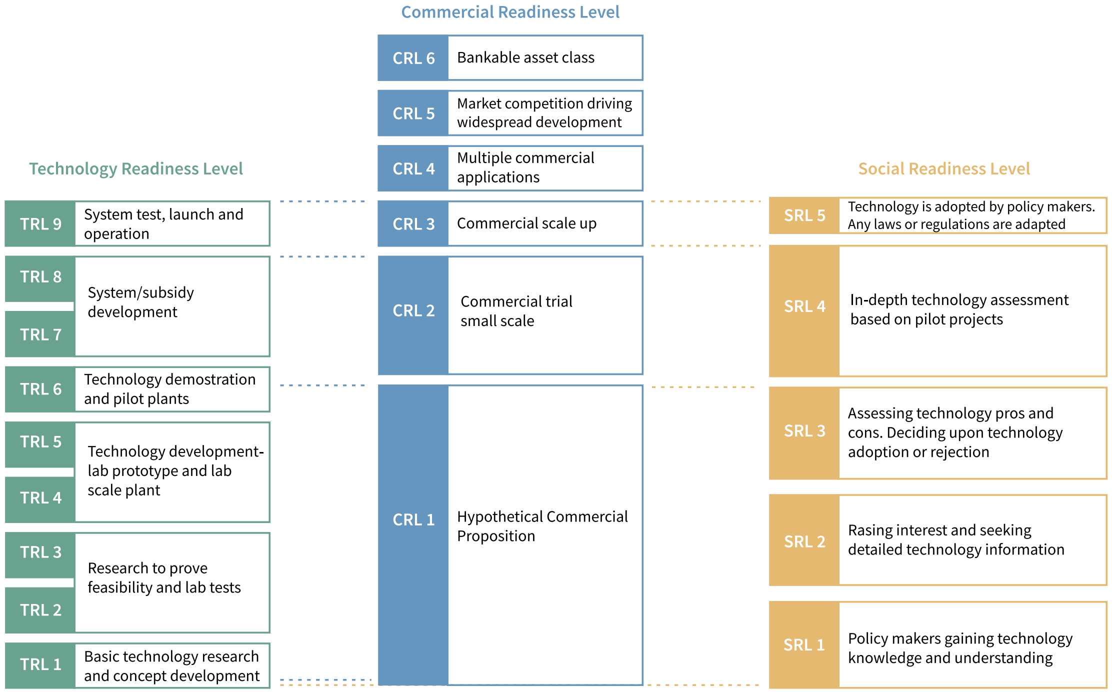
Many CCUS technologies are now at, or close to, TRL 9. Experience on other energy technologies indicates that applicable TRL1-9 research, including for upgrades in service, only stops when the last plants are closed. Many of the technologies required to move towards carbon neutrality would benefit and progress faster with the appropriate public sector alignment and support. Governments should fund R&D that will evolve CCUS technologies on CRL scale to continue beyond CRL 3 and TRL 9 and kick off with commercial scale up of CCUS technologies.

Policy makers risk delaying CCUS deployment because they are lagging behind in embracing CCUS technologies in their national action plans. There is a need for enabling policy and regulatory environment to allow full commercialization of CCUS technologies. Open access is required for two-way information flow between deployment and research and innovation activities, especially when most is government funded.

As can be seen on the next page, for many CCUS technologies, the Social Readiness Levels are lagging behind the Technology and Commercial Readiness Levels. This is delaying implementation, increases the costs incurred and contributing to even more drastic measures as the carbon budget is used up.

Figure 6.2.1 **Technology, Commercial and Social Readiness Level**

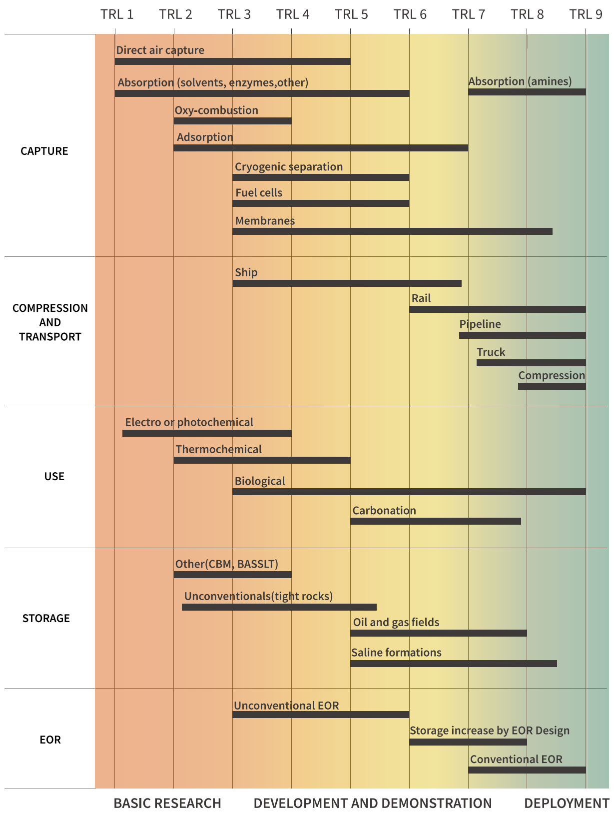
Carbon neutrality will need major changes to the way economies work. Any rapid introduction of change requires coordination of technology development, commercialization and the social acceptance. 'Readiness Levels' are a commonly used indicator of describing what needs to addressed during the introduction of a change. Figure 6.2.1 shows how these can be used coordinate public and private actors. If the steps are not synchonised there will be delays, additional costs and, potentially, a failure to enact the change.



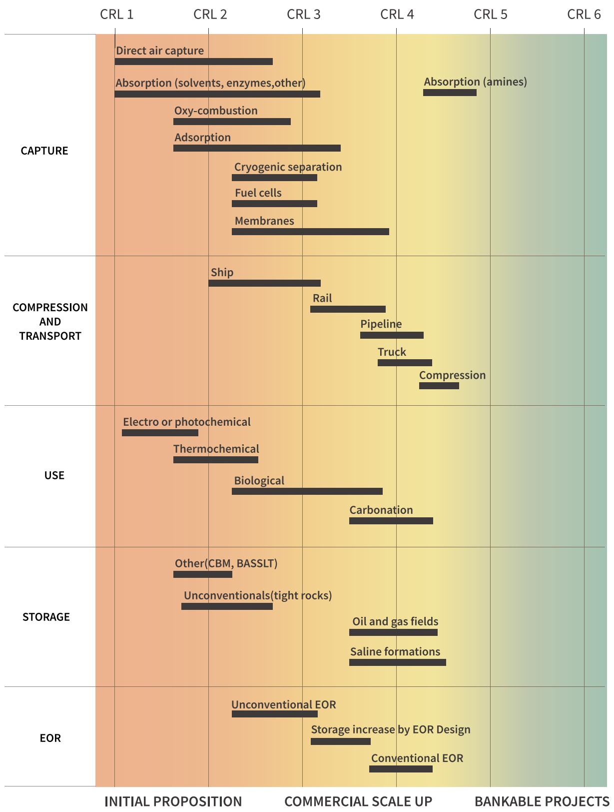
***Sources**: Developed based on Based on Bruce Adderley (et. al) 2016, Greg Kelsall 2020 and Denis Hicks 2020*

6.3 Comparative Analysis - CCUS Readiness Level

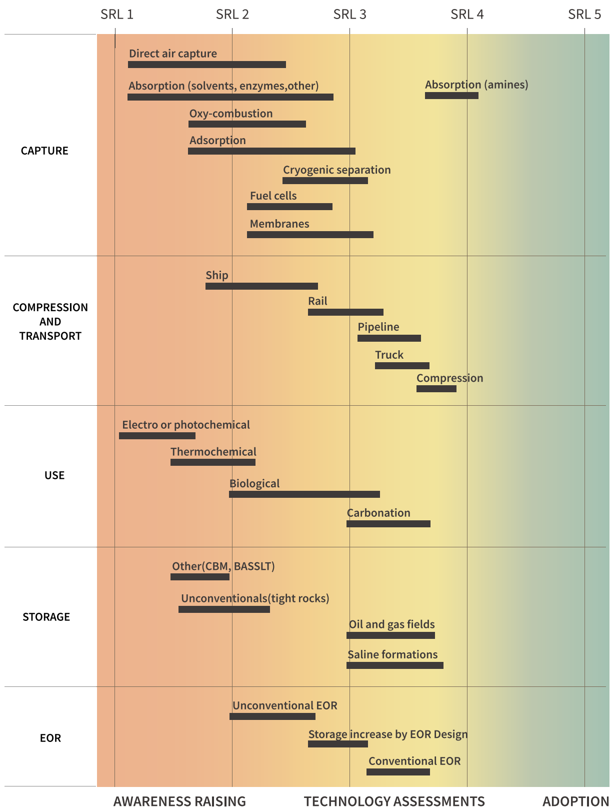
Technology Readiness Level



Commercial Readiness Level



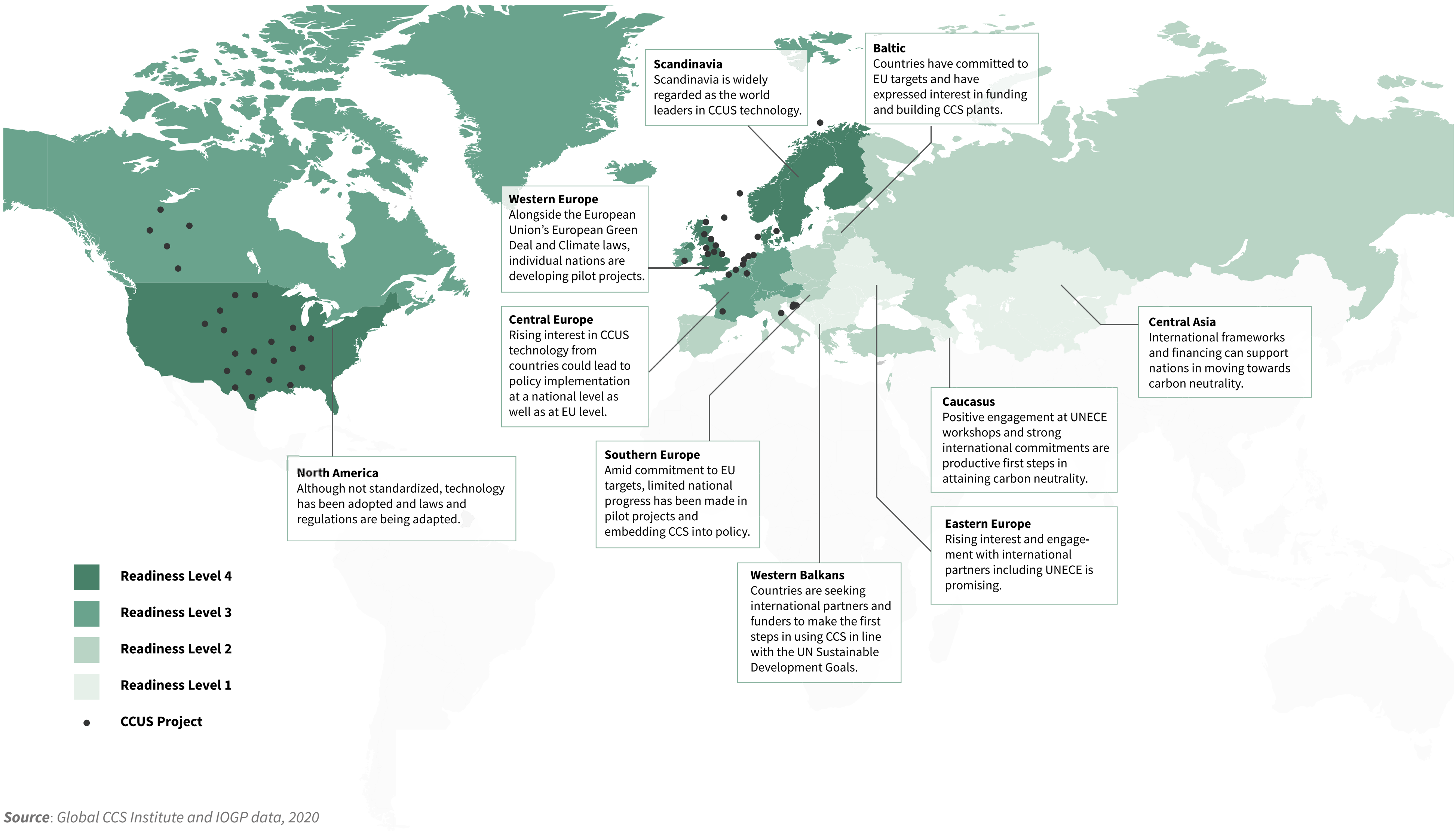
Social Readiness Level



***Source**: Natural Petroleum Council: Draft Summary Report, Meeting the Dual Challenge, A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage, December 2019 (adapted for commercial and social readiness level)*

6.4. Comparative Analysis - CCUS Readiness Level across UNECE Region

Full list of CCUS projects in appendix page 18



Scandinavia
Scandinavia is widely regarded as the world leaders in CCUS technology.

Baltic
Countries have committed to EU targets and have expressed interest in funding and building CCS plants.

Western Europe
Alongside the European Union's European Green Deal and Climate laws, individual nations are developing pilot projects.

Central Europe
Rising interest in CCUS technology from countries could lead to policy implementation at a national level as well as at EU level.

Central Asia
International frameworks and financing can support nations in moving towards carbon neutrality.

Caucasus
Positive engagement at UNECE workshops and strong international commitments are productive first steps in attaining carbon neutrality.

North America
Although not standardized, technology has been adopted and laws and regulations are being adapted.

Southern Europe
Amid commitment to EU targets, limited national progress has been made in pilot projects and embedding CCS into policy.

Eastern Europe
Rising interest and engagement with international partners including UNECE is promising.

Western Balkans
Countries are seeking international partners and funders to make the first steps in using CCS in line with the UN Sustainable Development Goals.

🟩 **Readiness Level 4**
🟩 **Readiness Level 3**
🟩 **Readiness Level 2**
🟩 **Readiness Level 1**
● **CCUS Project**

***Source**: Global CCS Institute and IOGP data, 2020*

APPENDIX I

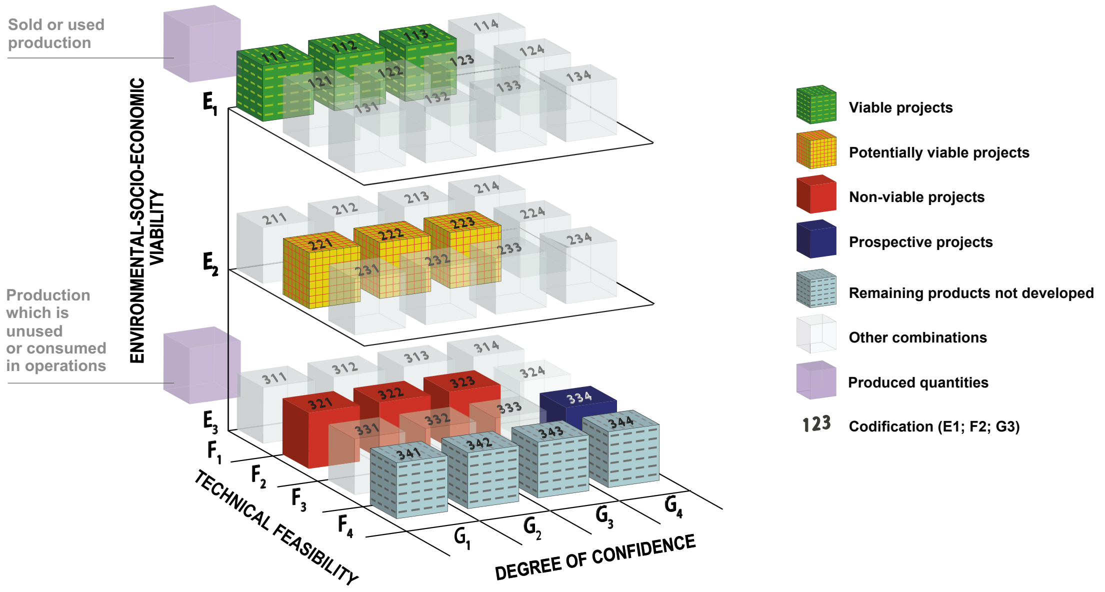
United Nations Framework Classification (UNFC) as Means to Verify CCUS Potential with International Cooperation

A number of resource classification systems have evolved over time in response to various sectoral needs and local requirements. These systems have witnessed progression towards a unifying global standard, UNFC. UNFC is a global, principles-based and user-friendly system for classifying, managing and reporting mineral, petroleum, renewable energy, groundwater, anthropogenic resources and injection projects. UNFC is a unique system in which resource quantities are classified on the basis of three fundamental criteria that reflect technical, socio-economic and planning dimensions.

Benefits of using UNFC:

- Structured framework of principles, rules and guidelines
- Aligned to major international and national classification systems
- Provides simplicity without sacrificing completeness or flexibility
- Leverages global communications
- Numerical and language independent coding scheme.

Figure 7 United Nations Framework Classification (UNFC)

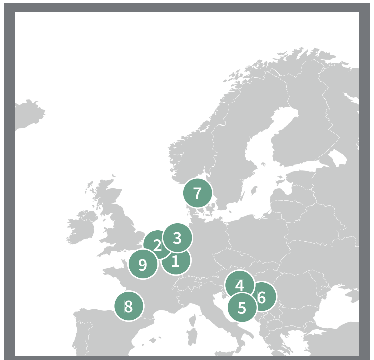


The UNFC classifies projects where categories marked 1 indicate most mature categories and highest confidence according to estimates.

Projects are classified by their E and F categories, while the G categories reflect the degree of confidence in the estimate. The E-F categorization is shown in Figure 7. Estimates have traditionally been evaluations of resource quantities. As the UNFC by nature is a classification of projects, also other quantitative information carried by the projects and the assets associated with them may be included. Examples are quantities of costs, revenues, emissions, labour etc. and indicators of environmental and social contingencies etc.

Source: *UNECE 2020b, United Nations Framework Classification (UNFC)*

APPENDIX 2

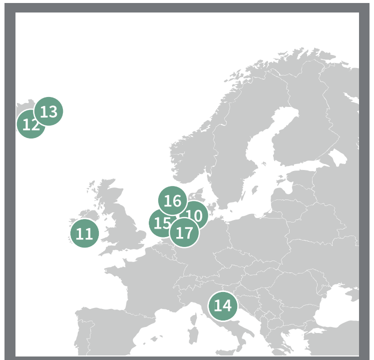


CCUS projects in **EUROPE**

1. Leilac
2. Port of Antwerp
3. Carbon Connect Delta (Port of Ghent)
4. CO₂ EOR Project Croatia
5. iCORD
6. Bio-Refinery plant
7. Greensand
8. Lacq
9. DMX Demonstration in Dunkirk

NO	LOCATION	PROJECT NAME	PROJECT TYPE	INDUSTRY	DESCRIPTION	CO_2 CAPTURED/ YEAR	STARTING DATE (OPERATION)	STATUS OF THE PROJECT	PARTICIPANTS	IOGP MEMBERS INVOLVED
1	Belgium	Leilac	Industrial capture	Cement	Cement plant carbon capture (pilot project)	N/A	2018-2020	2-year CO_2 capture test	Heidelberg Cement, Calix	
2	Belgium *Antwerp*	Antwerp@C (Port of Antwerp)	Industrial capture	N/A	CCS-equipped industrial cluster, CO_2 transportation and storage in the North Sea and reuse	N/A	N/A	Feasibility study	Air Liquide, BASF, Borealis, INEOS, ExxonMobil, Fluxys, Port of Antwerp and Total	ExxonMobil, Total
3	Belgium *Ghent*	Carbon Connect Delta (Port of Ghent)	Industrial capture	N/A	Connected to the cross-border Carbon Connect Delta in the Netherlands	1 Mt by 2023, 6,5 Mt by 2030	2023	Pre-feasibility	Smart Delta Resources, North Sea Port, ArcelorMittal, Dow Benelux, PZEM, Yara, Zeeland Refinery, Gasunie, Fluxys	
4	Croatia *Zagreb County*	CO_2 EOR Project Croatia	EOR	N/A	EOR project started in 2014. Injected 1.400 kt CO_2 in the EOR fields Ivanić and Žutica near Ivanic Grad (Zagreb County) .The pipeline Molve-Ivanić is 88 km long (30 bar)	0,560 Mt/y	2015	In operation	INA MOL	MOL
5	Croatia *Central Croatia*	iCORD	Industrial capture	Fertilizer	Capturing the CO_2 produced at a fertilizer plant at Location in central Croatia and at a concrete production plant at Location in eastern Croatia, and storing it at Moslavina basin oil fields and Pannonia basin oil fields as part of INA EOR project	Approx. 1Mt/y	2025	Feasibility study to be ordered by end of 2019, and to be prepared by Q3 2020	INA MOL	MOL
6	Croatia *Sisak-Moslavina County*	Bio-Refinery plant	Industrial capture	Bioethanol production	Bio-Refinery plant (bio-Ethanol production) on the9Sisak Refinery location. On the existing pipeline route, new pipe of 16km will be built for CO_2 storage, for the yearly production of 60kt of CO_2	0,06 Mt/y (additional potential on location 300-400 kt)	2024	Signing the contracts for basic design and technology selection	NA MOL	MOL
7	Denmark *Greensand*	Greensand	Capture storage	Natural gas	Project purpose is to prove that the Paleocene sand in the depleted Danish North Sea oil-and gas fields and the associated infrastructure can be used for safe, long-term storage of CO_2. When in operation, the Project will allow for storage of 0.5-1 mill ton/ CO_2 per year.	0.5-1 Mt stored CO_2/year	Pilot CO_2 injection project by 2023; full field by 2025	Phase 1: Feasibility study stage, current TRL 2-3, aim is TRL 6 for launching the pilot (Phase 2)	INEOS Oil & Gas Denmark, Wintershall Dea GmbH, Maersk Drilling	Wintershall Dea
8	France *Pyrenees*	Lacq	Capture storage (oxycombustion)	Natural gas	CCS Oxy fuel combustion CO_2 captured and storage in depleted natural gas field at Rousee (Pyrenees)	Approx. total 50,000 tonnes	2009	Capture and storge phase ended on 15/03/2013	Total	Total
9	France *Dunkirk*	DMX Demonstration in Dunkirk	Industrial capture	Steelmaking	CCS-equipped steel-making plant, CO_2 transportation and storage in the North Sea	Approx. 1 Mtpa	2025		ArcelorMittal, IFPEN, Axens, Total, ACP, Brevik Engineering, CMI, DTU, Gassco, RWTH, Uetikon	Total

__Source__: Global CCS Institute and IOGP data

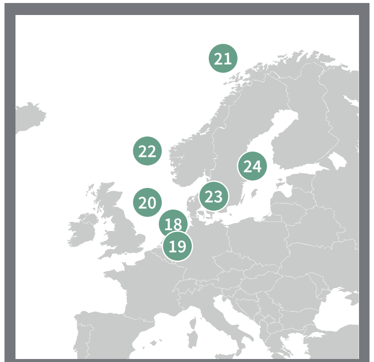


CCUS projects in **EUROPE**

10. H2morrow
11. ERVIA
12. Orca
13. Hellisheidi
14. CCS Ravenna Hub
15. Porthos
16. Athos
17. Magnum

NO	LOCATION	PROJECT NAME	PROJECT TYPE	INDUSTRY	DESCRIPTION	CO_2 CAPTURED/ YEAR	STARTING DATE (OPERATION)	STATUS OF THE PROJECT	PARTICIPANTS	IOGP MEMBERS INVOLVED
10	Germany *North Rhine-Westphalia*	H2morrow	Natural gas to H_2 (precombustion)	Natural gas	Reforming natural gas imported from Norway to hydrogen with CO_2 capture and storage offshore. Supplying industry and other end users in North Rhine-Westphalia with 8.6 terawatt hours of hydrogen per year from decarbonised natural gas	N/A	N/A	Feasibility study	Equinor, OGE	Equinor
11	Ireland	ERVIA	Power and capture (post-combustion)	Natural gas power and refining	CCS-equipped CCGTs and refinery, CO_2 transportation and storage in the Celtic Sea	2Mtpa	2028	Feasibility study	ERVIA	
12	Iceland	Orca	Direct air capture	Power generation	Orca will combine Climeworks' direct air capture technology with the underground CO_2 storage provided by Carbfix, capturing 4,000 tons/yr of CO_2 - making the largest direct air capture plant to date. The energy required to run the direct air capture process will be provided by ON Power's nearby Hellisheidi Geothermal Power Plant	4000 tonnes	N/A	Under construction	Carbfix, Climeworks, ON Power	
13	Iceland	Hellisheidi	Industrial capture	Power generation	The industrial scale capture at the Hellisheidi Geothermal Power Plant in Iceland has significantly reduce CO_2 and H_2S emissions from the power plant since 2014, following successful pilot-scale injections in 2012. The gases are co-captured in a scrubbing tower with annual capacity of about 12,000 tonnes of CO_2 and 6,000 tonnes of H_2S, about 30% and 75% of the plant's emissions respectively. Cost of industrial scale operations at Hellisheidi are less than $25/ton	12,000 tonnes	In operation	Under construction	Carbfix, ON Power	
14	Italy *Pianura Padana*	CCS Ravenna Hub	Power and capture (post-combustion), blue Hydrogen	Power generation and potential H_2 production	CO_2 capture in North of Italy (Pianura Padana Area) from Industrial Complex (i.e. Ravenna), transportation and storage exhausted natural gas fields. With a storage capacity of between 300 and 500 million tonnes	0.04-5,0 Mtpa phased program	2025-2028	Prefeasability study	Eni	Eni
15	The Netherlands *Port of Rotterdam*	Porthos	Industrial capture	Chemical, refining	CCS-equipped industrial cluster, CO_2 transportation and storage in the North Sea	Approx. 5Mtpa	2024	Feasibility study	Gasunie, the Port Authority and EBN	BP, Shell
16	The Netherlands *Ijmond*	Athos	Industrial capture	Steelmaking	CCUS network capturing CO_2 from TATA steel plant and reusing it or storing it in empty gas fields under the North Sea	7.5 MT CO_2 per year	2030	Feasibility study	Gasunie, Port of Amsterdam, EBN and TATA Steel	
17	The Netherlands *Eemshaven*	Magnum	Natural gas to H_2 (pre-combustion)	Hydrogen production	CCS-equipped production of hydrogen for power generation, CO_2 transportation and storage in the North Sea	Approx. 4 Mtpa	2023	Feasibility study	Equinor, Vattenfall, Gasunie, MHPS	Equinor

***Source**: Global CCS Institute and IOGP data*

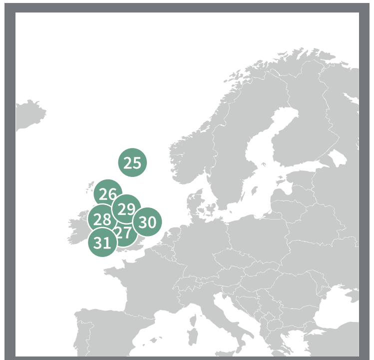


CCUS projects in **EUROPE**

18. Aramis
19. Carbon Connect Delta
20. Sleipner CO_2 Storage
21. Snøhvit CO_2 Storage
22. Longship (including Northern Lights)
23. Preem CCS
24. Stockholm Exergi Bio-CCS

NO	LOCATION	PROJECT NAME	PROJECT TYPE	INDUSTRY	DESCRIPTION	CO_2 CAPTURED/ YEAR	STARTING DATE (OPERATION)	STATUS OF THE PROJECT	PARTICIPANTS	IOGP MEMBERS INVOLVED
18	The Netherlands *Den Helder*	Aramis	Industrial capture		CO_2 supplied by third parties from Den Helder and stored in the North Sea floor. This CO_2 can be brought to Den Helder by boat2or by pipeline (for example from IJmuiden)	N/A	N/A	N/A	N/A	
19	The Netherlands *Ports of Terneuzen and Vlissingen*	Carbon Connect Delta	Industrial capture	N/A	With CCUS, CO_2 emissions can be reduced by 30% in the port area of North Sea Port. A consortium of Belgian and Dutch companies expects to complete the Carbon Connect Delta feasibility study at the end of 2020, after which the project will be further developed for realization. The consortium works simultaneously across industrial sectors (chemicals, petrochemicals and steel), as well as with relevant governments in both countries to create unique synergies and opportunities	1 Mt by 2023, 6,5 Mt by 2030	2023	Pre-feasibility	Smart Delta Resources, North Sea Port, ArcelorMittal, Dow Benelux, PZEM, Yara, Zeeland Refinery, Gasunie, Fluxys	
20	Norway *North Sea*	Sleipner CO_2 Storage	Industrial capture	Natural gas	CCS-equipped natural gas production, CO_2 directly injected into North Sea reservoirs	Approx. 1 Mtpa, and over 17 million tonnes has been injected since inception to date	1996	Operational	Equinor (operator), Vår Energi, Total	Equinor (operator), Vår Energi, Total
21	Norway *Barents Sea*	Snøhvit CO_2 Storage	Industrial capture	LNG facility	CCS-equipped LNG facility, CO_2 transportation and storage in the Barents Sea	0.70 Mtpa	2008	Operational	Equinor (operator) Petoro, Total, Engie, Norsk Hydro, Hess Norge	Statoil, Total, Hess
22	Norway	Longship (including Northern Lights)	Industrial capture	Cement and waste-to- energy	Capturing CO_2 from HeidelbergCement Norcem's cement factory in Brevik and Fortum Oslo Varme's waste incineration facility in Oslo and transporting it for offshore storage in the North Sea basin. Equinor, Shell and Total form the transport and storage consortium of Northern Lights.	0.8 Mtpa from possible 2 industrial plants: cement and waste to energy	2023–2024	Final investment decision (FID)	Shell, Equinor,Total	Shell, Equinor,Total
23	Sweden	Preem CCS	Industrial capture, natural gas-to-H_2 (pre-combustion)	Refining	CCS-equipped hydrogen production unit at a refinery, CO_2 transportation and storage in the North Sea	500,000 tonnes (at full scale)	2025	Pilot phase	Preem, Chalmers University of Technology, SINTEF Energy Research, Equinor and Aker Solutions	Equinor, Aker Solutions
24	Sweden *Stockholm*	Stockholm Exergi Bio-CCS	Power & capture (post-combustion), BECCS	Bioenergy	A pilot plant at the Värtan biomass-fired CHP plant enables the capture of CO_2 from the biomass fuel in the post-combustion flue gases. The CO_2 will be compressed into liquid form and stored in underground rock formations. A large-scale facility for BECCS will cover all parts from CO_2 capture to storage and will create major negative emissions each year.	Est. 0,8 Mt (at full scale)	N/A	Pilot phase	Stockholm Exergi, Northern Lights consortium (Equinor, Shell, Total)	Equinor, Shell, Total

Source: *Global CCS Institute and IOGP data*

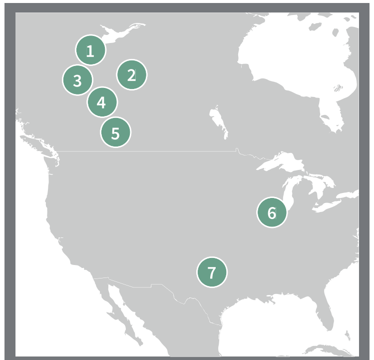


CCUS projects in **EUROPE**

25. Acorn
26. Caledonia Clean Energy
27. H21 North of England
28. Liverpool-Manchester Hydrogen Cluster
29. Net Zero Teesside
30. Humber Zero Carbon Cluster
31. Liverpool Bay Area CCS Project

NO	LOCATION	PROJECT NAME	PROJECT TYPE	INDUSTRY	DESCRIPTION	CO_2 CAPTURED/ YEAR	STARTING DATE (OPERATION)	STATUS OF THE PROJECT	PARTICIPANTS	IOGP MEMBERS INVOLVED
25	UK *Scotland St Fergus*	Acorn	Industrial capture	Natural Gas power	CCS-equipped natural gas processing plant, CO_2 transportation and storage in the North Sea	The Reference Case assumes a flat rate of 200,000T/ yr can be captured from one of the gas terminals at St Fergus	2023	Feasibility study	Project is led by Pale Blue Dot Energy, with funding and support from industry partners (Chrysaor, Shell and Total) the UK and Scottish Governments	Chrysaor, Shell, Total
26	UK *Scotland Grangemouth*	Caledonia Clean Energy	Power & capture	Natural gas power	Examining construction of a new natural gas feedstock power plant (The Caledonia Plant) with integrated CO_2 capture facilities. Power is developing the Caledonia Clean Energy Project (CCEP), an electricity generating station of up to 1GW located near Grangemouth, central Scotland. The project would use a natural gas feedstock with integrated carbon capture, and has the potential to also co-produce clean hydrogen for modern heat and transport applications	3 Mtpa	2023	Feasibility study	Summit Power	
27	UK *North of England*	H21 North of England	Natural gas to H_2 (pre-combustion)	Hydrogen production	Natural gas-to-hydrogen conversion with CCS, CO_2 transportation and storage in the North Sea and salt caverns	Approx. 3 Mtpa	2020s	Feasibility study	Northern Gas Networks, Cadent and Equinor	Equinor
28	UK *Liverpool Mancester*	Liverpool- Manchester Hydrogen Cluster	Natural gas to H_2 (pre-combustion)	Hydrogen production	Natural gas-to-hydrogen conversion with CCS, CO_2 transportation and storage in the North Sea	1.5Mtpa (10% H_2) - 9.5Mtpa (100% H_2)	2020s	Feasibility study	CADENT	
29	UK *Southern North Sea*	Net Zero Teesside	Power & capture (post-combustion)	Natural gas power	CCS-equipped natural gas power plant, CO_2 transportation and storage in the North Sea	5 Mtpa	2026	Technical evaluation and business model options	BP, OGCI	BP, Eni, Repsol, Shell, Equinor, Total
30	UK *North Sea*	Humber Zero Carbon Cluster	Industrial capture	H_2 production, bioenergy	CCS-equipped industrial cluster, CCS equipped hydrogen production, bioenergy with CCS (BECCS), CO_2 transportation and storage in the North Sea	N/A	2020s	Technical evaluation and business model options	Drax Group, Equinor, National Grid Ventures	Equinor
31	UK *East Irish Sea*	Liverpool Bay Area CCS Project	Carbon capture sequestration	Chemical, refining, hydrogen production	CO_2 capture from the existing industrial facilities and new hydrogen production plant in the North West of England	1-3 Mtpa phased program	2025	Concept selection phase	Eni	Eni

***Source**: Global CCS Institute and IOGP data*

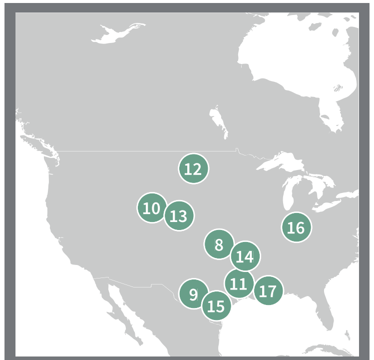


CCUS projects in **NORTH AMERICA**

1. Quest
2. Boundary Dam CCS
3. Alberta Carbon Trunk Line (ACTL) with North West Redwater Partnership's Sturgeon Refinery CO_2 Stream
4. Lehigh's Edmonton plant
5. Alberta Carbon Trunk Line (ACTL) with Agrium CO_2 Stream
6. Illinois Industrial Carbon Capture and Storage (ICCS)
7. Petra Nova

NO	LOCATION	PROJECT NAME	PROJECT TYPE	INDUSTRY	DESCRIPTION	CO_2 CAPTURED/ YEAR	STARTING DATE (OPERATION)	STATUS OF THE PROJECT	PARTICIPANTS	IOGP MEMBERS INVOLVED
1	Canada *Alberta*	Quest	Industrial capture, EOR	Hydrogen production for oil refining	Retrofitted CO_2 capture facility to steam methane reformers, transportation via pipeline to a dedicated geological storage	1 Mtpa	2015	Operational	Shell	Shell
2	Canada *Saskatchewan*	Boundary Dam CCS	Power and capture (post-combustion), EOR	Power generation	It combines post-combustion CCS with coal-fired power generation, some captured CO_2 goes for EOR use in the Weyburn oil unit, a portion of the CO_2 is stored permanently under the ground at the Aquistore project	1 Mtpa	2014	Operational	SaskPower	
3	Canada *Alberta*	Alberta Carbon Trunk Line (ACTL) with North West Redwater Partnership's Sturgeon Refinery CO_2 Stream	Industrial capture, EOR	Oil refining	Carbon dioxide captured from Agrium's Redwater fertiliser plant and the North West Redwater Partnership's Sturgeon refinery. CO_2 recovered from the fertiliser plant's emission streams put through inlet cooling, separation, compression, dehydration and refrigeration to produce liquefied CO_2.The project plans to transport CO_2 from a number of sources in the future coming from Alberta's Industrial Heartland	1.2-1.4 Mtpa	2020	Operational	Enhance Energy Inc. (and - North West Redwater Partnership)	
4	Canada *Alberta*	Lehigh's Edmonton plant	Industrial capture	Cement industry	Capture the majority of the carbon dioxide (CO_2) from the flue gas of Lehigh's Edmonton, Alberta cement plant	Estimated 600,000 tonnes annually		Feasibility study	Lehigh Cement and the International CCS Knowledge Centre	
5	Canada *Alberta*	Alberta Carbon Trunk Line (ACTL) with Agrium CO_2 Stream	Industrial capture, EOR	Fertilizer production	At the NWR refinery, CO_2 will be captured within the gasification hydrogen supply unit, which will use unconverted petroleum bottoms (asphaltene) as feedstock to create synthesis gas (syngas)	0.3-06 Mta	2020	Operational	Enhance Energy Inc.	
6	USA *Illinois*	Illinois Industrial Carbon Capture and Storage (ICCS)	Industrial capture	Ethanol production	CO_2 captured from the fermentation process used to produce ethanol at an industrial corn processing complex in Decatur, Illinois, Transportation to a dedicated geological storage site	1 Mtpa	2017	Operational	Administered by the U.S. Department of Energy's Office of Fossil Energy and managed by the National Energy Technology Laboratory and by a cost share agreement with the Archer Daniels Midland Company, University of Illinois through the Illinois State Geological Survey, Schlumberger Carbon Services, and Richland Community College	
7	USA *Texas*	Petra Nova	Power and capture (post-combustion), EOR	Power generation	Texas power plant retroffitted with post-combustion CO_2 capture facility, transportation near Houston for EOR	1.4 Mtpa	2017	Operational		

***Source**: Global CCS Institute and IOGP data*

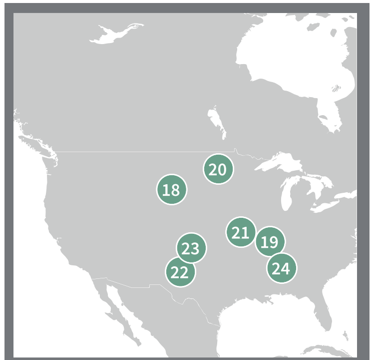


CCUS projects in NORTH AMERICA

8. Coffeyville Gasification Plant
9. Air Products Steam Methane Reformer
10. Lost Cabin Gas Plant
11. Century Plant
12. Great Plains Synfuels Plant and Weyburn-Midale
13. Shute Creek Gas Processing Plant
14. Enid Fertilizer
15. Terrell Natural Gas Processing Plant (formerly Del Verde)
16. Wabash CO_2 Sequestration
17. Lake Charles Methanol

NO	LOCATION	PROJECT NAME	PROJECT TYPE	INDUSTRY	DESCRIPTION	CO_2 CAPTURED/ YEAR	STARTING DATE (OPERATION)	STATUS OF THE PROJECT	PARTICIPANTS	IOGP MEMBERS INVOLVED
8	USA *Kansas*	Coffeyville Gasification Plant	Industrial capture, fertilizer production, EOR	Fertilizer production	Fertilizer plant in Coffeyville retrofitted with CO_2 compression and dehydrataion facilities, oil delivery to the North Burbank oil unit in Osage county, Ohklaoma for EOR	1 Mtpa	2013	Operational	Coffeyville Resources Nitrogen Fertilizers, LLC, Chapparal Energy and Blue Source	
9	USA *Texas*	Air Products Steam Methane Reformer	Industrial capture, EOR	Hydrogen production for oil refinery	Air products retrofitted of steam methane reformer within a refinery at Port Arthur, Texas, transportation to oil field in Texas for EOR	1 Mtpa	2013	Operational	Air Products, Covestro	
10	USA *Wyoming*	Lost Cabin Gas Plant	Industrial capture, EOR	Natural gas processing	Gas plantg in Wyoming supplies CO_2 to compression facolity, transport and delivery via pipeline to the Bell Creek oil firld in Montana for EOR	Approx. 1 Mtpa	2013	Operational	ConocoPhillips	ConocoPhillips
11	USA *Texas*	Century Plant	Industrial capture, EOR	Natural gas processing	Natural gas treatment facility in Texas, transportation via pipeline for EOR	8.4 Mtpa	2010	Operational	Occidental Petroleum	
12	USA *North Dakota*	Great Plains Synfuels Plant and Weyburn-Midale	Industrial capture (pre-combustion), EOR	Synthetic natural gas	The plant in North Dakota produces CO_2 as part of a coal gasification process, transportation to the Wyburn and Midale oil units for EOR	3 Mtpa	2000	Operational	Dakota Gasification Company	
13	USA *Wyoming*	Shute Creek Gas Processing Plant	Industrial capture, EOR	Natural gas processing	Gas treating facility in Wyoming, some CO_2 injected for sequestration/disposal, some for EOR	7 Mtpa	1986	Operational	ExxonMobil	ExxonMobil
14	USA *Oklahoma*	Enid Fertilizer	Industrial capture, fertilizer production, EOR	Fertilizer production	CO_2 captured from the manufacture of fertilizer, transportation for use in EOR at the Golden Trend oilfield and the Sko-Vel-Tum oilfield, south of Oklahoma City	0.7 Mtpa	1982	Operational	Koch Nitrogen Company	
15	USA *Texas*	Terrell Natural Gas Processing Plant (formely Del Verde)	Industrial capture, EOR	Natural gas processing	CO_2 capture at natural gas processing plant, CO_2 transportation via Valverde pipeline to McCamey, Texas, and the Canyon Reef Carriers CRC pipeline and the Pecos pipeline, CO_2 for EOR	Approx 0.5 Mtpa	1972	Operational	Blue Source and others	
16	USA *Indiana*	Wabash CO_2 Sequestration	Industrial capture	Fertilizer production	Gasification plant in Indiana to be converted into an anhydrous ammonia production plant and CCS plant, dedicated geological storage in the Wabash carbonSAFE CO_2 storage hub	1.5-1.75 Mtpa	2022	Advance development	WABASH Valley Resources (WVR)	
17	USA *Louisiana*	Lake Charles Methanol	Industrial capture, EOR	Chemical production	Gasification facility in Lousiana capturing from synthetic gas syngas to make methanol and other products, captured CO_2 to be used for EOR in Texas	Approx 4 Mtpa	2024	Advance development	Leucadia Energy	

Source: *Global CCS Institute and IOGP data*



CCUS projects in **NORTH AMERICA**

18. Dry Fork Integrated Commercial CCS
19. CarbonSAFE Illinois - Macon County
20. Project Tundra
21. Integrated Mid-Continent Stacked Carbon Storage Hub*
22. Oxy and White Energy Ethanol EOR Facility
23. Oxy and Carbon Engineering Direct Air Capture and EOR Facility
24. Project ECO_2S: Early CO_2 Storage Complex in Kemper County

NO	LOCATION	PROJECT NAME	PROJECT TYPE	INDUSTRY	DESCRIPTION	CO_2 CAPTURED/ YEAR	STARTING DATE (OPERATION)	STATUS OF THE PROJECT	PARTICIPANTS	IOGP MEMBERS INVOLVED
18	USA *Wyoming*	Dry Fork Integrated Commercial CCS	Power and capture (postcombustion), EOR	Power generation	Dry Fork coal-fired power station in Wyoming, targeting adjacent geological storage formations currently under study. EOR under consideration	3 Mtpa	2025	Advance development	The Basin Electric Power Cooperative	
19	USA *Illinois*	CarbonSAFE Illinois -Macon County	Power and industrial capture (postcombustion), EOR	Power genration and ethanol production	CCS integration of a compression and dehydration facilities to an ethanol plant, transportation and injection in a dedicated geological storage	2-5 Mtpa	2025	Advance development	Carbon Storage Assurance Facility Enterprise (CarbonSAFE) of the U.S. Department of Energy National Energy Technology Laboratory (DOENETL)	
20	USA *North Dakota*	Project Tundra	Power and capture (postcombustion), EOR	Power generation	Retrofit CO_2 capture plant to the MIlton R. Young coal fire power station in North Dakota with a dedicated storage site. EOR under study	3.1-3.6 Mtpa	2025-2026	Advance development	Minnkota Power Cooperative	
21	USA *Nebraska, Kansas*	Integrated Mid-Continent Stacked Carbon Storage Hub	Ethanol production, power generation and/or refinery, EOR	Ethanol production, power generation and/or refinery	CO_2 collection from ethanol plants, power plants and refineries with integrated storage in Kansas and Nebraska	Approx 2 Mtpa	2025-2035	Advance development	The team is led by Battelle Memorial Institute and includes: Archer Daniels Midland Company (ADM), the Kansas Geologic Survey (KGS), the Energy and Environmental Research Center (EERC) at the University of North Dakota, Schlumberger, the Conservation and Survey Division (CSD) at the University of Nebraska- Lincoln (UNL) and others	Schlumberger
22	USA *Texas*	Oxy and White Energy Ethanol EOR Facility	Industrial capture, EOR	Ethanol production	CO_2 capture from two ethanol facilities in Hereford and Plainview, Texas. The captured CO_2 will be stored via EOR at Occidental's oil fields in Premian basin	0.6-0.7 Mtpa	2021	Early development	Occidental Petroleum Corporation and White Energy	
23	USA *Texas*	Oxy and Carbon Engineering Direct Air Capture and EOR Facility	Direct air capture, EOR	N/A	CO_2 capture from an Occidental oil field in the Permian Basin, and used for EOR	1 Mtpa	2025	Early development	Oxy Low Carbon Ventures and Carbon Engineering Ltd	
24	USA *Mississippi*	Project ECO_2S: Early CO_2 Storage Complex in Kemper County	Under evaluation	N/A	Regional CO_2 storage hub near the Keper County Energy Facility in Missisipi from power and industrial sources	3 Mtpa	2026	Early development	In identification (capture) - Project ECO_2S, a DOE-supported CarbonSAFE program	

Source: *Global CCS Institute and IOGP data*

ABBREVIATIONS

BECCS	Biomass energy with carbon capture and storage
CCUS	Carbon capture, use and storage
CO_2	Carbon dioxide
CRL	Commercial readiness level
DACCS	Direct air carbon capture and storage
ECBM	Enhanced coal bed methane
EGR	Exhaust gas recirculation
EOR	Enhanced oil recovery
GHG	Greenhouse gas
Gt	Gigatonne
NET	Negative emissions technologies
R&D	Research and development
SRL	Social readiness level
TRL	Technology readiness level
UNECE	United Nations Economic Commission for Europe
UNFC	United Nations Framework Classification

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