TECHNOLOGY BRIEF
CARBON CAPTURE, USE AND STORAGE (CCUS)
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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 CO₂ 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.

**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.

**Sharing good practice is needed**

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

**Working together beyond borders**

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

**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.

**Act now, CCUS unlocks full decarbonization of energy sector**

Countries need to include CCUS in long-term strategies and commence retrofitting existing infrastructure.
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 utilization can unlock the commerciality of CCUS projects for the industrial, steel, cement and chemical sectors. CO\textsubscript{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.

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**Point Sources of CO\textsubscript{2} in Industry**
CO\textsubscript{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)**
Net negative emissions technologies are key to reach net-zero and then net negative emissions. In BECCS, CO\textsubscript{2} is taken out of the atmosphere by vegetation, then recovered from the combustion products when the biomass is burnt. In DACCS, CO\textsubscript{2} is captured directly from the air.

**Direct Air Carbon Capture and Storage (DACCS)**
Carbon utilization can unlock the commerciality of CCUS projects for the industrial, steel, cement and chemical sectors. CO\textsubscript{2} captured can be used as a feedstock to produce a range of products, such as concrete, methanol, ethanol, carbonates, plastics etc.

**Aquifers for Sequestration of CO\textsubscript{2}**
Aquifers are geological formations containing brine in porous rock at depths over 1km. CO\textsubscript{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\textsubscript{2}. Dependent on operational choices, the volume of CO\textsubscript{2} stored could exceed the CO\textsubscript{2} content of the produced hydrocarbons.
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 CO₂ 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.

The **reference scenario** is a forecast of CO₂ 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 CO₂ 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.

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 CO2 capture depends on the source of CO2 and separation method. We can differentiate between mobile and point CO2 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. CO2 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 CO2 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 CO2 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 CO2 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 CO2 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, CO₂ 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 CO₂ can be incorporated into products such as building materials, as long as they give the same long-term storage.

CO₂ 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 $/tCO₂. 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.

CO₂ 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 CO₂. 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 CO₂. 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 CO₂ 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 CO₂/yr by 2050, limited by CO₂ 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 CO₂ 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 CO₂ emission reductions.
- **Prepare international standards and arrangements to share CO₂ storage.** CO₂ transport and storage infrastructure needs to be as international as that for electricity, gas and oil supplies.

Source: Adapted from IPCC Special Report on CCS, 2005
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 CO₂ into the atmosphere back to permanent and secure storage underground.

In BECCS, CO₂ is taken out of the atmosphere by vegetation, then recovered from the combustion products when the biomass is burnt. In DACCS, CO₂ is captured directly from the air. In both cases, the captured CO₂ 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 CO₂ from the air from any fuel source anywhere in the world. BECCS is expected to be cheaper, at maybe $50-200/CO₂ removed and stored, while DACCS might be roughly twice the cost. But DACCS is able to remove large amounts of CO₂ from the atmosphere without the demands on natural systems required by growing biomass.

Often it will be cheaper to capture, or avoid, CO₂ emissions at source, rather than capture them from the air. BECCS and DACCS can capture the same quantity of CO₂ generated by mobile, natural or infrequent emissions.

NETs will also have to be used to remove CO₂ if net zero is not achieved quickly enough to avoid dangerous climate change.

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 CO₂ 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 CO₂/yr by 2050, limited by biomass availability; DACCS 5-20 Gt CO₂/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 CO₂ 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 CO₂ 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 CO₂. 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 CO₂

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.

CO₂ can be pumped down into the rock for sequestration. At such depths CO₂ is pressured to a density of 200-800kg/m³. In the aquifer, CO₂ displaces brine and forms a plume from the injection point that tends to move to the top of the aquifer. At the CO₂/brine interface, CO₂ will dissolve in brine about 1-2% solubility and some water will dissolve in CO₂ 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 CO₂ 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 CO₂ in the plume or brine cannot escape. It depends on the rate of CO₂ injection and how quickly the brine permeates through rock. Once injection stops, the pressure decreases over centuries as the CO₂ 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 CO₂ 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 CO₂ emissions from operations incur high cost penalties.

Sequestration Potential

- Estimated at “more than a trillion tonnes CO₂”. The costs of operations at the injection head are low, <$30/te storage cost only (excluding collection, transport and pressurisation of CO₂).

Appropriate Policy Action

- Recognise the scale and cost of the industry that needs to develop in a very short time – billions of tonnes CO₂ 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. CO₂ 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 CO₂.
- 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.

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

Figure 3.1 Simplified view of aquifer with a plume of CO₂ injected below a caprock
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 CO₂ into the well at pressure. At depths greater than 700m, CO₂ becomes supercritical and acts as a good solvent to release oil and gas from rock strata and flush them to the well head. CO₂ can also be co-injected with water. First tried in 1972, EOR is a common technique applied in mature oil & gas wells. Injected CO₂ can be used as a secondary drive mechanism to push remaining hydrocarbons in an oil and gas reservoir. CO₂-injection technology is an EOR method that is gaining most popularity. The source of CO₂ used is based on lowest locally available cost and the majority is from natural sources.

The interest in CO₂ EOR is that once the field is exhausted, some CO₂ can be left in the reservoir, sequestrating it for centuries or millennia. The reservoir, possibly including its aquifers, may have capacity to store CO₂ 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, CO₂ 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 CO₂ EOR depends on suitability of the reservoir, the payback period required because of the relatively high capital costs, the local cost of CO₂ 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 CO₂ so that it can be transported and used for EOR.

**Carbon Storage Potential**

- **Total**: 50 – 350 Gt (IEA 2015 estimate)
- Onshore has the largest CO₂ EOR potential globally, but some good offshore candidates exist. Based on Rystad Energy data, all global producing fields with potential for CO₂ storage, over 80% are onshore fields.

**Appropriate Policy Action**

- **Encourage the oil and gas industry to use CO₂ EOR**. A system of credits based on future CO₂ sequestration once the well is closed or hydrocarbons marketed from well using CO₂ EOR. Encourage more CO₂ to be sequestrated than is required just for oil recovery.
- **Incentivise CO₂ capture from anthropogenic sources**. Encourage collaboration between industrial sources of CO₂ and users of EOR.
- **Increase the amount of CO₂ stored (EOR+)**. Promote and disseminate research into techniques to increase CO₂ sequestration above that needed for EOR. Classify sources of hydrocarbons based on a net carbon emission after EOR (standardised life cycle analysis).

**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 CO2 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 Ural, West Siberia, Caspian subregion) nor in Kazakhstan, Azerbaijan Caspian Sea. (UNECE is also preparing a study on Geological CO2 storage in Eastern Europe, Caucasus and Central Asia.)

Access to secure geological CO2 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 CO2. There is an urgent need to cooperate on shared, regional CO2 transport and storage infrastructure, including via CO2 shipping, if CCUS is to be deployed at a scale capable of making a substantial contribution to attaining carbon neutrality.

5. SOLUTIONS FOR CARBON UTILIZATION

Carbon utilization is the use of CO₂ 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 CO₂ 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 CO₂ and to attain carbon neutrality.

Due to its current market size, the conversion of CO₂ into products makes a small but important contribution to GHG targets for climate change. In a future hydrogen economy, carbon from CO₂ 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 CO₂ into concrete has the most potential to become a large market for CO₂ 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**: CO₂ is currently used in small quantities to make urea fertiliser and some special polymers. In a future hydrogen economy, CO₂ could be combined with H₂ to make synthetic fuels, syngas and methanol. Syngas and methanol are basic chemical feedstock from which many chemicals and polymers can be made.

- **Biological**: CO₂ is used to promote plant growth and can be captured in soils by using biochar to increase soil quality.

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

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

- **CO₂ utilization** will require large energy consumption due to the many reaction and separation steps involved. Industrial scale carbon capture will create a source of CO₂ 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 CO₂ can be sequestered.

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**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 CO₂ utilization. Pursue large-scale demonstration for CCUS in industry in national and regional programmes.

- Set standards to help industry develop products with CO₂ and promote use of products that sink CO₂ (e.g. concrete industry).

- Introduce financing mechanisms, such as tax credits, carbon prices & taxes, mandate & standards, carbon financing in developing countries.

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**Emerging Uses for CO₂**

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

Products indicated in the table above can use CO₂ 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 CO₂ into products rather than into underground geological storage.

Aggregate and concrete produced from CO₂ have the greatest potential to sink CO₂ 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 CO₂ in products, but since liquid fuels are eventually burnt they are not considered as long-term CO₂ 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 CO₂ sink solutions, as markets for these products are small compared to the market for fossil fuels and processing costs are high.

As CO₂ use increases for aggregate, concrete and chemicals production, low-cost CO₂ 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 CO2 sequestered or below. CCUS cost of technologies that capture CO2 from point sources for the Industrial sector vary considerably for different technologies depending on the concentration of the CO2 with the Cement CCS and BECCS being the more expensive sources. DACCS technologies have the larger costs (more than USD 100/ton CO2). The uncertainty in DACCS cost is the highest with some costs reported as high as USD 400/ton CO2, however these technologies have a high potential to capture CO2 from sources beyond the industrial sector 28 Gt CO2 and up to 36 Gt CO2.

As the quantity of CO2 to be captures is far greater than any potential market for the CO2 (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.

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 these costs affect the cost of using fossil fuels in a transition period, the arrow indicates the cost of CCUS, $150 per tonne of CO2, that implies a doubling of energy costs, assuming an oil price of $60/barrel and approximately 0.4 tonnes of CO2 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.

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.
6.3 Comparative Analysis - CCUS 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

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.

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

<table>
<thead>
<tr>
<th>NO</th>
<th>LOCATION</th>
<th>PROJECT NAME</th>
<th>PROJECT TYPE</th>
<th>INDUSTRY</th>
<th>DESCRIPTION</th>
<th>CO₂ CAPTURED/YEAR</th>
<th>STARTING DATE</th>
<th>STATUS OF THE PROJECT</th>
<th>PARTICIPANTS</th>
<th>IOGP MEMBERS INVOLVED</th>
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<tbody>
<tr>
<td>1</td>
<td>Belgium</td>
<td>Leilac</td>
<td>Industrial capture</td>
<td>Cement</td>
<td>Cement plant carbon capture (pilot project)</td>
<td>N/A</td>
<td>2018-2020</td>
<td>2-year CO₂ capture test</td>
<td>Heidelberg Cement, Calix</td>
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<td>2</td>
<td>Belgium</td>
<td>Antwerp@C (Port of Antwerp)</td>
<td>Industrial capture</td>
<td>N/A</td>
<td>CCS-equipped industrial cluster, CO₂ transportation and storage in the North Sea and reuse</td>
<td>N/A</td>
<td>N/A</td>
<td>Feasibility study</td>
<td>Air Liquide, BASF, Borealis, INEOS, ExxonMobil, Fluxys, Port of Antwerp and Total</td>
<td>ExxonMobil, Total</td>
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<td>3</td>
<td>Belgium</td>
<td>Carbon Connect Delta (Port of Ghent)</td>
<td>Industrial capture</td>
<td>N/A</td>
<td>Connected to the cross-border Carbon Connect Delta in the Netherlands</td>
<td>1 Mt by 2023, 6.5 Mt by 2030</td>
<td>2023</td>
<td>Pre-feasibility</td>
<td>Smart Delta Ressources, North Sea Port, Arco-Iormittal, Dow Benelux, PZEM, Yara, Zeeland, Refinery, Gasunie, Fluxys</td>
<td></td>
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<td>4</td>
<td>Croatia</td>
<td>CO₂ EOR Project Croatia</td>
<td>EOR</td>
<td>N/A</td>
<td>EOR project started in 2014. Injected 1,400 kt CO₂ in the EOR fields in Croatia and Zetica near Ivanic Grad (Zagreb County). The pipeline Molve-Ivanic is 88 km long (30 bar)</td>
<td>0.560 Mt/y</td>
<td>2015</td>
<td>In operation</td>
<td>INA MOL</td>
<td>MOL</td>
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<tr>
<td>5</td>
<td>Croatia</td>
<td>iCORD</td>
<td>Industrial capture</td>
<td>Fertilizer</td>
<td>Capturing the CO₂ produced at a fertilizer plant at Location in central Croatia at and Zetica near Ivanic Grad (Zagreb County). Storing it at Moslavina basin oil fields and Pannonia basin oil fields as part of INA EOR project</td>
<td>Approx. 1Mt/y</td>
<td>2025</td>
<td>Feasibility study to be ordered by end of 2019, and to be prepared by Q3 2020</td>
<td>INA MOL</td>
<td>MOL</td>
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<tr>
<td>6</td>
<td>Croatia</td>
<td>Bio-Refinery plant</td>
<td>Industrial capture</td>
<td>Bioethanol production</td>
<td>Bio-Refinery plant (bio-Ethanol production) on the Sisak Refinery location. On the existing pipeline route, new pipe of 16km will be built for CO₂ storage, for the yearly production of 60kt of CO₂</td>
<td>0.06 Mt/y (additional potential on location 300-400 kt)</td>
<td>2024</td>
<td>Signing the contracts for basic design and technology selection</td>
<td>NA MOL</td>
<td>MOL</td>
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<tr>
<td>7</td>
<td>Denmark</td>
<td>Greensand</td>
<td>Capture storage</td>
<td>Natural gas</td>
<td>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 CO₂. When in operation, the Project will allow for storage of 0.5-1.1 million tonnes CO₂/year</td>
<td>0.5-1.1 Mt stored CO₂/year</td>
<td>2025</td>
<td>Pilot CO₂ 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)</td>
<td>INEOS Oil &amp; Gas Denmark, Winterhall Dea GmbH, Maersk Drilling</td>
<td>Winterhall Dea</td>
</tr>
<tr>
<td>8</td>
<td>France</td>
<td>Lacq</td>
<td>Capture storage (oxycombustion)</td>
<td>Natural gas</td>
<td>CCS Oxy fuel combustion CO₂ captured and storage in depleted natural gas field at Rousee (Pyrenees)</td>
<td>Approx. total 10,000 tonnes</td>
<td>2009</td>
<td>Capture and storage phase ended on 15/03/2013 Total</td>
<td>ArcelorMittal, IFPEN, Axens, Total, ACP, CMI, Brevik Engineering, CML, DTU, Gassco, RWTH, Uetikon</td>
<td>Total</td>
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<tr>
<td>9</td>
<td>France</td>
<td>DMX Demonstration in Dunkirk</td>
<td>Industrial capture</td>
<td>Steelmaking</td>
<td>CCS-equipped steel-making plant, CO₂ transportation and storage in the North Sea</td>
<td>Approx. 1 Mtpa</td>
<td>2025</td>
<td>Total</td>
<td></td>
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**Source:** Global CCS Institute and IOGP data
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<th>No</th>
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<th>Project Type</th>
<th>Industry</th>
<th>Description</th>
<th>CO₂ captured/Year</th>
<th>Starting Date (Operation)</th>
<th>Status of the Project</th>
<th>Participants</th>
<th>IOGP Members Involved</th>
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<tbody>
<tr>
<td>10</td>
<td>Germany</td>
<td>H2morrow</td>
<td>Natural gas to H₂ (pre-combustion)</td>
<td>Natural gas reforming natural gas imported from Norway to hydrogen with CO₂ 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</td>
<td>N/A</td>
<td>N/A</td>
<td>Feasibility study</td>
<td>Equinor, OGE</td>
<td>Equinor</td>
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<tr>
<td>11</td>
<td>Ireland</td>
<td>ERVIA</td>
<td>Power and capture (post-combustion)</td>
<td>Natural gas CCS-equipped CCGTs and refinery. CO₂ transportation and storage in the Celtic Sea</td>
<td>2Mtpa</td>
<td>2028</td>
<td>Feasibility study</td>
<td>ERVIA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Iceland</td>
<td>Orca</td>
<td>Direct air capture</td>
<td>Power generation</td>
<td>Orca will combine Climeworks’ direct air capture technology with the underground CO₂ storage provided by Carbfix, capturing 4,000 tons of CO₂—making the largest direct air capture plant to date. The energy required to run the direct air capture plant will be provided by ON Power’s nearby Hellisheidi Geothermal Power Plant</td>
<td>4,000 tonnes</td>
<td>N/A</td>
<td>Under construction</td>
<td>Carbfix, Climeworks, ON Power</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Iceland</td>
<td>Hellisheidi</td>
<td>Industrial capture</td>
<td>Power generation</td>
<td>The industrial scale capture at the Hellisheidi Geothermal Power Plant in Iceland has significantly reduce CO₂ and H₂S 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 CO₂ and 5,000 tonnes of H₂S, about 30% and 75% of the plant’s emissions respectively. Cost of industrial scale operations at Hellisheidi are less than $25/ton</td>
<td>12,000 tonnes</td>
<td>In operation</td>
<td>Under construction</td>
<td>Carbfix, ON Power</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Italy</td>
<td>Pianura Padana</td>
<td>Power and capture (post-combustion), blue Hydrogen</td>
<td>Power generation and potential H₂ production</td>
<td>CO₂ 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</td>
<td>0.04-5.0 Mtpa</td>
<td>2025-2028</td>
<td>Prefeasibility study</td>
<td>Eni</td>
<td>Eni</td>
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<tr>
<td>15</td>
<td>The Netherlands</td>
<td>Porthos</td>
<td>Industrial capture</td>
<td>Chemical, refining</td>
<td>CCS-equipped industrial cluster. CO₂ transportation and storage in the North Sea</td>
<td>Approx. 5Mtpa</td>
<td>2024</td>
<td>Feasibility study</td>
<td>Gasunie, the Port Authority and EBN</td>
<td>BP, Shell</td>
</tr>
<tr>
<td>16</td>
<td>The Netherlands</td>
<td>Athos</td>
<td>Industrial capture</td>
<td>Steelmaking</td>
<td>CCS-US network capturing CO₂ from TATA Steel plant and reusing it or storing it in empty gas fields under the North Sea</td>
<td>7.5 MT CO₂ per year</td>
<td>2030</td>
<td>Feasibility study</td>
<td>Gasunie, Port of Amsterdam, EBN and TATA Steel</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>The Netherlands</td>
<td>Magnum</td>
<td>Natural gas to H₂ (pre-combustion)</td>
<td>Hydrogen production</td>
<td>CCS-equipped production of hydrogen for power generation, CO₂ transportation and storage in the North Sea</td>
<td>Approx. 4 Mtpa</td>
<td>2023</td>
<td>Feasibility study</td>
<td>Equinor, Vattenfall, Gasunie, MHPS</td>
<td>Equinor</td>
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## Carbon Capture, Use And Storage (CCUS)

### CCUS projects in EUROPE

<table>
<thead>
<tr>
<th>No</th>
<th>Location</th>
<th>Project Name</th>
<th>Project Type</th>
<th>Industry Description</th>
<th>CO₂ Captured/Year</th>
<th>Starting Date (Operation)</th>
<th>Status of the Project</th>
<th>Participants Involved</th>
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</thead>
<tbody>
<tr>
<td>18</td>
<td>The Netherlands</td>
<td>Aramis</td>
<td>Industrial capture</td>
<td>CO₂ supplied by third parties from Den Helder and stored in the North Sea floor. This CO₂ can be brought to Den Helder by boat or pipeline (for example from IJmuiden)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>19</td>
<td>The Netherlands</td>
<td>Carbon Connect Delta</td>
<td>Industrial capture</td>
<td>N/A</td>
<td>1 Mt by 2023, 6.5 Mt by 2050</td>
<td>2023</td>
<td>Pre-feasibility</td>
<td>Smart Delta Resources, North Sea Port, ArcelorMittal, Dow Borealis, PZEM, Yara, Zeeland Refinery, Gasunie, Fluxys</td>
</tr>
<tr>
<td>20</td>
<td>Norway</td>
<td>Sleipner CO₂ Storage</td>
<td>Industrial capture</td>
<td>CCS-equipped natural gas production, CO₂ directly injected into North Sea reservoirs</td>
<td>Approx. 1 Mtpa, and over 17 million tonnes has been injected since inception to date</td>
<td>1996</td>
<td>Operational</td>
<td>Equinor (operator), Vår Energi, Total</td>
</tr>
<tr>
<td>21</td>
<td>Norway</td>
<td>Snøhvit CO₂ Storage</td>
<td>Industrial capture</td>
<td>CCS-equipped LNG facility, CO₂ transportation and storage in the Barents Sea</td>
<td>0.70 Mtpa</td>
<td>2008</td>
<td>Operational</td>
<td>Equinor (operator), Petoro, Total, Engie, Norsk Hydro, Heis Norge</td>
</tr>
<tr>
<td>22</td>
<td>Norway</td>
<td>Longship (including Northern Lights)</td>
<td>Industrial capture</td>
<td>Cement and waste-to-energy</td>
<td>0.8 Mtpa from possible 2 industrial plants: cement and waste to energy</td>
<td>2023–2024</td>
<td>Final investment decision (FID)</td>
<td>Shell, Equinor, Total</td>
</tr>
<tr>
<td>23</td>
<td>Sweden</td>
<td>Preem CCS</td>
<td>Industrial capture, natural gas-to-H₂ (pre-combustion)</td>
<td>CCS-equipped hydrogen production unit at a refinery, CO₂ transportation and storage in the North Sea</td>
<td>500,000 tonnes (at full scale)</td>
<td>2025</td>
<td>Pilot phase</td>
<td>Preem, Chalmers University of Technology, SINTEF Energy Research, Equinor and Aker Solutions</td>
</tr>
<tr>
<td>24</td>
<td>Sweden</td>
<td>Stockholm Exergi Bio-CCS</td>
<td>Power capture (post-combustion), BECCS</td>
<td>A pilot plant at the Vartian biomass-fired CHP plant enables the capture of CO₂ from the biomass fuel in the post-combustion flue gases. The CO₂ will be compressed into liquid form and stored in underground rock formations. A large-scale facility for BECCS will cover all parts from CO₂ capture to storage and will create major negative emissions each year.</td>
<td>Est. 0.8 Mt (at full scale)</td>
<td>N/A</td>
<td>Pilot phase</td>
<td>Stockholm Exergi, Northern Lights consortium (Equinor, Shell, Total)</td>
</tr>
</tbody>
</table>

**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

<table>
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<tr>
<th>No</th>
<th>Location</th>
<th>Project Name</th>
<th>Project Type</th>
<th>Industry</th>
<th>Description</th>
<th>CO2 Captured/YEAR</th>
<th>Starting Date (Operation)</th>
<th>Status of the Project</th>
<th>Participants Involved</th>
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<tr>
<td>25</td>
<td>UK Scotland St Fergus</td>
<td>Acorn</td>
<td>Industrial capture</td>
<td>Natural Gas power</td>
<td>CCS-equipped natural gas processing plant, CO2 transportation and storage in the North Sea</td>
<td>The Reference Case assumes a flat rate of 200,000 T/yr can be captured from one of the gas terminals at St Fergus</td>
<td>2023</td>
<td>Feasibility study</td>
<td>Project is led by Pale Blue Dot Energy, with funding and support from industry partners (Chrysaor, Shell and Total) the UK and Scottish Governments</td>
</tr>
<tr>
<td>26</td>
<td>UK Scotland Grangemouth</td>
<td>Caledonia Clean Energy</td>
<td>Power &amp; capture</td>
<td>Natural Gas power</td>
<td>Examining construction of a new natural gas feedstock power plant (The Caledonia Plant) with integrated CO2 capture facilities. Power is developing the Caledonia Clean Energy Project (CEEP), 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</td>
<td>3 Mtpa</td>
<td>2023</td>
<td>Feasibility study</td>
<td>Summit Power</td>
</tr>
<tr>
<td>27</td>
<td>UK North of England</td>
<td>H21 North of England</td>
<td>Natural gas to H2 pre-combustion</td>
<td>Hydrogen production</td>
<td>Natural gas-to-hydrogen conversion with CCS, CO2 transportation and storage in the North Sea</td>
<td>Approx. 3 Mtpa</td>
<td>2020s</td>
<td>Feasibility study</td>
<td>Northern Gas Networks, Cadent and Equinor Equinor</td>
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<td>28</td>
<td>UK Liverpool Manchester</td>
<td>Liverpool-Manchester Hydrogen Cluster</td>
<td>Natural gas to H2 pre-combustion</td>
<td>Hydrogen production</td>
<td>Natural gas-to-hydrogen conversion with CCS, CO2 transportation and storage in the North Sea</td>
<td>1.5Mtpa (10% H2) - 9.5Mtpa (100% H2)</td>
<td>2020s</td>
<td>Feasibility study</td>
<td>CADENT</td>
</tr>
<tr>
<td>29</td>
<td>UK Southern North Sea</td>
<td>Net Zero Teesside</td>
<td>Power &amp; capture (post-combustion)</td>
<td>Natural gas power</td>
<td>CCS-equipped natural gas power plant, CO2 transportation and storage in the North Sea</td>
<td>5 Mtpa</td>
<td>2026</td>
<td>Technical evaluation and business model options</td>
<td>BP, OGCI BP, Eni, Repsol, Shell, Equinor, Total</td>
</tr>
<tr>
<td>30</td>
<td>UK North Sea</td>
<td>Humber Zero Carbon Cluster</td>
<td>Industrial capture</td>
<td>Hydrogen production, bioenergy</td>
<td>CCS-equipped industrial cluster, CCS equipped hydrogen production, bioenergy with CCS (BECCS), CO2 transportation and storage in the North Sea</td>
<td>N/A</td>
<td>2020s</td>
<td>Technical evaluation and business model options</td>
<td>Drax Group, Equinor, National Grid Ventures Equinor</td>
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<td>31</td>
<td>UK East Irish Sea</td>
<td>Liverpool Bay Area CCS Project</td>
<td>Carbon capture sequestration</td>
<td>Chemical, refining, hydrogen production</td>
<td>CO2 capture from the existing industrial facilities and new hydrogen production plant in the North West of England</td>
<td>1-3 Mtpa phased program</td>
<td>2025</td>
<td>Concept selection phase</td>
<td>Eni Eni</td>
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Source: Global CCS Institute and IOGP data
# Carbon Capture, Use And Storage (CCUS)

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<tr>
<th>NO</th>
<th>LOCATION</th>
<th>PROJECT NAME</th>
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<th>STARTING DATE (OPERATION)</th>
<th>STATUS OF THE PROJECT</th>
<th>PARTICIPANTS</th>
<th>IOGP MEMBERS INVOLVED</th>
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<tbody>
<tr>
<td>1</td>
<td>Canada</td>
<td>Quest</td>
<td>Industrial capture, EOR</td>
<td>Hydrogen production for oil refining</td>
<td>Retrofitted CO₂ capture facility to steam methane reformers, transportation via pipeline to a dedicated geological storage</td>
<td>1 Mtpa</td>
<td>2015</td>
<td>Operational</td>
<td>Shell</td>
<td>Shell</td>
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<td>2</td>
<td>Canada</td>
<td>Boundary Dam CCS</td>
<td>Power and capture (post-combustion), EOR</td>
<td>Power generation</td>
<td>It combines post-combustion CCS with coal-fired power generation, some captured CO₂ goes for EOR use in the Weyburn oil unit, a portion of the CO₂ is stored permanently under the ground at the Aquistore project</td>
<td>1 Mtpa</td>
<td>2014</td>
<td>Operational</td>
<td>SaskPower</td>
<td></td>
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<tr>
<td>3</td>
<td>Canada</td>
<td>Alberta Carbon Trunk Line (ACTL) with North West Redwater Partnership’s Sturgeon Refinery CO₂ Stream</td>
<td>Industrial capture, EOR</td>
<td>Oil refining</td>
<td>Carbon dioxide captured from Agrium’s Redwater fertiliser plant and the North West Redwater Partnership’s Sturgeon refinery CO₂ recovered from the fertiliser plant’s emission streams put through inlet cooling, separation, compression, dehydration and refrigeration to produce liquified CO₂</td>
<td>1.2-1.4 Mtpa</td>
<td>2020</td>
<td>Operational</td>
<td>Enhance Energy Inc. (and - North West Redwater Partnership)</td>
<td></td>
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<tr>
<td>4</td>
<td>Canada</td>
<td>Lehigh’s Edmonton plant</td>
<td>Industrial capture</td>
<td>Cement industry</td>
<td>Capture the majority of the carbon dioxide (CO₂) from the flue gas of Lehigh’s Edmonton, Alberta cement plant</td>
<td>Estimated 600,000 tonnes annually</td>
<td>Feasibility study</td>
<td>Lehigh Cement and the International CCS Knowledge Centre</td>
<td></td>
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<td>5</td>
<td>Canada</td>
<td>Alberta Carbon Trunk Line (ACTL) with Agrium CO₂ Stream</td>
<td>Industrial capture, EOR</td>
<td>Fertilizer production</td>
<td>At the NWR refinery, CO₂ will be captured within the gasification hydrogen supply unit, which will use unconverted petroleum bottoms (asphaltene) as feedstock to create synthesis gas (syngas)</td>
<td>0.3-0.6 Mtpa</td>
<td>2020</td>
<td>Operational</td>
<td>Enhance Energy Inc.</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>USA</td>
<td>Illinois Industrial Carbon Capture and Storage (ICCS)</td>
<td>Industrial capture</td>
<td>Ethanol production</td>
<td>CO₂ 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</td>
<td>1 Mtpa</td>
<td>2017</td>
<td>Operational</td>
<td>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</td>
<td></td>
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<tr>
<td>7</td>
<td>USA</td>
<td>Petra Nova</td>
<td>Power and capture (post-combustion), EOR</td>
<td>Power generation</td>
<td>Texas power plant retrofitted with post-combustion CO₂ capture facility, transportation near Houston for EOR</td>
<td>1.4 Mtpa</td>
<td>2017</td>
<td>Operational</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 CO₂ Sequestration
17. Lake Charles Methanol

<table>
<thead>
<tr>
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<th>LOCATION</th>
<th>PROJECT NAME</th>
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<th>INDUSTRY</th>
<th>DESCRIPTION</th>
<th>CO₂ CAPTURED/YEAR</th>
<th>STARTING DATE (OPERATION)</th>
<th>STATUS OF THE PROJECT</th>
<th>PARTICIPANTS</th>
<th>IOGP MEMBERS INVOLVED</th>
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<tbody>
<tr>
<td>8</td>
<td>USA Kansas</td>
<td>Coffeyville Gasification Plant</td>
<td>Industrial capture, fertilizer production, EOR</td>
<td>Fertilizer production</td>
<td>Fertilizer plant in Coffeyville retrofitted with CO₂ compression and dehydration facilities, oil delivery to the North Burbank oil unit in Osage county, Oklahoma for EOR</td>
<td>1 Mtpa</td>
<td>2013</td>
<td>Operational</td>
<td>Coffeyville Resources Nitrogen Fertilizers, LLC, Chapparal Energy and Blue Source</td>
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<tr>
<td>9</td>
<td>USA Texas</td>
<td>Air Products Steam Methane Reformer</td>
<td>Industrial capture, EOR</td>
<td>Hydrogen production for oil refinery</td>
<td>Air products retrofitted of steam methane reformer within a refinery at Port Arthur, Texas, transportation to oil field in Texas for EOR</td>
<td>1 Mtpa</td>
<td>2013</td>
<td>Operational</td>
<td>Air Products, Covestro</td>
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<tr>
<td>10</td>
<td>USA Wyoming</td>
<td>Lost Cabin Gas Plant</td>
<td>Industrial capture, EOR</td>
<td>Natural gas processing</td>
<td>Gas plant in Wyoming supplies CO₂ to compression facility, transport and delivery via pipeline to the Bell Creek oil field in Montana for EOR</td>
<td>Approx. 1 Mtpa</td>
<td>2013</td>
<td>Operational</td>
<td>ConocoPhillips</td>
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<tr>
<td>11</td>
<td>USA Texas</td>
<td>Century Plant</td>
<td>Industrial capture, EOR</td>
<td>Natural gas processing</td>
<td>Natural gas treatment facility in Texas, transportation via pipeline for EOR</td>
<td>8.4 Mtpa</td>
<td>2010</td>
<td>Operational</td>
<td>Occidental Petroleum</td>
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<tr>
<td>12</td>
<td>USA North Dakota</td>
<td>Great Plains Synfuels Plant and Weyburn-Midale</td>
<td>Industrial capture (pre-combustion), EOR</td>
<td>Synthetic natural gas</td>
<td>The plant in North Dakota produces CO₂ as part of a coal gasification process, transportation to the Wyburn and Midale oil units for EOR</td>
<td>3 Mtpa</td>
<td>2000</td>
<td>Operational</td>
<td>Dakota Gasification Company</td>
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<td>13</td>
<td>USA Wyoming</td>
<td>Shute Creek Gas Processing Plant</td>
<td>Industrial capture, EOR</td>
<td>Natural gas processing</td>
<td>Gas treating facility in Wyoming, some CO₂ injected for sequestration/disposal, some for EOR</td>
<td>7 Mtpa</td>
<td>1986</td>
<td>Operational</td>
<td>ExxonMobil</td>
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<td>14</td>
<td>USA Oklahoma</td>
<td>Enid Fertilizer</td>
<td>Industrial capture, fertilizer production, EOR</td>
<td>Fertilizer production</td>
<td>CO₂ captured from the manufacture of fertilizer, transportation for use in EOR at the Golden Trend oilfield and the Sko-Val-Turn oilfield, south of Oklahoma City</td>
<td>0.7 Mtpa</td>
<td>1982</td>
<td>Operational</td>
<td>Koch Nitrogen Company</td>
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<td>15</td>
<td>USA Texas</td>
<td>Terrell Natural Gas Processing Plant (formerly Del Verde)</td>
<td>Industrial capture, EOR</td>
<td>Natural gas processing</td>
<td>CO₂ capture at natural gas processing plant, CO₂ transportation via Valverde pipeline to McCamey, Texas, and the Canyon Reef Carriers CRC pipeline and the Pecos pipeline, CO₂ for EOR</td>
<td>Approx 0.5 Mtpa</td>
<td>1972</td>
<td>Operational</td>
<td>Blue Source and others</td>
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<td>16</td>
<td>USA Indiana</td>
<td>Wabash CO₂ Sequestration</td>
<td>Industrial capture, EOR</td>
<td>Fertilizer production</td>
<td>Gasification plant in Indiana to be converted into an anhydrous ammonia production plant and CCS plant, dedicated geological storage in the Wabash carbonSAFE CO₂ storage hub</td>
<td>1.5-1.75 Mtpa</td>
<td>2022</td>
<td>Advance development</td>
<td>WABASH Valley Resources (WVR)</td>
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<td>17</td>
<td>USA Louisiana</td>
<td>Lake Charles Methanol</td>
<td>Industrial capture, EOR</td>
<td>Chemical production</td>
<td>Gasification facility in Louisiana capturing from synthetic gas syngas to make methanol and other products, captured CO₂ to be used for EOR in Texas</td>
<td>Approx 4 Mtpa</td>
<td>2024</td>
<td>Advance development</td>
<td>Leucadia Energy</td>
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<td>No</td>
<td>Location</td>
<td>Project Name</td>
<td>Project Type</td>
<td>Industry</td>
<td>Description</td>
<td>CO₂ Captured/Year</td>
<td>Starting Date (Operation)</td>
<td>Status of the Project</td>
<td>Participants</td>
<td>IOGP Members Involved</td>
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<td>18</td>
<td>USA</td>
<td>Dry Fork Integrated Commercial CCS</td>
<td>Power and capture (post-combustion), EOR</td>
<td>Power generation</td>
<td>Dry Fork coal-fired power station in Wyoming, targeting adjacent geological storage formations currently under study. EOR under consideration</td>
<td>3 Mtpa</td>
<td>2025</td>
<td>Advance development</td>
<td>The Basin Electric Power Cooperative</td>
<td></td>
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<td>19</td>
<td>USA</td>
<td>CarbonSAFE Illinois-Macon County</td>
<td>Power and industrial capture (post-combustion), EOR</td>
<td>Power generation and ethanol production</td>
<td>CCS integration of a compression and dehydration facilities to an ethanol plant, transportation and injection in a dedicated geological storage</td>
<td>2-5 Mtpa</td>
<td>2025</td>
<td>Advance development</td>
<td>Carbon Storage Assurance Facility Enterprise (CarbonSAFE) of the U.S. Department of Energy National Energy Technology Laboratory (DOENETL)</td>
<td></td>
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<td>20</td>
<td>USA</td>
<td>Project Tundra</td>
<td>Power and capture (post-combustion), EOR</td>
<td>Power generation</td>
<td>Retrofit CO₂ capture plant to the Milton R. Young coal fire power station in North Dakota with a dedicated storage site. EOR under study</td>
<td>3.1-3.6 Mtpa</td>
<td>2025-2026</td>
<td>Advance development</td>
<td>Minnkota Power Cooperative</td>
<td></td>
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<tr>
<td>21</td>
<td>USA</td>
<td>Integrated Mid-Continent Stacked Carbon Storage Hub*</td>
<td>Ethanol production, power generation and/or refinery, EOR</td>
<td>Ethanol production, power generation and/or refinery</td>
<td>CO₂ collection from ethanol plants, power plants and refineries with integrated storage in Kansas and Nebraska</td>
<td>Approx 2 Mtpa</td>
<td>2025-2035</td>
<td>Advance development</td>
<td>Schlumberger</td>
<td></td>
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<td>22</td>
<td>USA</td>
<td>Oxy and White Energy Ethanol EOR Facility</td>
<td>Industrial capture, EOR</td>
<td>Ethanol production</td>
<td>CO₂ capture from two ethanol facilities in Hereford and Plainview, Texas. The captured CO₂ will be stored via EOR at Occidental’s oil fields in Permian basin</td>
<td>0.6-0.7 Mtpa</td>
<td>2021</td>
<td>Early development</td>
<td>Occidental Petroleum Corporation and White Energy</td>
<td></td>
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<tr>
<td>23</td>
<td>USA</td>
<td>Oxy and Carbon Engineering Direct Air Capture and EOR Facility</td>
<td>Direct air capture, EOR</td>
<td>N/A</td>
<td>CO₂ capture from an Occidental oil field in the Permian Basin, and used for EOR</td>
<td>1 Mtpa</td>
<td>2025</td>
<td>Early development</td>
<td>Oxy Low Carbon Ventures and Carbon Engineering Ltd</td>
<td></td>
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<tr>
<td>24</td>
<td>USA</td>
<td>Project ECO²S: Early CO₂ Storage Complex in Kemper County</td>
<td>Under evaluation</td>
<td>N/A</td>
<td>Regional CO₂ storage hub near the Keper County Energy Facility in Mississippi from power and industrial sources</td>
<td>3 Mtpa</td>
<td>2026</td>
<td>Early development</td>
<td>In identification (capture) - Project ECO²S, a DOE-supported CarbonSAFE program</td>
<td></td>
</tr>
</tbody>
</table>

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 ECO²S: Early CO₂ Storage Complex in Kemper County

Source: Global CCS Institute and IOGP data
## ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbr.</th>
<th>Description</th>
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<tbody>
<tr>
<td>BECCS</td>
<td>Biomass energy with carbon capture and storage</td>
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<tr>
<td>CCUS</td>
<td>Carbon capture, use and storage</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
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<tr>
<td>CRL</td>
<td>Commercial readiness level</td>
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<tr>
<td>DACCS</td>
<td>Direct air carbon capture and storage</td>
</tr>
<tr>
<td>ECBM</td>
<td>Enhanced coal bed methane</td>
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<tr>
<td>EGR</td>
<td>Exhaust gas recirculation</td>
</tr>
<tr>
<td>EOR</td>
<td>Enhanced oil recovery</td>
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<tr>
<td>GHG</td>
<td>Greenhouse gas</td>
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<tr>
<td>Gt</td>
<td>Gigatonne</td>
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<tr>
<td>NET</td>
<td>Negative emissions technologies</td>
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<tr>
<td>R&amp;D</td>
<td>Research and development</td>
</tr>
<tr>
<td>SRL</td>
<td>Social readiness level</td>
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<tr>
<td>TRL</td>
<td>Technology readiness level</td>
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<tr>
<td>UNECE</td>
<td>United Nations Economic Commission for Europe</td>
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<tr>
<td>UNFC</td>
<td>United Nations Framework Classification</td>
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</table>
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GoldmanSachs, Equity Research, Carbonomics Q&A: Five key questions from investors, published on 3 February 2020

Greg Kelsall, “CCUS – status, barriers and potential”, April 2020, IEA Clean Coal Centre


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