Carbon Capture Utilization and Storage

Towards Net-Zero

2021

KEARNEY | Energy Transition Institute

Compiled by the Kearney Energy Transition Institute

Acknowledgements
The Kearney Energy Transition Institute wishes to acknowledge the following people for their review of this FactBook: Kamel Bennaceur, CEO at Nomadia Energy Consulting, Former Director of Sustainable Energy Policies and Technologies at IEA, former Minister of Industry, Energy and Mines of Tunisia; as well as Dr. Adnan Shihab-Eldin, Claude Mandil, Antoine Rostand, and Richard Forrest, members of the board for the Kearney Energy Transition Institute.

Their review does not imply that they endorse this FactBook or agree with any specific statements herein.

About the FactBook: Carbon Capture Utilization and Storage
This FactBook seeks to provide an overview of the latest changes in the carbon capture, utilization and storage landscape. It summarizes the main research and development priorities in carbon capture, utilisation and storage, analyses the policies, technologies and economics and presents the status and future of large-scale integrated projects.

About the Kearney Energy Transition Institute
The Kearney Energy Transition Institute is a non-profit organization that provides leading insights on global trends in energy transition, technologies, and strategic implications for private-sector businesses and public-sector institutions. The Institute is dedicated to combining objective technological insights with economical perspectives to define the consequences and opportunities for decision-makers in a rapidly changing energy landscape. The independence of the Institute fosters unbiased primary insights and the ability to co-create new ideas with interested sponsors and relevant stakeholders.

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Every energy transition scenario requires CCUS to achieve climate-change targets

The need for CCUS

(pages 11–22)

Definition of Carbon Capture, Utilisation and Storage, or CCUS

CCUS, is an emissions reduction technology that can be applied across the energy system. CCUS technologies involve the capture of carbon dioxide (CO_2) from fuel combustion or industrial processes, the transport of this CO_2 via ship or pipeline, and either its use as a resource to create valuable products or services or its permanent storage deep underground in geological formations. CCUS technologies also provide the foundation for carbon removal or "negative emissions" when the CO_2 comes from bio-based processes or directly from the atmosphere. (IEA 2021)

CO_2 atmospheric concentration has reached unprecedented levels

Between 1970 and 2000, total CO_2 emissions rose by +0.3 $GtCO_2$ per year and accelerated from 2000 to +0.7 $GtCO_2$ per year, increasing atmospheric CO_2 concentrations to a record high of **418 ppm in May 2021**. This rise is mostly the result of fossil-fuel consumption in heating/cooling, power generation, transport and industry. At current emission levels, the remaining carbon budget corresponding to the +1.5°C target could be exhausted by 2030.

CCUS development is not on track to meet IPCC and IEA climate-change scenario targets

CCUS is needed to achieve the goal of net-zero emissions, according to the IPCC and the IEA. The **global capture capacity was about 50 $MtCO_2$ per year in 2020**. The ongoing pipeline of projects forecasts about 220 $MtCO_2$ per year of global capture capacity in 2030, a huge gap compared with the 800 $MtCO_2$ per year target of the IEA's sustainable development scenario (SDS).

CCUS could help decarbonize sectors that are responsible for more than 45 percent of the world's CO_2 emissions

CCUS is a key technology to decarbonize hard-to-abate sectors with few other decarbonization options, such as the cement, iron and steel, and chemicals industries. CCUS is expected to be developed for multiple industries and mainly combined with storage solutions. Some technology solutions are being tested for marine vessels but have limited use in transportation overall.

Fuel transformation should be the fastest CCUS adopter with more than 80% of CO_2 emissions projected to be captured by 2030. The **cement** industry has only recently started using CCUS technology and but is projected to scale up over the next 10 years to capture almost 50% of all CO_2 emissions created during the production process. Therefore, CCUS appears to be among the most impactful solutions for reducing emissions from cement production. It is also emerging as the most cost-effective approach in many regions to curb emissions in **iron and steel** and chemicals manufacturing.

By 2050, CCUS could represent more than 25% of the emission reduction for iron and steel and more than 60% for cement, according to the IEA. The industry will remain the first for captured carbon emissions, bioenergy with carbon capture and storage (BECCS) is expected to grow as a negative emission solution and will represent more than 20% of the captured CO_2 by 2070. Overall, the captured CO_2 would most likely be stored rather than reused.

The development of CCUS is generally perceived to be challenging because of four main obstacles

Unfavourable economics for industries, a challenging scale-up, the regulation gap, and the lack of public support are the major obstacles for the development of CCUS.

The CCUS value chain includes three main steps: carbon capture, carbon transport, and carbon storage or utilization

Value chain and key technologies

(pages 23–43)

CCUS refers to a set of CO_2 capture, transport, utilization, and storage technologies combined to abate CO_2 emissions. CO_2 is generally captured from large and stationary emissions sources (power or industrial plants), transported in a gaseous or liquefied state by pipelines or ships and stored in geological formations or reused to promote carbon circularity.

The CO_2 capture mainly consists of separating CO_2 molecules from flue gases and relies on three technologies:

- **Absorption and adsorption** of the CO_2 by a liquid carrier (solvent) or solid carrier (sorbent) and regeneration of the liquid or solid by increasing the temperature or reducing the pressure
- **Membranes** (metallic, polymeric, or ceramic material) for gas separation, not suitable for post-combustion, most suitable for high pressure and high CO_2 concentration
- **Cryogenic** method using low temperature to liquefy and separate CO_2 from other gases

Adsorption and absorption capture is the dominant technology, but membranes and cryogenic capture have great potential.

Four capture technologies occur at different steps of the combustion value chain:

- **Post-combustion.** CO_2 is separated from flue gas after combustion with air and can be retrofitted to power and heavy industrial plants with relatively high costs and energy penalty. This technology is the most broadly used outside oil and gas.
- **Oxy-combustion.** Fuel is combusted in pure oxygen instead of air, producing a concentrated CO_2 stream in the flue gas, which is almost ready to be transported. Oxy-combustion could be retrofitted to existing plants, though with significant redesign.
- **Pre-combustion.** A hydrocarbon fuel source—coal, gas, or biomass – is gasified into shifted syngas (H_2/CO_2 mix), from which the CO_2 is separated. The H_2 is then used to fuel the power plant or to produce chemicals or synthetic fuels. In power generation, the pre-combustion process is more energy efficient than post-combustion but requires new and expensive plant design, such as an integrated gasification combined cycle.
- **Natural gas sweetening.** In this mature process, CO_2 is separated from raw natural gas at a gas processing plant.

Three options exist to store or reuse captured carbon:

- **Passive storage** includes underground geological storage in deep saline aquifers or depleted petroleum reservoirs. Underground CO_2 injection is achieved by pumping compressed CO_2 in fluid phase (supercritical) down to the formation through a well, where it remains trapped. Monitoring, verification, and accounting (MVA) is needed before the start (to set the baseline), during the injection, and after closure to ensure the CO_2 remains in place.
- **Beneficially reused** involves injecting CO_2 into a petroleum reservoir for enhanced oil recovery (CO_2-EOR) or into deep un-mineable coal seams to recover methane (CO_2-ECBM). Many operational CCUS projects in conjunction with CO_2-EOR capture CO_2 from natural gas processing rather than power production.
- **Industry use** is used to a lesser extent for greenhouses carbon concentration, mineral carbonation, chemicals, liquid fuel, or food processing.

CCUS development started in the 1970s and has been accelerating in the 2000s

Global overview of CCUS development

(pages 44–52)

CCUS appeared almost 50 years ago, but the number of projects has accelerated since the mid-2000s

CCUS projects have been slowly developing since 1972. The United States welcomed the first five projects, all dedicated to enhanced oil recovery (EOR), which consists of injecting CO_2 to enhance the oil recovery of natural reservoirs. Norway has been the first European country to develop CCUS but for a storage purpose. Indeed, the Sleipner project was the first one to capture CO_2 and store it into a dedicated geological storage site in the North Sea. In 2000, seven operational projects were located in the United States and one in Norway.
The development of CCUS projects accelerated post-2000, with about **60 operational projects in 2020**. The development of CCUS projects continued until 2020, but this period has also been characterized by a growing number of projects terminated or cancelled. **About 60% of CCUS projects have been terminated or cancelled** among the more than **150 projects and pilots developed across the globe since 1972**.

In 2020, the **global CCUS capacity reached about 50 Mtpa**. The current pipeline of projects should triple the global capacity in the coming years, achieving about 170 Mtpa in 2030.

So far, CCUS development mostly occurred in OECD countries

Today, about **70% of operational CCUS facilities are in OECD countries**. North America owns about 50% of the worldwide facilities. China is now the second country with about 14% of the total facilities. Even if North America is currently the main place for CCUS, Europe and Asia are planning to accelerate the development of CCUS (about 40 projects). In Europe, projects are mostly being developed in the United Kingdom and in Norway. Australia has one of the largest operating storage facility (Gorgon project). Other large projects are planned to occur in Europe, mostly because of the greater number of new CCUS hubs that aim to gather multiple local emissions sources of CO_2 emissions.

The Middle East is expected to catch up, leveraging a huge geological storage potential combined with EOR possibilities. But so far, CCUS projects in GCC countries only represent 10% of the projects in non-OECD countries, with three CCUS projects currently in operation, including two related to natural gas processing and one related to iron and steel production, capturing a total of 2.1 Mtpa of CO_2. GCC countries have an ambitious plan for CCUS hubs to promote carbon circularity in the region. Other emerging countries such as Brazil, India, South Korea, Taiwan, and South Africa have also launched CCUS projects in the past few years.

The maturity of CCUS applications varies by industries

Outlook of carbon capture development per sector

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Executive summary

Oil and gas along with power have been leading the CCUS development

The oil and gas sector and the power sector have been leading CCUS development and are expected to remain as such at least until 2030. These two sectors represent the vast majority of CCUS projects in 2020.

The CCUS industry has entered a new development phase (“industrialization”), which is characterized by the development of clusters grouping multiple sources of CO_2 emissions from different applications (such as blue hydrogen production as well as cement and steel applications) and thanks to the increasing regulatory pressure on CO_2 emissions (such as carbon pricing or net-zero targets from multiple countries and companies).

In the next decade, the number of CCUS projects is expected to increase by more than 70%, with about **120 projects in 2030**. The average size of the CCUS projects is also expected to grow, moving from below 1 Mtpa of CO_2 p to 5 Mtpa of CO_2 in the next decade, essentially triggered by large blue hydrogen production projects or hubs.

Blue hydrogen, steel, and cement industries are the newcomers investing in CCUS

For high-emitting sectors such as **iron and steel** and **cement production**, CCUS is listed as one of the best possibilities to drastically reduce CO_2 emissions. CCUS has been introduced recently for small commercial or pilot projects in the iron, steel, and cement industries. The number of heavy industry large-scale facilities is going to increase from three in 2020 to seven in 2030. Large-scale projects such as Lafarge-Holcim Cement added to eight industrial hubs in development with either a cement or iron and steel plant. Despite this increase, heavy industries remain the least-efficient sector in capturing GHG emissions with an average of less than 1 $MtCO_2$ captured per year per project.

In the upcoming years, industries such as **blue hydrogen production** and **chemicals** production are going to see more and more facilities. Hydrogen is even considered as the most ambitious field of application for CCUS with an average of almost 5 $MtCO_2$ captured per year per project, more than any other industry. The trend is supported by the development of high-capacity hydrogen energy projects and clusters, such as in United Kingdom with ambitious national plans to switch fuel for domestic and industrial applications from natural gas to hydrogen combined with CCUS.

CCUS in power is interesting to retrofit coal or gas-fired and biomass power plants to abate their carbon emissions and allow their continued operation. It has reached commercial scale with the opening in 2014 of the first large-scale CCUS power plant in Canada: the Sask Power Boundary Dam.

Specific technologies are being developed per sector

Retrofits on power plants are mostly **post-combustion** chemical absorption capture, but advanced technologies such as **pre-combustion** capture or **carbonate fuel cells** are under development. CCUS is applicable to **natural gas processing**, as in the Sleipner West project and to decarbonize refining activities, such as in Port Jérôme, where Air Liquid produces blue hydrogen for oil refining with **cryogenic carbon capture**.

Currently, CCUS is mostly used for EOR[1], with geological storage expected to become the main CO_2 utilization

Global overview of Utilization and Storage

(pages 99 – 115)

Once captured, CO_2 can be used for enhanced oil recovery (EOR), stored in geological settings, or used to produce chemicals (including advanced carbon materials), plants, or minerals

Today, captured CO_2 is mostly used for **EOR purposes representing more than 65% of the global captured capacity**, with very few other utilizations. CO_2–EOR projects now represent about 45% of all EOR projects (as opposed to thermal or chemical EOR). Nevertheless, the CO_2–EOR growth dynamic is strongly related to oil prices, which makes its perspectives hardly predictable. The COVID-19 crisis and the sharp drop in oil price in March and April 2020 has generated further uncertainties in the oil and gas market, jeopardizing the development of CCUS projects related to the oil and gas sector.

Once captured, CO_2 can be used for many other applications, including injecting in coal seam (CO_2-ECBM), chemicals (such as biofuel, urea, alcohol, and baking soda), mineralization (such as calcium looping and concrete), or biological (such as plant cultivation). However, these applications are very minor compared with EOR. In 2020, such utilization projects represented ~4% global capacity. But for most of the applications, CO_2 is generally not captured and therefore is ultimately released to the atmosphere.

Future CCUS growth relies on the development of hubs or clusters. Such projects composed of groups of emitters from various industries aim to share infrastructure and capture CO_2 from densely industrialized areas. CCUS is also part of the circular carbon economy plan developed in Golf Cooperation Council countries.

Identified global geological storage capacity largely overcomes the need for storage

Geological storage capacities of CO_2 remain unexplored in many areas of the world. Asia and North America own the biggest identified geological storage capacities. The estimated storage capacity of North America corresponds to hundreds of years of their own emissions (about 350 to 3,200 years). But in many areas of the world, the storage capacity of the sedimentary basins remained unexplored or not fully reported.

Executive summary

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(1) EOR - Enhanced Oil Recovery: processes related to improving the recovery of hydrocarbon trapped in geological reservoirs, commonly consists in injecting steam, solvent or CO_2

To achieve net-zero objectives, governments need to develop CCUS policies and regulations to incentivize companies to invest and to raise public awareness

Economics, Policies and Regulations

(pages 116 - 142)

Relatively high capture costs and a lack of efficient policies prevent the industrialisation of CCUS development; business models are still to be invented

The key element of comparison is the cost of one ton of CO_2 abated, which enables the comparison of CCUS technologies with other decarbonisation solutions, including renewables. One of the main drawbacks related to CCUS is the cost that can be higher than 100$/t. Over the past eight years, 14 potentially large-scale projects have been cancelled, including 11 for economics reasons. One of the main inconveniences related to CCUS is the high costs, which can easily go higher than $100/t. The capture part commonly represents about 75% of the total cost but can decrease with high-concentrated CO_2, such as in natural gas processing, hydrogen, or fertilizers production. Transport and storage usually represent 25% of the cost of the overall process. The most interesting storage option is direct use of CO_2 for enhanced oil recovery (EOR) or storage in onshore depleted oil and gas fields. Although CCUS has a strong CO_2 abatement potential, it increases the levelized cost of production for every sector. Thus, solutions to limit the investment risk need to be found to keep CCUS growing.

Many countries have recently committed to net-zero objectives by 2050–2060

At least 27 countries, representing more than 60% of the world's economy, have already announced their goal to become carbon neutral by 2050. Some have even put their objectives into law. These announcements represent around a third of the world CO_2 emissions. Moreover, by 2060, this number rises to 65% of CO_2 emissions. To achieve this objective, some countries will increase the part of renewables in their energy mix; others are setting carbon taxes or tax credits such as the US 45Q tax credit for carbon sequestration set in 2018. Major companies set CO_2 emissions reductions goals among their scope of emissions (scope 1, 2, or 3). As all companies are different, the decomposition of the CO_2 emissions according scopes are different from one company to another, and objectives are also different.

Carbon regulations and taxes are essential to the development of CCUS and the reduction of CO_2 emissions

Countries are considering policies or regulations to decrease CO_2 emissions. Nordic countries have been the first ones to introduce a carbon tax; they did it almost 30 years ago. Today, Sweden is the world's top taxer with a price of $137/t. Even if carbon taxes are a way to decrease emissions, some countries or regions also have emissions trade scheme (ETS) that give allowances to companies to trade carbon emissions at trading-based prices, such as stocks. European Union have the biggest ETS with around 1,7 $GtCO_2$ covered (45% of EU emissions) and a price above $40/t. However, in some regions, ETS doesn't cover as much as in the EU, or the prices are three or four times lower than in EU ETS.

The broader population still misunderstands and fears CCUS

Even though CCUS has existed since the 1970s, few people know it. The most common fear is a failure inside the storage process. Compared with other clean technologies, the CCUS reputation is quite low, even lower than natural gas or nuclear energy, and is usually linked with fossil fuels but not perceived as a tool to decarbonize industries. Opponents also argue that CCUS is expensive. On the other side, supporters say CCUS is necessary to limit global warming to 1.5°C, and there are a lot of current and future opportunities to reduce CO_2 emissions.

The United States remains by far the main contributor to CCUS development, but Asia and Europe are investing

Finance, R&D, and key players

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CCUS public funding appeared 15 years ago but remains relatively limited

CCUS public R&D started to be significant in the early 2000's and surpassed the $1 billion threshold between 2009 and 2013 before stabilizing at $650 million today. Global funding related to public energy R&D decreased between 2009 and 2017 and has stagnated since around $20 billion per year. The United States has always been the top financial contributor, except in 2012 and 2013. The country reached more than $500 million in 2009, but since 2014, the US contribution has reduced to about $200 million. Behind the United States, Canada and Japan are fighting for the second spot; Canada was the top contributor in 2012 and 2013, while Japan's interest has grown back since 2017 after a slight decrease between 2013 and 2016. In 2019, European Commission / EU in addition to European countries represent more than $120 million, or 20% of the total contribution.

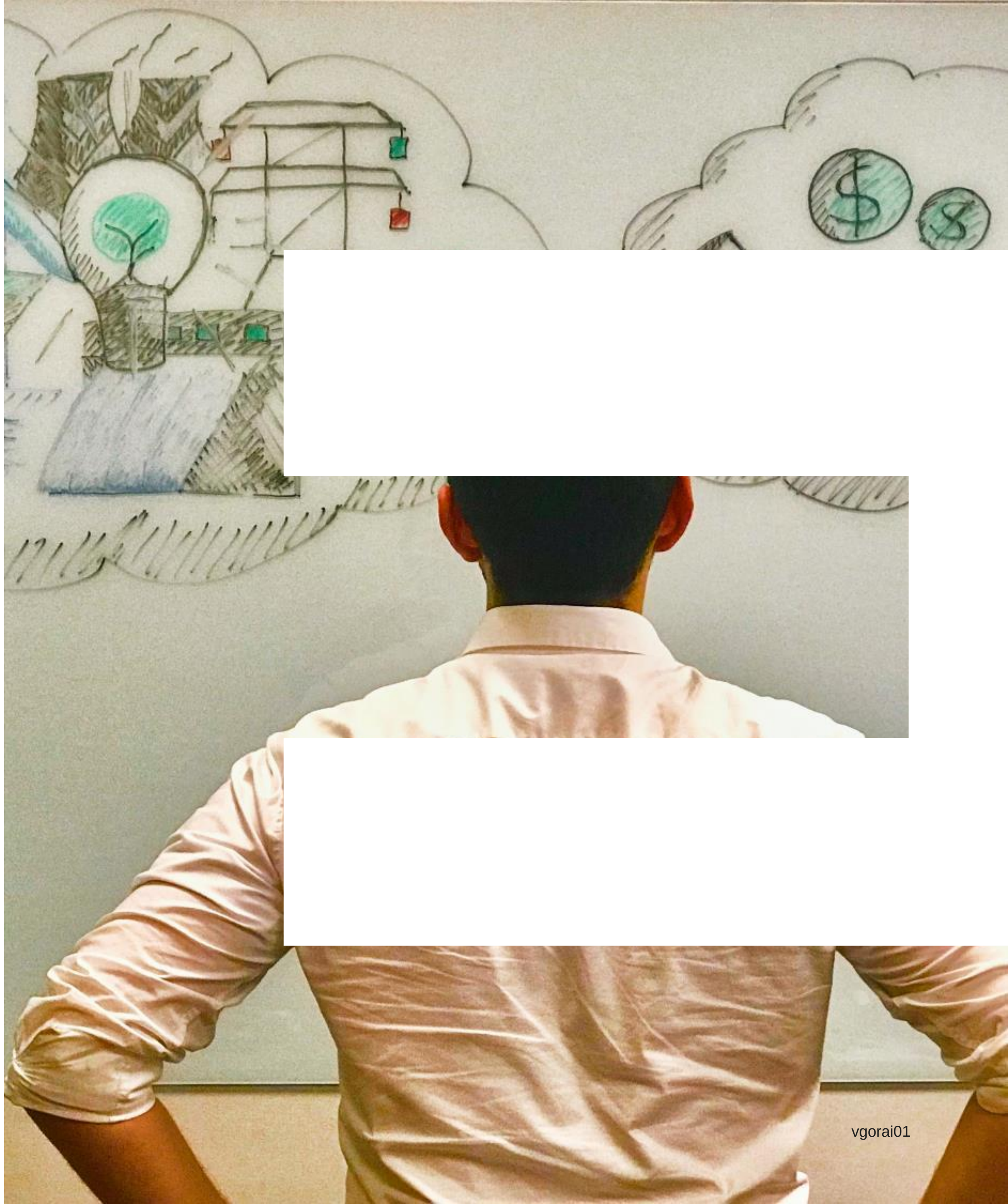
Although CCUS public R&D spending is quite low compared with other clean technologies, CCUS is ranked third behind solar and wind energy but above hydrogen, geothermal energy, or biofuels.

After a rise in CCUS patents since 1996, 2014 was the start of a decline

Energy patents are a direct conclusion of the variation of public R&D funding and private research. The number of patents for all kinds of low-carbon technologies rose between 1996 until 2011 and then decreased. Patents about CCUS had the same variation with an increase since 1996 until 2014 and reached about 700 patents. As for public R&D funding, the United States is the top patents provider and has always been since 2009. The country always maintains its patents production above 180 patents a year, with almost 260 in 2012 and 2013. Japan is fighting for the second rank, and South Korea overtook Japan in 2014 to become the second provider of CCUS patents in the world (92 patents in 2018). European countries arrived just after with a total of 70 patents.

The main aim of R&D is to improve capture technologies' cost and energy efficiency, find suitable reservoirs, and understand the behavior of CO_2 underground, for which field demonstration is essential.

1. The need for CCUS



Orders of magnitude

Carbon and Carbon dioxide equivalence

- 1 Gigatonne (Gt) = 1 billion tonnes
- 1 kg carbon (C) = 3.664 kg carbon dioxide (CO_2)

Energy-related CO_2 emissions per year

- One passenger car: 3-6 tCO_2
- Average CO2 emissions/capita: ~4.5 tCO_2
- New York City: 37 $MtCO_2$
- United Kingdom: 90 $MtCO_2$
- US: 5.1 $GtCO_2$
- World 31.5 $GtCO_2$

What does 1 tonne of CO_2 represent?

- CO_2 captured by 25 trees grown for 10 years
- One economy class air travel from Paris to New York
- Worldwide average CO_2 emissions *per capita* in 3.6 months
- 1.35 MWh of electricity produced in a supercritical pulverized black-coal power plant; approximately 5 seconds of emissions of a large unit (~1GW)

Financial indicators for CO2 emissions

- Environmental carbon taxes are generally below $\$20/tCO_2$
- Market prices for EOR reached $\$30/tCO_2$ when the oil price was averaging $100/bbl.
- Each tonne of CO_2 avoided by using CCUS in a coal power plant is likely to cost $\$50-\$150/tCO_2$
- If an offshore wind farm replaces a coal fired power-plant, the cost of 1 ton of CO_2 avoided is negative, as they have the same LCOE, but coal emits about 150 times more CO_2 per MWh.
- Developed economies generate $2,000-$6,000 of GDP per tonne of CO_2 emitted (carbon-emissions intensity)
- 1 tCO_2 in EOR allows the recovery of 2-3 additional barrels of oil

Size of CCUS projects

Largest global projects

1) Shute Creek CCUS-EOR facilities (ExxonMobil, USA - Wyoming)

- Operational since 1986, extended in 2010
- Captures and stores 7 $MtCO_2$/year from natural gas processing and refining

2) Century Plant CCUS-EOR facilities (Occidental Petroleum, USA - Texas)

- Operational since 2010
- Captures and stores 5 to 8 $MtCO_2$/year from natural gas processing

3) The Alberta Carbon Trunck Line (Canada)

- Operational since March 2020
- The highest CO_2 transport capacity infrastructure, with 14.6 $MtCO_2$/year (currently processing 1$MtCO_2$/year)

Standard coal power plant (mineral carbonation) without CCUS

- Nominal capacity: 500MW
- Average load factor: 0.85
- Produces 3,500 GWh of electricity per year
- Emits 3.4 $MtCO_2$/yr

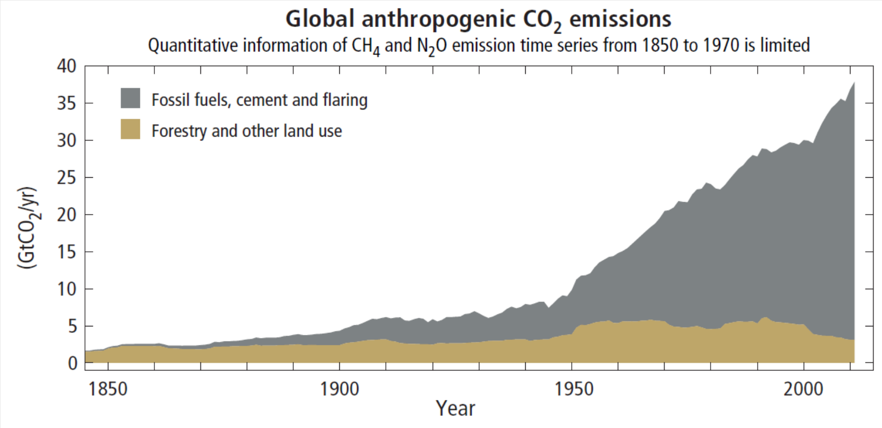
Coal power plant with post-combustion CCUS (20 MW, 400tCO_2/d)

- Produces 3,600 GWh per year (CCUS energy penalty: .8%)
- CO_2 emissions captured efficiency 85%
- Avoids 90,000 tCO_2/yr

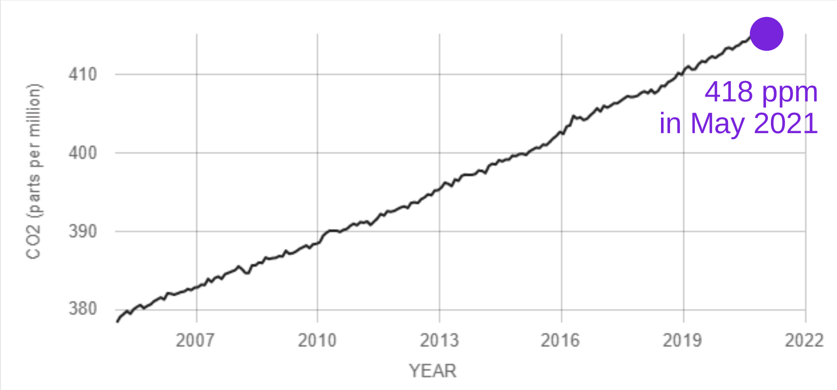
Fossil-fuel use is responsible for about 80% of anthropogenic CO_2 emissions, and atmospheric CO_2 concentration reached a record high in 2021

The Earth’s greenhouse effect is reinforcing, and oceans are acidifying worldwide. This phenomenon is called anthropogenic climate change and has a variety of negative consequences.

Global anthropogenic CO_2 emissions (1850–2011)



Atmospheric CO_2 concentration since 2005



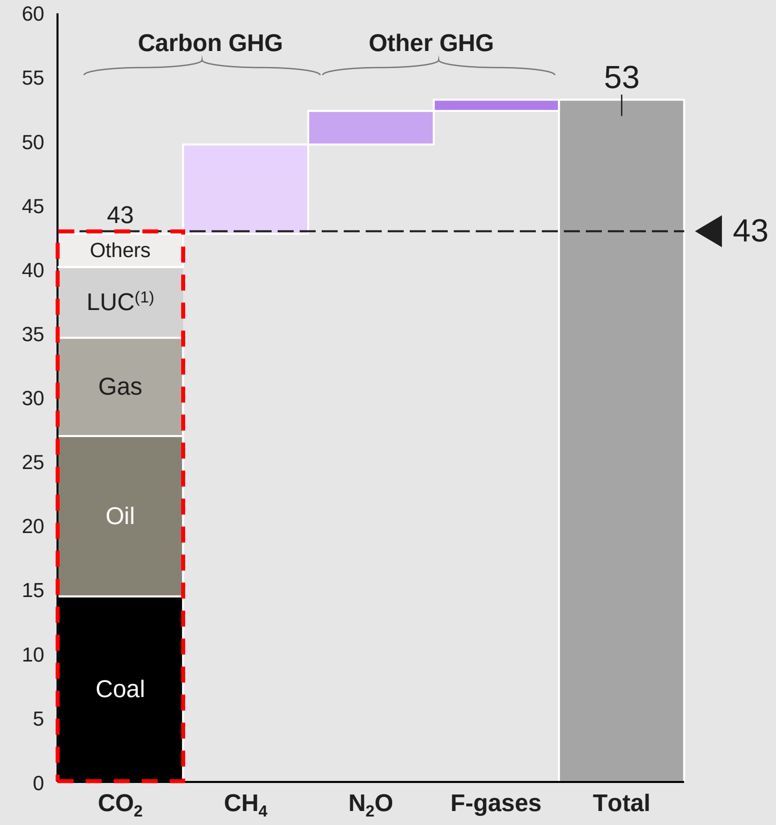
- Since 1970, global GHG emissions (including CH_4 and N_2O) have been increasing by **0.4 Gt of CO_2-eq per year** on average but have accelerated since 2000 to **1 Gt of CO_2-eq** on average per year.
- **Fossil-fuel consumption** has increased since the beginning of the Industrial Revolution. These carbon-intensive primary energy sources are the main component of anthropogenic CO_2 emissions.
- Annual average CO_2 emissions reached about **40Gt per year** compared with about 3Gt per year during the pre-industrial era.
- **About 40% of anthropogenic CO_2 emissions have remained in the atmosphere since 1750.** The rest was removed by land and ocean sinks. This has led to increasing atmospheric concentrations of CO_2, which has now breached 400 ppm.

Note: ppm is parts per million. Coal also includes solid fuels derived from biomass such as wood.
Sources: “AR5 Synthesis Report: Climate Change 2014,” Intergovernmental Panel on Climate Change; Kearney Energy Transition Institute analysis

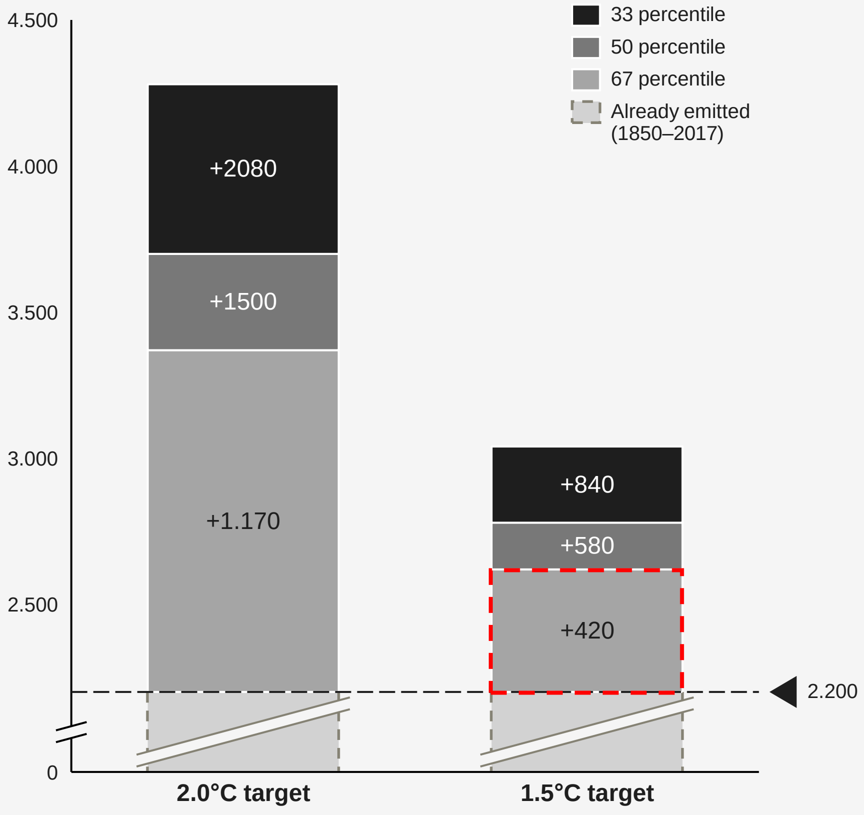
At current emission levels, the remaining carbon budget corresponding to the +1.5°C target could be exhausted in about 10 years

66% of global GHG emissions come from end-use combustion of coal, oil and gas (~35/53 GtCO2eq over)

GHG emissions
(2018, $GtCO_2eq$ per year)



Remaining carbon budget
(2018, $GtCO_2eq$)



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1 LUC : deforestation and other land use change; CO_2 emitted by LUC is very approximate due to high uncertainties related to its assessment

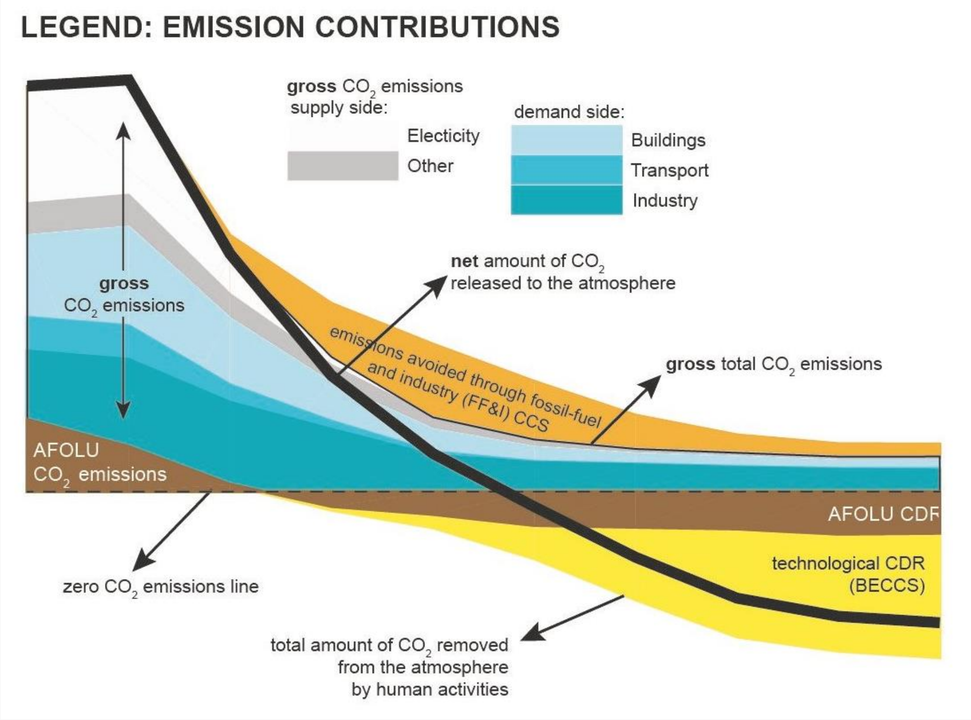
2 CH_4: the conversion of CH_4 GHG impact in terms of CO_2 equivalence depends on the time horizon used for the conversion. An equivalent quantity of methane would entail 84 and 28 more radiative forcing than CO_2 over 20- and 100-year horizons, respectively. The change over time is due to methane being short-lived into the atmosphere – it converts to CO_2 over decadal timescales

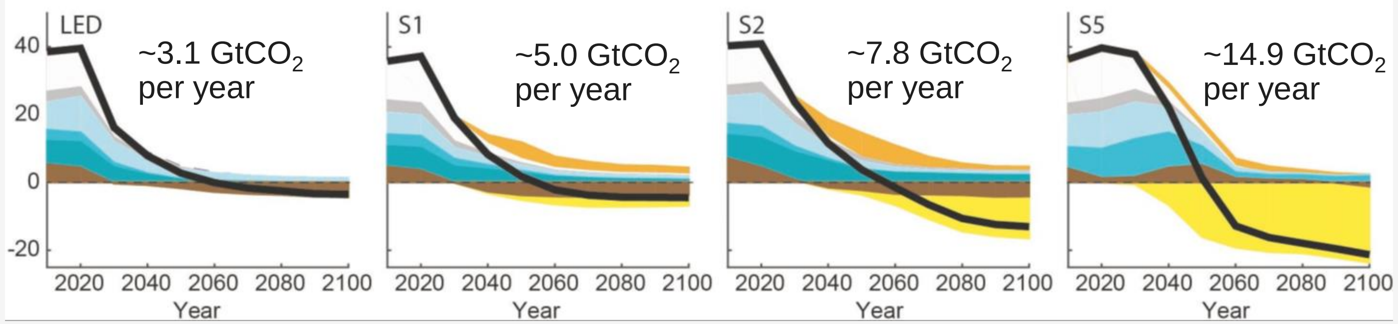
Sources: Global Carbon Budget 2018; IPCC (2018) "SR5–Chapter 2"; BP (2015) "Statistical review"; Kearney Energy Transition Institute analysis

CCUS technologies are required to achieve +1.5°C

Possible CO_2 emission pathways and required carbon dioxide removal - CDR(1) capacities for 1.5°C target

($GtCO_2$ per year)





- LED, S1, S2 and S3 (also referred to as P1, P2, P3, and P4) are four illustrative IPCC scenarios 1.5°C-consistent pathway archetypes. **CDR** technologies are integrated into all possible CO_2 emission pathways, except LED
- **S1** and **S2** require, among other measures, **a decrease of final energy demand** of 15% and 5% in 2030 relative to 2010, thus limiting the need of CDR technologies to an average of ~3.1 and ~5.0 $GtCO_2$ per year (from 2020 to 2100) respectively
- **S3** also relies on a **high share of renewables** in the electricity mix (48%) and **big reductions in coal** (-75% compared to 2010) in 2030. However, **oil** consumption is only **reduced 3%** and **gas even increases 33%**. With a **final energy demand increase** of 17%, an average of **~7.8 $GtCO_2$ per year** should be captured by CDR technologies from 2020 to 2100
- The **resource and energy intensive scenario S4** predicts an **overshoot** of the 1.5˚C target, followed by massive implementation of non-land CDR technologies (average **~14.9 $GtCO_2$ per year** from 2020 to 2100)

Depending on future energy efficiency and mix, CCS and negative emission technologies should represent between 3.1 and 14.9 $GtCO_2$ per year.

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(1) Carbon dioxide removal, also called "negative emissions technologies" (pls refer to the Negative Emissions Technologies FactBook) are *anthropogenic activities removing CO2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage but excludes natural CO2 uptake not directly caused by human activities* (IPCC). BECCUS: Bioenergy with Carbon Capture and Storage (CCUS)
Sources: IPCC (2018) "SR1.5 – Summary for Policymakers" and "Chapter 2" – figure 2.5

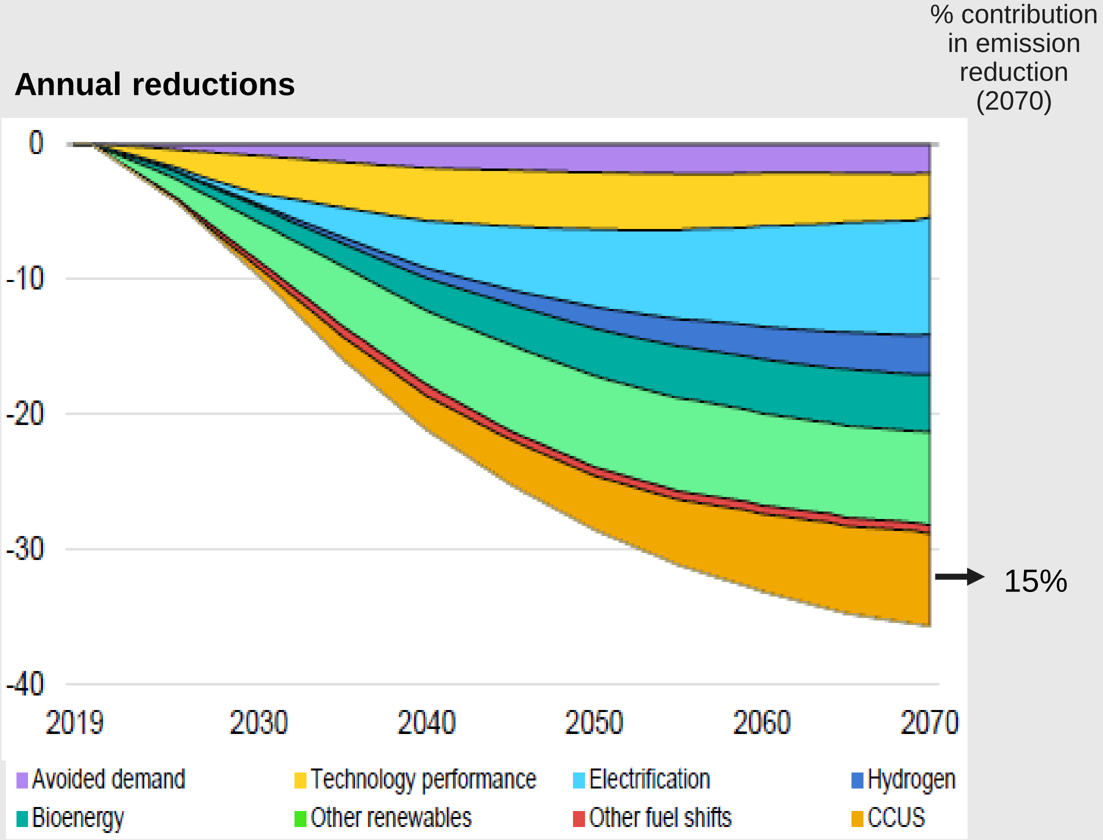
CCUS must be deployed with other solutions to decarbonize the energy sector

The IEA's **sustainable development scenario**, in which global CO_2 emissions from the energy sector fall to zero on a net basis by 2070 worldwide compared with the **stated policies scenario**, which considers current national energy- and climate-related policy commitments

CCUS scenarios and sectoral applications

Global energy sector CO_2 emissions reductions by measure in the sustainable development scenario relative to the stated policies scenario, 2019–70

($GtCO_2$ per year)



Note: CCUS will contribute to the top three drivers of emission reduction, contributing 19% of the CO_2 emission reduction in 2070.
Sources: IEA (2020) "CCUS in Clean Energy Transitions"; Kearney Energy Transition Institute analysis

CCUS can play four crucial roles in the transition to net zero:

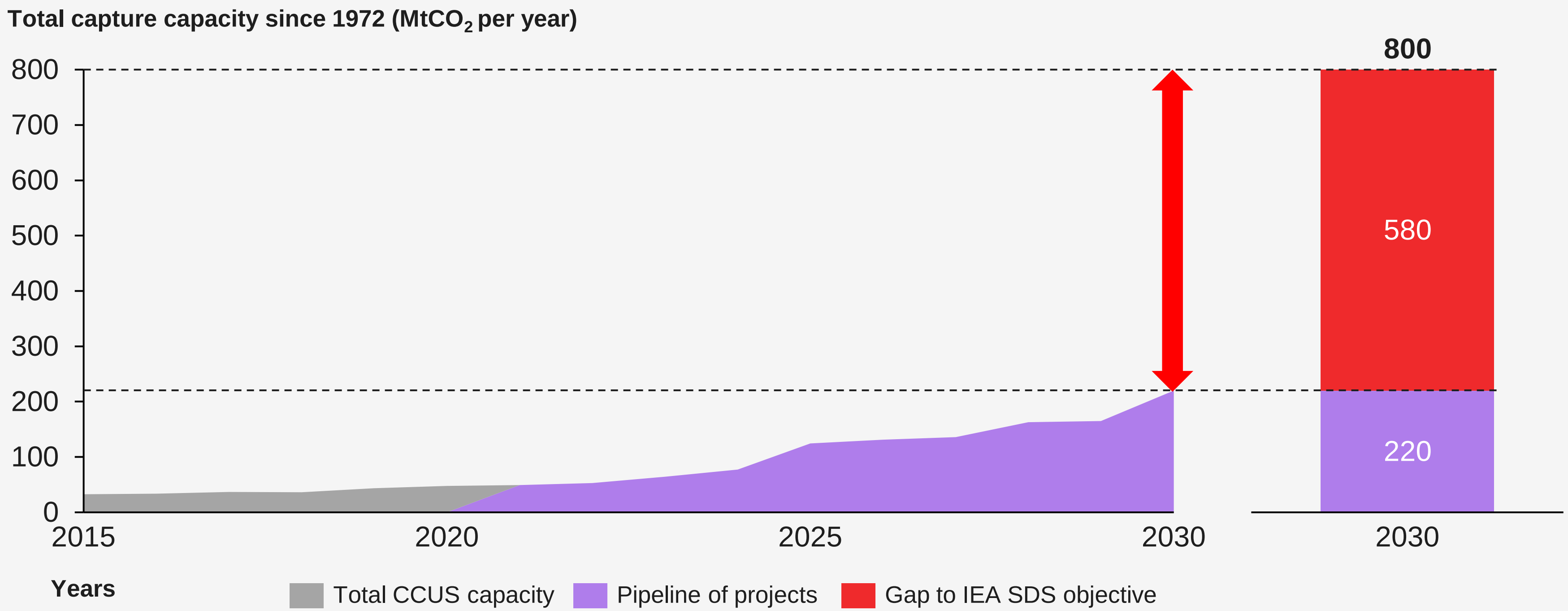
- Tackling emissions from existing energy assets
- As a solution for sectors where emissions are hard to abate
- As a platform for clean hydrogen production
- Removing carbon from the atmosphere to balance emissions that cannot be directly abated or avoided

The CCUS contribution to emissions reductions grows over time as the technology progresses, costs fall, and other cheaper abatement options are exhausted.

IEA forecasts stocking more than 2 $GtCO_2$ per year until 2060 to follow the Paris agreement.

Ongoing CCUS developments are far below the required targets to achieve net zero

Potential CO_2 capture capacity of the current announced projects



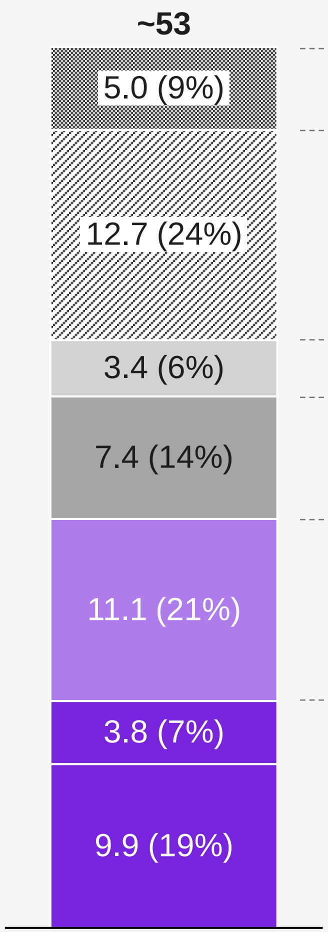
Even if the CO_2 capture capacity is expected to deeply increase from 2022-2023, the global capacity remains quite low compared to IEA objectives and the sustainable development scenario (SDS). The SDS, been created by the IEA, is a roadmap with guidance and advices in order to follow the energy transition and to respect the Paris Agreement, to keep temperatures well below 2°C above pre-industrial era. The capture capacity of **the current pipeline of projects need needs to be multiplied by ~4-fold by 2030**.

(1) According to the latest IEA report (*Net Zero by 2050 - A Roadmap for the Global Energy Sector*), CCUS should reach 1670 Gt/year in 2030 to match the Net Zero scenario in 2050
Sources: GCCSI and NREL databases, IEA Energy Technology Perspective 2020 (2020); Kearney Energy Transition Institute analysis

CCUS could help decarbonize sectors that are responsible for more than 45 percent of the world's CO_2 emissions

Gross estimate of greenhouse gas emissions by segment

(2019, %, $GtCO_2eq$ per year)



	Use case	Direct CO_2 capture	Indirect application of CCUS
5.0 (9%)	**Others**		
12.7 (24%)	**Agriculture, forestry, and other land use**[1]	○	
3.4 (6%)	**Building**	○	– Use of CCUS for the production of synthetic fuels and hydrogen fuels – Use of decarbonized electricity and heat leveraging CCUS
7.4 (14%)	**Transportation**	◐ [2]	
11.1 (21%)	**Industry** (including steel, cement, and refining)	●	
3.8 (7%)	**Electricity and heat** Oil and gas, others	●	
9.9 (19%)	Coal		

Maturity of technologies: ● Commercial stage ◐ Pilot stage ◔ Research stage ○ Not an option

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[1] Includes land use and emissions from cattle; Land-use change emissions are highly uncertain, with no clear trend in the last decade

[2] Under development for marine vessels

Sources: IPCC, International Energy Agency, Food and Agriculture Organization; Kearney Energy Transition Institute analysis

CCUS is a particularly relevant option for hard-to-abate heavy industries for which there are few alternative solutions

Cement, Iron & Steel, and Chemical sectors emit carbon due to their industrial inter-wined processes and high temperature heat requirement (that powered technologies cannot achieve). CCUS technologies are therefore essential to decarbonize those hard-to-abate sectors.

CCUS substitution matrix

		Maturity of potential application of other decarbonisation technologies (2030+ time horizon)				Potential role of CCUS	
Industries	2019 CO_2 emissions ($GtCO_2$)	Biomass (Bio-fuels and biogas)	Electrification (renewables + storage)	Hydrogen applications	Overall score for decarbonisation solutions (other than CCUS)	CCUS current maturity	Opportunity for CCUS
Cement	**2,4**	●	○	◔	+++	◑	▲
Chemicals	**1,4**	◑	◔	◑	++	◑	▲
Iron & Steel	**2,6**	●	◔	◑	+++	◑	▲
Oil and gas refining	**1,6**	○	○	◑	++	●	▶
Power generation	**14,0**	◔	●	◑	+++	●	▶
Transport	**8,1**	◑	●	◔	+++	○	▼

Maturity of technologies:

- ● Commercial stage
- ◑ Pilot stage
- ◔ Research stage
- ○ Not an option

Scoring criteria:

- +++ At least one commercial option
- ++ At least one pilot project
- + Ongoing R&D investment

Maturity

- ● Commercial stage
- ◑ Pilot stage
- ◔ Research stage
- ○ Not an option

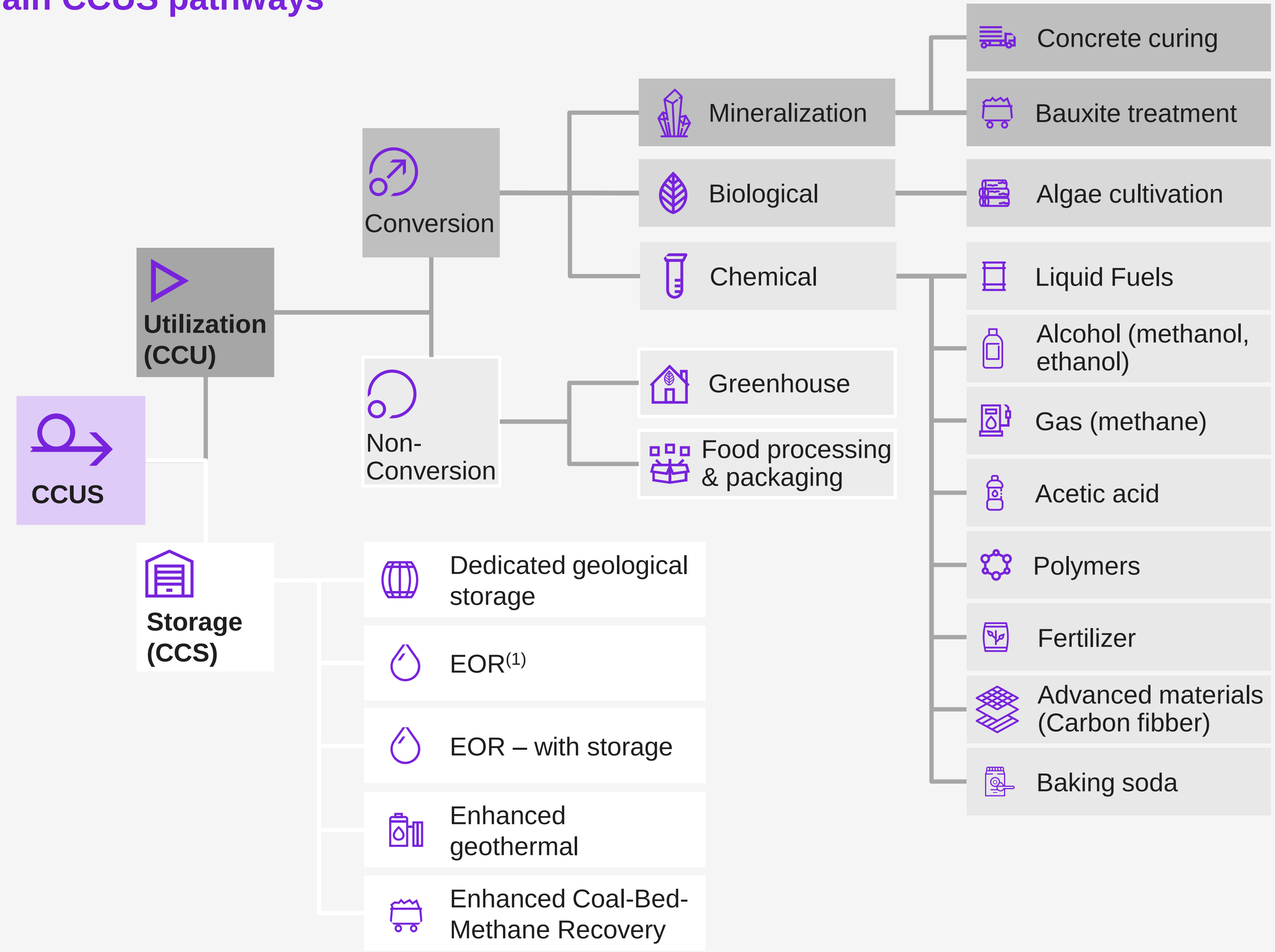
CCUS Opportunity

- ▲ High
- ▶ Medium
- ▼ Low

Sources: Kearney Energy Transition Institute ; IEA - website and Energy Technology Perspective (2020) ; Goldman Sachs - Carbonomics (2020) ; IPC AR5 Climate Change 2014: Mitigation of Climate Change (2015)

CCUS covers a broad range of solutions to either Use (CCU) or Store (CCS) carbon dioxide

Main CCUS pathways



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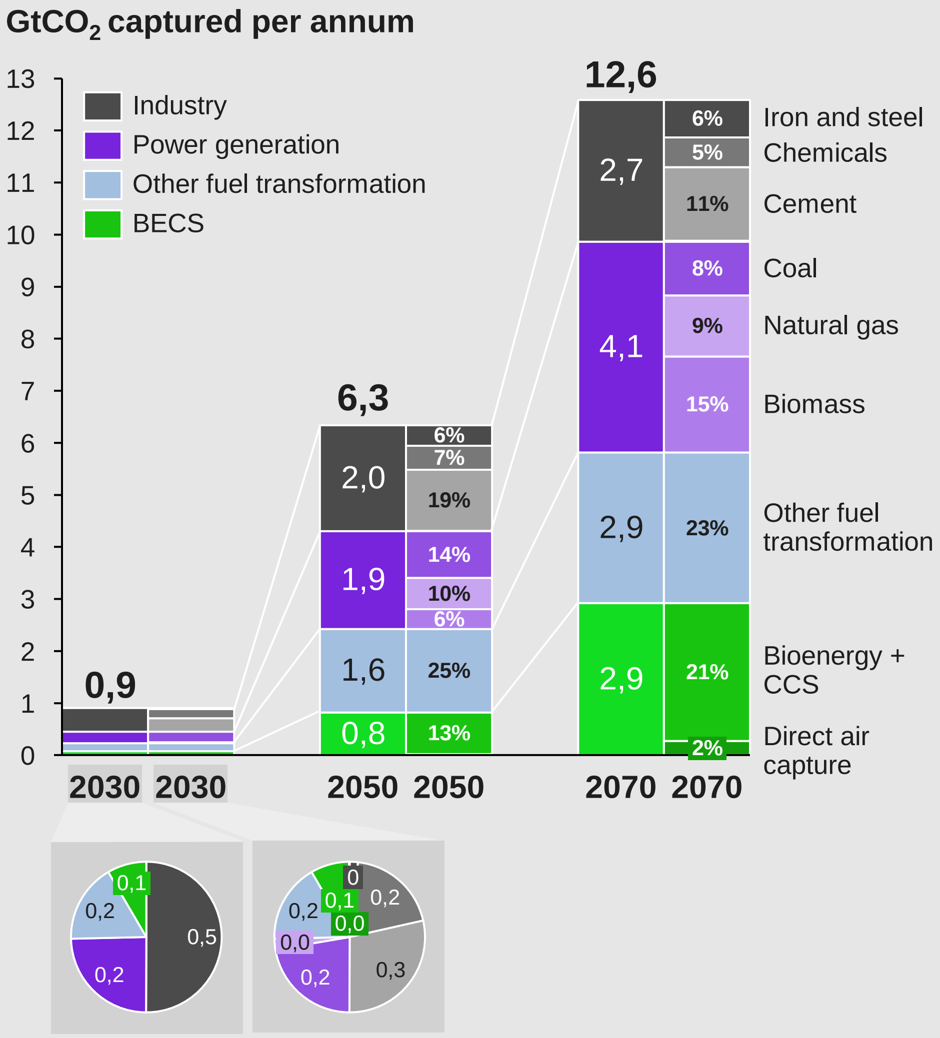
(1): EOR - Enhanced Oil Recovery; “EOR – with storage” allows to inject larger quantities of CO2 compared to traditional EOR

CCUS is expected to be developed for multiple industries and mainly combined with storage solutions

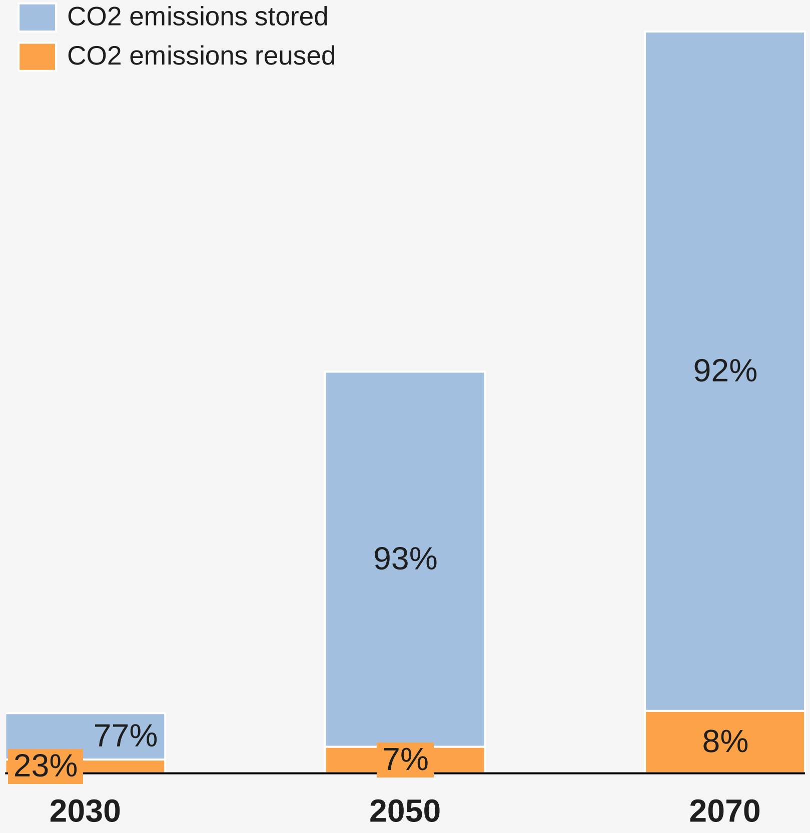
In 2050, industry will remain the first sector of CO_2 emissions captured, with the cement industry accounting for half of these emissions. However, in 2070, among the 12.5 Gt of captured CO_2, a third come from power generation (and 50% of it from biomass). Even if CCUS utilization increases through the years, the captured CO_2 is most likely to be stored rather than being used.

CO_2 capture forecasts for 2030, 2050, and 2070



Sources: IEA CCUS in clean energy transition (2020); Kearney Energy Transition Institute analysis

CO_2 utilization forecasts for 2030, 2050, and 2070



The development of CCUS is generally perceived to be challenging because of four main obstacles

CCUS cost should be compared to the cost of other means to avoid CO_2 release

Main obstacles

Unfavorable economics for industries

The development of CCUS requires important upfront investments that significantly impact the profitability of industries (not compensated by sufficient carbon pricing mechanisms). At present, CO_2 is most valuable for oil and gas (EOR), but its application to other heavy industries (such as cement and steel) is more challenging. Hence, CCUS development is an economic challenge in many industries.

However, the global cost to achieve +2°C could more than double without CCUS deployment, according to the IPCC.

Challenging scale-up

CCUS technologies are mature, and CCUS facilities have been operating for decades in certain industries but at relatively small scale (pilot). CO_2 storage capacities are huge in many geographies, but the deployment of CCUS at industrial scale lacks dedicated infrastructure and clear incentive mechanisms.

Reaching the industrial scale requires developing clusters (group of emitters) to reach scale that is sufficient to support the development of massive infrastructures and make the case for geological storage.

Regulation gap

CCUS development is highly dependent on policy support, but current regulations lack scope and clarity. Governments have a vital role to play through policies that establish a sustainable and viable market for CCUS:

- Create conditions for investment in CCUS projects.
- Coordinate and underwrite the development of industrial hubs with shared CO_2 infrastructure.
- Develop adequate guidelines for monitoring, verification, and accounting

Lack of public support

CCUS development faces headwinds due to weak momentum in public and NGO support forums. Key reasons for limited support include:

- Less awareness of CCUS benefits
- Less experience in technology application
- Fears around storage, NIMY (not in my backyard)
- Unfavourable perception of the technology in general due to an association with fossil fuel (environmental groups oppose CCUS as it extends late life coal plants for example)

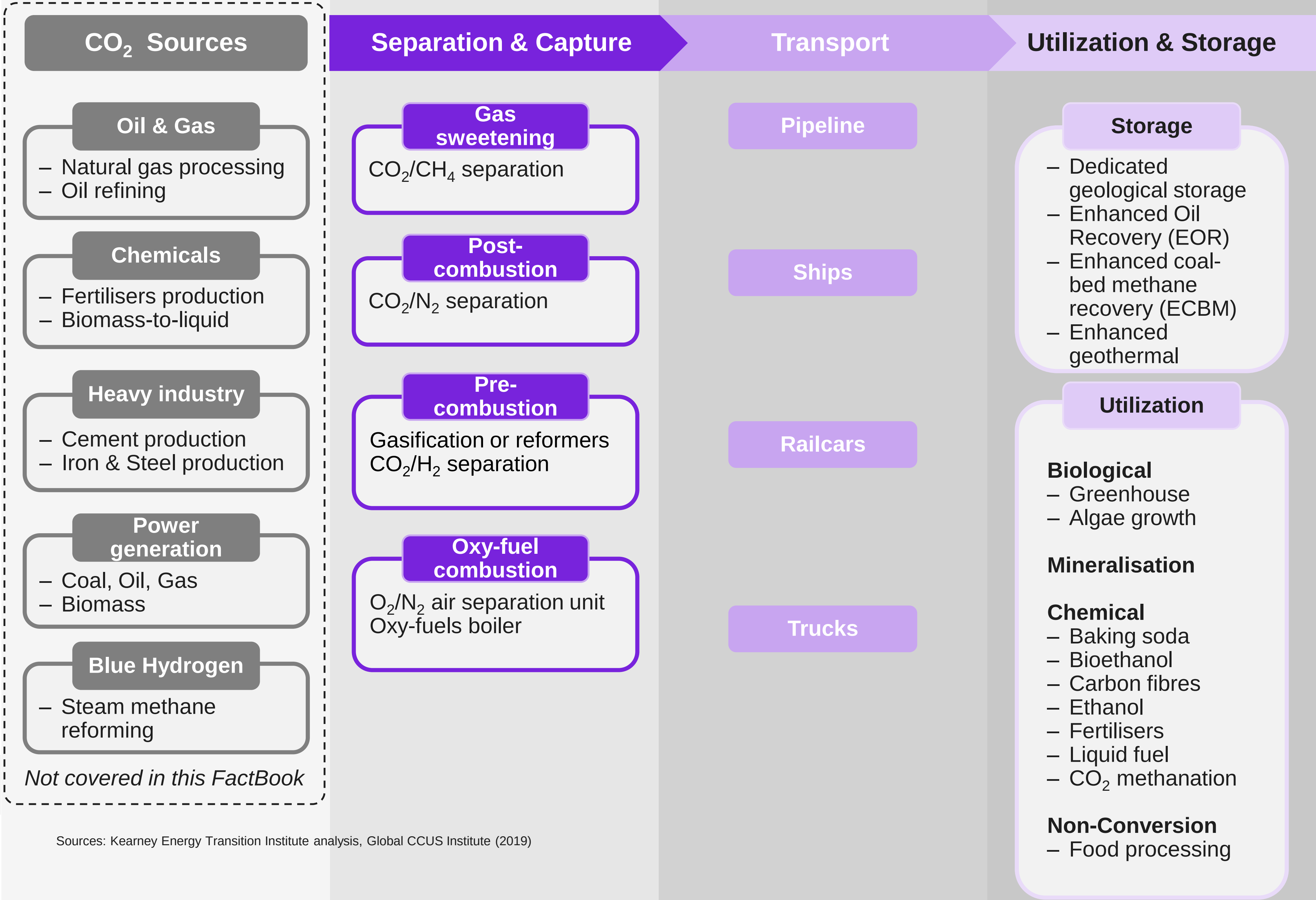
Source: IEA – "Special Report on Carbon Capture Utilisation and Storage, 2020", Kearney Energy Transition Institute analysis

2. Value chain and key technologies

CCUS refers to a set of CO_2 capture, transport, utilization, and storage technologies combined to abate CO_2 emissions

Non-Exhaustive

CCUS Value Chain



CO_2 Sources

Oil & Gas
- Natural gas processing
- Oil refining

Chemicals
- Fertilisers production
- Biomass-to-liquid

Heavy industry
- Cement production
- Iron & Steel production

Power generation
- Coal, Oil, Gas
- Biomass

Blue Hydrogen
- Steam methane reforming

Not covered in this FactBook

Separation & Capture

Gas sweetening
CO_2/CH_4 separation

Post-combustion
CO_2/N_2 separation

Pre-combustion
Gasification or reformers
CO_2/H_2 separation

Oxy-fuel combustion
O_2/N_2 air separation unit
Oxy-fuels boiler

Transport

- Pipeline
- Ships
- Railcars
- Trucks

Utilization & Storage

Storage
- Dedicated geological storage
- Enhanced Oil Recovery (EOR)
- Enhanced coal-bed methane recovery (ECBM)
- Enhanced geothermal

Utilization

Biological
- Greenhouse
- Algae growth

Mineralisation

Chemical
- Baking soda
- Bioethanol
- Carbon fibres
- Ethanol
- Fertilisers
- Liquid fuel
- CO_2 methanation

Non-Conversion
- Food processing

Sources: Kearney Energy Transition Institute analysis, Global CCUS Institute (2019)

The separation of CO_2 molecules contained in exhausting gases can be realized through four main technologies (1/3)

Key CO_2 separation technologies

Carbon separation technologies

Absorption (solvents based)	**Adsorption** (sorbents based)	**Membranes**	**Liquid or supercritical CO_2**	**Novel technologies**
Chemical: Ethanolamine (MEA), caustic, ammonia solution, etc. **Physical:** Selexol^{TM}, Rectisol, Fluorinated solvents, N-Methyl-2-Pyrrolidone (Purisol®)etc.	**Physical:** alumina, zeolite, activated carbon**,** CaO, MgO, Li_2ZrO_3, Li_4SiO_4	**Polymer based:** Polyphenylene oxide, Polyethylene oxide Poly ionic liquid **Inorganic membrane:** ceramic based, zeolite based	Dry ice formation at low temperature; separation affected by a series of compression, cooling, and expansion steps	**Microbial and algal systems** **Electrochemical pumps** **Chemical looping** **Molten carbonate fuel cell** **Mineral carbonation**

Require to be regenerated: pressure swing, temperature swing, moisture swing, or a combination thereof

Source: Kearney Energy Transition institute analysis

The separation of CO_2 molecules contained in exhausting gases can be realized through four main technologies (2/3)

Key CO_2 separation technologies

Separation technologies

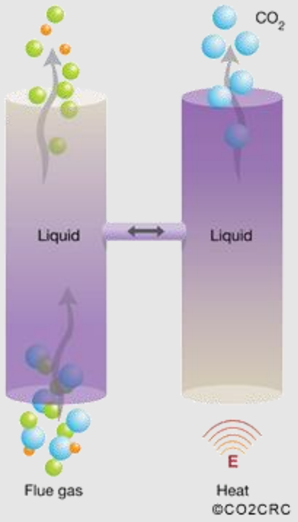
Brief description of key separation technologies

Absorption	**Absorption refers to the dissolution of CO_2 from a gas phase into a liquid phase called solvents**. CO_2 removal from the solvent often requires energy on the form of heat or steam. Solvent-based CO_2 capture involves chemical or physical absorption of CO_2 into a liquid carrier and regenerating the absorption liquid by increasing the temperature or reducing the pressure to break the absorbent-CO_2 bond. The absorbent should have a suitable capacity for CO_2 absorption, high kinetic rate for CO_2 absorption, negligible vapor pressure, and high chemical and thermal stability.
Adsorption	**Adsorption refers to the accumulation of CO_2 on the surface of a sorbent, often very porous and with a large surface-to-weight ratio**. Sorbent-based CO_2 capture involves the chemical or physical adsorption of CO_2 using a solid sorbent. Like solvents, solid sorbents are usually regenerated by increasing temperature or reducing pressure to release the captured CO_2. Solid sorbents may have lower regeneration energies compared with solvents because of lower heat capacities.
Membranes	Gas separation using membranes is a pressure-driven process. Because of the low pressure of flue gases, driving force is too low for membrane processes in post-combustion (low pressure and low CO_2 concentration). Membrane processes offer increased separation performances when CO_2 concentration in the feed mixture increases. Membrane designs include metallic, polymeric, or ceramic materials capable of operating at elevated temperatures and that use a variety of chemical and/or physical mechanisms for separation.
Liquid or supercritical CO_2 (Inherent CO_2 capture)	The Liquid or supercritical CO_2 method uses low temperatures for condensation, separation, and purification of CO_2 from flue gases. (The freezing point of pure CO_2 is 195.5 K at atmospheric pressure.) It enables direct production of liquid CO_2 that can be stored or sequestered at high pressure via liquid pumping.
Novel technologies	Novel technologies (experimental stage) for post-combustion capture include hybrid systems that combine attributes from multiple technologies (such as solvents and membranes) as well as alternative technologies and processes such as electrochemical pumps and chemical looping. Electrochemical pumps include carbonate and proton conductors and molten carbonate and aqueous alkaline fuel cells have been studied for use in separating CO_2 from both air and flue gases. Research is conducted on biological fixation (from natural photosynthesis) and mineral carbonation to transform CO_2 into carbon material.

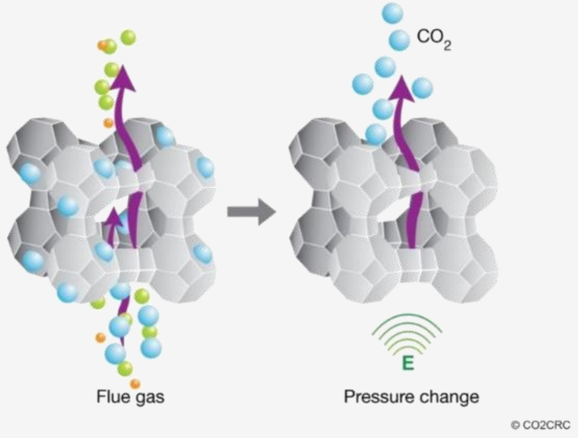
Sources: “Carbon Dioxide Separation from Flue Gases: A Technological Review Emphasizing Reduction in Greenhouse Gas Emissions” (2014); Kearney Energy Transition Institute analysis

The separation of CO_2 molecules contained in exhausting gases can be realized through four main technologies (3/3)

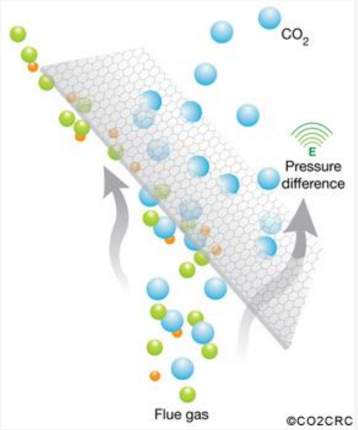
Amine-based absorption technology



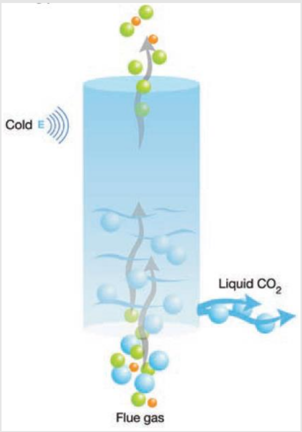
Pressure swing absorption technology



Membrane separation technology



Liquid or supercritical CO_2 (cryogenic) distillation



Sources: CO2CRC; Kearney Energy Transition Institute analysis

Absorption is the most mature technology for CO_2 separation

Flue gas properties (mainly concentration of CO_2, temperature, and pressure) are the most effective factors for selecting a suitable process for CO_2 separation.

Separation technologies

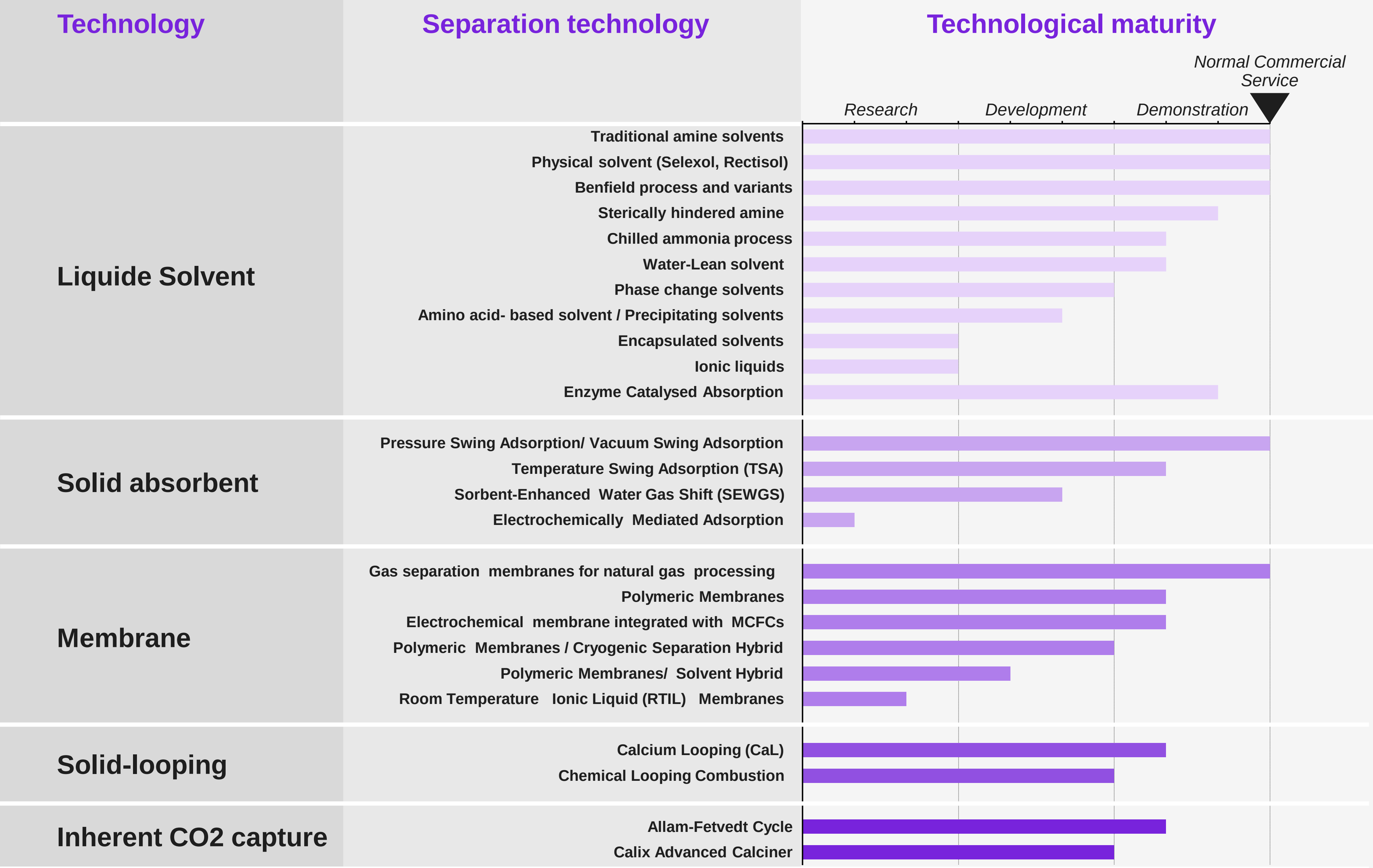
Comparison of key separation technologies

	Advantages	Disadvantages	Scale	Applications
Absorption	– Reacts rapidly – Flexible – High capacities possible	– Equipment corrosion – High energy requirements	– **Industrial**	– Suitable for flue gases from post-combustion capture
Adsorption	– Low energy consumption – Lower cost of CO_2 capture – Suitable for separating CO_2 from dilute stream	– Low adsorption capacities (in flue gases conditions)	– **Pilot**	– Suitable for flue gases from post-combustion capture
Membrane separation	– Continuous, steady-state technology	– Require high energy for post-combustion CO_2 capture	– **Pilot / Industrial**	– Not suitable for post-combustion capture – Works with oxy-fuel combustion capture
Liquid or supercritical CO_2 (Inherent CO_2 capture)	– Liquid CO_2 production – Not requiring solvents or other components – Can be scaled up	– Require a large amount of energy	– **Experimental**	– Efficient for gas streams with high CO_2 concentration (for pre-combustion and oxy-fuel combustion capture)

Sources: "Carbon Dioxide Separation from Flue Gases: A Technological Review Emphasizing Reduction in Greenhouse Gas Emissions" (2014); Kearney Energy Transition Institute analysis

Several CO_2-separation technologies are already mature

Technological maturity of CO_2 separation technologies.



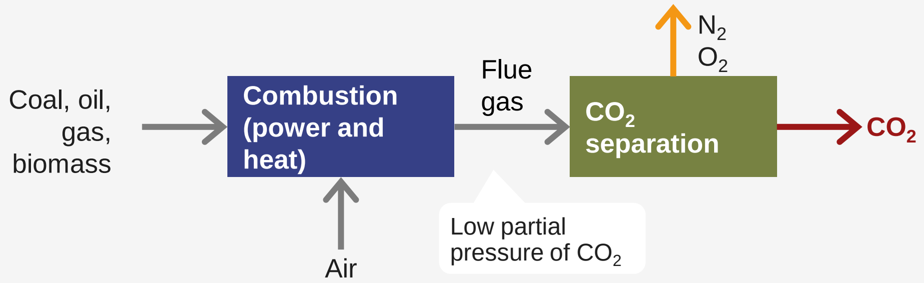
Technology	Separation technology
Liquide Solvent	Traditional amine solvents Physical solvent (Selexol, Rectisol) Benfield process and variants Sterically hindered amine Chilled ammonia process Water-Lean solvent Phase change solvents Amino acid- based solvent / Precipitating solvents Encapsulated solvents Ionic liquids Enzyme Catalysed Absorption
Solid absorbent	Pressure Swing Adsorption/ Vacuum Swing Adsorption Temperature Swing Adsorption (TSA) Sorbent-Enhanced Water Gas Shift (SEWGS) Electrochemically Mediated Adsorption
Membrane	Gas separation membranes for natural gas processing Polymeric Membranes Electrochemical membrane integrated with MCFCs Polymeric Membranes / Cryogenic Separation Hybrid Polymeric Membranes/ Solvent Hybrid Room Temperature Ionic Liquid (RTIL) Membranes
Solid-looping	Calcium Looping (CaL) Chemical Looping Combustion
Inherent CO2 capture	Allam-Fetvedt Cycle Calix Advanced Calciner

Sources: GCCSI (March 2021) - Technology Readiness and Costs od CCS

CO_2 capture systems may be classified into four categories (1/2)

Main carbon capture processes

Post-combustion



Coal, oil, gas, biomass

Combustion (power and heat)

Air

Flue gas

Low partial pressure of CO_2

CO_2 separation

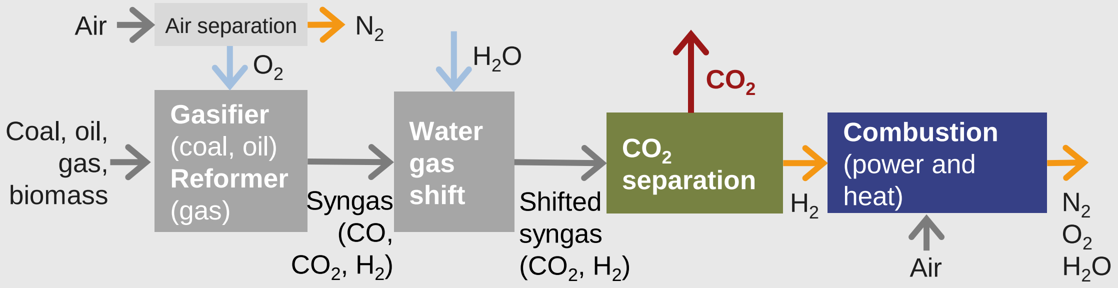
N_2
O_2

CO_2

Thermal power plants burn fuel with air to produce heat and emit flue gases that generally consist of a hot gas at standard pressure, with 80% N2, **10% CO_2**, some oxygen, vapor, and other pollutants (such as NOx). The CO_2 is then separated from the flue gases. Additional drying, purification and compression are required before transportation.

Post-combustion systems are the most mature capture technology (late demonstration stage) and are expected to be retrofitted to modern and efficient thermal power plants: SPC and NGCC. Post-combustion capture can be retrofitted to almost any existing plant with a large and steady source of CO_2 by adding the capture process to the exhaust-gas circuit. Post-combustion is the only system that does not require an additional oxygen-production plant. However, the process is still highly inefficient, given the low partial pressure of CO_2 in the flue gas.

Pre-combustion



Air

Air separation

N_2

O_2

Coal, oil, gas, biomass

Gasifier (coal, oil) **Reformer** (gas)

Syngas (CO, CO_2, H_2)

H_2O

Water gas shift

Shifted syngas (CO_2, H_2)

CO_2

CO_2 separation

H_2

Combustion (power and heat)

Air

N_2
O_2
H_2O

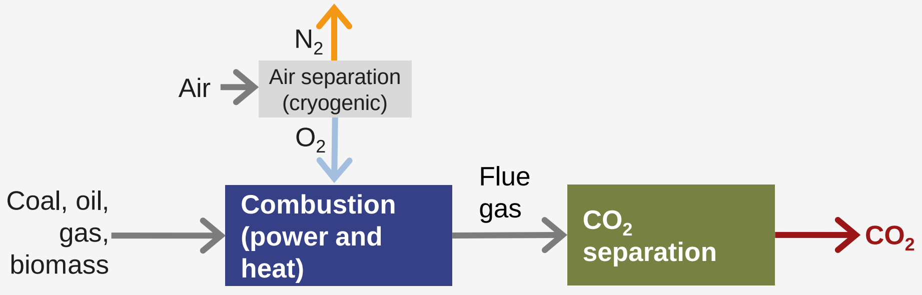
The pre-combustion process includes industrial processes that transform hydrocarbon sources to generate 'syngas' as an intermediate step. Water gas shift is then applied to the syngas, providing a shifted syngas mostly composed of H_2 and CO_2 with concentration of **17% to 38%**. Advantages are the relative ease with which CO_2 can be separated from H_2, compared with flue gases, and the versatility of potential end-products from hydrogen beyond electricity. Drawbacks lie mostly in the high capital cost and complexity of the IGCC plant.

Note: SPC is supercritical pulverized coal; NGCC is natural gas combined cycle.
Source: GCCSI (2021), *Technology Readiness and Costs of CCS*; Kearney Energy Transition Institute analysis

CO_2 capture systems may be classified into four categories (2/2)

Main carbon capture processes

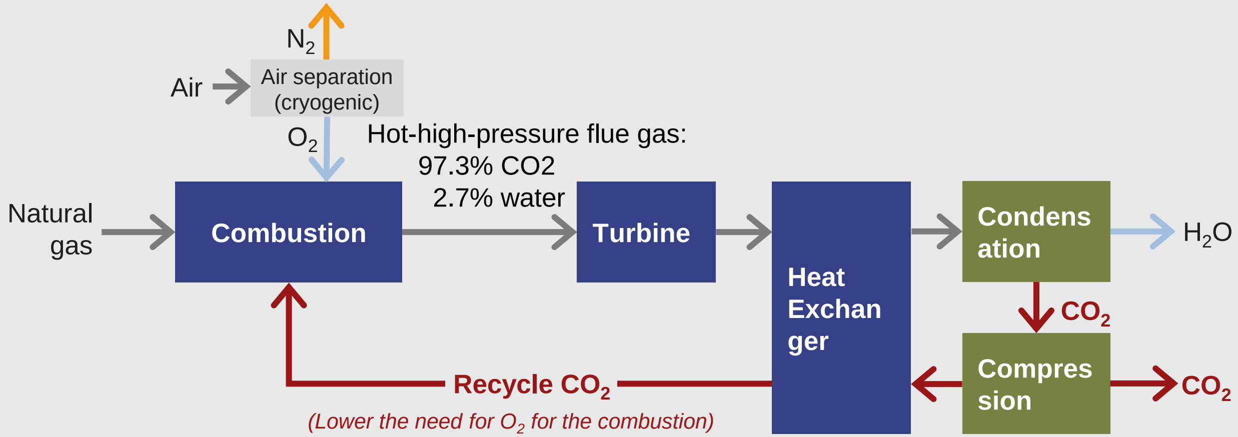
Oxy-combustion



Flue gas mainly consists of CO_2 and H_2O which are separated by condensing water

Thermal power plant burners are modified to burn fuel with nearly pure oxygen instead of air. As a result, concentration in flue gas varies between **80% to 98% CO_2**, mixed with vapor, resulting in a stream almost ready to transport. Additional drying, purification and compression are also needed before transportation. Burning fuel in pure oxygen instead of air produces a pure stream of CO_2 and avoids the difficult process of CO_2/N_2 separation. Another benefit is greater energy efficiency than in post-combustion. The main hurdle is the very large stream of oxygen required, and extremely high temperature reached in the oxy-combustion chamber. Another important issue is the insufficient purity of CO_2 in flue gases, which was problematic in early demonstration projects.

Liquid or supercritical CO_2: Allam- Fetvedt Cycle



Inherent CO_2 capture technologies such as the Allam-Fetvedt Cycle are **specific oxy-fuel technologies that use produced supercritical CO_2 (~1000°C to 1,200°C, 200 to 400 bar) as a working fluid to drive a turbine enabling CO_2 capture, compression, dehydration, and elimination of NOx and SOx gases.** This technology is the first CO_2 spined power turbine developed. While it produces electricity, the technology provides flue gas with CO_2 concentration above 97%, ready to be transported, as it does not require additional work or energy to separate CO_2. This technology could combine power generation and steam methane reforming to produce cost-competitive blue hydrogen production.

Note: SPC is supercritical pulverized coal; NGCC is natural gas combined cycle.
Source: GCCSI (2021), *Technology Readiness and Costs of CCS*; Kearney Energy Transition Institute analysis

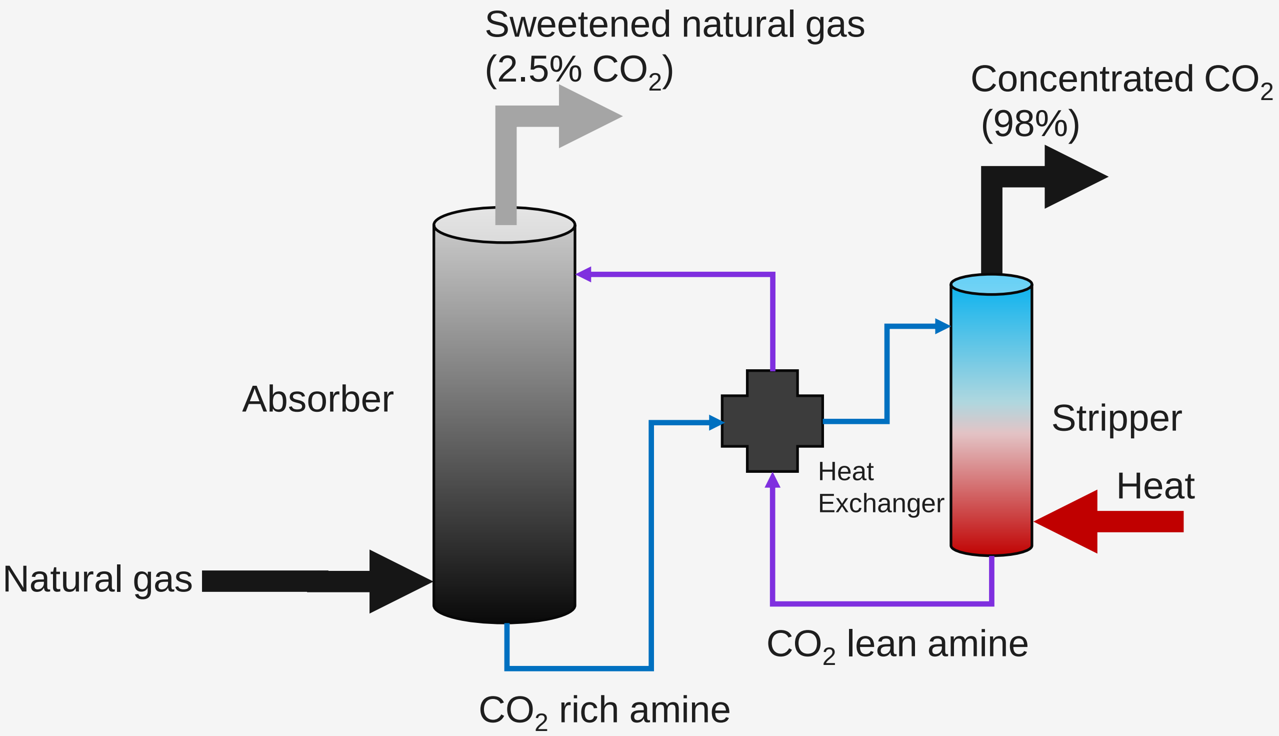
Capture technologies

Depending on the geological and reservoir condition, natural gas may contain CO_2 at different levels that needs to be removed prior to transportation and consumption

Natural gas sweetening process (natural gas processing)

Gas sweetening process:

- CO_2 is removed through amine absorption using methyl-diethanolamine (MDEA) as solvent.
- Resulting CO_2 stream with 98% concentration is transported and used or stored.



Some gas may fields may contain more than 50% CO_2

About half of the raw natural gas produced worldwide contains more than 4% CO_2 by volume, which is above specifications for its transport (2% for pipelines and 0.2% for LNG).

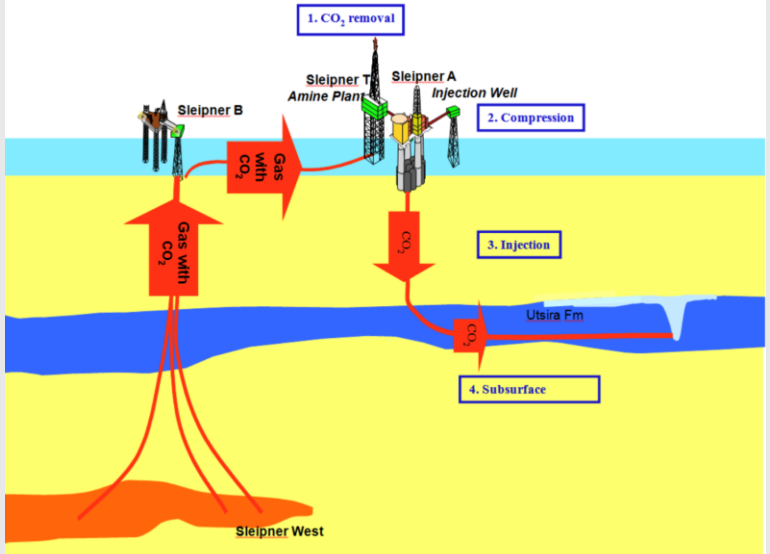
Natural gas processing facilities includes a “gas sweetening” step, which separates and removes CO_2. It is the lower-cost opportunity to create a large flow of CO_2 ready to be stored: CO_2 flow rate can be very high; separation is inherent to the process of natural gas production and operates at already high pressure, reducing further cost of compression.

The first large-scale integrated CCS projects were gas processing facilities, and CO_2/CH_4 separation system is already commercialized and mature.

Sources: GCCSI 2017, Equinor; Kearney Energy Transition Institute analysis

Sleipner West project combines gas extraction and processing with CO_2 removal followed by direct injection and storage

Combined gas sweetening and carbon storage project: Sleipner West CCS



Country: Norway
Operational date : 1996
CAPEX: 90 M$
CO_2 savings : 0,9 Mt/year
Project leaders: Equinor, ExxonMobil, Lotos, Kufpec

Sleipner is a producing gas field, since the Utsira reservoir has been used as a CO_2 storage reservoir (deep saline aquifer) by Equinor as operator and a group of partnering companies. This is the longest ongoing project on CO_2 storage in the world with about 1 Mt CO_2 / year. 4D seismic surveys were run at different times to monitor the movement of CO_2 in the reservoir during the injection.

*"**For over 20 years we have had a first-hand experience of safe storage of CO_2 in a reservoir**. We believe this insight can be valuable for both our industry, research communities, and others working on making CO_2 storage a central part of the ongoing energy transition into the low carbon future," says Torbjørn F. Folgerø, chief digital officer and senior vice president in Equinor.*

Project characteristics	Details
Business type	CO_2 removed from natural gas processing
CO_2 capture capacity	0,9 Mt/year
Government funding	None – motivated by Norwegian carbon tax
CAPEX	90 M$ - 82% on the compression system, 16% on the injection well
Planning	Started in 1996, 25 years lifetime
Capture type	Amine solvent (MDEA) absorption
Transport type	None – direct injection
Storage type	Utsira aquifer geological formation

Source: Kearney Energy Transition Institute; GCCSI; Equinor https://www.equinor.com/en/news/2019-06-12-sleipner-co2-storage-data.html

If gas sweetening solely applies to gas processing, other capture technologies can be used in multiple sectors

Characteristics of the four main capture processes and their separation technologies

	Post-combustion	Pre-combustion	Oxy-combustion	Gas sweetening
Main application and sector	Power and cement	Power and industrial hydrogen	Power and steel	Gas processing
Main separation	CO_2/N_2	CO_2/H_2	O_2/Air	CO_2/CH_4
Main separation technology	Amine solvents	Pressure swing adsorption sorbents	Cryogenic air separation units	Membranes solvents
Main axis of R&D	– Solvents – Sorbents – Flue gas recirculation – Carbonate Looping – Cryogenic CO_2 capture – Fuel cells CO_2 capture	– Solvents – Sorbents – Membranes – Process integration – Hydrogen turbine – Air separation units	– Air separation units – Chemical looping- – Direct oxy-combustion – turbine – Oxyfuel retrofit – Allam-Fetvedt Cycle	– Solvent – Membranes

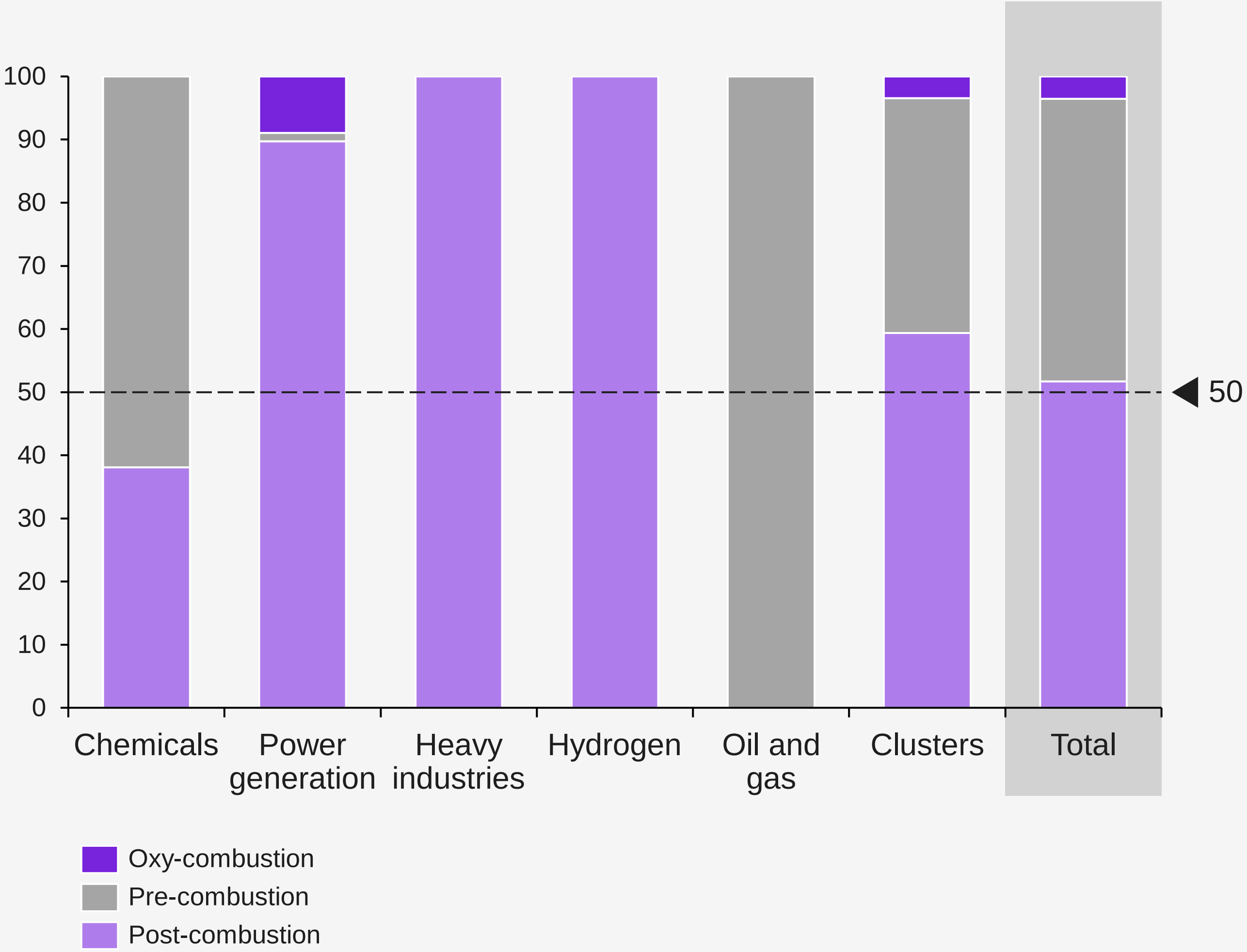
Source: Kearney Energy Transition institute analysis

Post-combustion and pre-production capture technologies are the most broadly used solutions

Non-Exhaustive

Distribution of CO_2 capture technologies per sector

(selection of operating projects in 2020, % of capacity)



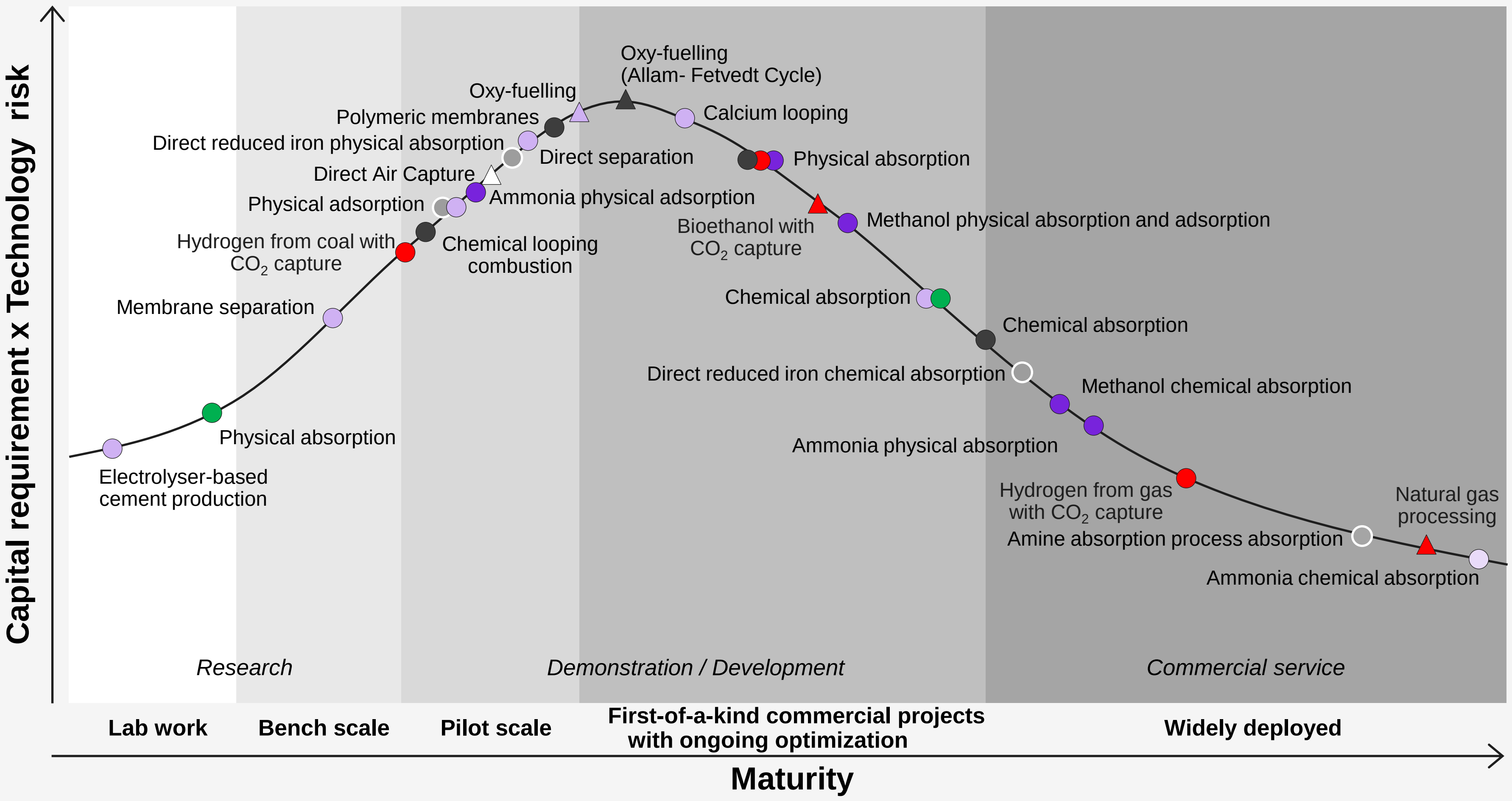
Pre- and post-combustion capture are the two main capture types used in large-scale CCUS facilities. Oxy-combustion technologies are less mature but are being implemented in new projects.

The oil and gas industry uses pre-combustion technologies, notably for projects related to gas processing.

Notes: Some facilities can do several CO_2 capture methods, such as both pre- and post-combustion.
Sources: GCCS and NREL databases; Kearney Energy Transition Institute analysis

Most of separation technologies are still in the demonstration phase

Maturity curve of CO_2 separation and capture technologies



○ Separation technologies
△ Capture Technologies

● Biomass industry
● Cement industry
● Chemical industry
● Iron and steel industry
● Power generation
● Fuel production
○ Cross industries

Note: The maturity of Capture Technologies (Post-combustion, Oxy-combustion, Pre-combustion) varies with their associated separation technologies, from early lab work to commercial deployment – see next slide
Source: Kearney Energy Transition Institute ; IEA - ETP Clean Energy Technology Guide (2020)

For long-distance transportation of high volumes, pipelines are mature, and shipping is being studied

Pipeline

Volumes: cost effective for large volumes, high CAPEX, low OPEX

Distances: long distances

Transformation for transport: Compression under the form of supercritical fluid

Ship

Volumes: technically feasible to transport large volumes, low CAPEX, high OPEX

Distance: long distances

Transformation for transport: liquefaction[1]

Railcars

Volumes: cost-effective for small and medium volumes, low capex, high opex

Distances: over long distances

Transformation for transport: Liquefaction[1]

Trucks

Volumes: cost effective for very small volumes, low capex, high opex

Distances: traveling short distances

Transformation for transport: liquefaction[1]

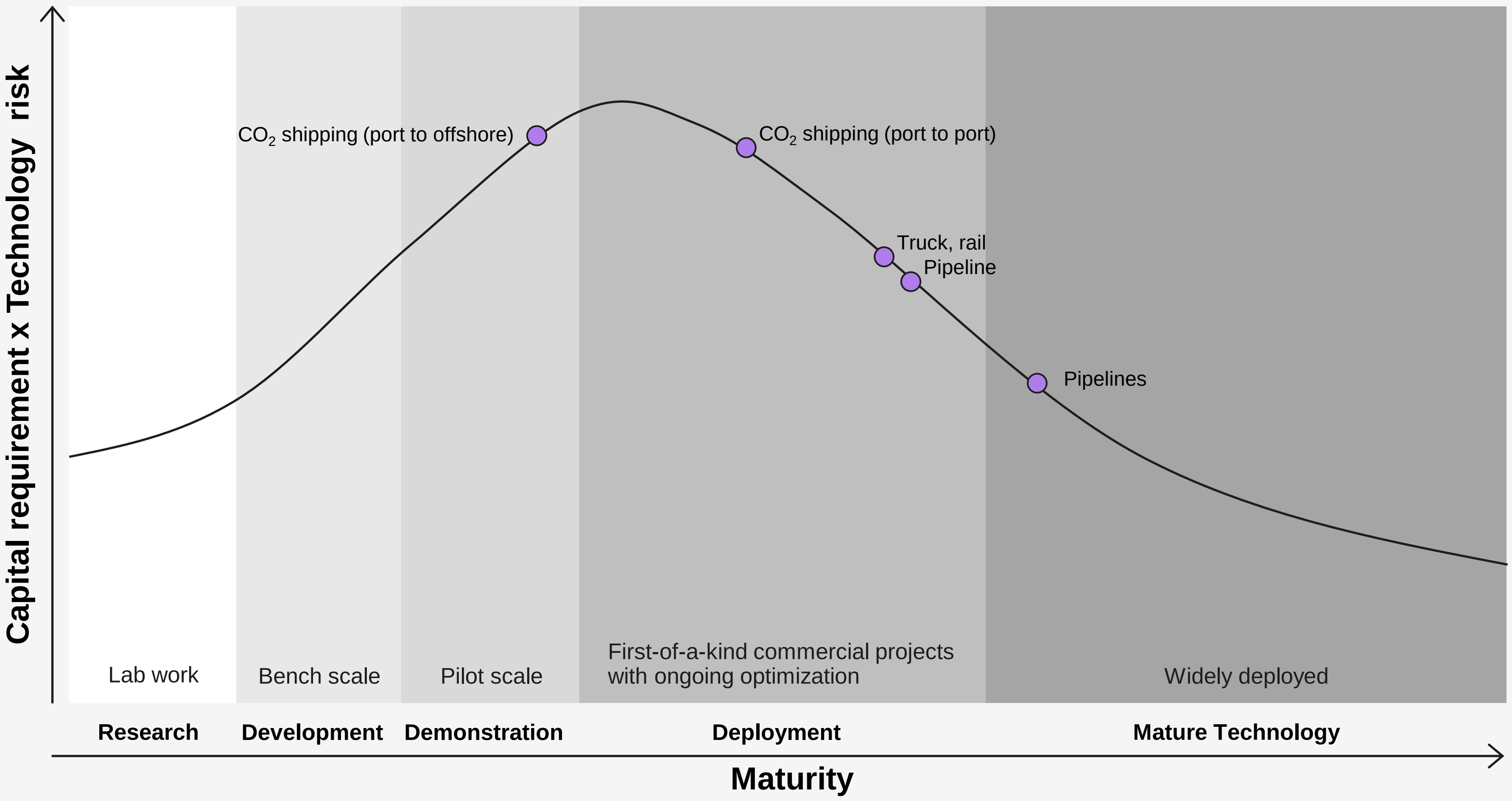
- CO_2 transportation is already well-established and poses no greater risk than natural gas transportation, with compression of CO_2 being a mature technology
- 50 CO_2 pipelines, with a combined length of 6,600 km, already operate in North America, transporting more than 60 $MtCO_2$ annually, mostly for enhanced oil recovery (EOR) purposes. The technical challenges presented by CO_2 pipelines differ from those associated with natural gas and include impurities in the CO_2 stream and managing corrosion and pressure (both much higher than in natural gas pipelines).
- Maritime transportation of CO_2 is already in use at a small scale in the drinks industry and could be a promising and flexible transport option for the bulk transportation of CO_2 in CCUS, in large vessels similar to those used to transport liquefied petroleum gas.
- Truck and rail transport are unlikely to play a significant role in CCUS deployment.

[1] Requires the construction of a liquefaction facility at the point of origin

Sources: The Costs of CO_2 Transport: Post-Demonstration CCUS in the EU, Zero Emission Platform 2011; The Costs of CO_2 Capture, Transport and Storage, 2021; Kearney Energy Transition Institute analysis

Transport technologies are mainly already used at a large-scale level

Maturity curve of CO_2 transport and storage technologies



● Transport technology

Transport technologies

*Technology Readiness Level
Source: Kearney Energy Transition Institute ; IEA - ETP Clean Energy Technology Guide (2020)

The characteristics of CO_2 geological storage vary by type of reservoir

Storage and utilization of CO_2

CO_2 storage

Main storage risks are generally related to leaks from wells (completions) or formation sealing

Geological storage	Depleted oil and gas reservoir	Deep saline aquifer	Coal bed methane	Basalt /ultra-mafic rocks
Reservoir description	**Underpressurized porous reservoirs** can store CO_2 in structural or stratigraphic traps without risking over-pressurization.	**Vast open structures** where CO_2 can spread slowly upward are limited by the cap rock. CO_2 is hydrodynamically trapped in micro pores during migration.	**Coal beds** display fractures that greatly improve permeability of the media and allow CO_2 to migrate throughout the coal seams and be physically adsorbed by coal micro pores.	**Basalt and ultra-mafic rocks** with high porosity and permeability provide ideal medium for CO_2 injection and storage. Injected CO_2 reacts with in situ glass and alteration minerals and replicates natural crystallization in pore spaces in a few years (for example, calcite).
Monitoring and safety	Very **localized storage** is easy to monitor and proven **leakproof.**	Seismic monitoring of the slow spread of CO_2, results in a **diffuse storage**. The **additional risk of over-pressurization** can be mitigated by careful monitoring.	CO_2 replaces methane adsorbed in coal micro pores, allowing for enhanced coal bed methane recovery.	Pilots consisted of injecting water and CO_2 separately with proportions insuring the complete dissolution of CO_2 in water at depth.

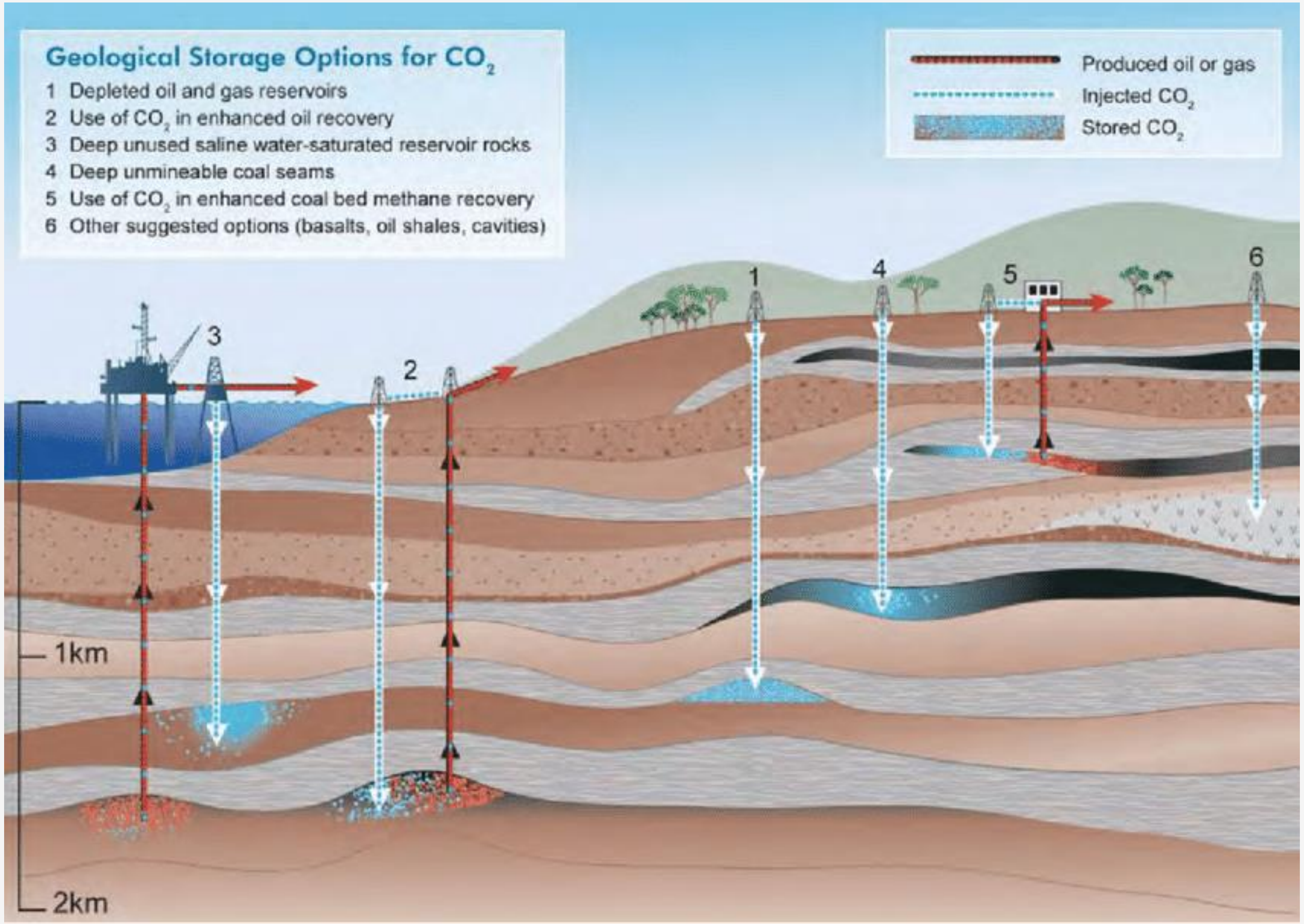
CO_2 utilization:

- **Oil and gas industry** for enhanced oil recovery or enhanced coal bed methane recovery
- **Chemical industry** for food processing, bio-ethanol, fertilizers
- **Biological** for green houses
- **Mineralization**

Sources: Kearney Energy Transition Institute

Captured CO_2 can be stored in appropriate geological formations or used in the industry

Utilization and storage options for CO_2



Sources: Meeting the Dual Challenge: A Roadmap to At-Scale Deployment of CCUS, "Ch. 2: CCUS Supply Chains and Economics; The Costs of CO_2 Transport Post-Demonstration CCUS in the EU," Zero Emission Platform 2011, CO_2 Underground Sequestration, Intergovernmental Panel on Climate Change, Strogen, Dominic, Opportunities for Underground Geological Storage of CO_2 in New Zealand, Report CCS 08/7, Onshore Taranaki Neogene reservoirs; Kearney Energy Transition Institute analysis

Beyond geological storage, CO_2 could also be reused for various revenue-generating purposes

Options for carbon use

CO_2–EOR
Injection of CO_2 into nearly depleted petroleum reservoirs acts as a solvent that reduces the viscosity of the oil and allows enhanced oil recovery of the reservoir. Once the field is depleted, it can be utilized to store additional CO_2 permanently.

Enhanced coal bed methane (ECBM)
Injection of CO_2 in coal seams adsorbs and captures CO_2 while releasing methane. This process is unproved on a commercial scale but has the potential to utilize diluted CO_2 in flue gas and avoids capture and compression costs.

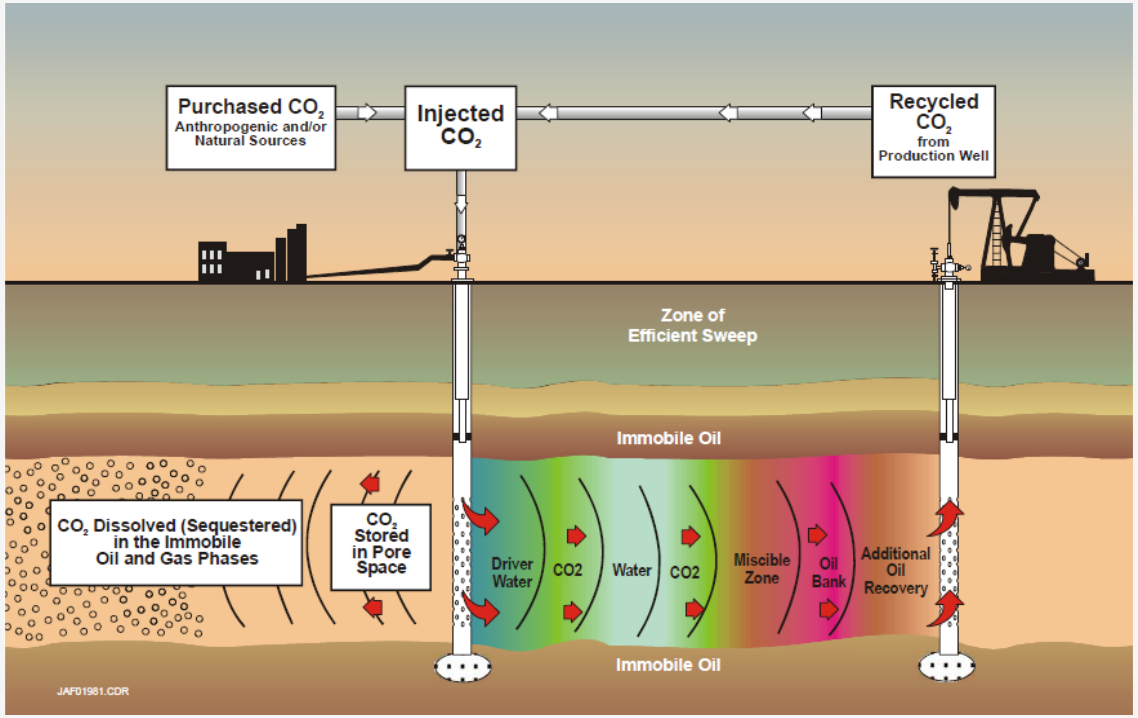
Urea yield boosting
Production of urea (a fertilizer) through the reforming of natural gas requires more CO_2 than obtained in the reforming process. It is a proven technology.

Algae fixation
The engineered capture of CO_2 by photosynthesis, where algae are fed with a pure stream of CO_2 to convert them directly into liquid fuels is still in the early stage of demonstration.

Mineralization
CO_2 is stored in the form of limestone or other calcium carbonates and integrated within concretes and cements.

CO_2–EGS: this alternative to enhanced geothermal systems uses CO_2 as working fluid in place of water.

Enhanced oil recovery (EOR) principles



- 1 ton CO_2 injected leads to the recovery of an additional 2–3 barrels of oil.
- CO_2 is recycled in the reservoir as part the injected volumes when they go back to the surface with the produced oil

Sources: IEA Greenhouse Gas R&D Program (IEA GHG), “CO_2 Storage in Depleted Oilfields: Global Application Criteria for Carbon Dioxide Enhanced Oil Recovery”; Kearney Energy Transition Institute analysis

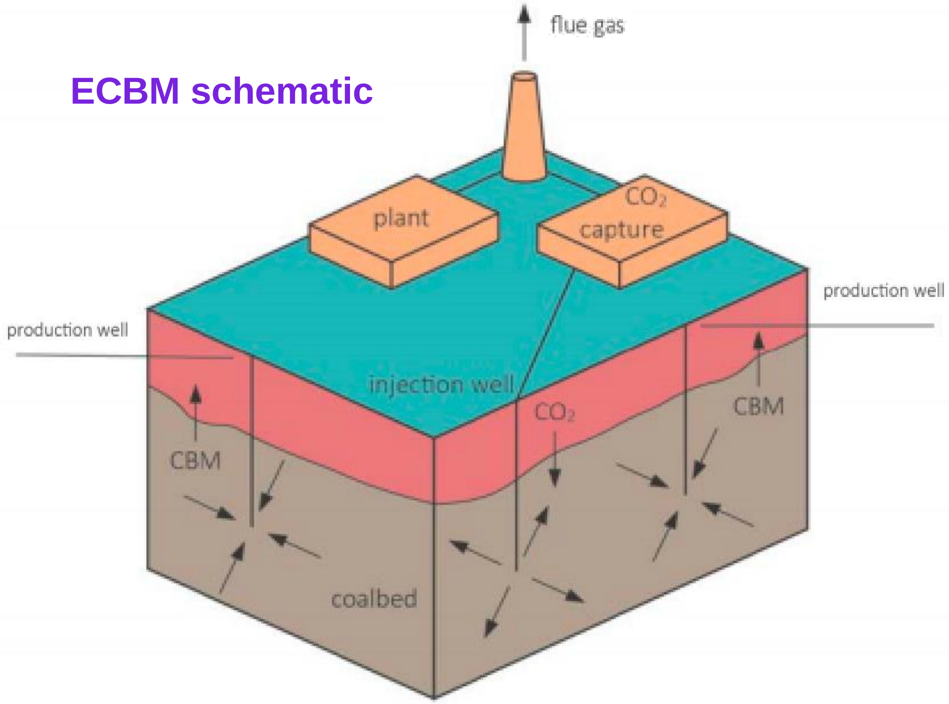
In Enhanced coalbed methane (ECBM) process, CO_2 is injected into a CBM well to enhance recovery of methane whilst storing CO_2 underground

Compared to other storage media, it is much more difficult to provide estimates of the realistic (or matched) global storage capacity potential due to the complexity of the CO_2-coal-methane-water system

Principle of ECBM

- When CO_2 is injected in the coalbed layer, both the gaseous and adsorbed-state of CH_4 and CO_2 will exist in equilibrium. However, since the coalbed has a much stronger adsorption capacity for CO_2 than CH_4, the injection of CO_2 will make the adsorbed CH_4 desorb, thus enhancing the CH_4 recovery
- A proportion of the injected CO_2 will be stored in the coalbed formation, making it difficult for it to leak to the surface
- The successful injection of CO_2 to enhance coalbed methane recovery has been proved by many experimental and numerical studies but large-scale commercial plants are absent

ECBM schematic



Advantages

- Methane recovery from existing wells can be increased from **below 50% to over 95%**
- CO_2 can be stored in the methane-depleted coal seams
- Revenue could be obtained from both increased gas production as well as from **greenhouse gas funding mechanisms**

Challenges

In theory, CO_2 is highly suited for injections in coal seams, but in practice, the situation is more complex

- As the CO_2 adsorbs to the coal surface it causes localized swelling and reduced permeability–issues resulting in lower or even halted production rates
- Potential solutions include alternating CO_2 injection with N_2, by using flue gas, by allowing resting periods between injections, or by performing different drilling approaches, but all these options add complexity and cost to a project making it economically unviable
- Lack of proper monitoring, verification, and accounting (MVA) guidelines and technologies

Source: IEA CLEAN COAL CENTRE (2015) “Potential for enhanced coalbed methane recovery”, Press search, Kearney Energy Transition Institute analysis

Only a few new CO_2 applications are in development

△ Storage technologies

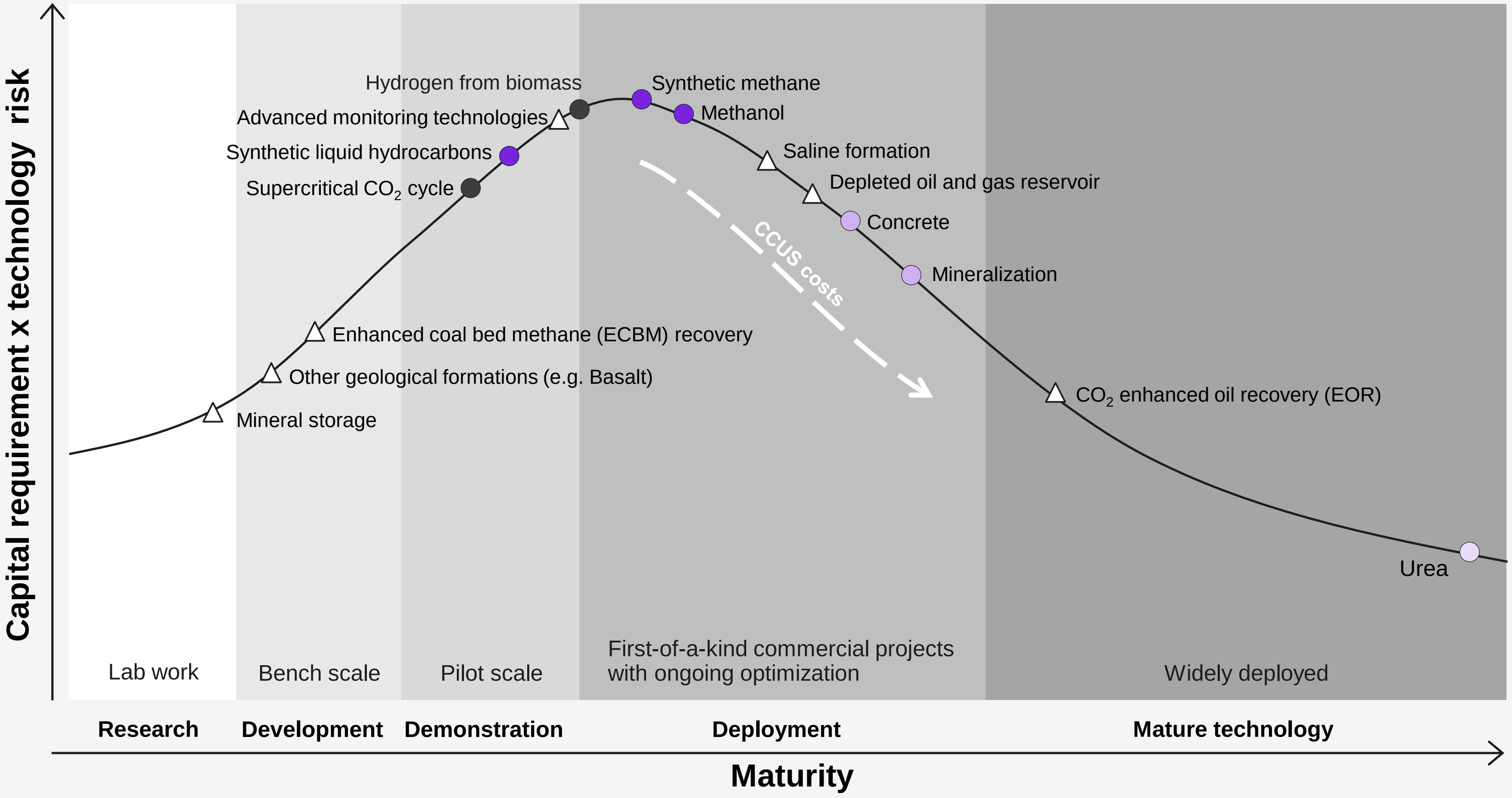
Utilization technologies

● Power generation

● Fuel production

● Cement industry

Maturity curve of CO_2 utilization technologies



Sources: IEA–ETP Clean Energy Technology Guide (2020); Kearney Energy Transition Institute analysis

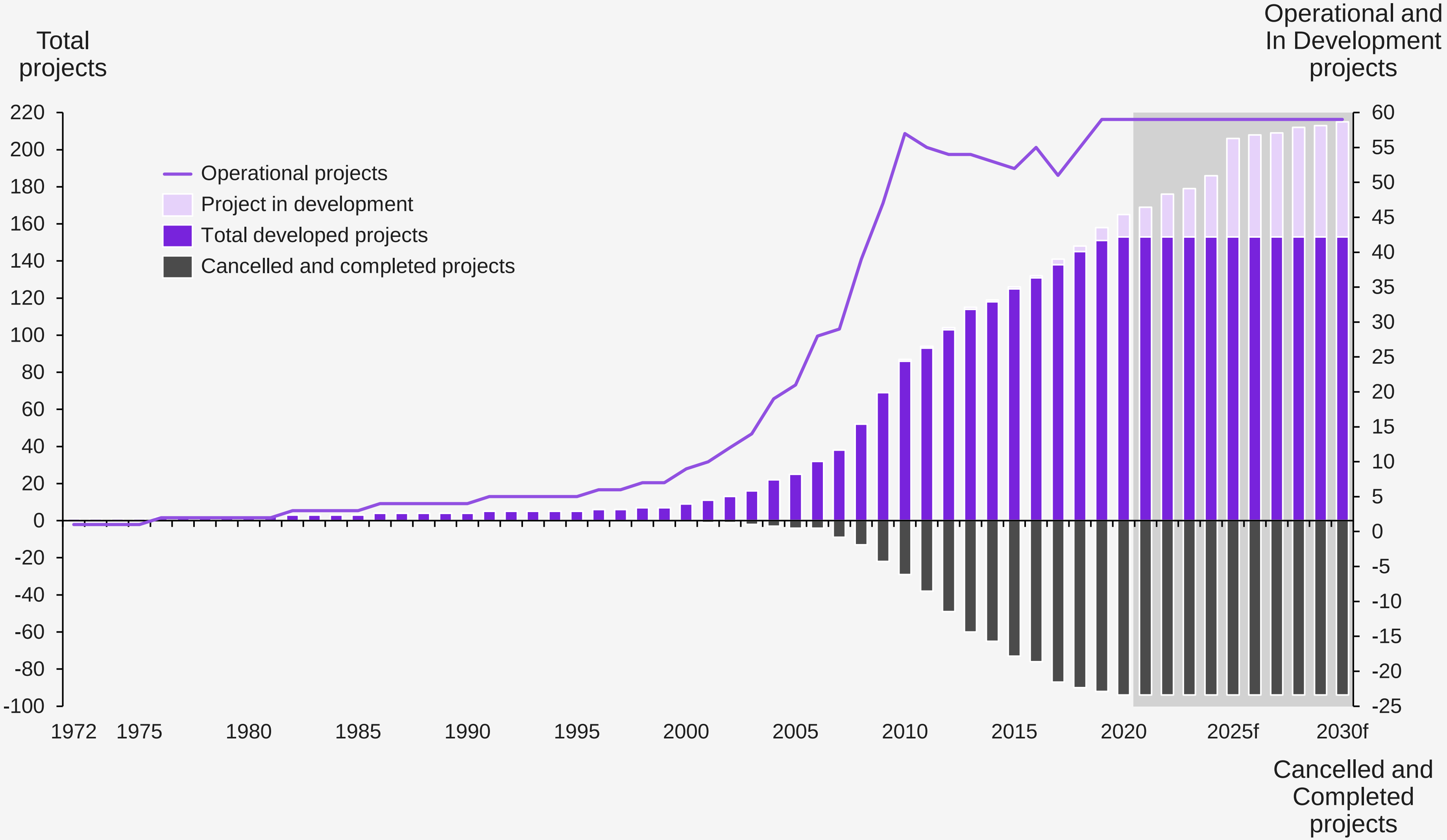
3. Global overview of CCUS development

About 60[1] CCUS projects were operational in (or advanced development phase) in 2020

Since about 2000, the number of CCUS projects in operation have taken off, **but about 60% of developed projects have been terminated or cancelled.**

Global perspective

Overview of global CCUS projects



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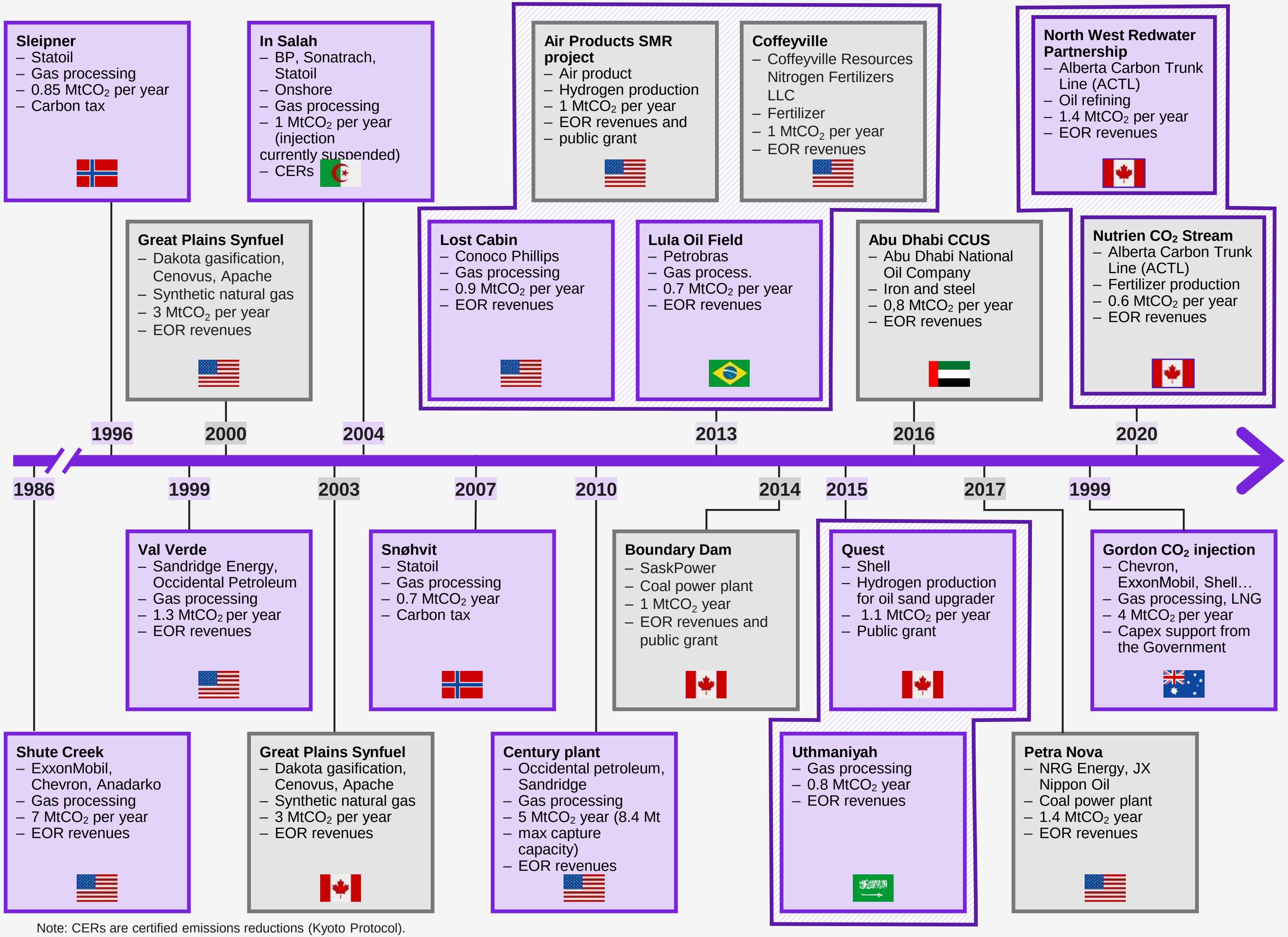
(1) All types of projects included: pilot, demonstration, single-industry application, and clusters (CO_2 captured from multiple sources).
Sources: GCCSI and NREL databases, IEA (2020); Kearney Energy Transition Institute analysis

Most integrated projects in operation are associated with the oil and gas industry

Project name
- Plant owner
- Plant type
- CO_2 storage rate
- Rationale for investment

🟪 Oil and gas processing plant
⬜ EOR storage



Sleipner
- Statoil
- Gas processing
- 0.85 $MtCO_2$ per year
- Carbon tax

Great Plains Synfuel
- Dakota gasification, Cenovus, Apache
- Synthetic natural gas
- 3 $MtCO_2$ per year
- EOR revenues

In Salah
- BP, Sonatrach, Statoil
- Onshore
- Gas processing
- 1 $MtCO_2$ per year (injection currently suspended)
- CERs

Air Products SMR project
- Air product
- Hydrogen production
- 1 $MtCO_2$ per year
- EOR revenues and
- public grant

Coffeyville
- Coffeyville Resources Nitrogen Fertilizers LLC
- Fertilizer
- 1 $MtCO_2$ per year
- EOR revenues

Lost Cabin
- Conoco Phillips
- Gas processing
- 0.9 $MtCO_2$ per year
- EOR revenues

Lula Oil Field
- Petrobras
- Gas process.
- 0.7 $MtCO_2$ per year
- EOR revenues

Abu Dhabi CCUS
- Abu Dhabi National Oil Company
- Iron and steel
- 0,8 $MtCO_2$ per year
- EOR revenues

North West Redwater Partnership
- Alberta Carbon Trunk Line (ACTL)
- Oil refining
- 1.4 $MtCO_2$ per year
- EOR revenues

Nutrien CO_2 Stream
- Alberta Carbon Trunk Line (ACTL)
- Fertilizer production
- 0.6 $MtCO_2$ per year
- EOR revenues

Shute Creek
- ExxonMobil, Chevron, Anadarko
- Gas processing
- 7 $MtCO_2$ per year
- EOR revenues

Val Verde
- Sandridge Energy, Occidental Petroleum
- Gas processing
- 1.3 $MtCO_2$ per year
- EOR revenues

Great Plains Synfuel
- Dakota gasification, Cenovus, Apache
- Synthetic natural gas
- 3 $MtCO_2$ per year
- EOR revenues

Snøhvit
- Statoil
- Gas processing
- 0.7 $MtCO_2$ year
- Carbon tax

Century plant
- Occidental petroleum, Sandridge
- Gas processing
- 5 $MtCO_2$ year (8.4 Mt
- max capture capacity)
- EOR revenues

Boundary Dam
- SaskPower
- Coal power plant
- 1 $MtCO_2$ year
- EOR revenues and public grant

Quest
- Shell
- Hydrogen production for oil sand upgrader
- 1.1 $MtCO_2$ per year
- Public grant

Uthmaniyah
- Gas processing
- 0.8 $MtCO_2$ year
- EOR revenues

Petra Nova
- NRG Energy, JX Nippon Oil
- Coal power plant
- 1.4 $MtCO_2$ year
- EOR revenues

Gordon CO_2 injection
- Chevron, ExxonMobil, Shell…
- Gas processing, LNG
- 4 $MtCO_2$ per year
- Capex support from the Government

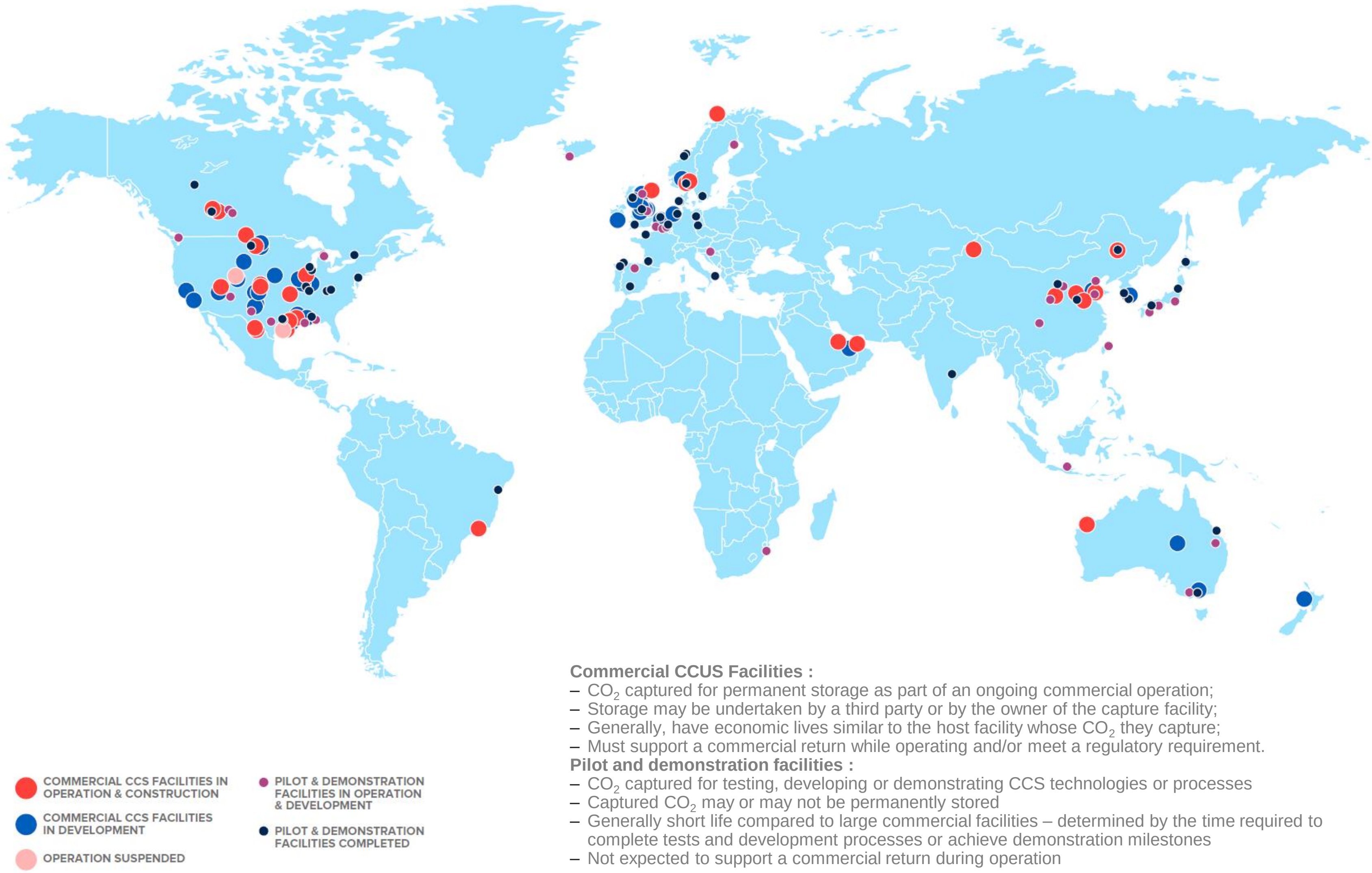
Note: CERs are certified emissions reductions (Kyoto Protocol).
Source: Kearney Energy Transition Institute analysis

The USA houses most of the CCS projects and facilities worldwide

CCUS is mostly being developed in North America, then Europe followed by APAC. Middle East and Brazil are ramping up.

According to the GCCSI definition of commercial facilities(2) in 2020:

- 26 were in operation
- 2 were suspended
- 3 were under construction
- 24 were in early or advanced development



Commercial CCUS Facilities :

- CO_2 captured for permanent storage as part of an ongoing commercial operation;
- Storage may be undertaken by a third party or by the owner of the capture facility;
- Generally, have economic lives similar to the host facility whose CO_2 they capture;
- Must support a commercial return while operating and/or meet a regulatory requirement.

Pilot and demonstration facilities :

- CO_2 captured for testing, developing or demonstrating CCS technologies or processes
- Captured CO_2 may or may not be permanently stored
- Generally short life compared to large commercial facilities – determined by the time required to complete tests and development processes or achieve demonstration milestones
- Not expected to support a commercial return during operation

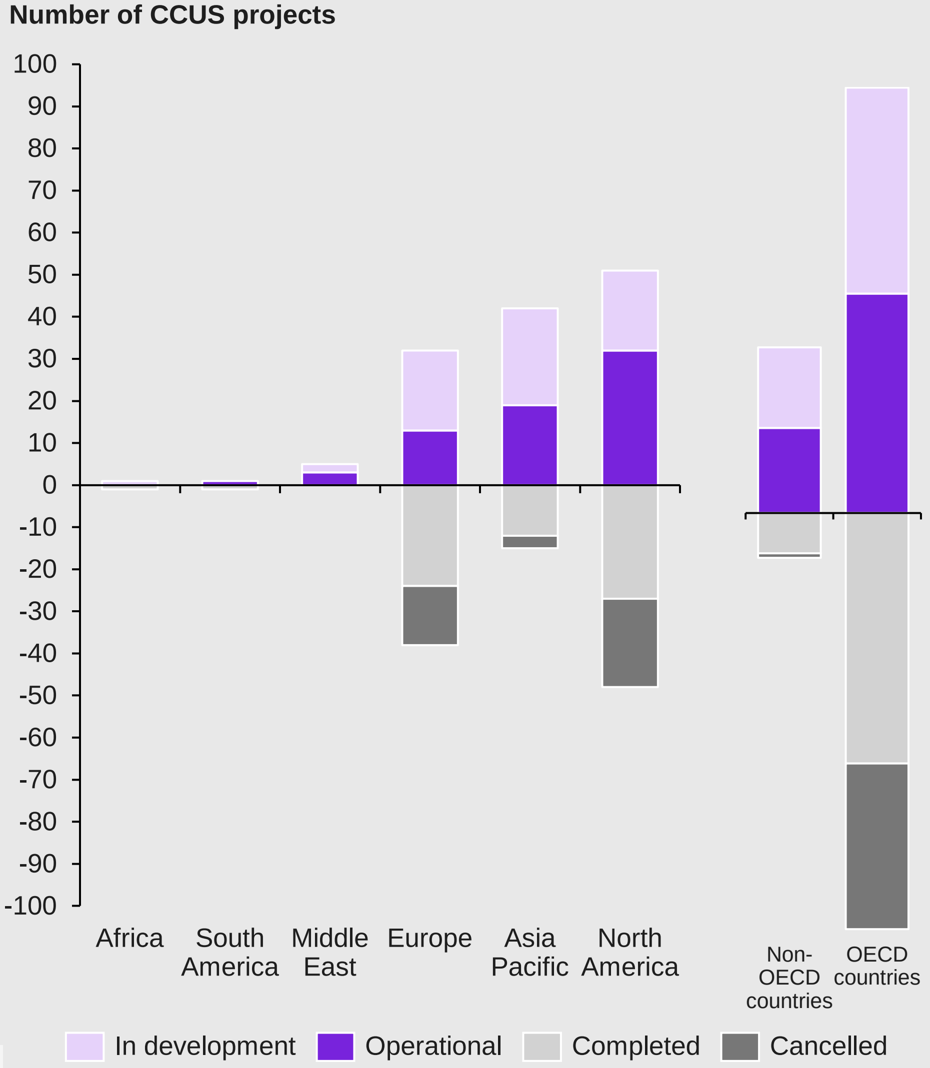
Source: GCCSI – *Global Status of CCS 2020*

Most CCUS facilities are in OECD countries, but many projects have been terminated or cancelled (1/2)

In 2020, about 60 (1) projects are operational and about 60 are in development. CCUS has been a risky business as illustrated by the roughly 90 projects terminated or cancelled since 1972, essentially for economic reasons and lack of public acceptance.

Geographic focus

Overview of global CCUS projects (1972–2020)



(1): Operational: currently running projects; in development: early development, advanced development, or in construction projects; terminated: pilots projects successfully over; cancelled: expected projects cancelled. Both facilities and hubs are taken into account.
Sources: GCCSI database, IEA (2020); Our World in Data: CO_2 and Greenhouse Gas Emissions (2020); Kearney Energy Transition Institute analysis

Considered as the pioneer of CCUS projects, North America, especially the United States, remains the most important place for CCUS by having almost half of the current operational CCUS projects. Although the region has more than 40 in-development projects, more than 35 projects have been cancelled in the past, mostly for economic reasons and lack of public acceptance.

Europe was the second continent to see CCUS projects appearing (in Norway in 1996) and stay the second-largest CCUS place, thanks to North Sea storage area.

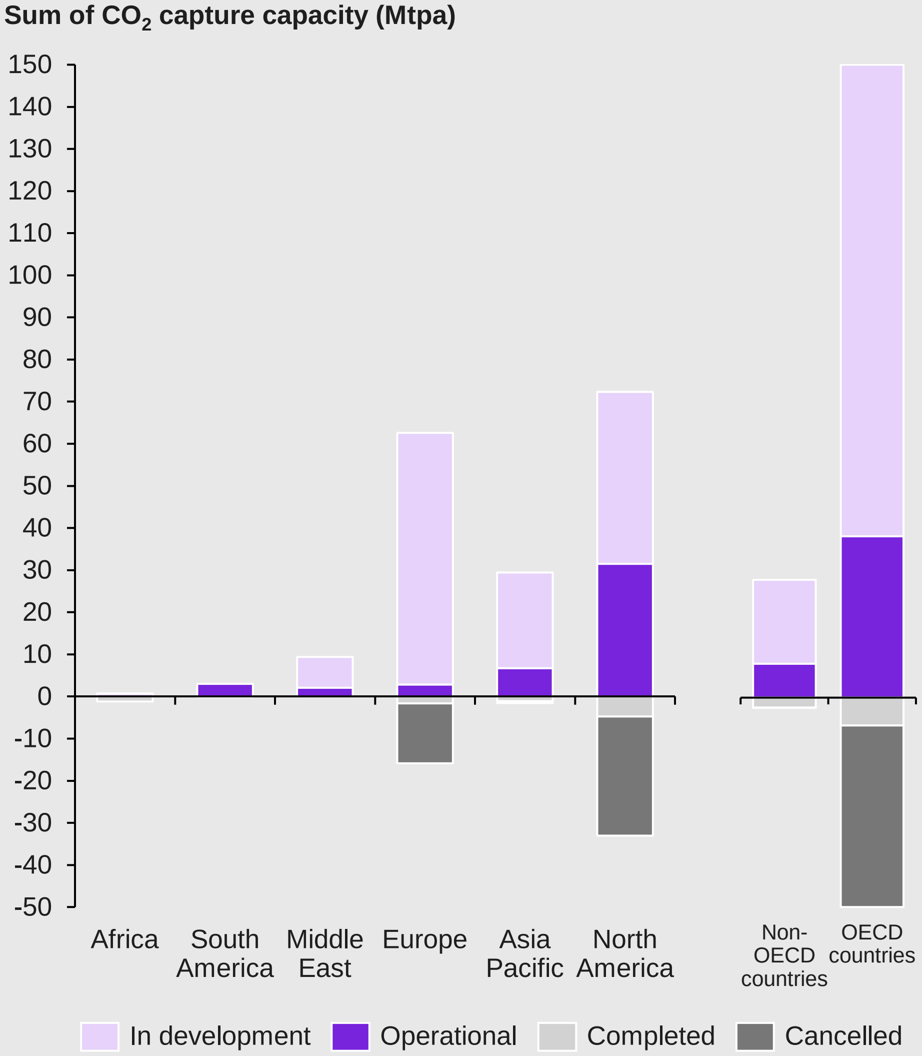
The current pipeline is expected to double the number of projects in the coming years in OECD countries.

Australia, China, and Japan lead the APAC CCUS development and are catching up with Europe either in numbers of operational or in-development projects but have less completed projects so far. Unlike in Europe and in North America, where several projects have been cancelled, APAC seams to be proportionally less concerned by such issues.

Despite oil and gas legacy the Middle East and its huge EOR application potential there has been little CCUS development so far.

Most CCUS facilities are in OECD countries, but many projects have been terminated or cancelled (2/2)

Overview of global CCUS projects (1972–2020)



Notes: Operational: currently running projects; in development: early development, advanced development, or in construction projects; terminated: pilots projects successfully over; cancelled: expected projects cancelled. Both facilities and hubs are taken into account.
Sources: GCCSI database, IEA (2020); Our World in Data: CO_2 and Greenhouse Gas Emissions (2020); Kearney Energy Transition Institute analysis

In 2020, the **global CCUS capacity reached about 50 Mtpa**. The current pipeline of projects should more than quadruple the global capacity in the coming years, targeting about 170 Mtpa.

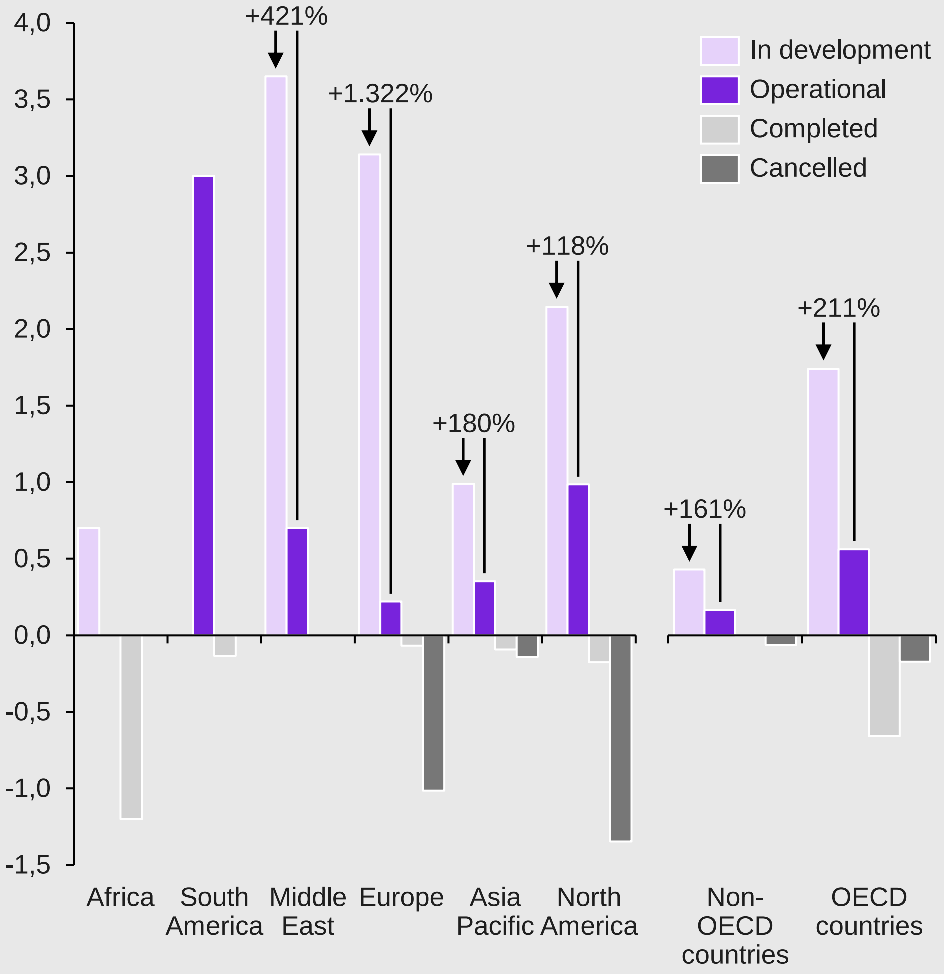
OECD countries have about five times more operational CO_2 capture capacities than the rest of the world. Europe and North America are expected to capture almost three-fourths of the future capacity development.

Most of non-OECD projects are Chinese projects (60% of the projects and 50% of capture capabilities). Middle East represents 10% of the projects and more than 25% of capture capabilities. Other emerging countries such as Brazil, India, South Korea, Taiwan, or South Africa also have launched CCUS projects in the past few years.

Geographic focus

The size of CCUS projects is expected to more than double in the coming years

Median of CO_2 capture of projects (in Mtpa)



The size of CCUS projects has been increasing over the years. Initial projects, either operational, terminated, or cancelled, generally had a storage capacity bellow 1 Mtpa of CO_2. Projects under development often are two to four times bigger in terms of storage capacity.

Operational CCUS projects **commonly range between 0.5 to 1 Mtpa**. Project under development show larger capacity than operating ones, with median capacity ranging from about 2 to 4 Mtpa across most regions, except in APAC, where median of project averages 1 Mtpa. The operating Gordon project (natural gas processing facility in Australia) is expected to reach **4 Mtpa** at full scale. Targeting a storage capacity of **20 Mtpa** (by 2035), the "H21 North of England" is the largest CCUS project under development (operational in 2028). The second ongoing project "Prairie State Generating Station Carbon Capture" target between **10 Mtpa** in 2021 (retrofit of a 816 MWe coal power plant).

If North America is leading the CCUS development sector thanks to EOR. the development of large clusters in the Middle East and Europe may rebalance the importance of CCUS capacity development globally. With hubs and clusters, Europe is going to gather emissions form industrial areas and mostly store it into the North Sea.

The high range of South America relies on one single 3 Mtpa project: Petrobras Santos Basin Pre-Salt Oil Field CCS in Brazil).

Geographic focus

Notes: Operational: currently running projects; in development: early development, advanced development, or in construction projects; terminated: pilots projects successfully over; cancelled: expected projects cancelled. Both facilities and hubs are taking into account. This chart bar has been made in median of CO_2 capture capacity to avoid bias generated from few huge CCUS clusters (for example, the 200 Mtpa CCUS cluster to be developed in the Gulf of Mexico resulting from the aggregation of several small hubs).
Sources: GCCSI database, IEA (2020); Our World in Data: CO_2 and Greenhouse Gas Emissions (2020); Full-Scale Feed Study for Retrofitting the Prairie State Generating Station with an 816 MWe Capture Plant Using Mitsubishi Heavy Industries of America Post-Combustion CO_2 Capture Technology; Kearney Energy Transition Institute analysis

North America is leading the global CCUS development

Leading CCUS countries in 2020	Capture Capacity (Mtpa)	Number of operational projects	Type of storage		
			EOR	Geological storage	Utilisation
United States	27,2	24	95%	4%	
Australia	4,3	5		93%	7%
Canada	4,3	8	72%	28%	
Brazil	3,0	1	100%		
China	2,3	12	85%		15%
Norway	1,7	3		100%	
Saudi Arabia	1,3	2	100%		
United Arab Emirates	0,8	1	100%		
Croatia	0,6	2	100%		
Sweden	0,5	1		100%	
Rest of the world	Not available	9		100%	

North America is by far the current main place for CCUS projects. 60% of the current operational projects take place either in Canada or in the United States, but they mostly represent 84% of the current operational worldwide capture capacity of CO_2 emissions. By adding Brazil in the stats, the last number increases to ~90%. Asia have currently 7 ongoing projects (including 6 in China) for a total capture capacity of 2,6 Mtpa. 4 projects are operational in Europe which capture almost 2,8 $MtCO_2$ per year. Finally, there are 3 operational projects in Middle East with a total capture capacity of 2,1 Mtpa.

Even if these numbers are quite low, many more projects and clusters are in development, mostly in Europe, North America. These projects are starting in the next few years.

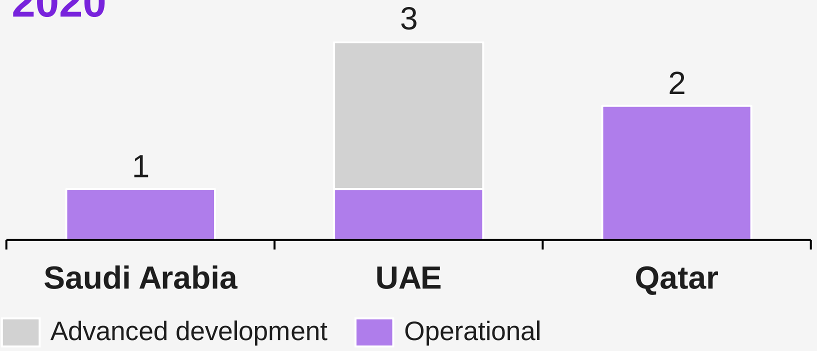
Note : only countries with a capture capacity greater than 0,5 Mtpa are reported
Source : Kearney Energy Transition Institute based on GCCSI and NETL databases

GCC countries have great potential and ambition in CCUS development

GCC countries have huge potential for CCUS

- Up to 30 Gt of CO_2 can be stored underground in the region.
- The Middle East emits 1.9 $GtCO_2$ in 2018 (~5% of global emissions).
- The Middle East benefits from large geological storage capacities, possibly linked to EOR opportunities.

CCUS projects in GCC countries in 2020



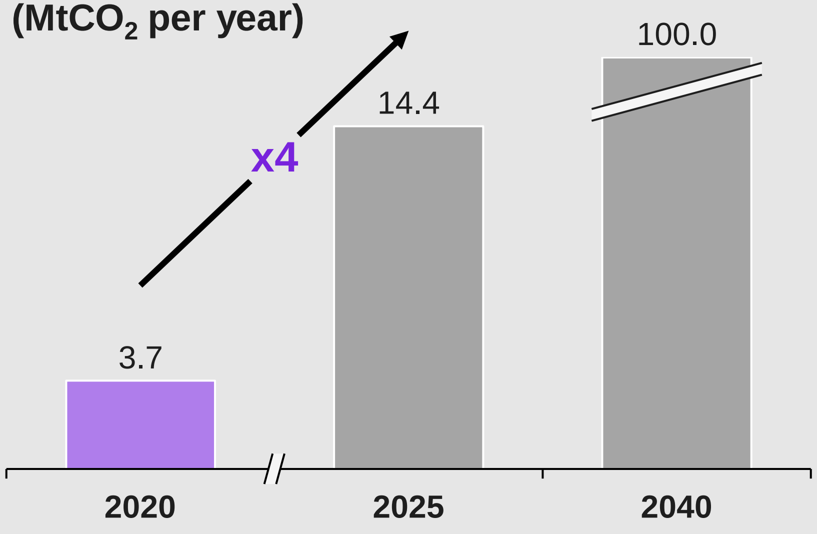
- Three CCUS projects **are in application**: two in **natural gas processing** and one in **iron and steel production** capturing a total of 2.1 Mtpa of CO_2.

CCUS is in governments' minds in their way to decrease CO_2 emissions

- CCS is a strong component of the GCC countries low-carbon plans.
- Capturing CO_2 will permit replacing natural gas used for EOR.

Capture capacity in the GCC region

($MtCO_2$ per year)



Geographic focus

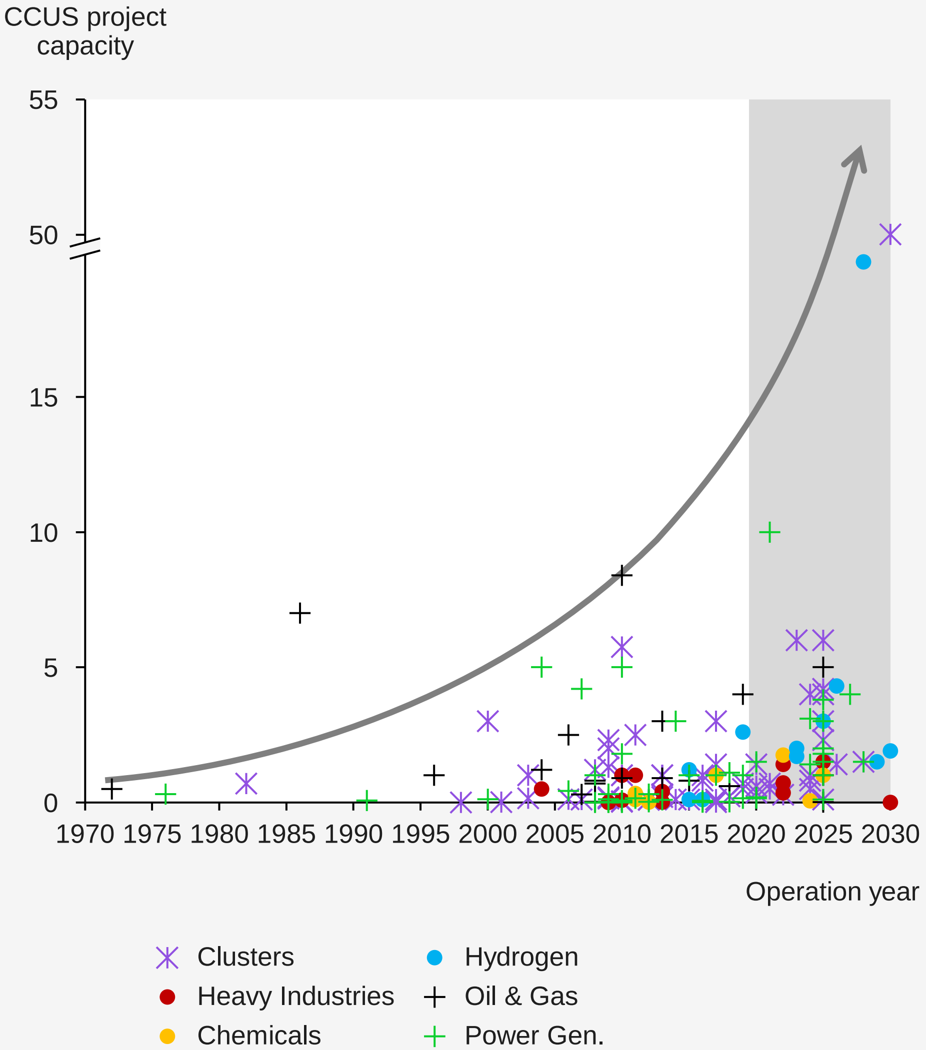
Sources: GCCSI Global Status Report 2020, Our World in Data Annual CO_2 emissions (2018); Kearney Energy Transition Institute analysis

4. Outlook of carbon capture development per sector


Image by rrinch01

Oil & Gas and Power Generation and sectors have been leading the CCUS development

Size of carbon capture projects per industry application (1972-2030, max capacity in Mtpa)



[1]Operational : currently running projects; [2]In development : “early development”, “advanced development” or “in construction” projects
Source: GCCS; NETL; Kearney Energy Transition Institute

The graph represent the main CCUS projects developed and planned to be developed, since the first CCCS project (Terrell Natural Gas Processing Plant) was developed in 1972 in the United States.

Clusters are CCUS projects that capture CO_2 emissions from at least two different types of industrial sources, by opposition to single industry projects (Heavy Industries, Oil & Gas, Chemicals, Hydrogen and Power Generation) that capture CO_2 emissions from a single type of industry. Hydrogen has been treated as a specific entity but could in fact be included in the Oil & Gas category, as Hydrogen projects results from the processing of fossil fuels, generally operated by the Oil & Gas industry.

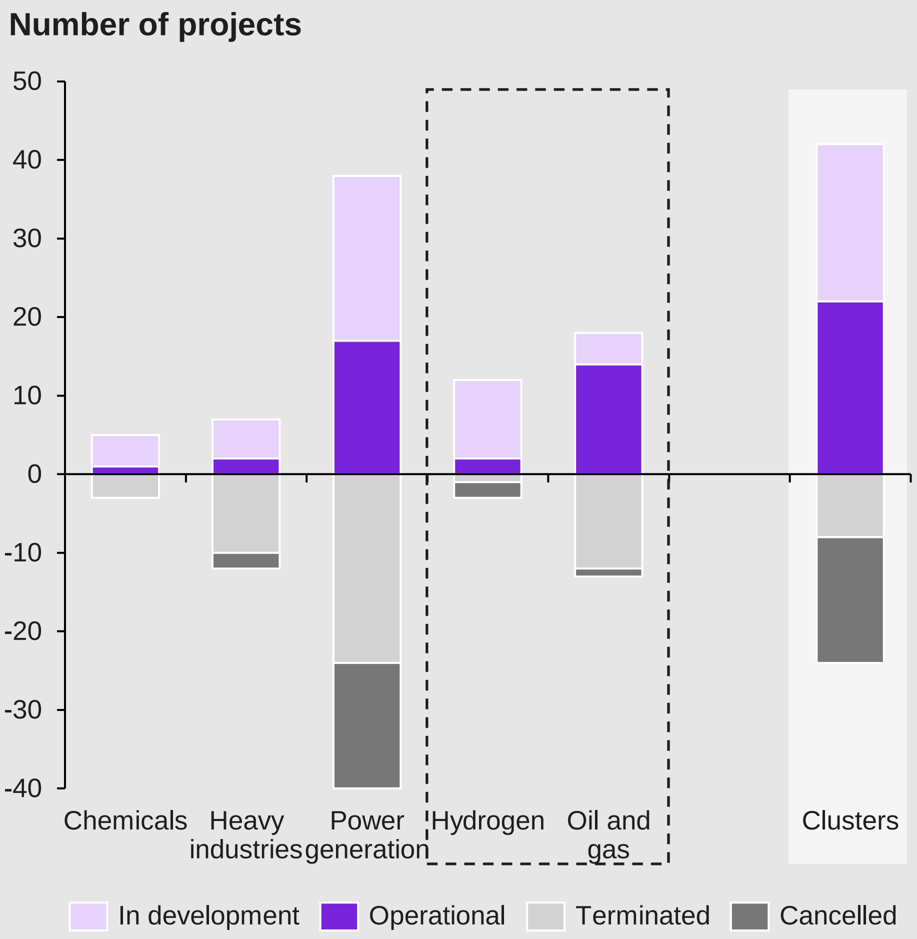
The **Oil & Gas** industry developed the first CCUS project in 1972, capturing CO_2 from natural gas processing and reinjecting it in petroleum reservoir for Enhanced Oil Recovery.

The emerging **blue hydrogen** industry is accelerating the need for CCS projects, with 3 dedicated operating projects. Although Hydrogen projects are treated as a specific industry, they also rely to the **Oil & Gas** industry as they generally result from the processing of natura gas.

The **power generation** started developing CCUS project in 1976 (in the US) capturing CO_2 from coal-fired boiler and was used for soda production.

Application of CCUS projects is extending to other large emitting sectors, including heavy industries, blue hydrogen, and chemicals

CCUS projects dedicated to industry (1972–2020)[1]



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1. New clusters and hubs (such as Exxon's GoM project to capture 50 MT CO_2 / year) are not included as they have been announced recently and are in the planning stage.
Notes: Operational: currently running projects. In development: early development, advanced development, or in construction projects. Terminated: pilots projects successfully over. Cancelled: expected projects cancelled. Hubs serving multiple industries were not included.
Sources: GCCS; NETL; Kearney Energy Transition Institute analysis

Chemicals applications (such as fertilizers or biofuels production) of carbon capture is gaining momentum, with several projects being under development. The purpose of most projects is to combine the production of bio-energies with CCS (BECCS) or recombine the CO_2 captured with low-carbon hydrogen to produce synthetic fuels (bio-jet fuels). (See the Biomass to Energy FactBook.)

Other **heavy industries** (such as cement production or iron and steel) only show a few CCUS project development, mostly because of both high technological and financial barriers to make CCUS a standard in the industry. CCUS projects related to heavy industries are expected to increase four times their current capture capacity.

The largest growth should come from the **power generation** industry with about 20 CCUS projects under development. However, the power sector has developed then cancelled and terminated many projects in the past, which illustrates a high level of abandonment of CCUS projects in that sector.

CCUS projects related to **blue hydrogen** development are currently relatively limited but generally trigger the largest project capacities, comprise between 4 to 5 Mtpa each. Europe, and especially the United Kingdom, have started several H_2 production as a vector of energy projects to become a strong place. The projects under development are expected to catch almost 5 $MtCO_2$ per year. The largest CCUS project in development (H21 North of England) targets 20Mtpa capacity by 2035.

Oil and gas operational CCUS projects capture on average 1.3 $MtCO_2$ per year and are going to slightly increase to 1.7 Mtpa. Chemicals projects are also expected to increase their carbon capacity in order to reach 1 Mtpa. Blue hydrogen production is likely to significantly increase the size of CCUS project in oil and gas.

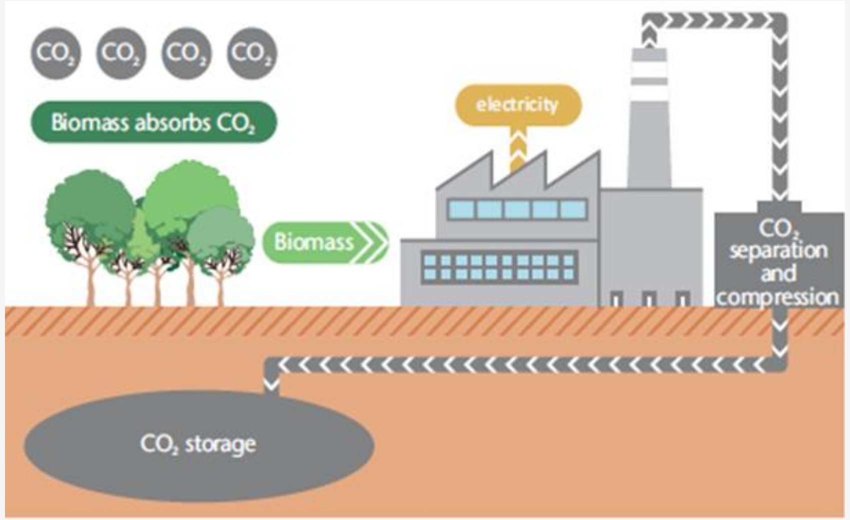
BECCS (Bioenergy and Carbon capture and storage) is a group of technologies to produce energy from biomass and store the CO_2

Fact card: BECCS

Description

- BECCS involves the utilisation of biomass as an energy source and the capture and permanent storage of CO2 produced during the conversion of biomass to energy
- CCS used in the framework of bioenergy represents both a negative carbon solution and a way of producing sustainable energy.
- **CO_2 is captured during bioenergy combustion or in the manufacture of biofuels and can be then stored or used.**
- A few pilot plants of BECCS are already producing electricity while storing carbon, **but mostly at small scale**

Overview of technology



Pros

- Mature technology
- Provides both sustainable energy and negative carbon emission

Cons

- High cost
- Land competition
- Competitiveness on energy price
- Significant efficiency penalties cause the failure of many projects

Key features estimates

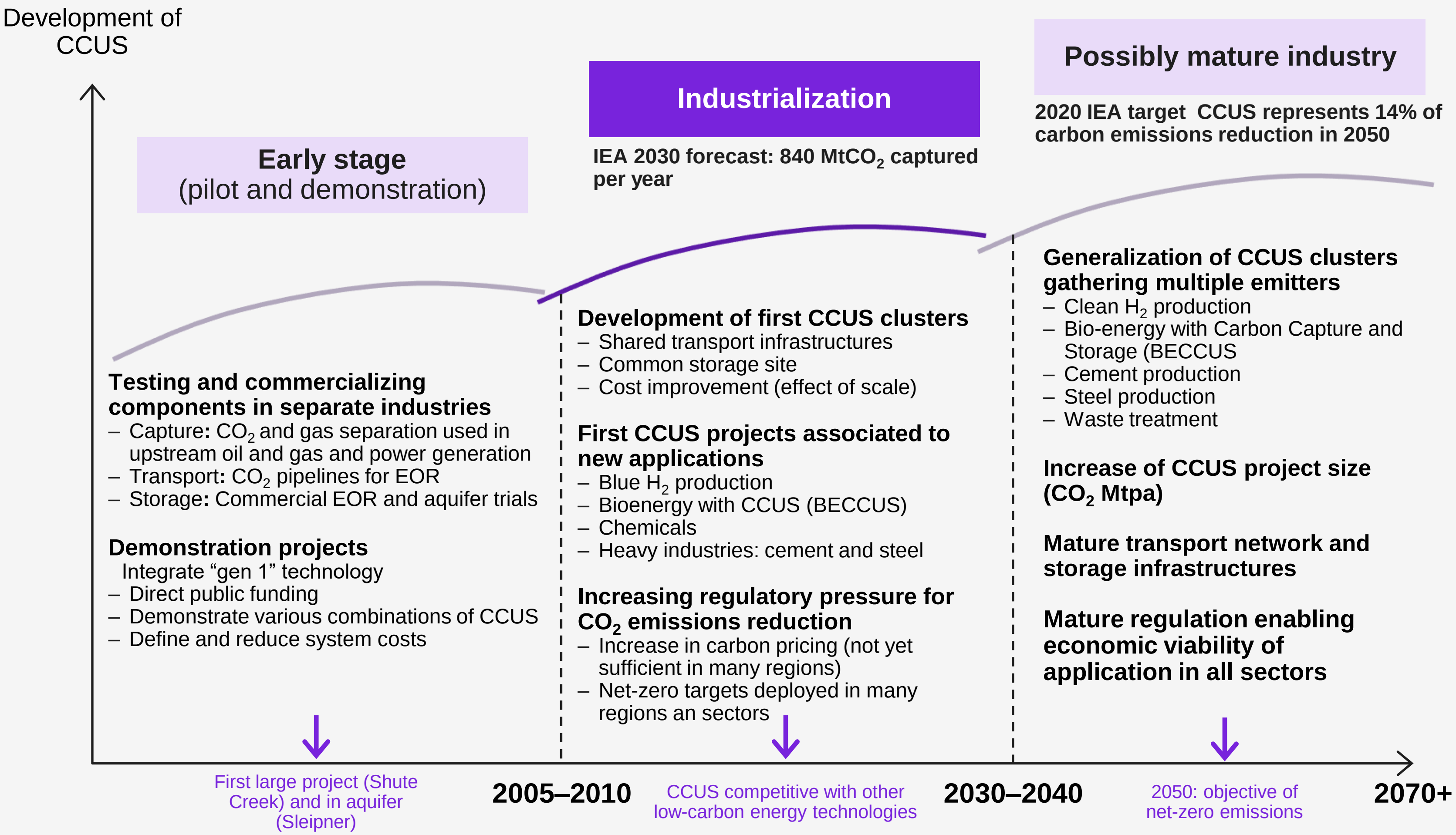
Cost (\$ per t-CO_2)	**\$100 to \$200**	🟥
Potential (Gt-CO_2 per year)	**0.5–5**	🟨
Water Consumption (km^3 per Gt-CO_2)	**60**	🟥
Risk of reversal	**Dependent on storage**	🟨
Verifiability	**Yes**	🟩
Thermal Energy (GJ per t-CO_2)	**<0**	🟩
Electrical Energy (MWh per t-CO_2)	**<0**	🟩
Land use (m^2 per t-CO_2 per year)	**310–580**	🟥

Advantage 🟩 🟨 🟥 **Drawback**

Sources: "Technology Roadmap Delivering Sustainable Bioenergy," IPPC "SR1.5 – chapter 3 and 4" (2018); Kearney Energy Transition Institute analysis

CCUS deployment has entered an industrialization stage that is characterized by the execution of larger projects and clusters

Stage of CCUS development



Development of CCUS

Early stage
(pilot and demonstration)

Testing and commercializing components in separate industries
- Capture**:** CO_2 and gas separation used in upstream oil and gas and power generation
- Transport**:** CO_2 pipelines for EOR
- Storage**:** Commercial EOR and aquifer trials

Demonstration projects
Integrate “gen 1” technology
- Direct public funding
- Demonstrate various combinations of CCUS
- Define and reduce system costs

First large project (Shute Creek) and in aquifer (Sleipner)

2005–2010

Industrialization

IEA 2030 forecast: 840 $MtCO_2$ captured per year

Development of first CCUS clusters
- Shared transport infrastructures
- Common storage site
- Cost improvement (effect of scale)

First CCUS projects associated to new applications
- Blue H_2 production
- Bioenergy with CCUS (BECCUS)
- Chemicals
- Heavy industries: cement and steel

Increasing regulatory pressure for CO_2 emissions reduction
- Increase in carbon pricing (not yet sufficient in many regions)
- Net-zero targets deployed in many regions an sectors

CCUS competitive with other low-carbon energy technologies

2030–2040

Possibly mature industry

2020 IEA target CCUS represents 14% of carbon emissions reduction in 2050

Generalization of CCUS clusters gathering multiple emitters
- Clean H_2 production
- Bio-energy with Carbon Capture and Storage (BECCUS
- Cement production
- Steel production
- Waste treatment

Increase of CCUS project size (CO_2 Mtpa)

Mature transport network and storage infrastructures

Mature regulation enabling economic viability of application in all sectors

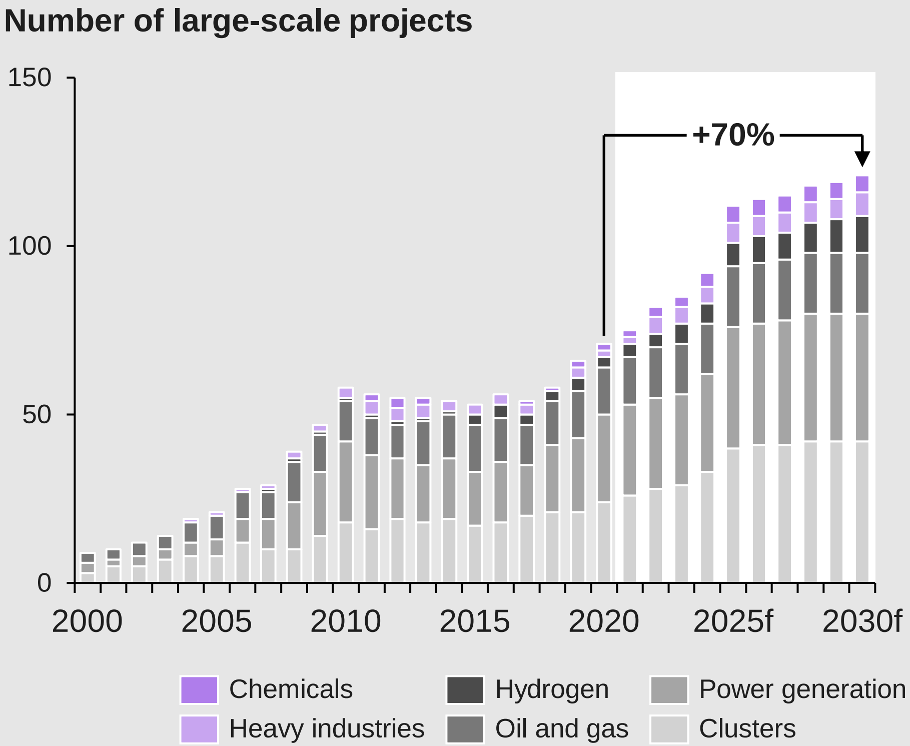
2050: objective of net-zero emissions

2070+

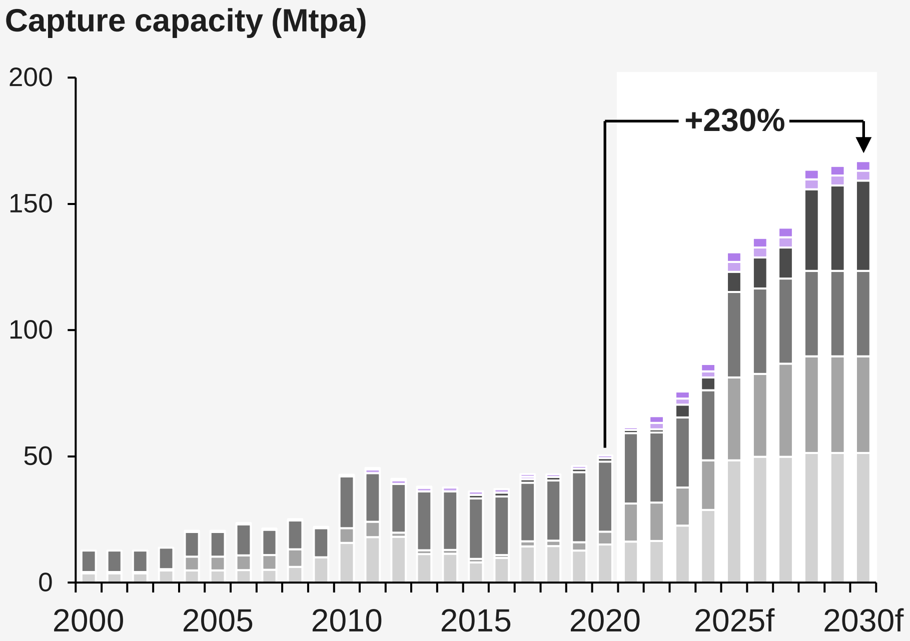
Note: Large projects refers to integrated CCUS projects larger than 0.6 $MtCO_2$ per year.
Sources: IEA and GCCSI reports; Kearney Energy Transition Institute analysis

Global CCUS capacity is expected to more than double in the next decade, with the emergence of larger projects and clusters

Number of operational CCUS projects



Total capture operational CCUS projects



Power plants with CCUS is the sector with more large-scale facilities than any other industries (17 new projects between 2015 and 2030). Those facilities are expected to capture a total of 64 $MtCO_2$ per year. The chemicals industry plans to develop eight new large-scale facilities by 2030, capturing almost 8 $MtCO_2$ (on average 1 $MtCO_2$ per project).

In contrast, the blue hydrogen industry is expected to increase its capture capacity from 2 to 46 $MtCO_2$ (on average 5 $MtCO_2$ per project).

Note: CCUS clusters projects (serving multiple industries and applications) have been included for the realization of the graphs.
Sources: GCCS, NETL; Kearney Energy Transition Institute analysis

CCUS facilities have been operating for decades in natural gas processing sector

CCUS is the only solution to address CO_2 emissions from natural gas processing which assumes importance given the projected high share of natural gas across energy systems over the next few decades

Context

- Natural gas deposits can contain large amounts of CO_2 – even up to 90% – which, for technical reasons, must be removed before the gas is sold or processed for liquefied natural gas (LNG) production
- Till 2000s, almost all the CO_2 captured globally at large-scale facilities was captured from gas processing plants, but now make up about two-third of the total
- Relatively mature application area where CO_2 can be captured at relatively low cost and high concentration. Captured CO_2 can be reinjected into geological formations or used for EOR.

Challenges

- Location dependency i.e. a large-scale gas processing plant requires near-by gas fields (for gas supply) and CO_2 transport infrastructure (for ease in utilization ex: pipeline connectivity to EOR storage sites)
- Natural gas processing requires very high capture rates to meet product gas specifications for pipeline transport typically less than 0.5% CO_2 by volume) and liquefaction (0.005% CO_2 by volume)

Physical separation is currently the main capture method used in natural gas processing with most of the large-scale gas processing plants using proprietary solvents

Key technologies	Description
Physical adsorption	Physical absorption uses a liquid solvent to absorb CO_2 from flue gases that have high CO_2 partial pressures, without a chemical reaction occurring. Common physical solvents include Selexol (dimethyl ethers of polyethylene glycol) and Rectisol (methanol).
Physical absorption	In physical adsorption, molecules are captured on the surface of selective materials called adsorbents. Desorption of the CO_2 (release from the surface) may be achieved using pressure swing adsorption (PSA), performed at high pressure, or vacuum swing adsorption (VSA), which operates at ambient pressure. A hybrid configuration also exists, known as Vacuum Pressure Swing Adsorption (VPSA)
Cryogenic Separation	Cryogenic separation is a commercial process that takes place at very low temperature, where the component of feed gas starts to liquefy. Cryogenic process for separation involves cooling of the gas to a very low temperature so that CO_2 can be liquefied and separated. The cryogenic distillation method is commonly used in sweetening of natural gas, it separates and liquefies CO_2 in the natural gas stream. The main advantage of the cryogenic distillation is the capability of the process to produce liquid CO_2 ready for transportation.
Membrane separation	Membrane separation uses a semi-selective membrane (a polymeric membrane that allows some gases to pass through but not others) to concentrate CO_2 on one side of the membrane, thus separating it from a stream. In natural gas processing, this technology is at the demonstration stage currently

Sources: “Special Report on Carbon Capture Utilisation and Storage” International Energy Agency 2020, Press search,Kearney Energy Transition institute analysis

Globally, the biggest commercial CCUS plants in operation are in natural gas processing sector

Natural Gas Processing

Shute Creek Gas Plant, La Barge, Wyoming

Operator	ExxonMobil
Start date	1986
Size	7 Mtpa
CO_2 Source	Natural gas stream from fields in Wyoming, including LaBarge field
Separation	Cryogenic Separation
Transport	142-mile pipeline
Oil Field EOR Storage Site	A series of fields in Wyoming, Colorado, and Montana
Key Highlights	A concentrated acid gas stream of about 60% hydrogen sulfide and 40% CO_2 is injected into a section of the same reservoir from which it was produced, safely disposing of the hydrogen sulfide and CO_2. In 2008, an expansion of the CO_2 capture facility brought the capacity up to 7 Mtpa.

Century Plant, Pecos County, Texas

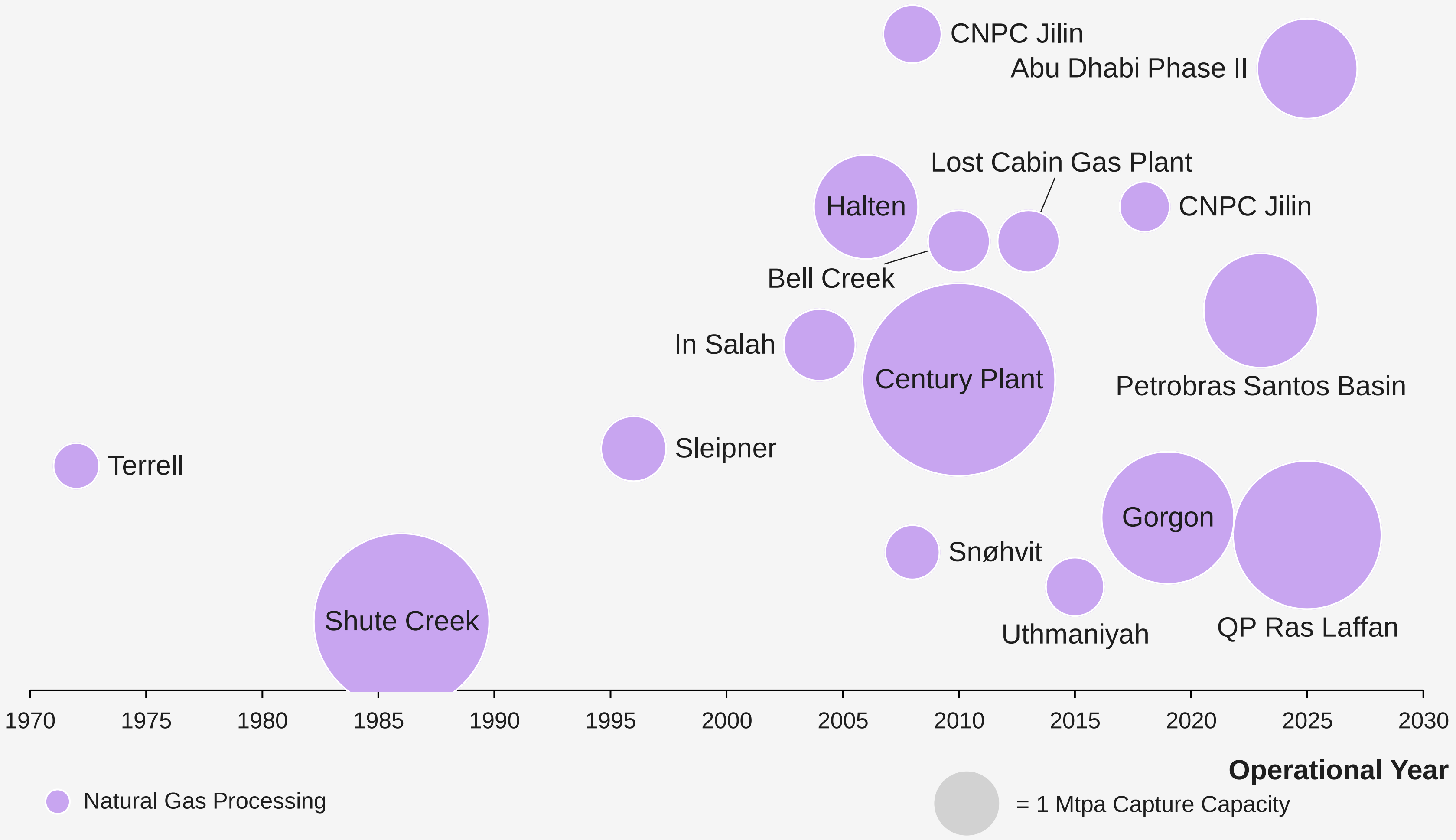
Operator	Occidental Petroleum
Start date	2010
Size	8.4 Mtpa
CO_2 Source	Nearby fields in the Val Verde sub-basin
Separation	Physical separation using solvents
Transport	100-mile pipeline
Oil Field EOR Storage Site	Permian Basin Fields
Key Highlights	The largest single industrial source CO_2 capture facility in North America. Since 2010, the plant has supplied CO_2 for enhanced oil recovery operations via a 100-mile pipeline linking the facility to the CO_2 distribution hub in Denver City, Texas. The plant was designed in 2008 with a maximum capacity of 5 Mtpa and brought online in 2010. An expansion in 2012 increased capacity to 8.4 Mtpa

Source: MEETING THE DUAL CHALLENGE, APPENDIX C – CCUS PROJECT SUMMARIES, National Petroleum Council report (2020), Carbonbrief.org, Kearney Energy Transition Institute analysis

Natural gas processing pioneered the CCS application in 1972, but really took off forty years later

Natural Gas Processing combined with CCUS projects

Non-exhaustive



Note: some Pilots and Demonstration CCS facilities are not included in this graph when their capture capacity remains unknown
Source: Kearney Energy Transition Institute, WEO (2019), International Energy Agency (2019), The Future of Hydrogen, Seizing today's opportunities, GCCSI Global Status of CCUS 2019

Several technology solutions are applicable to the power generation sector

CCUS can allow existing plants to continue operations after CO_2 capture retrofits and lifetime extensions

Power Generation

Context

- Globally, the power sector is the largest emitter of CO_2 today, at **about 40% of global energy** related CO_2 emissions and is expected to witness robust growth with electricity demand almost tripling over the period to 2070.
- Carbon capture is projected to contribute about **20% to the cumulative decarbonization** efforts of the powers sector over the period to 2070.
- CCUS development for fossil fuel power generation could help provide dispatchable power sources and therefore support the development of intermittent / renewable power sources

Barriers

- Relatively young age of many fossil fuel-fired power plants, in particular coal plants, notably in China
- Integrating increasing amounts of variable renewables into power systems is a major task in the transition to clean electricity

Key technologies	Description
Chemical absorption	At a coal-fired power plant with post-combustion capture using chemical absorption, the carbon dioxide is separated from the combustion flue gas by using a chemical solvent (such as amine-based). The CO_2 is released at elevated temperatures, the solvent regenerated and recycled back for further operation.
Physical absorption	In an integrated gasification combined-cycle coal power plant, coal is gasified into a synthesis gas, consisting of hydrogen and carbon monoxide. The synthesis gas is shifted in a water-gas-shift (WGS) reaction to produce additional hydrogen and convert the carbon monoxide into carbon dioxide. The carbon dioxide is then captured from the shifted syngas using physical separation processes, such as adsorption, and afterward, the remaining hydrogen (H_2) is combusted in a combined-cycle gas turbine that generates power.
Oxy-fueling	An oxy-fueling coal-fired power plant involves the combustion of coal using nearly pure oxygen instead of air, resulting in a flue gas composed of CO_2 and water vapor, which can be dehydrated to obtain a high-purity CO_2 stream.
Membranes polymeric	At a coal-fired power plant with post-combustion capture using chemical absorption, the carbon dioxide is separated from the combustion flue gas by membranes, which are polymeric films and act as a selective barrier able to separate CO_2 from a stream.
Chemical looping combustion	Chemical looping systems use small particles of metal (such as iron and manganese) to bind oxygen from the air to form a metal oxide (first reactor), which is then transported to the other reactor where it releases the oxygen for the combustion of the fuel, thus generating energy and a concentrated stream of CO_2 (second reactor).
Supercritical CO_2 cycle	While in conventional power plants flue gas or steam is used to drive one or multiple turbines, in supercritical CO_2 (sCO_2) cycles supercritical CO_2 is used (CO_2 at or above its critical temperature and pressure, where liquid and gaseous phases of CO_2 are indistinguishable). sCO_2 cycles offer many potential advantages, including higher plant efficiencies, lower air pollutant emissions, lower investment costs and high CO_2 capture rates.

Sources: "Special Report on Carbon Capture Utilisation and Storage" International Energy Agency 2020; Kearney Energy Transition institute analysis

Chemical absorption is the most mature carbon capture technology option in power generation

Overview of key carbon capture technologies in power generation

Not exhaustive

	Chemical absorption	Physical absorption	Oxy-fueling	Membranes	Chemical looping
Stage	Post combustion	Pre combustion	Oxy-fuel	Post combustion	Oxy-fuel
Capture rates	~90%	~90%	90%	80–90%	Up to 98%
Operating temperature (°C)	120°–150°C	120°–150°C	High	High	600°–900°C
Importance for net zero	High	Moderate	Moderate	Moderate	Moderate
Key countries	United States, Canada, United Kingdom, Japan	China, Japan, United States	Australia, Spain	Australia, Brazil, Norway, United States	NA
Key projects	– Boundary Dam Carbon Capture Project, Canada – Petra Nova Carbon Capture, United States, largest post-combustion carbon capture system installed on a coal-fired power plant (can capture up to 1.4 MtCO$_2$ per year for use in enhanced oil recovery and received $163 million (2008)	– In Japan, CO$_2$ capture tests started end of 2019 at an oxygen-blown IGCC power plant (160 MW) – In Belgium, a 20 MW pilot plant tested pre-combustion capture at the 253-MW Buggenum IGCC power plant between May 2011 and October 2013	– Coal-fired Callide power station (30 MW) in Australia – Circulating fluidized bed coal-fired boiler (30 MW) in Spain (Compostilla project) – Schwarze Pumpe lignite power station (30 MW) in Germany	– Membrane-based separation of carbon dioxide has been performed at demonstration and large scale (respectively in Australia and Brazil) for natural gas processing. Moreover, the Polaris membrane is available commercially for CO$_2$	– No major large-scale demonstration projects but around 40 pilot plants with varying capacities (0.2 kW to 3 MW) have operated chemical looping combustion under various conditions relevant for combustion of coal, gas, oil, and biomass

Technology readiness level

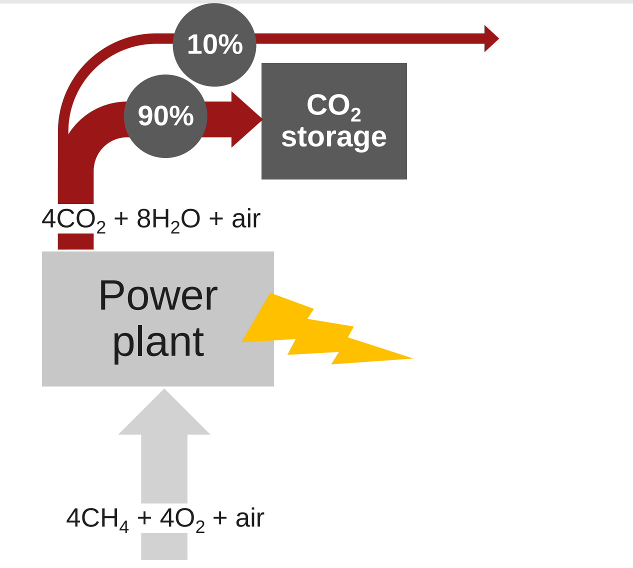
High → Low

Sources: "Special Report on Carbon Capture Utilisation and Storage" International Energy Agency 2020; Kearney Energy Transition institute analysis

Carbonate fuel cell is a promising technology innovation in the power sector that produces electricity while increasing the concentration of CO_2 in the flue gas

CO_2 is concentrated by a fuel cell process as a side reaction of power generation. For example, a 500 MW plant would produce an additional 120 MW using MCFC instead of consuming 50 MW for conventional capture.

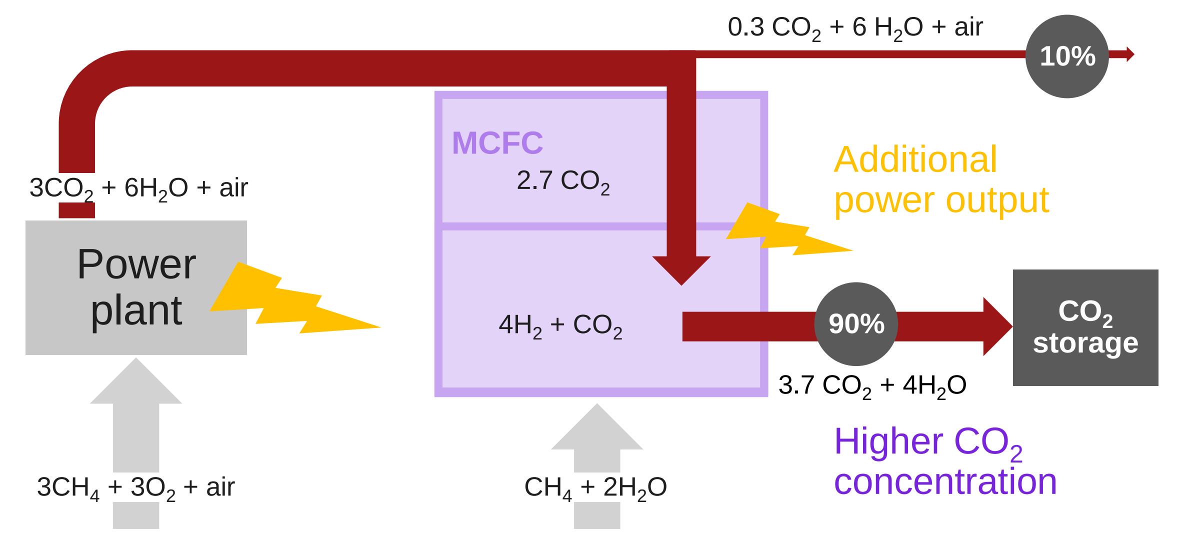
Conventional gas power plant with CCS



Power output: 400MW for a 500MW plant
Estimated carbon intensity: ~**60g CO_2/kWh**

- A conventional combined cycle gas turbine (CCGT) **produces power** from methane combustion.
- About 20% of the power generated is consumed by the CO_2 storage process (90% CO_2 captured).
- Exhausted gases **release CO_2** in the atmosphere.

Gas power plant with molten carbonate fuel cell capture unit



Power output: +50% to + 200% (depending on CO_2 capture intensity)
Estimated carbon intensity:**~40 to 25g CO_2/kWh**

- Conventional cycle gas turbine **produces power** from methane combustion
- Exhausted gases are **cleaned from 90% of their CO_2** by the molten carbonate fuel cell, which is powered by methane (reformed into hydrogen).
- The molten carbonate fuel cell **produces additional decarbonized power** during the electrochemical reaction of capturing CO_2.

Note: Cost analysis for SureSource technology in a 550MW coal-fired plant equippedforty90% CCUS
Sources: CCUS Talks: The Technology Cost Curve, GCCSI, 2020; Molten Carbonate Fuel Cell Performance for CO_2 Capture from Natural Gas Combined-Cycle Flue Gas, Journal of the Electrochemical Society, 2020; Exxon Mobil Advanced Carbonate Fuel Cell Technology in Carbon Capture and Storage, FuelCell Energy: Carbon Capture with Molten Carbonate Fuel Cell Power Plants, 2017; Kearney Energy Transition Institute analysis

Chemical innovations are helping reduce cost in extracting CO_2 from post-combustion gas.

PNNL team has also identified the ideal rock and process (time efficient) of injecting captured carbon in it to transform it into a carbonate rock i.e. **mineralisation**

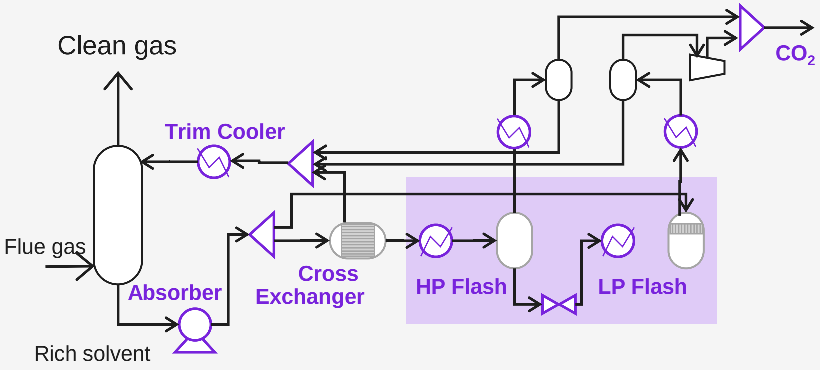
Since this process transforms CO_2 from gas to solid state, it is stable for geologic time and would not cause earthquakes

Power Generation

Overview

- U.S. DOE's Pacific Northwest National Laboratory (PNNL) – along with partners from Fluor Corp and the Electric Power Research Institute – are using the unique properties of a solvent, known as EEMPA (N-(2-ethoxyethyl)-3-morpholinopropan-1-amine), that allow it to sidestep the energetically expensive demands incurred by traditional solvents
- The method demonstrated 90% CO_2 capture and release from power plant flue gas for $47.10 per metric ton (vs $58.30 per metric ton for current commercial solutions)
- Pivoting to plastic equipment (from steel) further optimizes the costs (by $5 per metric ton)

Two-stage flash model



Advantages

- **Reduces costs by 19% and requires 17% less energy** compared to commercial counterparts (aqueous amines-based absorption solutions)
- Captures carbon without high water content, so it's **water-lean**
- **Much less viscous** than other water-lean solvents hence no diluent needed
- Low solvent volatility
- Can be used in existing infrastructure

R&D roadmap

- In 2022, PNNL team will produce 4,000 gallons of EEMPA to test in the facilities (0.5-megawatt scale) at the National Carbon Capture Center in Shelby County, Alabama, in a project led by the Electric Power Research Institute in partnership with Research Triangle Institute International
- Key research areas would be to test increasing scales and further refine the solvent's chemistry, with the aim to reach the U.S. DOE's goal of deploying commercially available technology that can capture CO_2 at a cost of $30 per metric ton by 2035

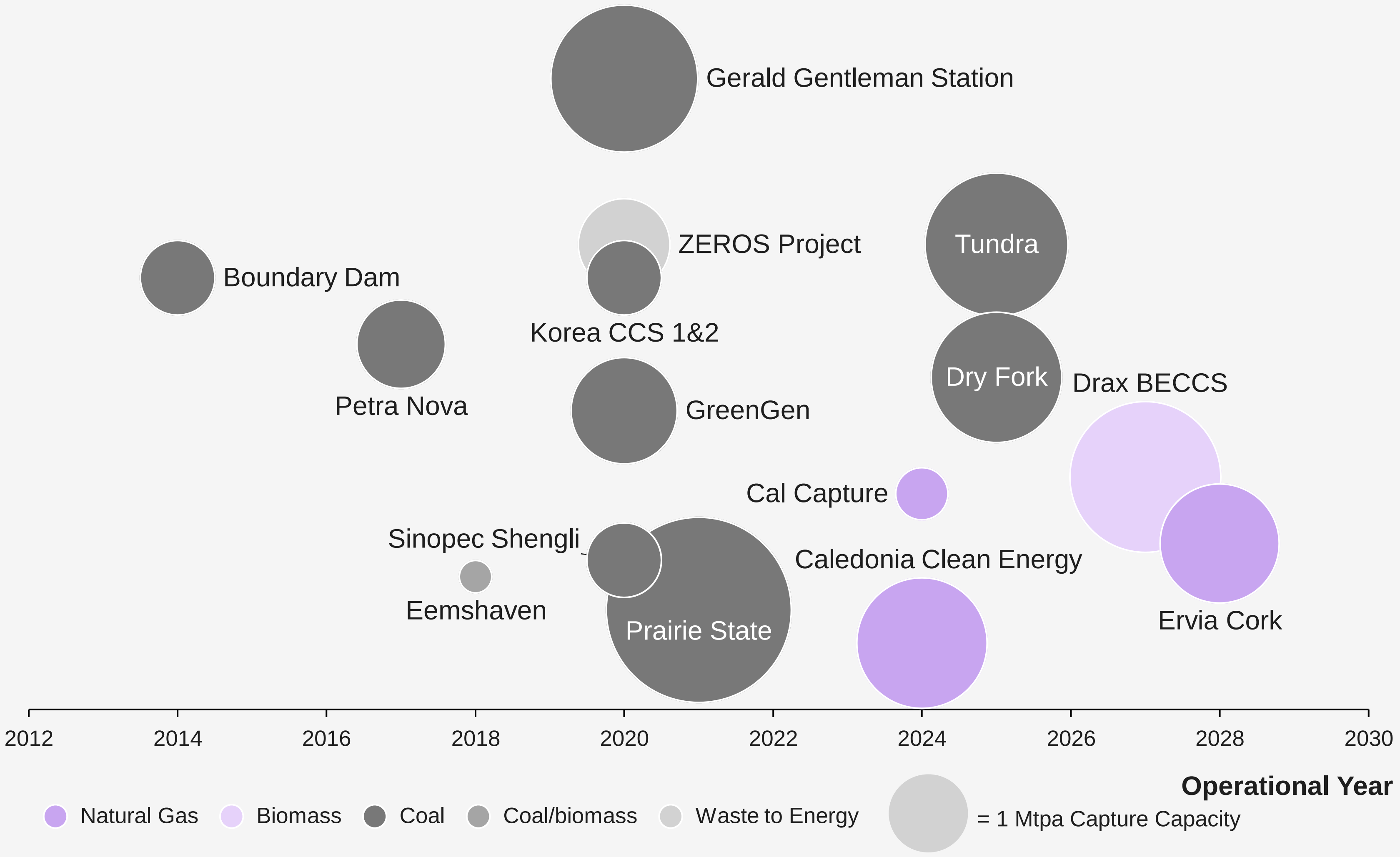
Source: DOE/PACIFIC NORTHWEST NATIONAL LABORATORY, Techno-economic comparison of various process configurations for post-combustion carbon capture using a single-component water-lean solvent (Jian et all 2021), Press search, Kearney Energy Transition Institute analysis

CCUS use has been introduced to retrofit biomass, natural gas, or coal-fired power plants and abate their CO_2 emissions

In 2019, 60% of the electricity generation relied on coal or natural gas use, and the global electricity generation is forecasted to grow by 23% from 2019 to 2030. In the World Energy Outlook 2020 Stated Policies Scenario, CCUS will be needed to mitigate the additional emissions.

Power generation combined with CCUS projects

Non-exhaustive



Note: some Pilots and Demonstration CCS facilities are not included in this graph when their capture capacity remains unknown
Source: Kearney Energy Transition Institute, WEO (2020), International Energy Agency (2019), The Future of Hydrogen, Seizing today's opportunities, GCCSI Global Status of CCUS 2019

The first large-scale CCUS power plant began operation in October 2014 in Canada, marking a landmark in clean fossil-fuel power generation

Saskpower Boundary Dam CCUS Project

Project characteristics	Details
Power capacity with CCUS	115 MW, 90% CO_2 emissions captured, 1 $MtCO_2$ per year (more than 4 Mt CO_2 cumulatively has been captured by March 2021, including 0.73 Mt in 2020)
Total capital costs	$1.42 billion (8% over budget)
Carbon capture unit cost	$620 million
Government funding	$314 million
Capture type	Post-combustion by Cansolv (Shell)
Transport type	Pipeline (built and owned by Cenovus)
Storage type	EOR (sold to Cenovus)
Planning	Plan start: February 2008 Construction start: April 2011 Operation status: Fully operational in Q1-2016

Sources: BNEF "Operational CCUS in Canada: Blueprint or One-Hit Wonder?" (2014); picture credit: adapted from SaskpowerCCUS.com; Kearney Energy Transition Institute analysis

After more than six years in planning, **CCUS for power generation has finally become a reality** with the opening of the SaskPower Boundary Dam, the first large-scale CCUS power plant in operation.

After initial start-up hiccups, the plant appears to be running "exceptionally well" as of Q1 2016, and has captured 0.75$MtCO_2$ since operational start-up

This project illustrates the substantial upfront costs required by each large integrated CCUS project: $640 million in pure capture costs excluding pipelines (~$20 million for 100 km), storage site characterization and storage facilities (up to a dozen injection wells, depending on reservoir quality).

Although of commercial-scale, Boundary Dam is not a commercial initiative: SaskPower, a state-owned utility monopoly, has received public grants and increased electricity tariffs to finance the project.

Other facilitating factors for SaskPower include low-cost local fuel (lignite), CO_2 sales for EOR, and the absence of transport costs, as Cenovus is building and owns the related transport pipeline.

Saskpower CEO estimates the LCOE for Boundary Dam to be similar to that of a new-build gas combined cycle plant in the region.

Post-combustion capture in a natural gas-fired power plant for low carbon electricity

Caledonia Clean Energy Project is a natural gas power plant using post-combustion carbon capture technology to remove up to 90% of CO_2 emissions. The captured CO_2 is then stored into the North Sea for geological storage.

Caledonia Clean Energy Project

Country: United Kingdom

Operational date: 2025

Capex: around £50M for pre-feed

CO_2 savings: 3.1 Mt year

Project leaders: Summit Power Group

Project characteristics	Details
Capacity	1.3 GW of low carbon power
CCUS efficiency	90% of CO_2 emissions
Government funding	$4.2 millions
CO_2 capture capacity	Up to 3.1 $MtCO_2$ per year
Business type	Natural gas power plant
Planning	2014: project announcement 2017–2020: pre-FEED phase 2024: expected operational start
Capture type	Post-combustion type
Transport type	Pipeline
Utilization type	Geological storage

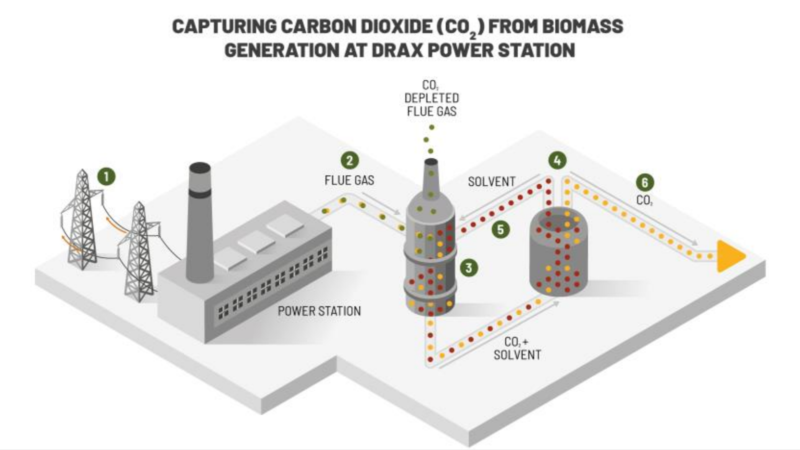
Sources: Steelanol, LanzaTech, Cordis Europa; Kearney Energy Transition Institute analysis

CCUS combined with bioenergy at Drax biomass-fired power plant to reach negative emissions

Drax Group wants to add carbon capture facilities to its current biomass power plant in North Yorkshire. The power plant would become one of the first bioenergy carbon capture and storage (BECCUS) facilities in Europe. The project is part of Zero Carbon Humber.

Power Generation

Drax BECCUS Plant



Country: United Kingdom

Operational date : 2027

Investment : £400,000 for the pilot project

CO_2 savings: Currently 300 kg per day

Project leaders: Drax Group and Mitsubishi Heavy Industries Group

Project characteristics	Details
Capacity	4 660 MW biomass units
Government funding	Project is concerned by a £800 millions envelope of subsidies of the UK government.
CO_2 capture capacity	Pilot: 300 kg per day, aim of 8 $MtCO_2$ per year by 2024 and 50 $MtCO_2$ per year by 2050
Business type	Biomass power with carbon capture
Planning	2018–2019: first pilot 2020: second pilot 2020–2027: development of CCUS-technology on one biomass unit 2030: installation on a second unit 2035: installation on all four units
Capture type	Post-combustion
Transport type	Pipeline
Utilisation type	Geological storage + works to turn CO_2 into fish food

Sources: Drax; Kearney Energy Transition Institute analysis

First demonstration of Allan-Fetvedt Cycle gas-power plant

NET Power has developed a semi-closed loop Allam-Fetvedt Cycle leveraging oxy-combustion technologies to produce emissions-free power, burning methane with pure oxygen in an industrial process involving turbine, heat exchanger, and compressor.

Power Generation

NET Power – Allam-Fetvedt Cycle

Source: NET Power, https://netpower.com/technology/

Country: United States / Texas

Operational date : March 2016

Investment : $ 150M

CO_2 savings: n.a.

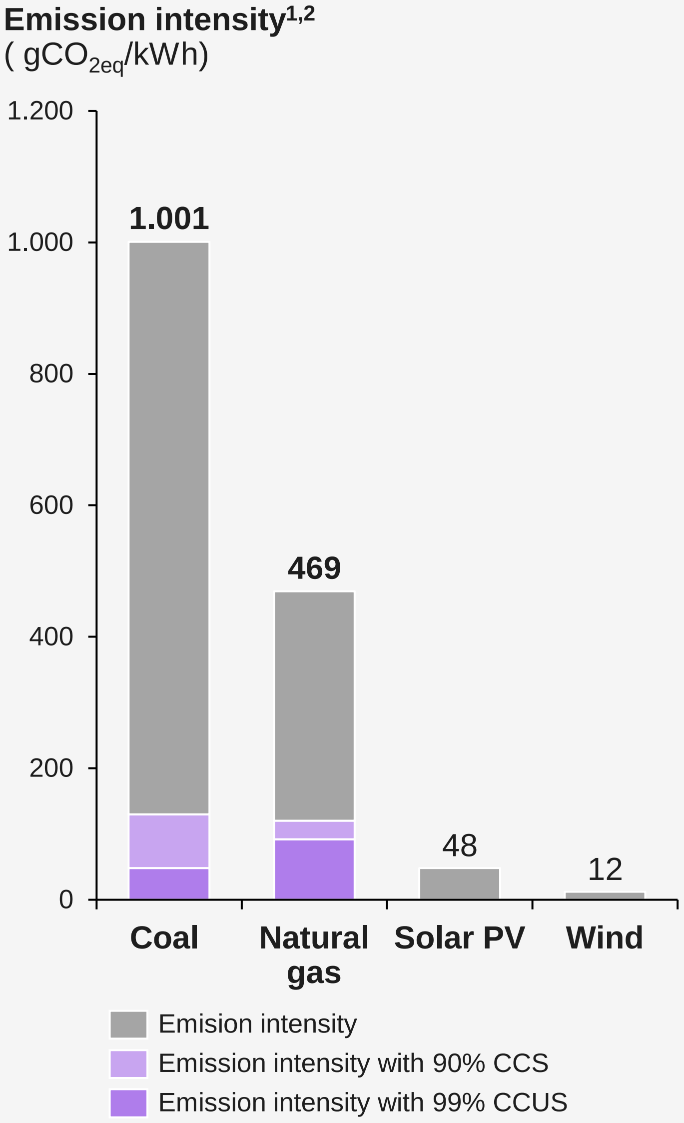
Project leaders: NET Power, 8 Rivers Capital

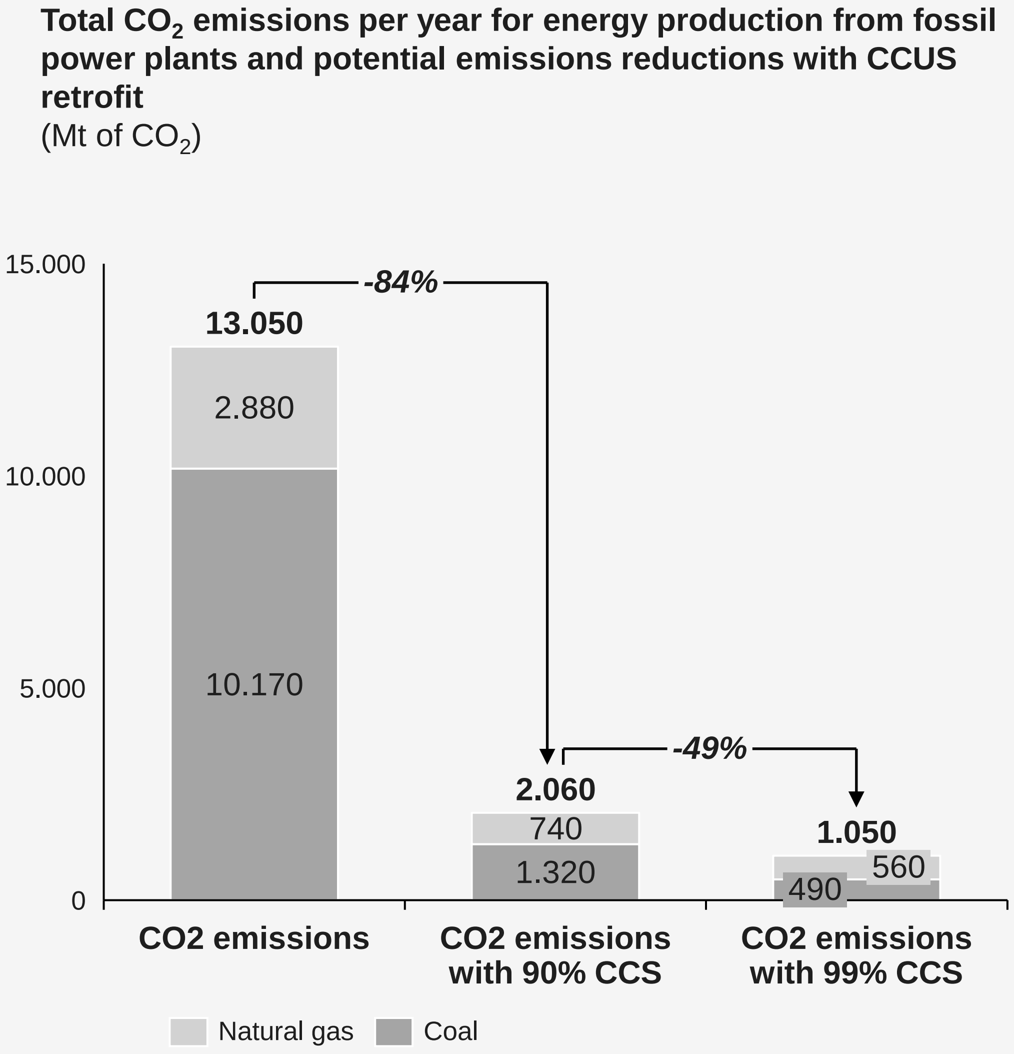
Project characteristics	Details
Capacity	50 MWth (25 Mwe), natural gas-fired power demonstration plant
Net energy efficiency	55% (potentially up to 59%)
CO2 capture efficiency	100%
Ramp-up-rate	2% to 5% per minute from warm to hot start
Government funding	$44 M from USDOE, potential leverage of 45Q carbon capture tax credit
Business type	Power generation combined with carbon capture, utilization, and/or storage
Planning	2018: First-fire reached at the La Porte Project (50-MWth, Texas) 2019: Pre-FEEDs of Allam Cycle plants (280-300 MW) USA 2020: Pre-FEED for a 300 MW power plant in Teesside area, United Kingdom 2021: Announcement of 2 initial commercial facilities in progress in CO and IL (280 MW) USA 2025: Expected commercial operation of first 280 MWe gas-power plant, USA
Capture type	Post-combustion, providing high pressure CO_2 (30 to 300 bar)
Transport type	TBD
Utilisation type	Large range of potential uses including storage

Sources: NET Power; powermag.com (link); Kearney Energy Transition Institute analysis

Retrofitting coal and gas-fired power plants with 90% CCUS would save 11 Gt of CO_2 emissions per year

Potential CO_2 emissions reduction from CCUS on thermal power plants





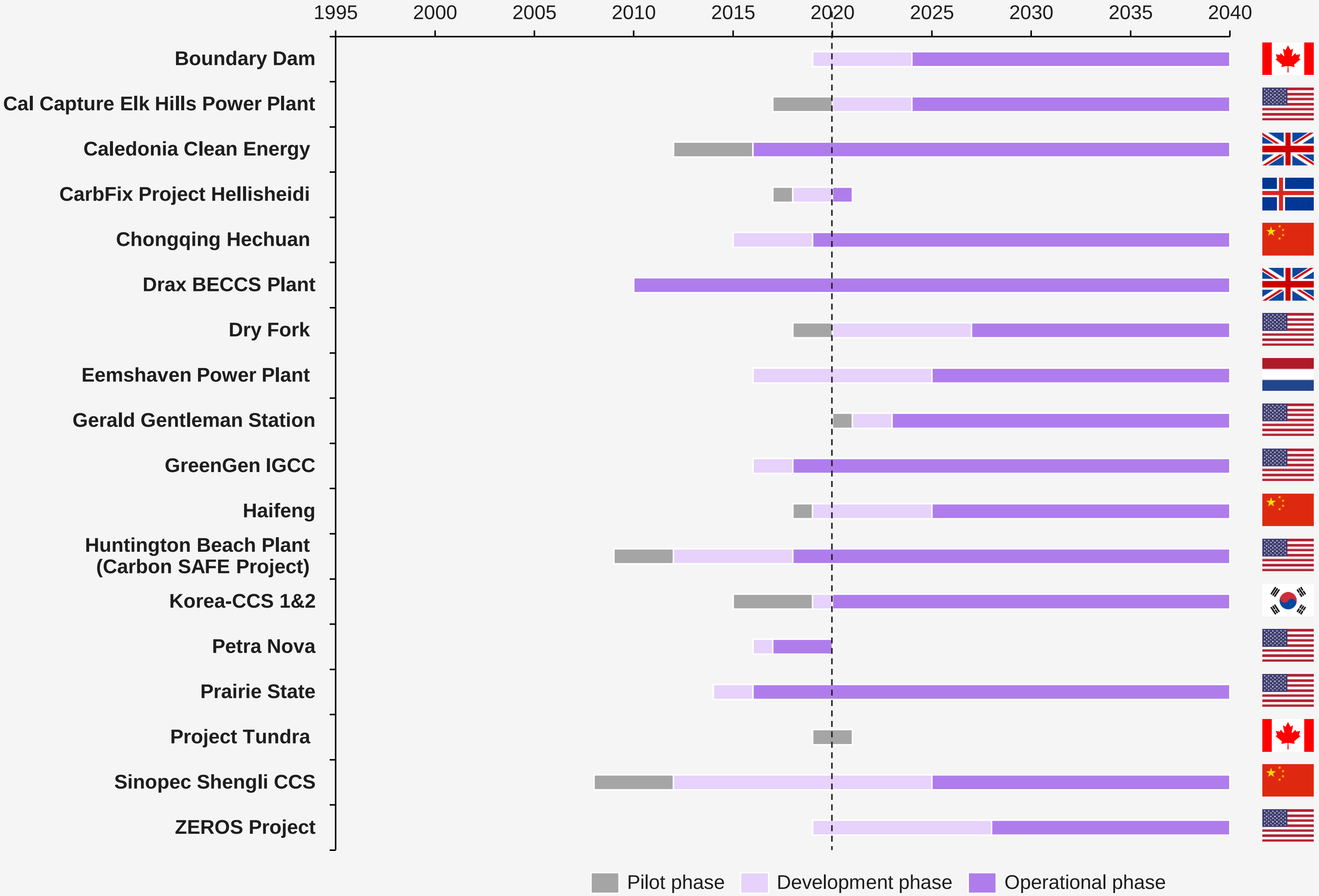
Power Generation

1. For conventional subcritical power plant units
2. 90% CCUS and 99% CCUS are more efficient on coal emissions since they are mostly direct emissions and natural gas emissions also have a significant share of indirect emissions not tackled with CCUS..

Sources: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation; Kearney Energy Transition Institute analysis

CCUS equipment or retrofitting thermal plants is starting and expected to strengthen in the next few years

Timeline of power plants projects



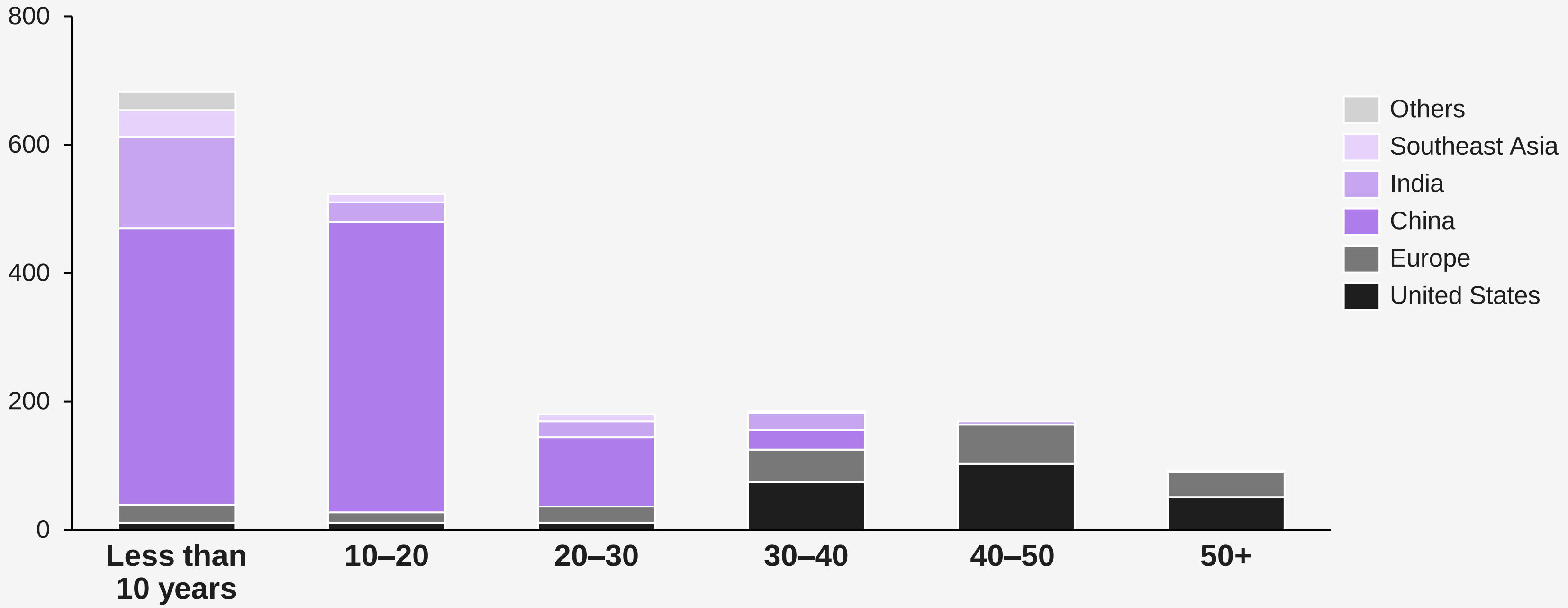
Power Generation

Recent coal power plants built in China and India provide huge potential for CCUS development

Power Generation

Age structure of coal capacity per region

GW, world, 2019



- 2,080 GW of coal-fired power plants are in operation in the world, accounting for about **38% of the electricity production.**
- Almost **60% of the world's coal fleet is 20 years old or younger,** and a coal power plant design lifetime is 50 years.
- Over the past 20 years, **Asia accounted for 90% of all coal-fired capacity built worldwide**: China (880 GW), India (173GW), and Southeast Asia (63 GW)
- Modern coal plants (ultrasupercritical, supercritical, and combined heat and power) are more efficient than old generation (subcritical plants), in terms of carbon emissions intensity.
- Subcritical plant represent 40% of the coal fleet emissions and more than half of them are under 20 years of age.

Sources: WEO 2019; Kearney Energy Transition Institute analysis

In the cement industry, CO_2 capture can be accomplished using post- and oxyfuel combustion

Application to **cement**

Post-combustion technologies are assessed as easier to retrofit than the integrated oxy-fuel technologies

Context

- Because of its size and the inherent characteristics of its production process, the cement sector is one of the main sources of anthropogenic CO_2, accounting **for 8% of global emissions.**
- Carbon footprint depends on the ratio of clinker to cement, the manufacturing process (dry or wet method), the level of heat recovery, the fuel used, the moisture content of the raw materials, and the capacity of the plant, among other factors. **Process emissions account for approximately 65% of the direct CO_2 emissions, whereas fuel combustion is responsible for the remainder.**

Challenges

- High reliance on coal for high temperature heat
- Large share and quantity of process emissions
- Low-margins
- Need to locate capacity relatively near to the point of use

Process emissions results from the conversion of limestone to calcium oxide: $CaCO_3 \rightarrow CaO + CO_2$

Key technologies	Description
Chemical absorption	Chemical absorption of CO_2 is a common process operation based on the reaction between CO_2 and a chemical solvent (such as amine-based). It can be applied to kilns, the main unit producing clinker for cement production.
Calcium looping	In the first reactor, lime (CaO) is used as a sorbent to capture CO_2 from a gas stream to form calcium carbonate ($CaCO_3$). The $CaCO_3$ is subsequently transported to the second reactor where it is regenerated, resulting in lime and a pure stream of CO_2. The lime is then looped back to the first reactor.
Oxy-fueling	Oxyfuel CO_2 capture involves combusting a fuel using nearly pure oxygen instead of air. The flue gas will be composed of CO_2 and water vapor, which can be dehydrated to obtain a high-purity CO_2 stream. The technology can be applied to kilns, the main unit producing clinker for cement production.
Direct separation	Direct separation involves indirectly heating limestone for clinker production in a calciner using a special steel vessel. This enables pure CO_2 from limestone (process emissions) to be captured as it is released since fuel combustion emissions are kept separate.
Physical adsorption	The adsorbents are made from new classes of materials such as functionalized-silica or metal-organic frameworks, which can catch and release CO_2 at very rapid rates.
Membrane separation	Membrane separation uses a semi-selective membrane (a polymeric membrane that allows some gases to pass through but not others) to concentrate CO_2 on one side of the membrane, thus separating it from a stream. This remains in a development stage.
Novel approaches	Electrochemical process to convert calcium carbonate into calcium hydroxide ($Ca(OH)_2$) in an electrolyzer, producing a concentrated CO_2/O_2 steam (to which CO_2 capture could be applied) and hydrogen (that could be used in subsequent stages of production). The calcium hydroxide can then be converted to calcium silicates needed for cement in a kiln.

Sources: “Special Report on Carbon Capture Utilisation and Storage” International Energy Agency 2020; Kearney Energy Transition institute analysis

Chemical absorption is currently the most mature carbon capture technology option for the cement sector

Application to **cement**

Overview of key carbon capture technologies in cement[1]

Not exhaustive

	Chemical absorption	Calcium looping	Oxy-fueling	Physical adsorption	Direct separation
Stage	Post combustion	Oxy-fuel	Oxy-fuel	Post combustion	Post combustion
Capture rates	~90%	Up to 98%	90%	80—90%	Being evaluated
Operating temperature (°C)	120°C to 150°C	600°C to 900°C	High	High	1000°C
Importance for net zero	Very high	Very high	High	Moderate	Moderate
Key countries	USA, China, Norway, Canada, India	Germany, Italy, Chinese Taipei	Italy, Austria, Denmark, Germany	Canada, United States	Belgium
Key projects	– A commercial-scale post-combustion CCU facility opened in 2014 at Capitol Aggregates plant in Texas. – A pilot plant (50 kt CO_2 per year) began operation in 2018 by Anhui Conch in China.	– A pilot-scale demonstration was completed by CEMCAP at the University of Stuttgart (Germany). – Taiwan Cement has been testing calcium looping capture at its Heping Plant in Hualien, Taiwan since 2017, with successful pilot-scale trials completed.	– In Dania, Denmark, oxy-fuel capture was successfully piloted in a kiln precalciner (cooperation between Airliquide and FLSmidth) – "Westküste 100" project—green H_2 and decarbonization on an industrial scale (Germany) – A special focus area is industrial gas producers such as Air Liquide, Air Products, Linde, Praxair.	– The CO2MENT project in Canada launched trials in 2019 of Svante's (formerly Inventys) CO_2 capture technology at a LafargeHolcim cement plant and has successfully captured CO_2.	– A successful pilot-scale demonstration of the technology, developed by Calix, occurred at the Heidelberg Cement plant in Lixhe, Belgium by LEILAC project in 2019.

Technology readiness level

High → Low

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[1] Membrane based separation and electrolyzer-based process for decarbonating calcium carbonate not profiled due to low technological readiness level

Sources: "Special Report on Carbon Capture Utilisation and Storage" International Energy Agency 2020; https://www.westkueste100.de/, Kearney Energy Transition institute analysis

CCUS can be an important decarbonization lever for the iron and steel sector

Application to
Steel

Energy efficiency and material efficiency are the top two biggest decarbonization levers for the sector.

Context

- Globally, the sector's direct CO_2 emissions amounted to 2.6 Gt in 2019, or **7% of total energy sector emissions and 28% of industrial emissions**. When indirect emissions from electricity and heat generation are included, the total emissions amount to around 3.6 Gt.
- **The CO_2 intensity of steel production is high**, with ~1.4 ton of direct CO_2 emissions per ton of crude steel, or 2.0 t when including indirect emissions from imported electricity and heat generation. CO_2 is emitted by consumption of coal or natural gas that act as a reducing agent in the DRI (Direct Reduced Iron) necessary to process iron ore.

Challenges

- High reliance on coal for high temperature heat and iron reduction
- Limits to the availability of scrap for steel recycling
- Globally traded commodity with relatively low margins

Key technologies	Description
Chemical absorption	Direct reduced iron plants—in which iron ore is reduced to iron without melting typically using natural gas or coal—could be equipped with chemical absorption-based CO_2 capture.
Physical adsorption	Direct reduced iron plants—in which iron ore is reduced to iron without melting typically using natural gas or coal—could be equipped with physical adsorption-based CO_2 capture, in which molecules are captured on the surface of selective materials called adsorbents.
Recycling of waste gases to fuel	Recycling of waste gases from steel plants (such as blast furnace gas and coke oven gas) into synthetic fuels, thus using the CO_2 twice and delaying its release
Recycling of waste gases to chemicals	Recycling of waste gases from steel plants (such as blast furnace gas and coke oven gas) into chemicals, thus using the CO_2 twice and delaying its release
Smelting reduction	A new oxygen-rich smelting reduction technology for producing steel is being developed, consisting of a reactor in which iron ore is injected at the top while powder coal at the bottom. The use of pure oxygen makes the new smelting reduction process well-suited to integrate CCUS as it generates a high concentration of CO_2 off-gas and emissions are delivered in a single stack compared with a standard steel mill plant with multiple emission points.

Sources: " International Energy Agency "Special Report on Carbon Capture Utilisation and Storage" (2020); Kearney Energy Transition institute analysis

Chemical absorption is the most mature carbon capture technology option

Application to ***Steel***

Overview of key carbon capture technologies in iron and steel

Not exhaustive

	Chemical absorption	**Waste gases to fuel**	**Waste gases to chemicals**	**Smelting reduction**	**Physical adsorption**
Stage	Post combustion	Post combustion	Post combustion	Post combustion	Post combustion
Capture rates	~90%	NA	NA	NA	80—90%
Operating temperature (°C)	120°C to 150°C	NA	NA	NA	High
Importance for net zero	Very high	Moderate	Moderate	Very high	Very high
Key countries	Mexico, United Arab Emirates, and Venezuela	Belgium, China	Germany	Netherlands	NA
Key projects	– Two operating plants of Ternium in Mexico have captured 5% of emissions (0.15-0.20 Mt per year combined) since 2008 for use in the beverage industry, with planning under way to upscale capture capacity.	– A large-scale demonstration plant is under construction in Ghent, Belgium under the Steelanol project by Arcelormittal and Lanzatech, is to be completed by early 2021 with a capacity of 80 million liters of ethanol.	– The Carbon2Chem initiative led by Thyssenkrupp aims to commercially demonstrate the production of chemicals (such as ammonia and methanol) from steel WAG in Europe.	– A pilot plant is located at Ijmuiden, Netherlands, developed by Tata Steel, with testing having been completed. The plant now produces 60kt of steel (carbon capture and storage not implemented yet).	– None. The existing commercial DRI natural gas project with CCS uses chemical absorption technologies, but it is possible and would likely be less costly to use (vacuum pressure swing adsorption) VPSA. This CCS technology has been proven in other applications.

Technology readiness level

High → Low

Sources: International Energy Agency “Special Report on Carbon Capture Utilisation and Storage” (2020); Kearney Energy Transition institute analysis

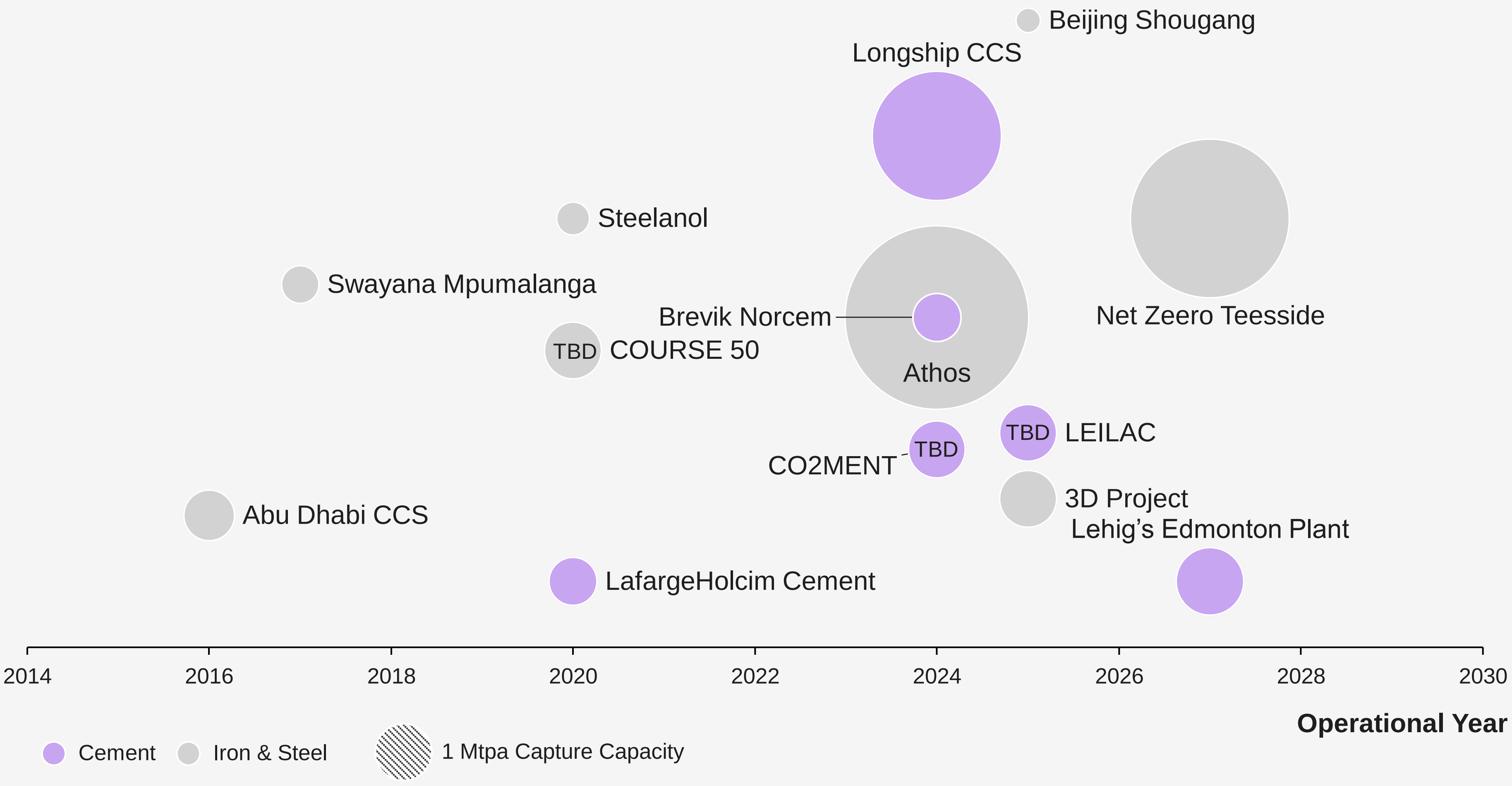
CCUS has been introduced recently for small commercial or pilot projects in the iron and steel industry while cement-related CCUS projects are expected for 2024

The cement, iron, and steel industries are still new in the CCUS business. The first project appeared in 2017, but more are likely to come in the next few years, including three clusters (Athos, Longship, and Net Zero). However, the projects have a low carbon capture capacity (average of 0.7 Mtpa).

Cement, Iron and Steel

Cement, iron and steel productions combined with CCUS projects

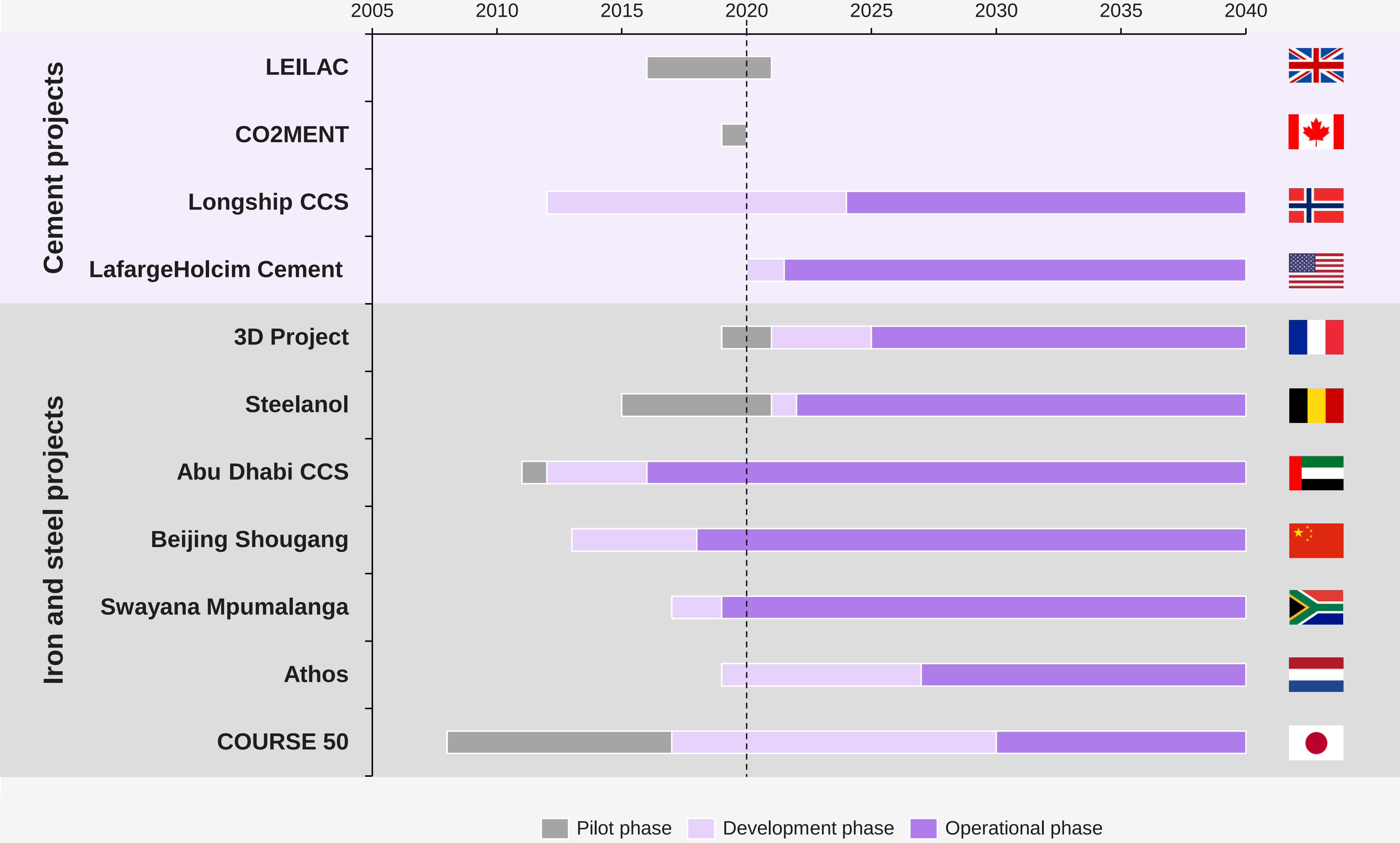
Non-exhaustive



Note: some Pilots and Demonstration CCS facilities are not included in this graph when their capture capacity remains unknown – for example the operating Leilac project in Belgium
Source: Kearney Energy Transition Institute, WEO (2019), International Energy Agency (2019), The Future of Hydrogen, Seizing today’s opportunities, GCCSI Global Status of CCUS 2019

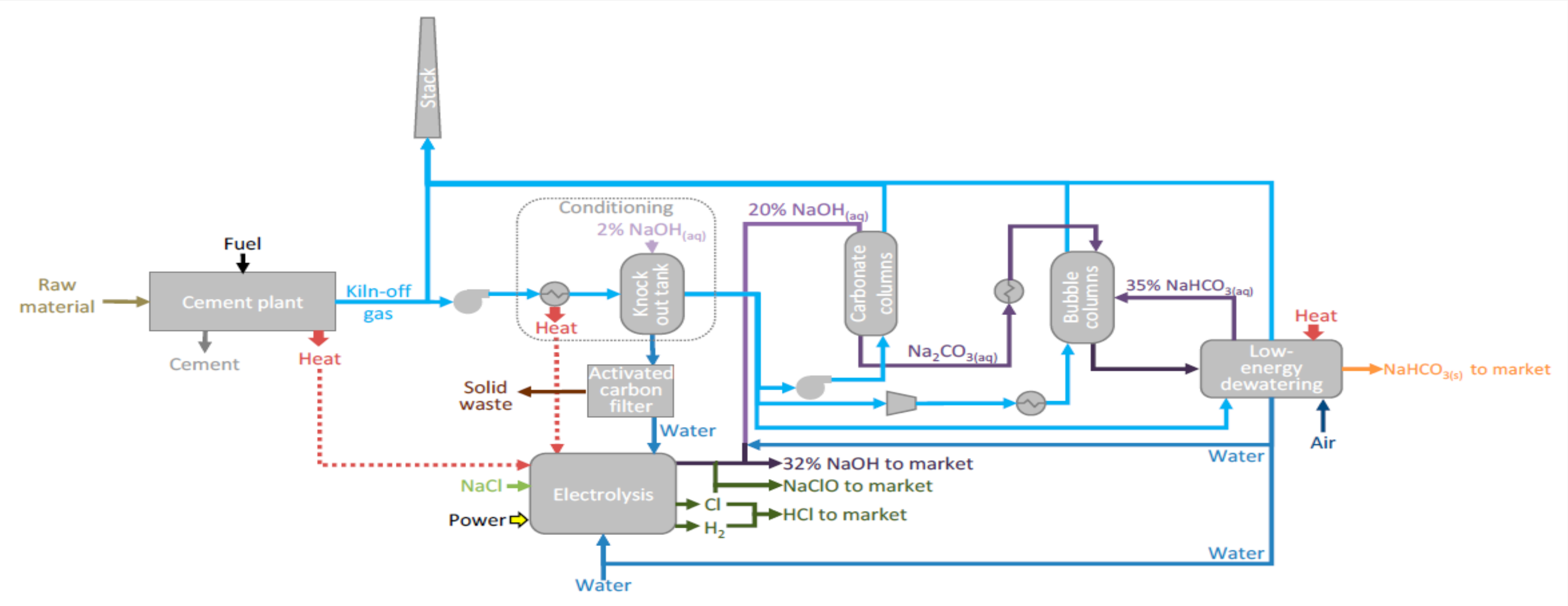
CCUS for the iron and steel industry is emerging while the speed of development is expected to increase in the cement industry over the next few years with large-scale projects

Timeline of the projects



The largest demonstration plant of CCUS in the cement sector is based on the chemical absorption process

SkyMine® process integrated in San Antonio cement plant



Description	Pros	Cons
– Conditioned flue gas is fed to a multicolumn chemical absorption system, where a concentrated NaOH solution reacts counter currently with the CO_2 from the flue gas in two packed absorbers working in parallel to form Na_2CO_3. – The SkyMine® process produces marketable by-products, such as baking soda, hydrochloric acid, and bleach. – Key reactions: – $2NaOH(aq) + CO_2 (g) \rightarrow Na_2CO_3(aq) + H_2O(l)$ – $Na_2CO_3 (aq) + H_2O(l) + CO_2 (g) \rightarrow 2NaHCO_3(s)$	Additional CO_2 savings by product displacement	High energy demand, mostly driven by the solvent regeneration

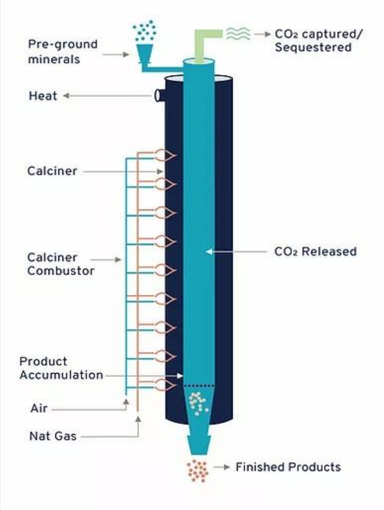
Sources: “Special Report on Carbon Capture Utilisation and Storage” International Energy Agency 2020, Kearney Energy Transition institute analysis

New capture technology to lower emissions in cement production plant

Direct separation technology uses indirect heating in which the process CO_2 and furnace combustion gases do not mix, resulting in the simple capture of high-quality CO_2. This innovation requires minimal changes to the conventional processes for cement, replacing the calciner in the preheater-calciner tower.

Cement, Iron and Steel

LEILAC: direct separation calcining technology



Country: Belgium

Operational date: 2025

Capex: €20.7 million (pilot)

CO_2 savings: 185t per day

Project leaders: Calix, HeidelbergCement, and Imperial College

Project characteristics	Details
Technology features	Captures CO_2 directly at the release of the limestone; no additional energy or chemical products needed
CCUS efficiency	95% of produced CO_2 during calcination
Government funding	€11.9 million of the €20.7 million (Europe H2020)
CO_2 capture capacity	185 tCO_2 per day
Business type	CO_2 from cement facility is captured thanks to direct separation calcining technology.
Planning	2016–2021: pilot project
Capture type	Direct separation calcining theory
Transport type	None
Storage type	

Sources: LEILAC, Horizon 2020; Kearney Energy Transition institute analysis

A commercially self-sustaining project in iron & steel industry with no government subsidies

The plant can help create a CO_2 network & hub in order to achieve flexibility between CO_2 supply and injection requirements

ADNOC's Al Reyadah facility

1

800,000 tons of CO_2 capture from Emirates Steel manufacturing complex (3.2 Mtpa steel)

2

CO_2 transferred to Al Reyadah plant for compression & dehydration

3

Metered and exported through a 43km buried pipeline for EOR to ADNOC's NEB (Al Rumaitha) and Bab onshore oilfields

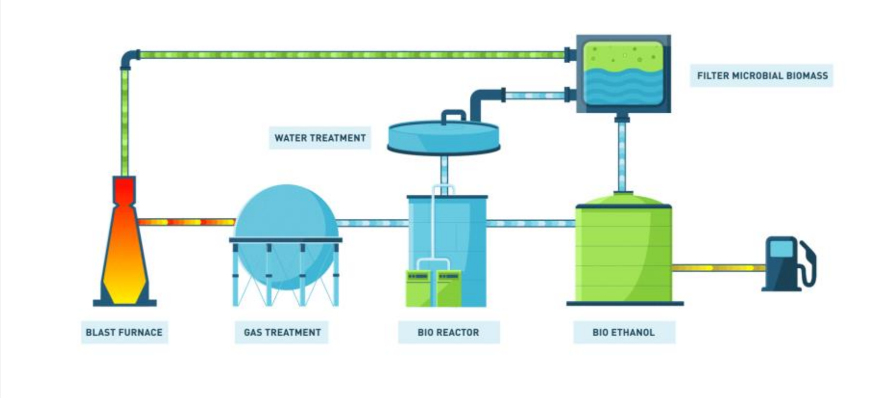
Description	Unique project	Future plan
• Al Reyadah was a joint venture of ADNOC and Masdar. However, ADNOC bought out Masdar share in January 2018 – Seed capital (USD 15 billion) for Masdar city project was provided by government of Abu Dhabi. EPC contract for the facility and pipeline was worth $122 million • Key objectives: – Supply on-spec CO_2 for EOR – Free-up critical natural gas for power generation – Reduce carbon footprint	• World's 1st fully-commercial CO_2 capture from iron & steel Industry • Middle-East's 1st commercial-scale CO_2 capture plant, started in 2016 • Operating highest pressure (240 bar) CO_2 transfer pipeline in the world	ADNOC plans to expand the capacity by over 500 percent capturing CO_2 from its own gas plants, with the aim of reaching 5 million tonnes of CO_2 every year by 2030

Sources: CSLF, GCSSI, ADNOC, Pres search, Kearney Energy Transition institute analysis

Post-combustion treatment of steel industry's waste gases fermented into ethanol and chemicals

CarbonSmart^{TM} has the ambition to transform CO_2 emissions from recycles wastes into fuels dans chemicals. The process is based on microbial fermentation. The microbes grow on the gases and transform them into chemicals and fuel

Steelanol–LanzaTech's CarbonSmart^{TM}



Country: Belgium

Operational date: 2025

Capex: €14.5 million (pilot); €215 million (total)

Capture cost: €30–€40/t

CO_2 savings: 0.35 Mt per year

Project leaders: ArcelorMittal, Primetals Technologies, and LanzaTech

Project characteristics	Details
Technology features	Industrial waste gases are compressed and then cooled, cleaned, and injected into a vessel for fermentation with microbes and a liquid media. The microbes consume the gases to make ethanol and chemicals.
CCUS efficiency	Up to 90% of CO_2 produced Production of 25 000 t of ethanol per year (2.5 Mt if fully deploy)
Government funding	€10.1 million of the €14.5 million for the pilot test (Europe H2020)
CO_2 capture capacity	0.35 $MtCO_2$ per year
Business type	Carbon is captured from ArcelorMittal steel plant and then used to make bioethanol.
Planning	2015–2021: pilot project 2022: operational project
Capture type	Post-combustion
Transport type	None
Utilisation type	LanzaTech to produce bio-ethanol

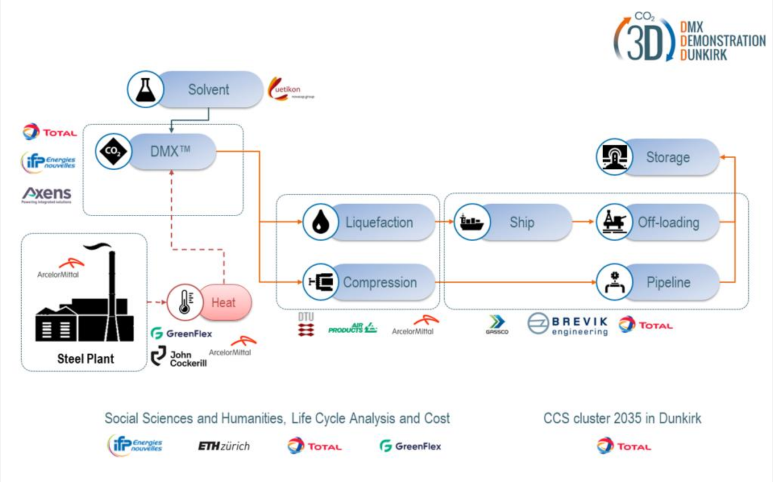
Sources: Steelanol–LanzaTech–Cordis Europa; Kearney Energy Transition institute analysis

New post-combustion capture technology to lower emissions in iron and steel facilities

The project aims to show the efficiency of a new amine-based solvent, which decreases the capture cost of 30%. This solvent has a highly cyclic capacity and decants in two phases. It also makes possible to save two compressions stages compared with other separation process

Cement, Iron and Steel

3D Project–DMX^{TM} Technology



Country: France

Operational date: 2025

Capex: €19.3 million (pilot)

Capture cost: €30–€40/t

CO_2 savings: 1.0 Mt per year

Project leaders: IFPEN, ArcelorMittal, Total, and Axens

Project characteristics	Details
Technology features	Separation uses a demixing solvent (made of two amines) to absorb CO_2. This technology will lead to 30% cost reduction (price between €30 and €40 per ton).
CCUS efficiency	At least 90% of emissions from steelworks or coal-fired power plant with a 99.7% CO_2 purity
Government funding	€14.7 million of the €19.3 million for the pilot test (Europe H2020)
CO_2 capture capacity	0.5 tCO_2 per hour for the pilot test; more than 1.0 $MtCO_2$ per year for the industrial unit
Business type	Carbon capture from steel plant and geological storage in the North Sea
Planning	2019–2021: pilot test for DMX^{TM} technology 2021–2025: development of the industrial unit at ArcelorMittal site 2025: operational phase with ambition to create a North Sea storage cluster by 2035
Capture type	DMX^{TM} solvent
Transport type	Ship or pipeline
Storage type	Geological storage in the North Sea. Possible link to Steelanol project for ethanol production

Sources: ArcelorMittal–IFPEN–Project 3D; Kearney Energy Transition institute analysis

CCUS is projected to be the single largest emissions-reduction lever in chemicals production, ahead of fuel switching

A large proportion of the carbon in the energy inputs ends up in the final product

Context

- The chemical subsector is **the third-largest industrial** source of CO_2 emissions.
- Oil and natural gas are the primary feedstocks for producing chemicals, with coal also being used to a lesser extent. **The share of hydrocarbons in the overall sector's energy use is very high at 85%.**
- The energy intensity of production varies considerably from product to product. It is particularly energy intensive to produce primary chemicals (accounting for two-thirds of the chemicals sector's energy consumption) vs. secondary chemicals.

Challenges

- The large share of process emissions makes it difficult to decarbonize.
- Fossil fuels used as feedstock are difficult to fully substitute with bioenergy or electrolytic hydrogen.
- Globally traded commodities have highly complex supply chains.

Key technologies	Description
Chemical absorption	Chemical absorption of CO_2 is a common process operation based on the reaction between CO_2 and a chemical solvent (such as amine-based).
Physical absorption	Physical absorption uses a liquid solvent to absorb CO_2 from flue gases that have high CO_2 partial pressures, without a chemical reaction occurring. Common physical solvents include Selexol (dimethyl ethers of polyethylene glycol) and Rectisol (methanol).
Physical adsorption	In physical adsorption, molecules are captured on the surface of selective materials called adsorbents. Desorption of the CO_2 (release from the surface) may be achieved using pressure swing adsorption (PSA), performed at high pressure, or vacuum swing adsorption (VSA), which operates at ambient pressure. A hybrid configuration also exists, known as vacuum pressure swing adsorption (VPSA).

Sources: International Energy Agency "Special Report on Carbon Capture Utilisation and Storage" (2020); Kearney Energy Transition institute analysis

Chemical absorption is the most mature carbon capture technology option

Overview of key carbon capture technologies in chemicals

Not exhaustive

	Chemical absorption	Physical absorption	Physical adsorption
Stage	Post-combustion	Post-combustion	Post-combustion
Capture rates	~90%	~90%	80–90%
Operating temperature (°C)	120°C–150°C	120°C–150°C	High
Importance for net zero	High	High	High
Key countries	Malaysia, Japan, India, United Arab Emirates, Pakistan, and Vietnam	United States, Canada, and China	China
Key projects	– Multiple commercial fertilizer plants are using the Mitsubishi KS-1 amine-based solvent CO_2 capture process in Malaysia (Petronas) and India (Indian Famers Fertilizer Co-Operative plant).	– In 2019, Wabash Valley Resources announced plans to convert a gasification plant in Indiana to an anhydrous ammonia production plant with CSS (expected capacity 1.5-1.75 Mt per year CO_2).	– Xinjiang Dunhua 100,000 t/a CO_2 capture project using PSA relaxation gas from a methanol plant, was commissioned in 2016.

Technology readiness level

High → Low

Sources: International Energy Agency “Special Report on Carbon Capture Utilisation and Storage” (2020); Kearney Energy Transition institute analysis

CCUS application to refineries looks challenging with limited technical options

The fluid catalytic cracking (FCC) unit is responsible for 20–55% of total CO_2 emissions from a typical refinery.

Context

- Globally, the other energy transformation sector (excluding the power sector) accounts for annual emissions of 1,400 $MtCO_2$, or around 4% of total energy sector emissions, mostly from refineries and oil and gas production.
- The oil and gas industry is utilizing this captured CO_2, either by selling it to industrial facilities or by injecting it into the subsurface to boost oil recovery.
- CCUS-based solutions would allow reduction of CO_2 emissions from 50% to 70% (theoretical)

Challenges

- There are high energy penalty and equipment requirements for the application of CCS technologies in refineries. It is important to note that the CO_2 produced in the refineries come from several different units such as FCC, hydrogen production, sulfur recovery plants in addition to boilers and process heaters (combustion-related CO_2 sources).

Key technologies	Description
Chemical absorption	In FCC post-combustion capture, the CO_2 in the flue gas can be captured using an amine scrubbing method. Post-combustion technology to capture the CO_2 from the flue gas with a volumetric CO_2 concentration of 10–20% is available but **has not yet been demonstrated** in a refinery context.
Oxy-fuelling	High-purity oxygen is used in the regenerator to produce a flue gas consisting of mainly CO_2 and H_2O. Due to the flue gas compression, partial bypass to the stack is not required, which gives oxyfuel combustion an inherent boost on CO_2 recovery compared to post combustion capture. A pilot scale demonstration of the oxy-FCC process was performed at a Petrobas refinery in the CO_2 Capture Project. The test showed that it is technically feasible to operate an oxy-FCC unit.
Chemical looping combustion	The chemical looping combustion process is based on oxygen transfer from an air reactor to fuel reactor using a solid oxygen carrier. The main advantage of the CLC process compared to conventional combustion is that CO_2 is not diluted with N2 in the combustion gases, and so highly concentrated CO_2 is obtained without any extra energy needed.

Sources: “Special Report on Carbon Capture Utilisation and Storage” International Energy Agency 2020, Kearney Energy Transition institute analysis

Multiple technical CCUS options can apply to blue hydrogen production

Around 40% of low-carbon hydrogen supply can be linked to CCUS in 2070

Context

- Current hydrogen production (~75 Mt H_2 annually chiefly from fossil fuels) produces 800 MtCO_2, corresponding to the combined total energy sector CO_2 emissions of Indonesia and the United Kingdom.
- Unabated production of hydrogen from fossil fuels results in emissions of 9 tCO_2/t H_2 in the case of natural gas (76% share of H_2 production) and 20 tCO_2/t H_2 in the case of coal (23% share of H_2 production).
- Pre-combustion carbon capture technologies can be applied to capture CO_2 before combustion takes place to produce blue hydrogen

Challenges

- Blue hydrogen might seem necessarily more expensive with end-use CCUS, because the additional step of methane reforming entails capital, energy, and operating costs to produce the hydrogen
- The cost of electrolytic Hydrogen is expected to come down substantially in the long term driven by declining prices of renewable electricity and scaling up of electrolysers

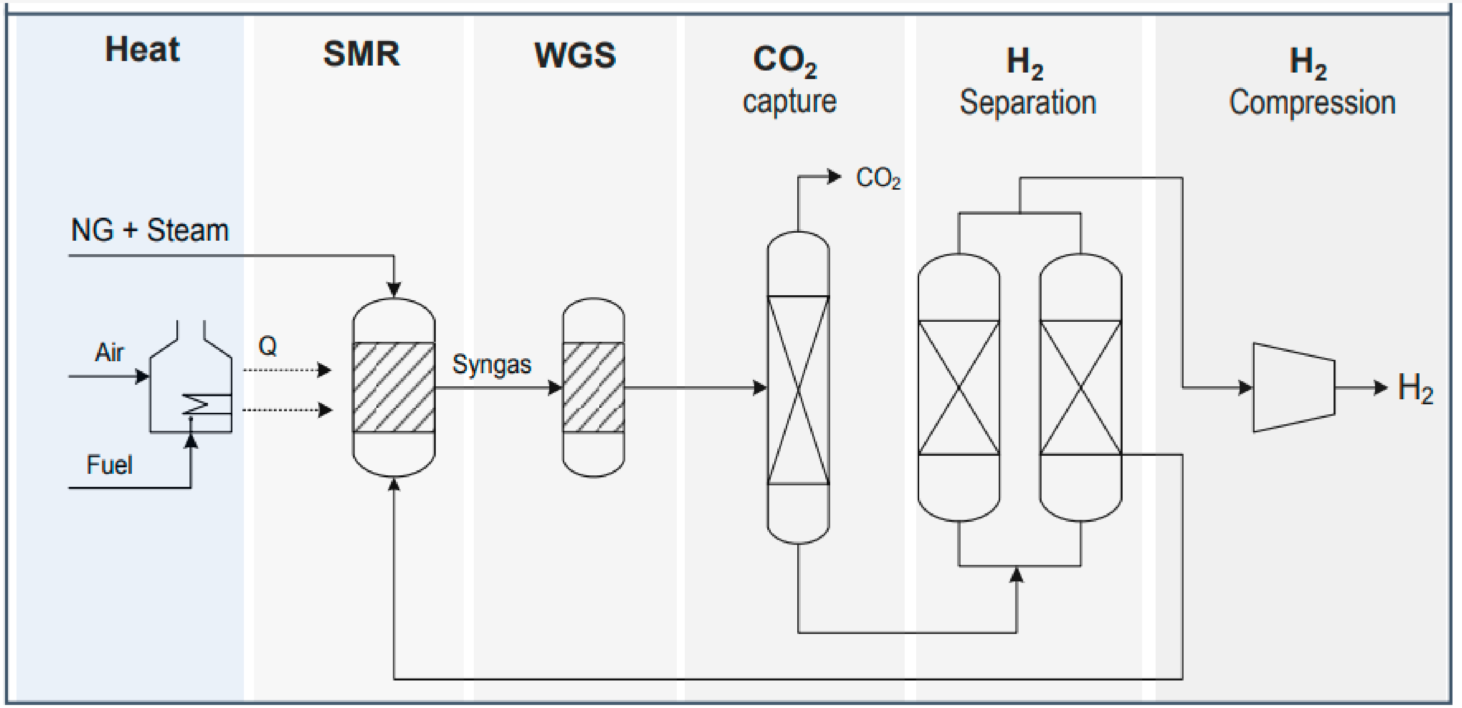
Key technologies	Description
Steam methane reforming	Steam methane reformation is a catalytic reaction in which CH_4 reacts with high temperature (800°C) steam to generate H_2 and CO (syngas). This process requires an input of heat, which leads to lower efficiencies and a diluted CO_2 stream which is costly to capture. The reforming process is followed by a water gas shift process in which the CO reacts with water at lower temperatures to generate more H_2 and CO_2. Then, CO_2 is captured and a stream of high-purity H_2 is obtained. **(H-Vision and Magnum projects in the Netherlands)**
Natural gas autothermal reforming	Autothermal reformation is a variation of SMR in which the methane reacts in an O2-deficit atmosphere instead of using high temperature steam, avoiding the need for an external input of heat. Once the syngas is produced, the rest of the process is similar to SMR with the difference that the H_2–CO ratios are different and the operating and designing conditions of downstream processes have to be adapted. **(HyNet and H21 projects in the United Kingdom)**
Natural gas autothermal reforming with gas heated reforming	The combination of autothermal reforming (ATR) with a Gas Heated Reformer (GHR) is an improved design of ATR that allows achieving higher efficiencies, lower CO_2 production and lower oxygen consumption. The ATR and GHR are in series and the GHR acts both as a pre-heater and cooler of the inlet/outlet of the ATR. The GHR benefit is that it pre-reforms the gas going to ATR using the heat from the exhaust gases of the ATR and performs part of the reforming that would otherwise take place in the ATR. The main technical challenge for GHR is carbon deposition (metal dusting) on the shell side (high temperature from the ATR outlet at around 1100C to 600-800C). This can be solved by either material selection that can withstand the conditions and thermal cycling (cost) or by either decreasing the operating pressure or adding more steam, both of which come with penalty in process efficiency.
Gasification	Gasification is a thermochemical process in which a solid feedstock (coal / biomass / waste) is transformed into a gas mixture of H_2, CO, CO_2 and other light hydrocarbons (called syngas), along with other byproducts (char and tars). The gaseous fraction is treated to maximize H_2 and CO proportions. Following treatment, the gas is passed through a water gas shift reactor in which steam reacts with CO in the presence of a catalyst to generate H_2 and CO_2. Then, CO_2 is captured and a high-purity H_2 stream is obtained (99.9and% vol if Pressure Swing Adsorption is used).
Methane Splitting	Methane pyrolysis (or splitting) is an emerging technology. It involves splitting methane at high temperatures, for example in a plasma generated by electricity, to produce hydrogen and solid carbon, but no CO_2. Monolith Materials operates a pilot methane pyrolysis plant in California and a commercial demonstration plant in Nebraska.

Sources: “Special Report on Carbon Capture Utilisation and Storage” International Energy Agency 2020, Kearney Energy Transition institute analysis

Blue hydrogen is derived from the fossil fuel-based production processes as CO_2 emissions are captured, utilized, and stored

Currently only about 1% of hydrogen production from fossil fuels includes carbon capture and storage (CCS)

Steam Methane Reforming with Carbon capture [1,2]



Description	Pros	Cons
• Steam methane reformer converts feedstock and steam to syngas (mainly hydrogen and carbon monoxide) at high temperature and moderate pressure. Water-gas shift reaction then converts this carbon monoxide to carbon dioxide which is captured in the next step. This leaves behind hydrogen which proceeds for purification and compression to achieve the final product. • Production of clean hydrogen from biomass through anaerobic digestion, fermentation, gasification, or pyrolysis (all with CCS) are at earlier stages of commercialization.	• Existing infrastructure can be used with retrofitting • Less costly than shifting toward green hydrogen • Can be a bridge toward green hydrogen	• Implementation may involve technical issues (higher water consumption and more costly than grey hydrogen) • Social acceptability due to concerns around CCS

1. SMR = Steam Methane Reforming, WGS = Water-gas shift, NG = Natural gas

Sources: GCCSI – Blue Hydrogen (April 2021), SINTEF CSLF WORKSHOP STATUS OF HYDROGEN PRODUCTION WITH CO2 CAPTURE (Nov 2019), Kearney Energy Transition institute analysis, For more details on Blue Hydrogen pls refer to the latest Hydrogen factbook (2020) published at https://www.energy-transition-institute.com/insights/hydrogen

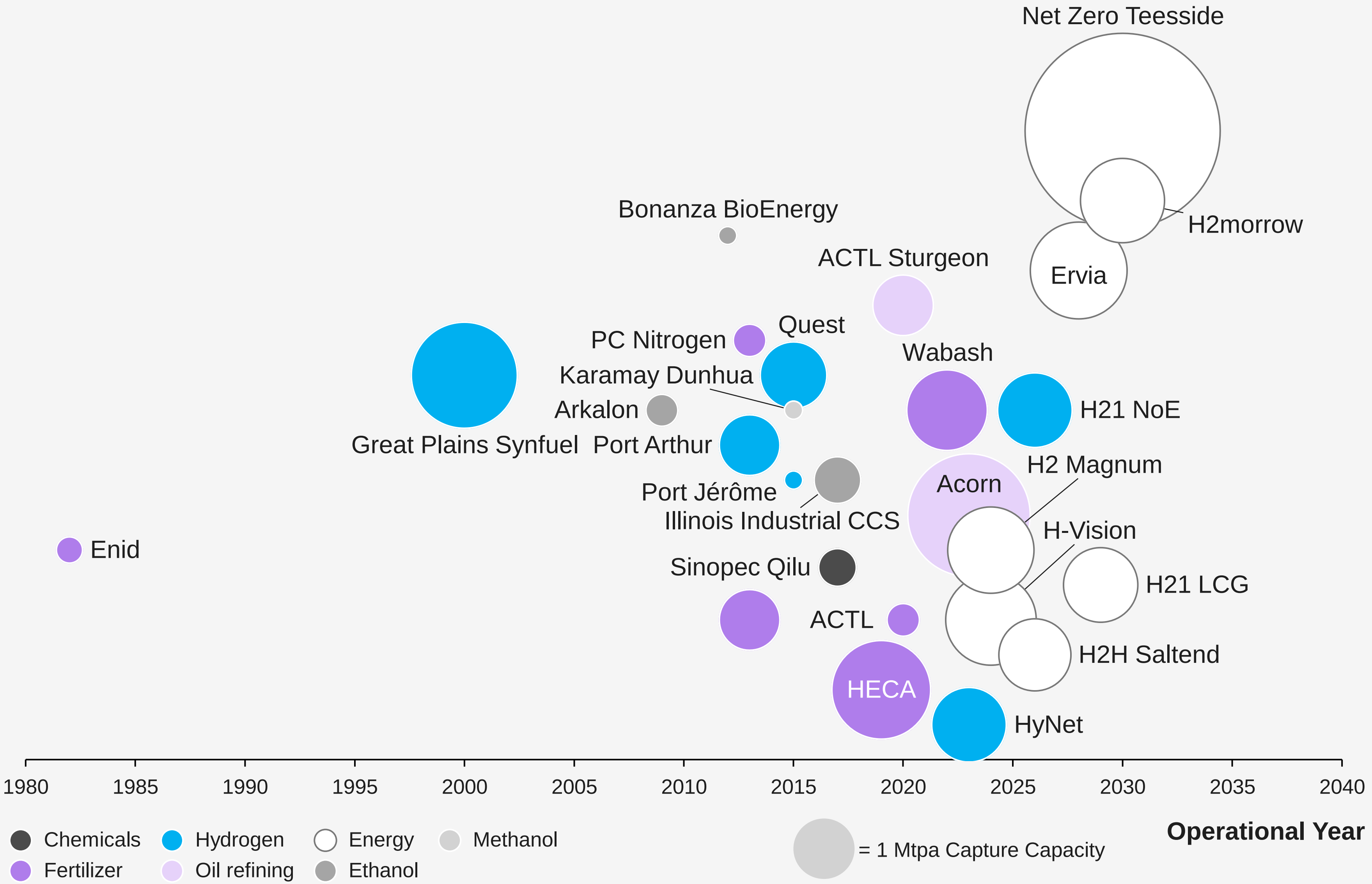
CCUS is being developed to produce blue hydrogen for multiple industrial applications

Today, hydrogen is produced at 98% from fossil resources and represent 830Mtpa of CO_2 emissions, CCUS is a solution to decarbonize this economical production pathway, retrofitting existing facilities and developing new projects to produce hydrogen from natural gas.

Other Sectors: Blue H_2 / fertilizers / refining

Hydrogen production combined with CCUS projects for energy and industries

Non-exhaustive

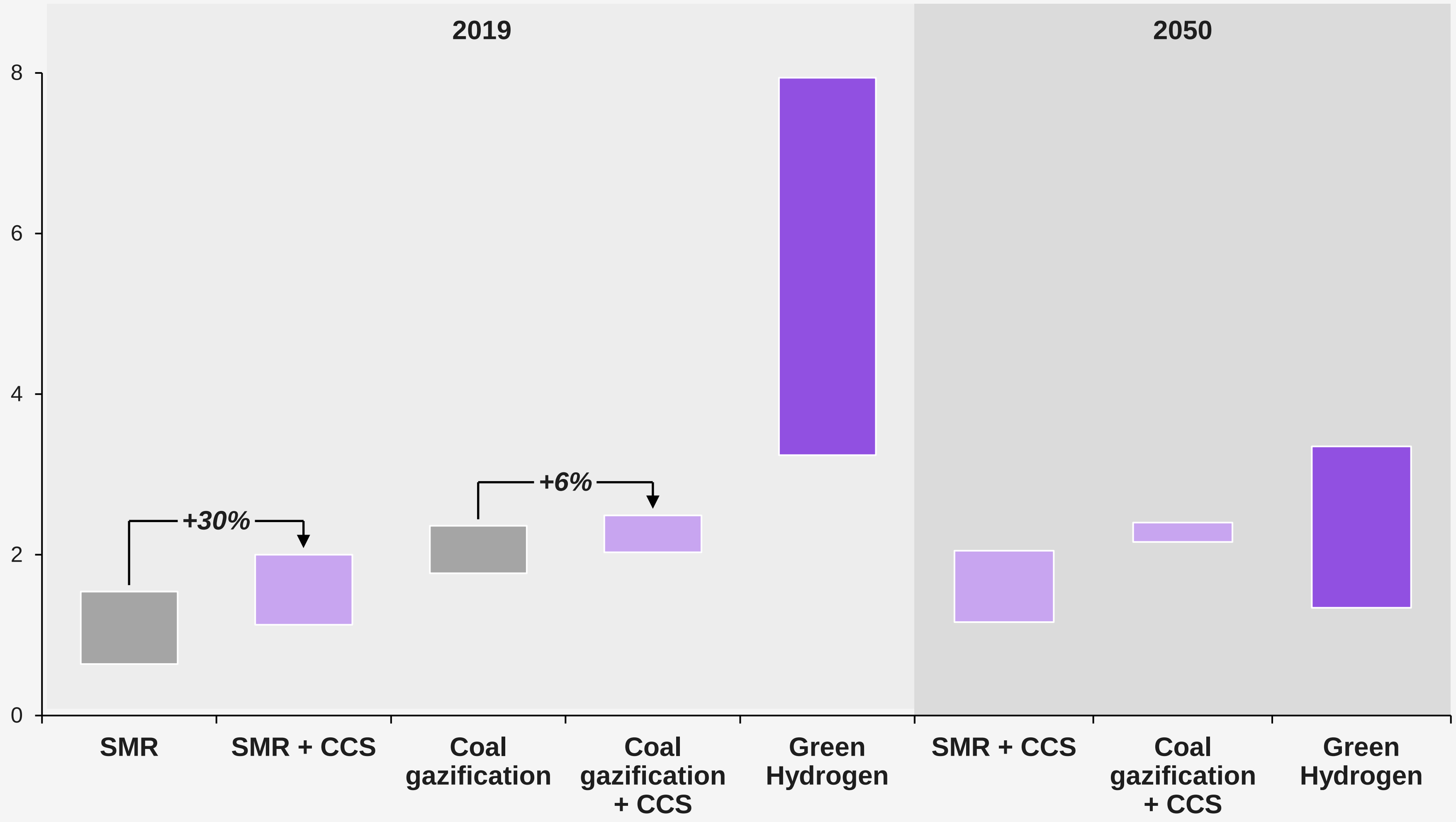


Source: Kearney Energy Transition Institute, International Energy Agency (2019), The Future of Hydrogen, Seizing today's opportunities, GCCSI Global Status of CCUS 2019

Fossil fuels with CCUS are competitive to decarbonize hydrogen production even with the reduction of low carbon electricity prices

Estimated levelized cost of hydrogen from different sources

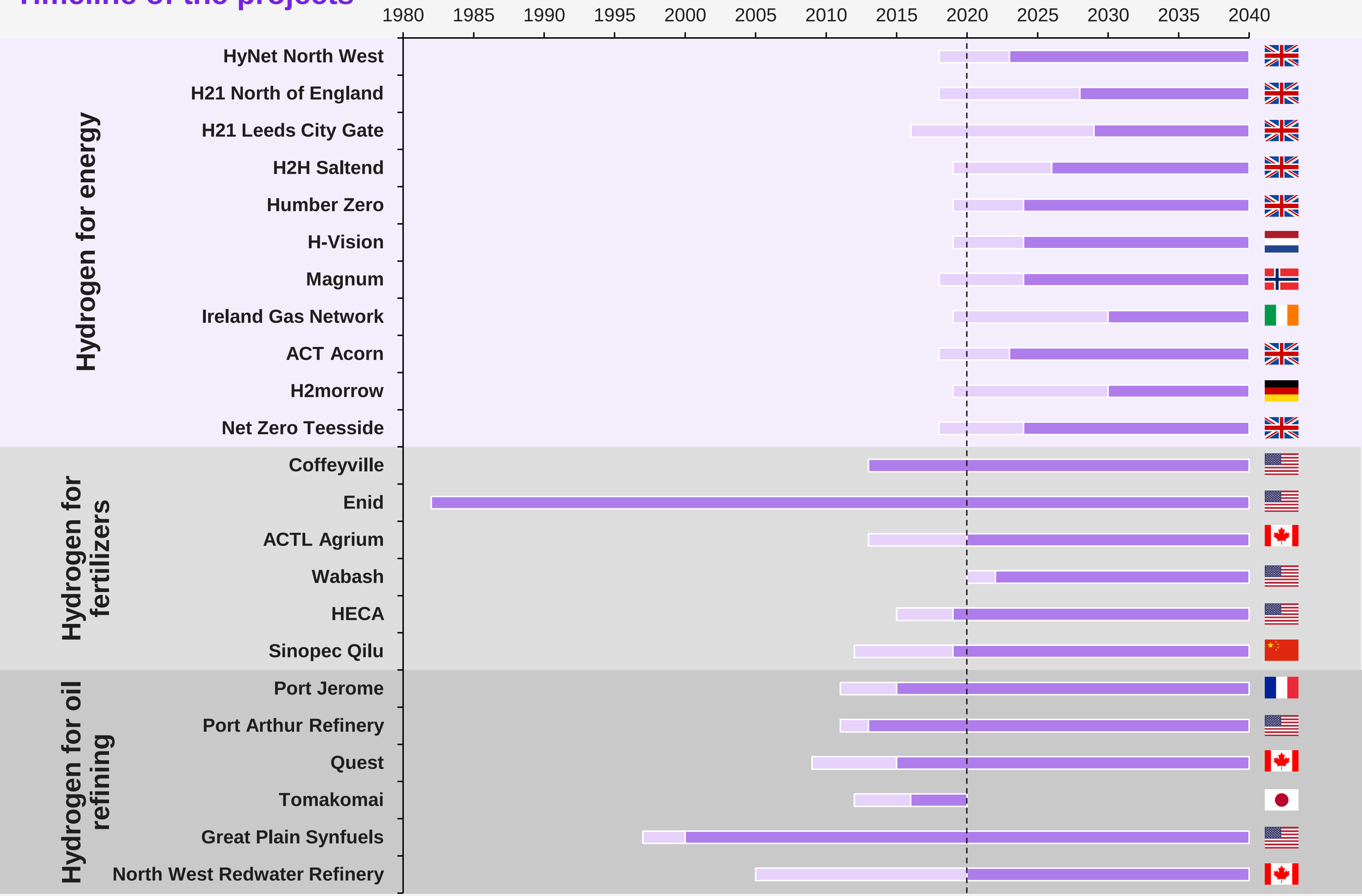
$/kg, World, 2019



SMR: Steam Methan Reforming
Source: Kearney Energy Transition Institute, The role of CCUS in low-carbon power systems, IEA, 2020

Hydrogen utilization for energy projects is expected to come onstream in the next few years, whereas its use in fertilizer industries and oil refining is already mature

Timeline of the projects



▨ Development phase
■ Operational phase

Other Sectors: Blue H_2

There is strong momentum in the United Kingdom to develop H_2 clusters and switch fuel from natural gas for domestic and industrial applications

All the projects are based on pre-combustion carbon capture, transport by pipeline and geological storage.

HyNet North West

H_2 capacity:
890 MW
CO_2 reduction:
1.1 Mt/year
CAPEX:
£0.92 billion

Description:
Produce hydrogen combined with CCUS and blend it with natural gas to supply homes or use it as transport fuel.

Planning:
- Start: 2018
- Government funding: 2020
- Construction: 2021
- Deliverable: 2026

H21 North of England

H_2 capacity:
12.15 GW
CO_2 reduction:
N.A.
CAPEX:
£1.34 billion

Description:
Produce low carbon hydrogen from natural gas with CCUS, to fully supply industries and blend it for home supply.

Planning:
- Delivery: 2028–2034

H21 Leeds City Gate

H_2 capacity:
1 GW
CO_2 reduction:
1.5 Mt/year
CAPEX:
£2 billion

Description:
Power Leeds urban area with hydrogen and replace natural gas.

Planning:
- Feasibility study: 2016
- Delivery: 2023
- Extension to North of England: 2035

H2H Saltend

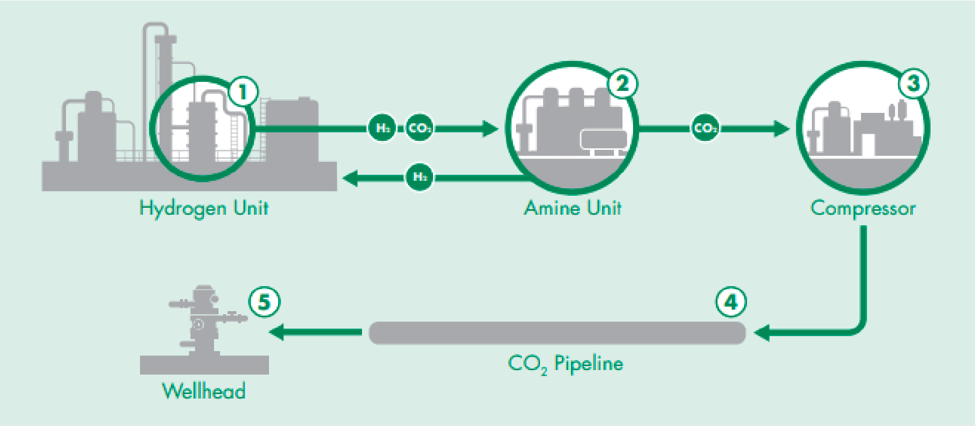
H_2 capacity:
600 MW, 3GW by 2030
CO_2 reduction:
0.9 Mt/year
CAPEX: N.A.

Description:
Fuel switching from natural gas to hydrogen combined with CCUS to power industries and decarbonize domestic heat.

Planning:
- Project matured: 2021–2023
- Engineering and construction: 2024–2026
- Production: 2026–2027

Source: Kearney Energy Transition Institute, H21 NoE Report 2018, Report – Cadent Your Gas Network, HyNet North West Delivering Clean Growth, HyNet North west from Vision to reality, Equinor Saltend https://www.equinor.com/en/what-we-do/h2hsaltend.html

Quest



Country: Canada

CAPEX: $1,35 billion

OPEX: $41 million/y

CO_2 savings: 1,2 Mt/y captured

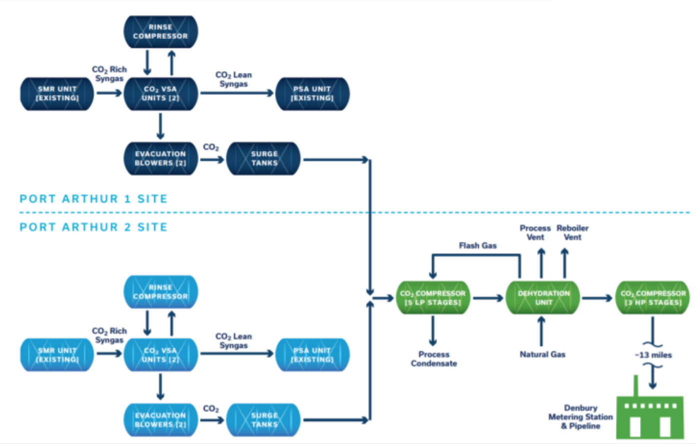
Partnership: Shell Canada, Chevron Canada and Marathon Oil Sands

Project characteristics	Details
Production technology	SMR hydrogen production
CCUS	Around 80% of CO_2 is captured
Government funding	$865 million (both Canada and Alberta governments)
CO_2 storage capacity	1,2 $MtCO_2$ per year
Business type	Captured carbon from hydrogen production facility and then stored into 2km deep aquifers.
Planning	2009 : Launch of the project 2015 : First capture of carbon
Capture type	Amine type solvent
Transport type	Pipeline
Storage type	Geological storage (saline aquifer)
Current Status	Operational, the facility reached 5Mt of CO_2 stored in dedicated geological storage till July 2020

Source: Shell - CCUS Technologies@ MIT, GCCSI Database

Hydrogen production to provide a refinery combined with carbon capture used for EOR

Port Arthur Refinery



Country: USA

Capacity: 240 000 Nm^3/h

CAPEX: $431 million

CO_2 savings: 1,0 Mt/y captured

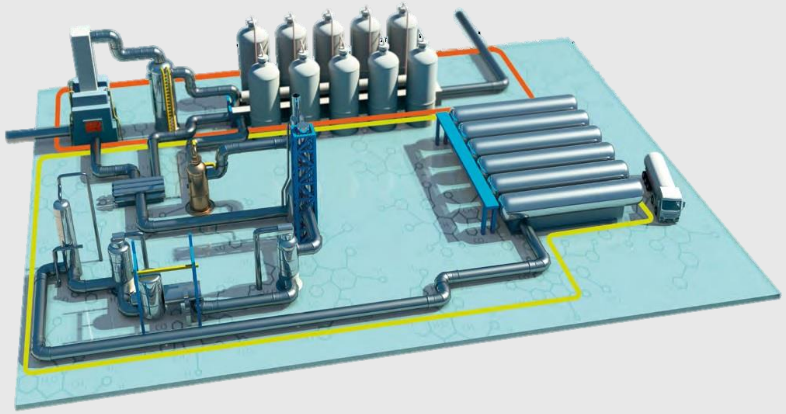
Project leader: Air Products

Project characteristics	**Details**
Production technology	Steam Methane Reformer (SMR) Hydrogen production
CCUS	90% of CO_2 is captured
Government funding	DOE : $284 million (2/3 of the total costs)
CO_2 storage capacity	1 MtCO_2 per year
Business type	Hydrogen production with carbon capture used for EOR
Planning	2011 : start of the construction Q1 2013 : start of the operations
Capture type	Post-combustion
Transport type	Pipeline
Storage type	EOR
Current Status	Operational, the facility had cumulatively captured and stored over 6Mt of CO_2 by April 2020

Source: CCUS Technologies@ MIT, GCCSI Database

Hydrogen production capture to provide a refinery combined with cryogenic carbon

Port Jérome



Country: France

Capacity: 50 000 Nm^3/h

CAPEX: 60 M€

CO2 footprint: 0,1 Mt/y captured

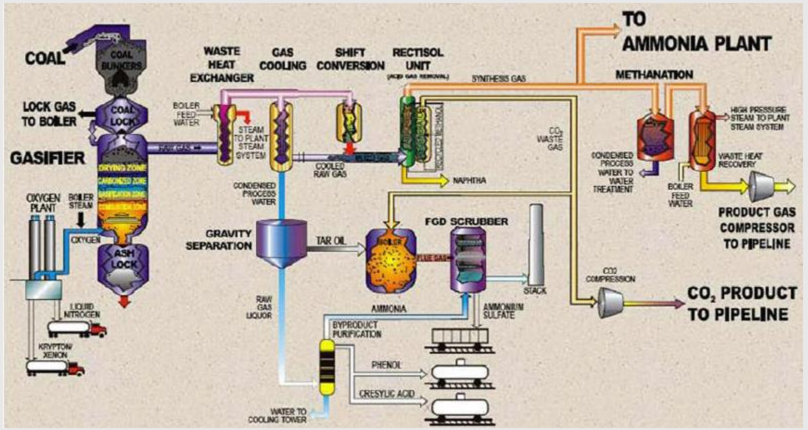
Partnerships: Air Liquide and ExxonMobil

Project characteristics	Details
Production technology	Low carbon hydrogen from natural gas via autothermal reforming units
CCUS	60 to 90% of CO_2 is captured (99% purity)
Government funding	NA
CO_2 storage capacity	0,1 MtCO_2 per year
Business type	Hydrogen production with carbon capture to store and sell captured liquefied CO_2 to Air Liquide clients (like agricultural producers, food industry or also retailers to maintain the cold chain)
Planning	2002 : signature of partnership between Air Liquide and ExxonMobil 2011 : start of the project 2015 : inauguration of Cryocap technology at Port-Jerome
Capture type	Cryocap technology (separate CO_2 from gas mix by cryogenic process)
Transport type	Air Liquide trucks
Storage type	Commercial use
Current Status	Commercial scale demonstration is operational currently

Source: Air Liquide press release

Hydrogen as an industrial resource to produce ammonia combined with carbon capture for EOR

Great Plains Synfuel



Country: USA

Capacity: 160 million cubic ft/ per day

CAPEX: $2.1 billion

CO_2 savings: 3,0 Mt/y

Project leader : Dakota gas

Project characteristics	Details
Production technology	Methanation
CCUS	50% of the CO_2 produced is captured
Government funding	$1.3 billion
CO_2 storage capacity	3,0 MtCO_2 per year
Business type	Coal-to-liquid facility which produces synthetic natural gas. CO_2 is produced during the methanation process, CO_2 is then captured and then sent to Canada for EOR.
Planning	Plant is operational since 1984 CO_2 injection started in 2000
Capture type	Pre-combustion
Transport type	Pipeline
Storage type	EOR in Canada
Current Status	Operational, the facility produces 1300 tonnes per day of hydrogen (2020)

Source: ZEROCO2.NO - NETL

Other Sectors: Blue H_2

Industrial CCS technology is being transposed to marine vessels

First Marine-based CO_2 Capture System

Conceptual drawing of the CO_2 recovery demo plant

Description: Carbon-capture system for vessels (diesel or LNG based engine) are being developed, promising to reduce ship emissions by 85% to 90%. The pilots consist in converting and installing existing design CO_2 capture system of onshore power plants to vessel.

Challenge: The CO_2 captured would be much heavier than the carried fuel, requiring additional fuel to join destination and additional space for onboard CO_2 storage.

Opportunity: This CCS solution would enable the retrofitting of existing vessels, without modifying their propulsion systems or switching to decarbonized fuels such as biodiesel or low-carbon hydrogen.

Cost: Some ongoing designed solutions estimate minimal cost of CO_2 captured around €100 per ton of CO_2 (€1.8 million equipment for a 3,000 kW engine ship).

Other Sectors: Marine Vessels

Source: https://www.euractiv.com/section/energy-environment/news/worlds-first-carbon-capture-at-sea-set-for-shipping-trials/; Mitsubishi (link); M. Feenstra et al., *Ship-based carbon capture onboard of diesel or LNG-fueled ships* (International Journal of Greenhouse Gas Control, vol. 85, June 2019)

5. Outlook of carbon utilization and storage

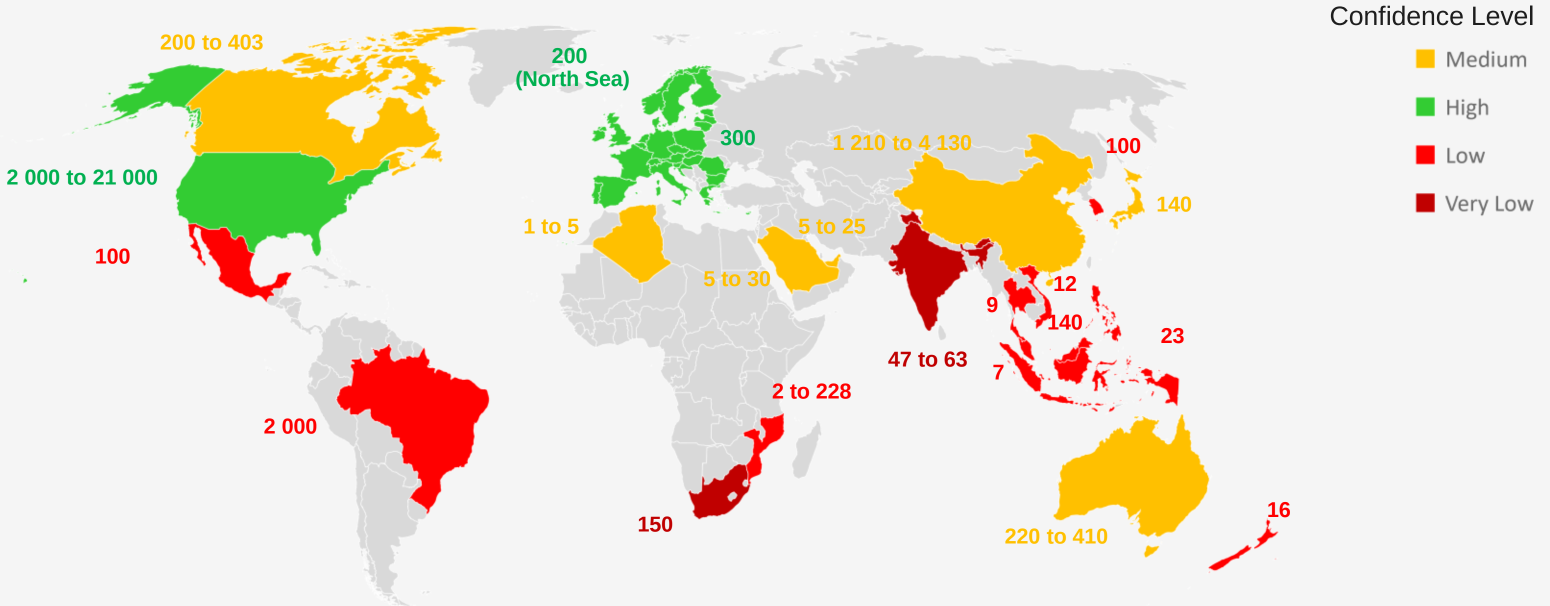
Image by Itung01

The geological storage capacities of CO_2 are unexplored in many areas of the world

Asia and North America own the biggest identified geological storage capacities.

Global Storage Capacity

Global geological storage ($GtCO_2$)



The IEA forecasts stocking more than 2 $GtCO_2$ per year until 2060 to follow Paris agreement. For the IPCC, 1200 $GtCO_2$ need to be stored by 2100. In total, the currently identified world storage capacity is from 6,800 $GtCO_2$ to almost 30,000 $GtCO_2$.

There are a lot of uncertainties in the Middle East because only two countries are reported (Saudi Arabia and United Arab Emirates) whereas the region is known for its oil fields. Most Southeast Asian countries seem to have geological storage capacities; however, they did not announce any CCUS projects.

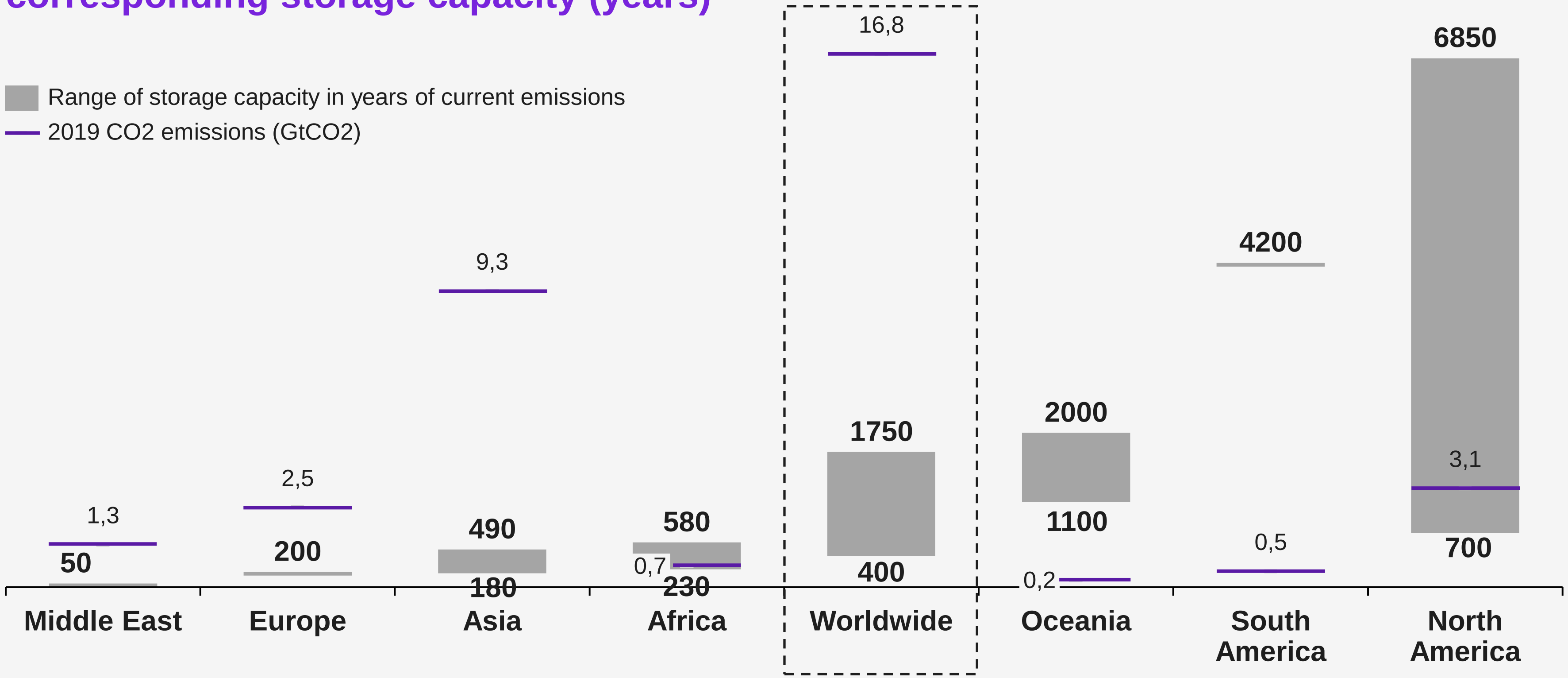
The map above has been made from several national reports and gathered by the Global CCUS Institute.
Sources: Global CCUS Institute : 2019 Report (2019) – IEA (2020)

More mature areas, like North America, already show huge geological storage capacities, corresponding to hundreds of years under current emissions levels

Storage capacity is not a constraint

Global Storage Capacity

Annual regional CO_2 emissions (Gt) from power generation and industries[(1)], and corresponding storage capacity (years)



The worldwide total geological carbon storage capacities are important, and in some regions the estimates are uncertain as they remain unexplored at this stage.

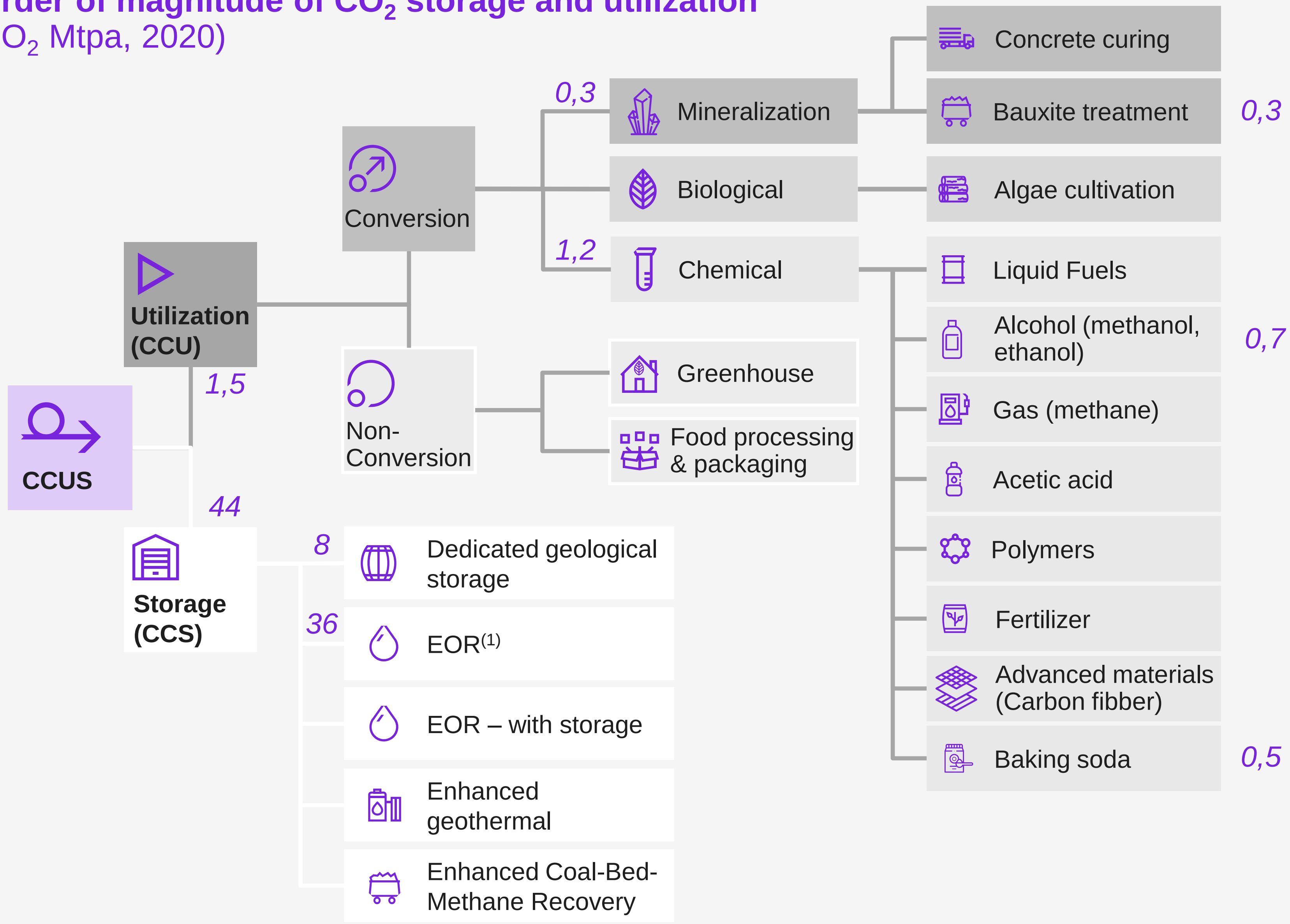
Middle East and Europe have large unexplored geological storage capacities. But North and South Americas would have already identified enough storage capacities for hundreds of years of current emissions. On the basis of the current knowledge, the distribution of storage capacities looks unequal between the regions

(1) CO_2 emissions from industries, power and heat generation were estimated to represent 46% of national emissions on average
Note : this analysis is made with GCCSI storage capacities estimation (from previous slide) and the CO_2 data of “Our World is data”; some actual storage areas may not have been shown
Sources: Kearney Energy Transition Institute analysis based on GCCSI 2019 Report (2019) – Our World is Data

CCUS potentially covers a broad range of solutions to either use or store carbon dioxide

Order of magnitude of CO_2 storage and utilization

(CO_2 Mtpa, 2020)



CCUS

1,5

Utilization (CCU)

Conversion

0,3

Mineralization

Concrete curing

Bauxite treatment

0,3

Biological

Algae cultivation

1,2

Chemical

Liquid Fuels

Alcohol (methanol, ethanol)

0,7

Gas (methane)

Acetic acid

Polymers

Fertilizer

Advanced materials (Carbon fibber)

Baking soda

0,5

Non-Conversion

Greenhouse

Food processing & packaging

44

Storage (CCS)

8

Dedicated geological storage

36

EOR(1)

EOR – with storage

Enhanced geothermal

Enhanced Coal-Bed-Methane Recovery

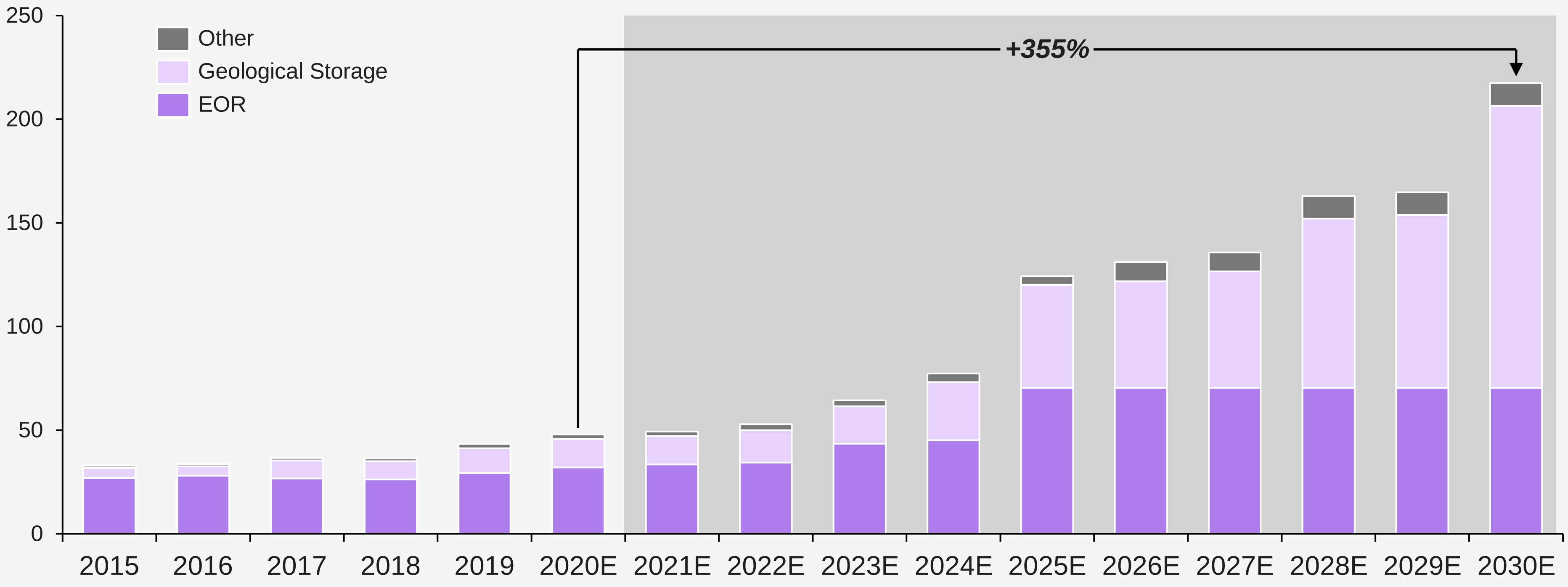
(1): EOR - Enhanced Oil Recovery; "EOR – with storage" allows to inject larger quantities of CO2 compared to traditional EOR

Note: global CO_2 capture is estimated to ~50Mtpa in 2020, which higher than the value tracked in the figure, some storage and applications of CO_2 capture could not be properly tracked, which explain the difference.

Once captured, CO_2 is mostly used for enhanced oil recovery, but geological storage should become the main application around 2030

Operational CO_2 capture capacity per utilization and storage

(including cancelled projects, in $MtCO_2$ per year)



Currently, the captured CO_2 is mostly used for EOR purposes, but by 2030, geological storage is expected to become the main CO_2 utilization pathway and should reach more than 85 $MtCO_2$ per year around 2030. Intention to develop additional large clusters (a 200 Mtpa capture capacity in the Gulf of Mexico (no confirmed date) may complement this projection.

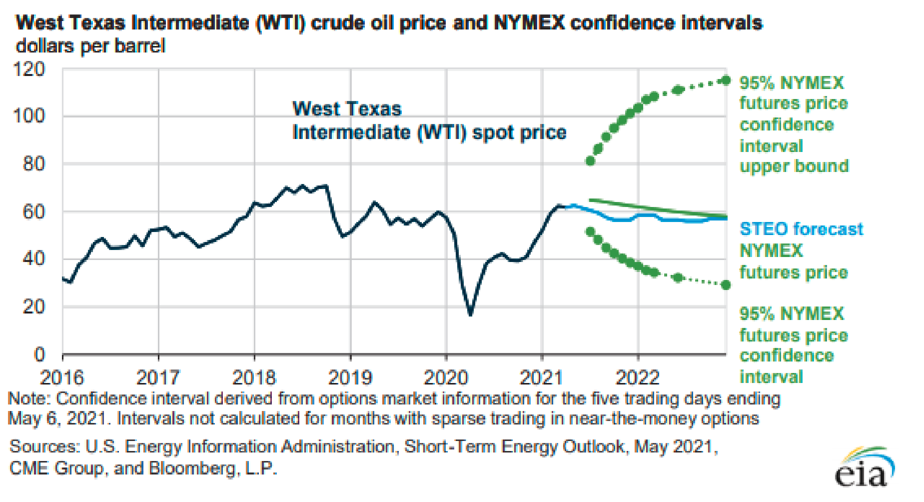
Several projects have been announced with supposed starting date in 2025 (assuming a five-year project development phase). Some of them may actually not be developed.

[1] Other includes commercial purposes, urea production, biofuels, mineralisation etc…

Source: Kearney Energy Transition Institute analysis based on GCCSI database

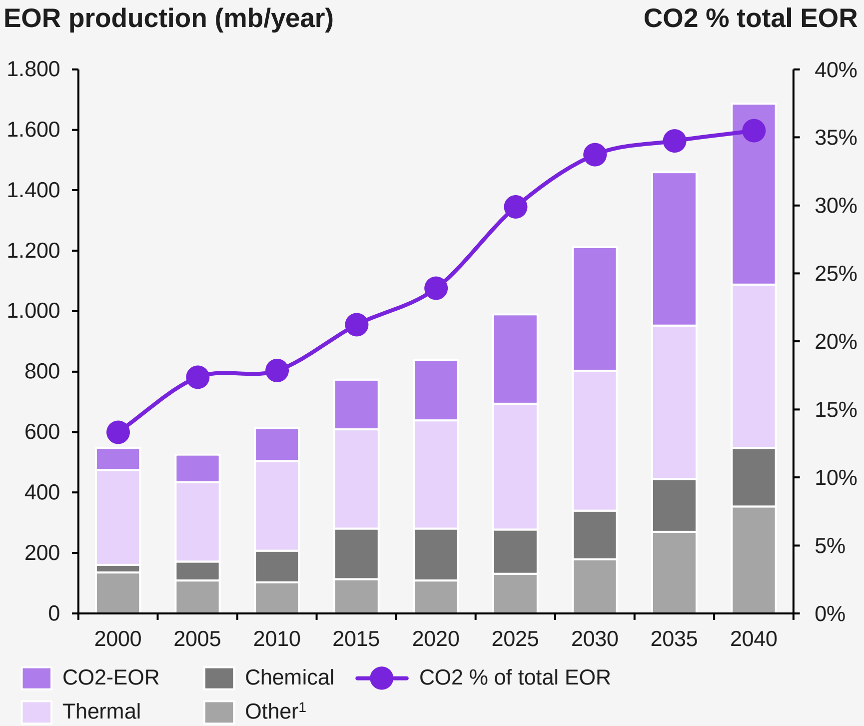
Weak oil prices may undermine demand for CO_2–EOR in the future

Oil price scenarios and associated US CO_2-EOR production forecasts



Note: Confidence interval derived from options market information for the five trading days ending May 6, 2021. Intervals not calculated for months with sparse trading in near-the-money options

Sources: U.S. Energy Information Administration, Short-Term Energy Outlook, May 2021, CME Group, and Bloomberg, L.P.



CO_2-EOR almost represents ~50% of all EOR projects, it currently produces 200 million of barrels per day, which is only 24% of the total EOR production. This part is expected to grow and to reach 35% by 2035 but mainly due to the increase of CO_2-EOR projects.

The COVID-19 crisis and large oil price uncertainties and fluctuations has generated further uncertainties on the oil and gas market, jeopardizing the development of CCUS projects related to the Oil and Gas sector.

**before COVID-19 pandemic*

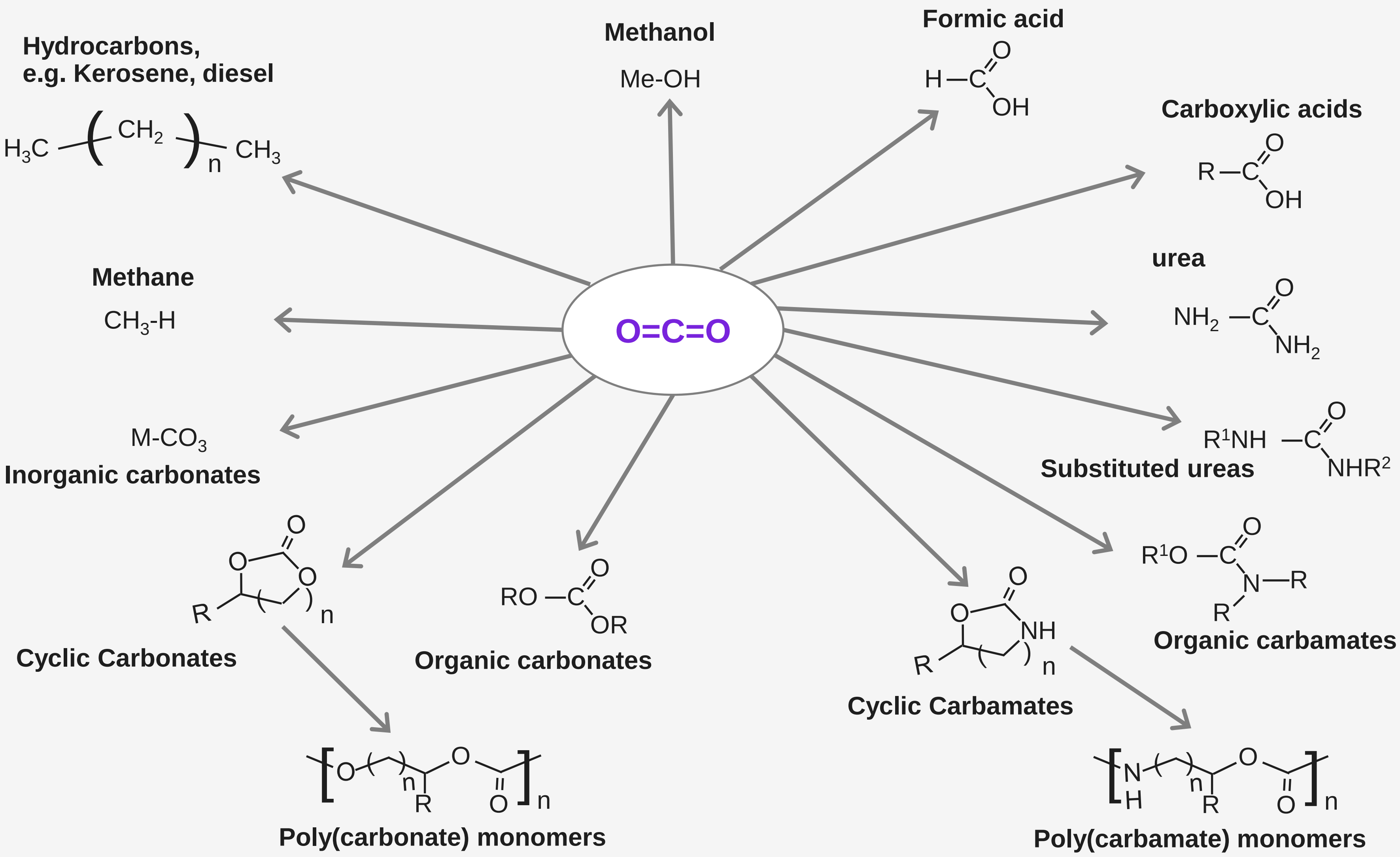
1. Other = other gas injections (like CO_2-EOR), combustion EOR, microbial EOR

Source: Kearney Energy Transition Institute analysis; IEA (2018) ‘*Whatever happened to enhanced oil recovery?,* US EIA *“Short-term energy outlook”* (October 2020)

CO_2 can be reused through multiple chemical pathways

These routes offer an opportunity for the chemical industry to reduce its dependence on fossil fuels, to reduce industrial CO_2 emissions as well as to recycle and valorize emitted CO_2.

Multiple chemical pathways from CO_2



Hydrocarbons,
e.g. Kerosene, diesel

Methanol

Me-OH

Formic acid

Carboxylic acids

urea

Methane

CH_3-H

O=C=O

M-CO_3

Inorganic carbonates

Substituted ureas

Cyclic Carbonates

Organic carbonates

Organic carbamates

Cyclic Carbamates

Poly(carbonate) monomers

Poly(carbamate) monomers

Source: Carbon capture and utilization in the green economy (Styring, Jansen et all 2011)

Reacting CO_2 with hydrogen, derived using low carbon electricity, can be an alternative to fossil carbon feedstocks for producing chemicals and synthetic fuels

However, the energy demand of these low-carbon synthesis routes is very high

Comparison of hydrogen based low-carbon synthesis routes

Product	**Electricity (MWh)**	**CO_2 as feed (t)**	**Avoided CO_2 (t)**	**Costs (€)**	**Avoided CO_2 as kg**	
Chemicals	**per ton of product**				**per MWh[1]**	**per €[2]**
Ammonia	12.5	-	1.71	700-800	137	2.1-2.4
Urea	8.1	0.73	2.05	450-550	253	4.1-4.5
Methanol	11.02	1.373	1.53	300-650	139	2.4-5.1
Olefins	26.6	3.2	1.89	670-1900	71	1-2.8
BTX	48.9	5.9	1.7	1300-2800	34	0.6-1.3~
Fuels	**per ton of product**			**per L**	**per MWh**	**per €**
Diesel	18.4	3.15	2.3a)	1.2-1.5	125	1.3-1.6
Kerosene	18.4	2.85	1.85a)	1.2-1.5	100	1-1.2
SNG	26.9	2.7	1.31	2000-3500	49	0.4-0.7~

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1. Expressed as a function of required electricity
2. Expressed as a function of production costs

a. Well-to-wheel

Source: Low carbon energy and feedstock for the European chemical industry (Bazanella and Ausfelder 2017)

CO_2-based chemical product formation pathways are at various stages of maturity

An integration of CO_2-emitting industrial technologies with CO_2-converting systems (such as biological system using algae, photo bacteria, and enzymatic catalysts) can be helpful in achieving sustainable value-added products.

Different CO_2-based products and the current status of deployment

Compounds[1]		**Products**
■ **Salicylic acid (29 kt)**	→	Aspirin
■ **Cyclic carbonates (40 kt)**	→	Solvents, Electrolytes, Intermediate for polymer synthesis
■ **Urea (115 Mt)**	→	Fertilizer, Resins
▨ **Methanol**	→	Acetic acid, Ethylene, Propylene, Polymer precursor
▨ **Formic acid**	→	Preservatives, Adhesives, Substrates in fuel cells
▨ **Polycarbonate etherols**	→	Polyurethane foam
▨ **Inorganic carbonate**	→	Mineral fillers, Cement, Soil stabilization
▨ **Polypropylene carbonate**	→	Packing foils/sheets
□ **Alcohols**	→	Solvents, Detergents
□ **Aldehydes**	→	Polymers, Solvents, Dyes, Cosmetics
□ **DME**	→	Fuel additives, LPG substitute
□ **Organic acids**	→	Surfactants, Food and Pharma industry products
□ **Organic carbamates**	→	Pesticides, Polymer precursor, Isocynate, Agrochemicals, Cosmetics

■ Commercial ▨ Lab-scale □ Demonstration

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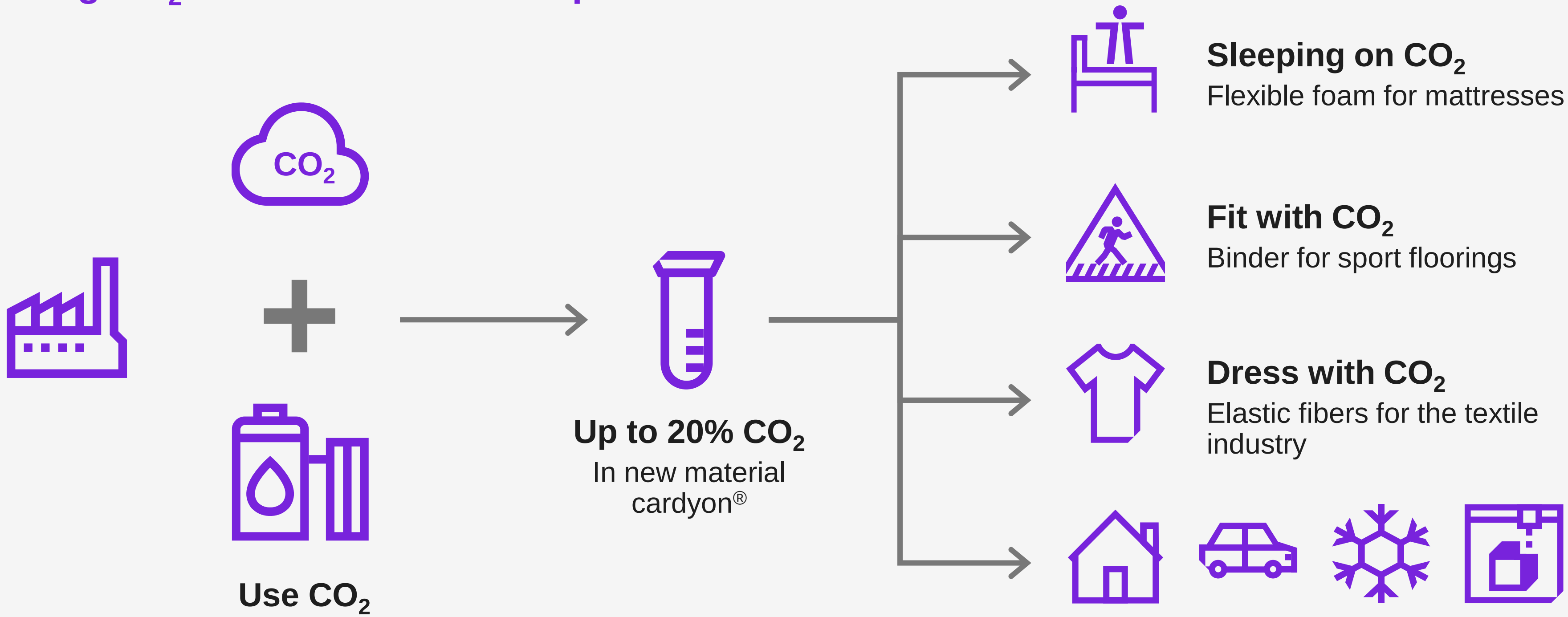
1. Quantity of CO_2 utilized per annum globally to produce the compound

Source: Kearney Energy Transition Institute, CO_2 Catalysis (Kleji, North and Urakaw 2017), Advanced Routes of Biological and Bio-electrocatalytic Carbon Dioxide (CO_2) Mitigation Toward Carbon Neutrality (2020), Low carbon energy and feedstock for the European chemical industry (Bazanella and Ausfelder 2017)

Covestro has developed an innovative technology that enables carbon capture and utilization by partly substituting oil-based raw materials with CO_2

Using CO_2 as a raw material for plastics



Use CO_2
Save crude oil

Up to 20% CO_2
In new material cardyon®

Sleeping on CO_2
Flexible foam for mattresses

Fit with CO_2
Binder for sport floorings

Dress with CO_2
Elastic fibers for the textile industry

Projects in the pipeline
Building, driving, cooling, washing with CO_2

Cardyon® is manufactured with an innovative method that uses a new catalyst, which causes the CO_2 to react with propylene oxide to produce certain plastic components known as polyols. This results in a new type of polyols with a CO_2 share of up to 20 percent substituting crude oil feedstock completely.

Covestro has been manufacturing the new material in a production plant in Dormagen, Germany since 2016. Up to 5,000 tons of polyols can be produced there each year. This broadens the resource base and supports a circular economy in the chemicals and plastics industry.

Source: Kearney Energy Transition Institute, https://www.covestro.com/

Bio-electrochemical systems (BES) offers benefits of synthesizing value-added chemicals from CO_2 via electrogenic fermenting cathode microbes (biocathode)

Bio electrochemical generation of solvents and biofuels from CO_2 under various operational and nutritional conditions

Reactor	Substrate	Operational condition	Dominant catalyst	Products
H-type double chamber	Calcium carbonate	Batch type; anaerobic fermentation	*Clostridium Sporogenes BE1*	Butanol, Ethanol, Fatty acids
Double chamber fuel cell	Butyraldehyde + TRIS-HCl buffer	Batch type; enzymatic fuel cell	*Alcohol dehydrogenase enzymes*	Butanol
H-type double chamber	P2 electron carrier medium + Glucose	Batch type; anaerobic fermentation	*Clostridium beijerinckii IB4*	Acetone, Butanol
Two compartment cell	CAB medium with electron carrier in buffer	Batch type; electrochemical cell	*Clostridium Acetobutylicum ATCC 4259*	Acetone, Butanol
H-type double chamber	CO_2 injection + DSMZ medium	Continuous mode operation	*Sporomusa, Geobacter Clostridium, Morella*	Acetate, Formate, Butyrate, Propanol
H-type double chamber	CO_2	Batch type; electrochemical cell	*Clostridium species + Carboxydotropic mixed culture*	Ethanol, Butanol, Acetate, Butyrate
H-type double chamber	Modified P2 medium + SMM medium	Batch type; electrochemical cell	*C. Pasteurianum*	Butanol and by-products
Double chamber	CO_2	Batch type; electrochemical cell	*NA*	Methane

Source: Advanced Routes of Biological and Bio-electrocatalytic Carbon Dioxide (CO_2) Mitigation Toward Carbon Neutrality (2020)

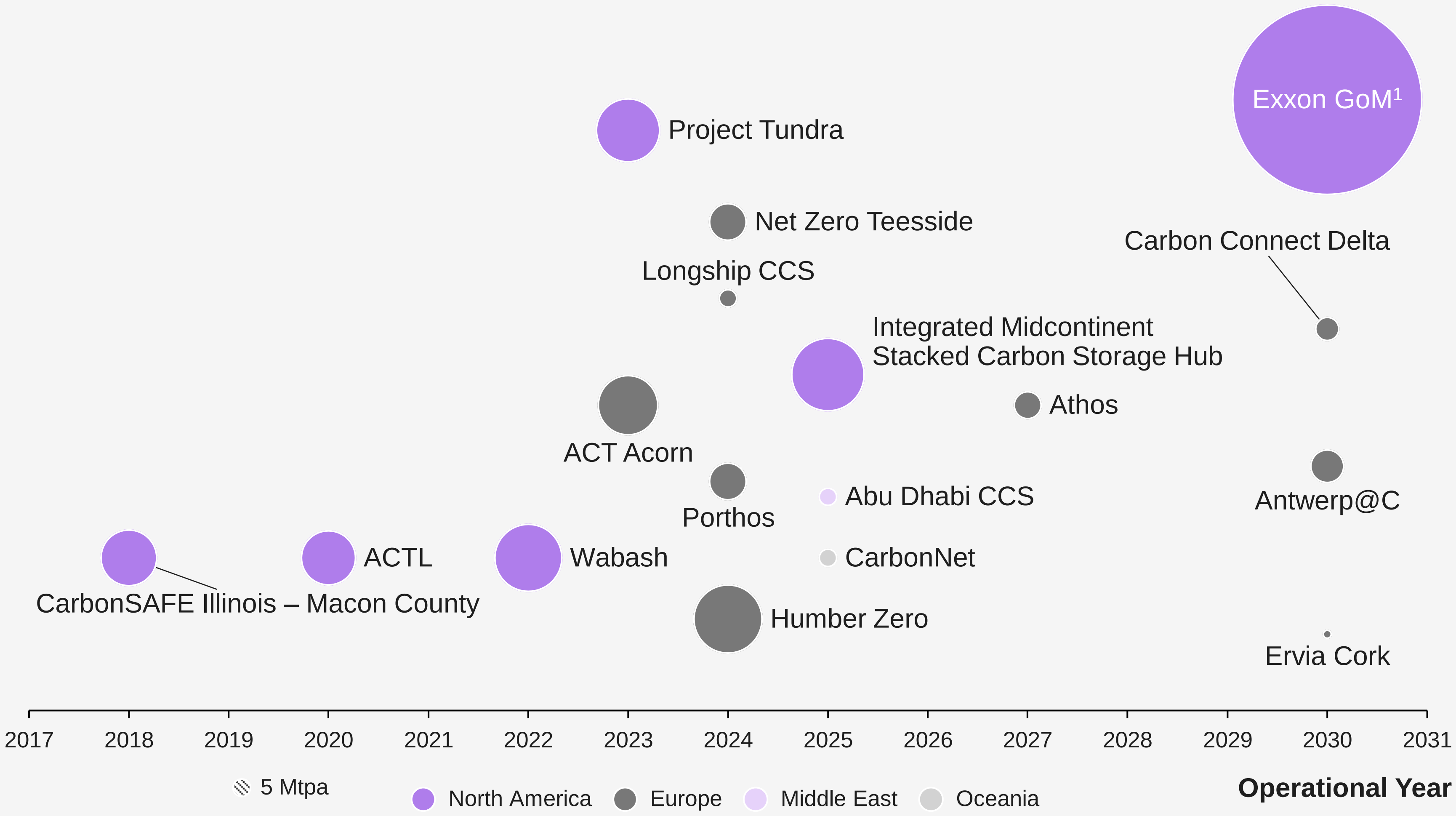
Europe and North America are expecting to develop cross-industries CCUS clusters in the next few years

CCUS hubs will gather CO_2 emissions from industrial areas and stock it or use it without building new facilities and searching for new storage areas.

Sectoral Overview: Clusters / Hubs

Upcoming new CCUS clusters

Non-exhaustive



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[1] The proposed project would cost $100 billion and the hub could draw up to 50 million mt of CO2 from the air by 2030, and 100 million mt by 2040

Source: Kearney Energy Transition Institute – GCSSI (2019), Press search

The development of CCUS clusters and hubs is gaining prominence, especially in Europe

Clusters
Geographic concentration of related businesses, facilities, factories, etc.

Hubs
Central CO_2 points from capture clusters or distribution CO_2 points to storage clusters

Sectoral Overview: Clusters / Hubs

CCUS hubs and clusters

Advantages

- Catch CO_2 emissions from an area with several high-emitting facilities.
- Permit the capture of small CO_2 volume by gathering it with other CO_2 sources.
- Reduce storage costs thanks to economies of scale.
- Create possible commercial synergies that lower the risk of investment for the development of CCUS installations.
- Use shared infrastructure to transport and store CO_2.

Challenges

- Lack of supportive public policies, especially CCUS-specific laws, are needed to keep developing these kind of initiatives.
- Financial support from governments are requested to completely fill the gap between costs and revenues.
- Complexity of shared pipelines can increase the time of the project.

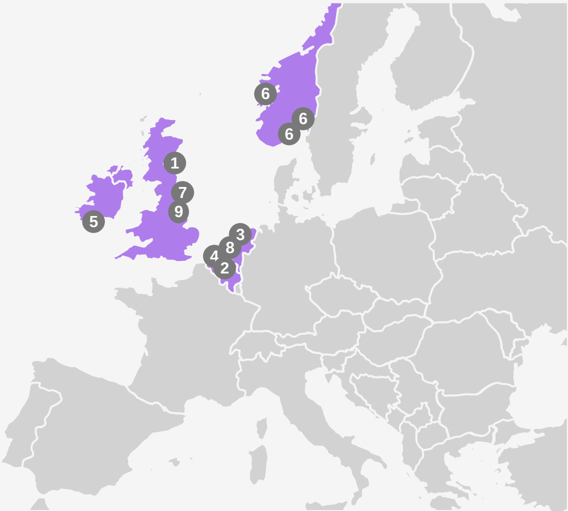
	Europe	North America	Asia and Pacific	Middle East	South America
# of hubs	9	6	2	1	1
Sum of capture capacity (Mtpa)	84,8	119	8,0	5,0	3,0
Average capacity (Mtpa)	9,4	19,8	4,0	-	-

Source: GCCSI – *Global Status of CCS 2019* (2019) & *Understanding Industrial CCS Hubs and Clusters* (2016)

CCUS hubs in Europe

- Biomass
- Cement production
- Chemicals industry
- Ethanol production
- Fertilisers production
- H_2 Hydrogen production
- Natural gas production
- Iron and steel production
- Industrials applications
- EOR
- Power plant (coal)
- Power plant (gas)
- Waste incineration

#	Project Name	Country	Maximum CO_2 Capture capacity (Mtpa)	Operational Year	Industries
1	ACT Acorn	🇬🇧	16	2023	Chemicals industry, H_2, EOR, Power plant (gas)
2	Antwerp@C	🇧🇪	9	2030	Chemicals industry, Fertilisers production, Power plant (gas)
3	Athos	🇳🇱	6	2027	Fertilisers production, H_2, Iron and steel production, Waste incineration
4	Carbon Connect Delta	🇧🇪 🇳🇱	6,5	2030	Chemicals industry, EOR, Iron and steel production, Power plant (gas)
5	Ervia Cork, Ireland Gas Network	🇮🇪	2,5	2030	Industrials applications, EOR, Power plant (gas)
6	Longship CCUS	🇳🇴	5	2024	Chemicals industry, Cement production, H_2, Iron and steel production, Power plant (gas), Waste incineration
7	Net Zero Teesside	🇬🇧	10	2024	Chemicals industry, Fertilisers production, H_2, Iron and steel production, Power plant (gas)
8	Porthos	🇳🇱	10	2023	Chemicals industry, H_2
9	Zero Carbon Humber	🇬🇧	18,3	2024	Ethanol production, Cement production, Chemicals industry, H_2, Iron and steel production, EOR

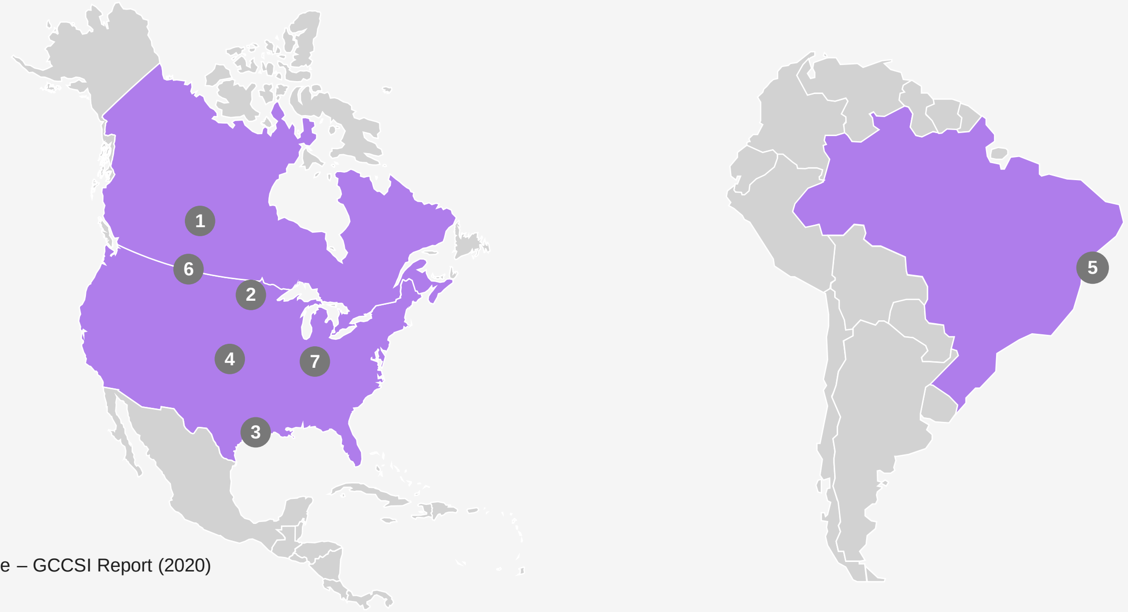


Sources : Kearney Energy Transition Institute – GCCSI Report (2019)
Oil and Gas Climate Initiative (2020)

CCUS hubs in Americas

- 🌱 Biomass
- 🚚 Cement production
- 🧪 Chemicals industry
- 🌽 Ethanol production
- 🛍 Fertilisers production
- H_2 Hydrogen production
- 🔥 Natural gas production
- 🔩 Iron and steel production
- 🏭 Industrials applications
- 💧 EOR
- 🏭 Power plant (coal)
- 🏭 Power plant (gas)
- 🗑 Waste incineration

#	Project Name	Country	Maximum CO_2 Capture capacity (Mtpa)	Operational Year	Industries
1	ACTL	🇨🇦	14,6	2020	🛍 H_2 💧
2	CarbonSAFE Illinois Macon County	🇺🇸	15	2018	🌽 🏭
3	Gulf of Mexico CCUS hub	🇺🇸	35	TBD	🧪 🛍 H_2 🏭
4	Integrated Midcontinent Stacked Carbon Storage Hub	🇺🇸	19,4	2025	🌽 H_2 🏭 🚚
5	Petrobras Santos Basin	🇧🇷	3	TBD (Pilot ongoing)	🔥 💧
6	Project Tundra (North Dakota CarbonSafe)	🇺🇸	17	2023	💧 🔩
7	Wabash CarbonSafe	🇺🇸	18	2022	🚚 🧪 H_2 🌽 🛍 🏭

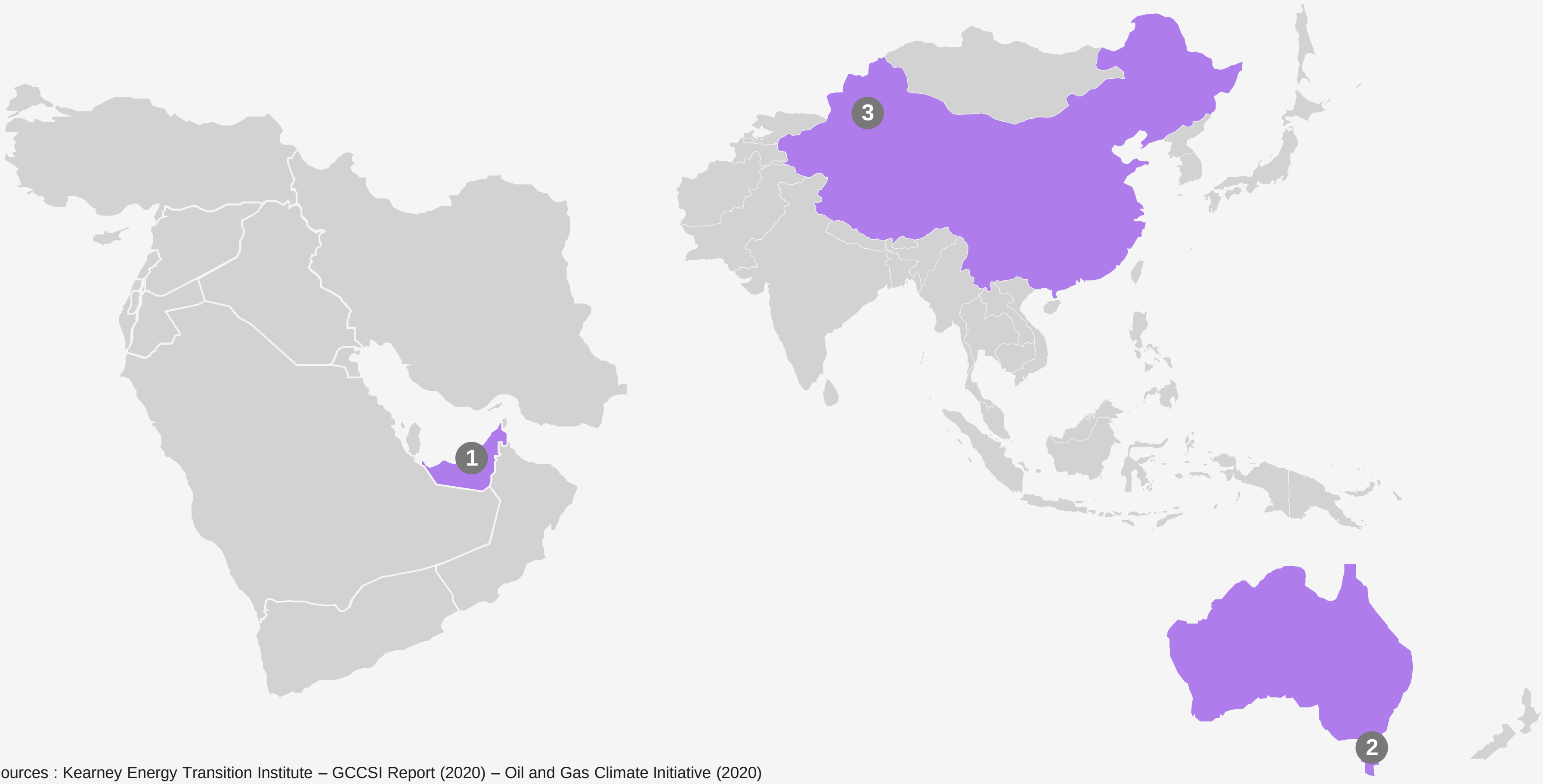


Sources : Kearney Energy Transition Institute – GCCSI Report (2020)
Oil and Gas Climate Initiative (2020)

CCUS hubs in the Middle East and APAC

- Biomass
- Cement production
- Chemicals industry
- Ethanol production
- Fertilisers production
- H_2 Hydrogen production
- Natural gas production
- Iron and steel production
- Industrials applications
- EOR
- Power plant (coal)
- Power plant (gas)
- Waste incineration

#	Project Name	Country	Maximum CO_2 Capture capacity (Mtpa)	Operational Year	Industries
1	Abu Dhabi Cluster	🇦🇪	5	2025	H_2 🔥 ▨ 💧
2	CarbonNet	🇦🇺	5	2025	🧪 🛍 H_2 🏭
3	Xinjiang Junggar Basin CCUS Hub	🇨🇳	3	TBD	🚚 🧪 H_2 🏭



Sources : Kearney Energy Transition Institute – GCCSI Report (2020) – Oil and Gas Climate Initiative (2020)

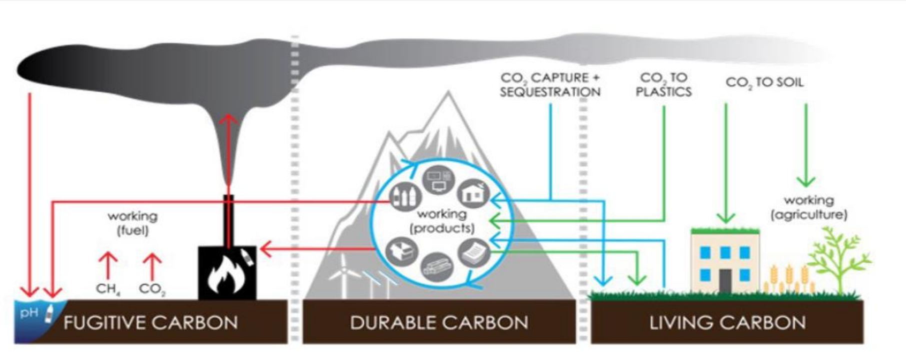
Circular carbon economy in the Golf Cooperation Council

Circular Carbon Economy Concept

The circular carbon economy is based on the four Rs :

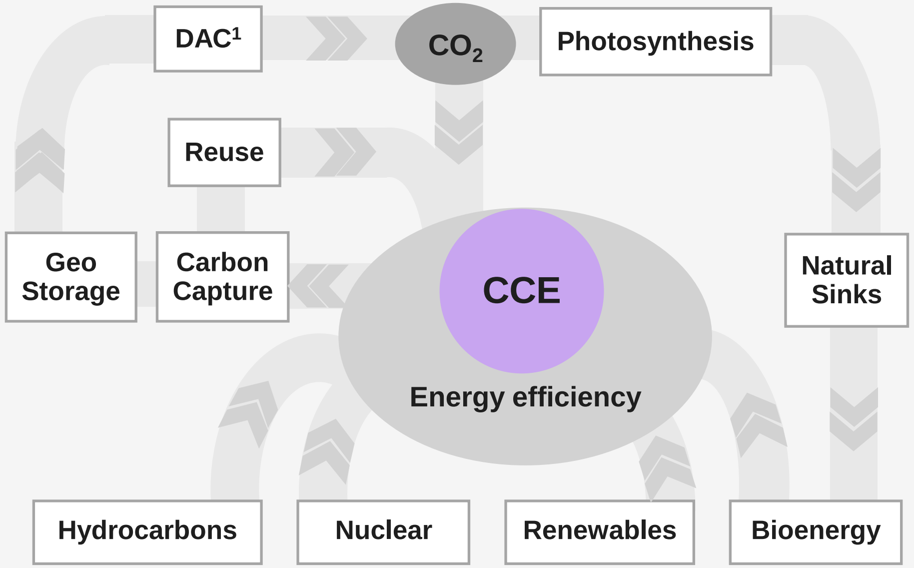
- **Reduce:** energy efficiency, non-bio renewables, nuclear
- **Re-use:** carbon utilization
- **Recycle:** bioenergy
- **Remove:** carbon capture and storage, direct air capture

Cross-cutting: hydrogen, policies



Distinction between:

- Living carbon (plants and soil)
- Fugitive carbon (such as methane and CO_2 gases)
- Durable carbon (for example, locked in plastics)



1. Direct Air Capture
Sources : GCCSI – *Global Status Report 2020* (2020), CCE Guide Overview, KAPSARC ‘2020)

GCC potential for CCE

- Great **geological storage capacity** available for CO_2 or hydrogen
- Unparalleled **solar resources**, **natural gas, and oil resources** that can be used in industrial **carbon storage clusters** to produce blue hydrogen
- Saudi Arabia’s King Abdullah Petroleum Studies and Research Center (**KAPSARC**) interest for CCE in the GCC region

6. Economics, policies, and regulations

van de Voorde, Denis

Some CCUS projects have not reached a final investment decision despite large public grants

Most projects were cancelled for economical reasons, such as a lack of funding from the companies involved in the projects or a lack of subsidies from the related governments or states.

However, some projects have been cancelled because of local public opposition, including government bans on onshore storage in Germany and the Netherlands.

Promising CCUS projects cancelled in advanced stage of planning

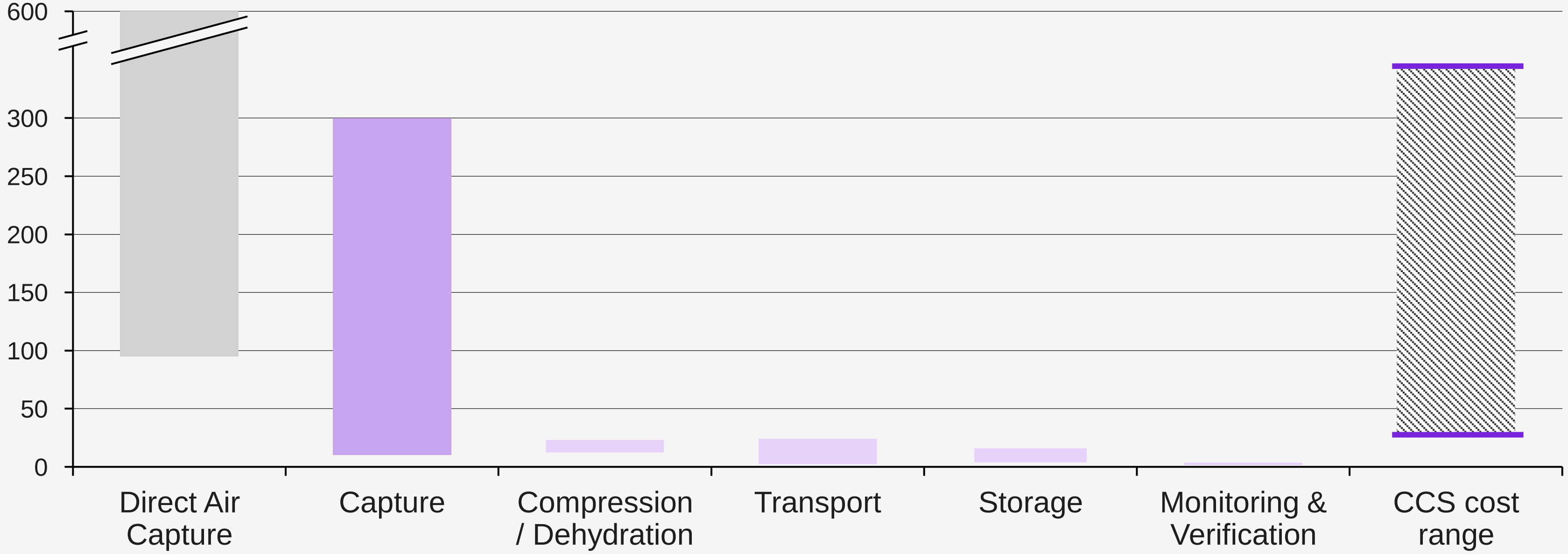
Project (Date)		Project Type & Grants	Reason For Cancellation
Barendrecht (2010)	🇳🇱	Store up to 400,000 t of CO_2 from Shell's oil refinery	***Local public opposition :*** Citizens of the town feared of the storage of CO_2 in a former gas tank located under the city.
Pioneer (2012)	🇨🇦	Coal & passive storage $782 million granted	***Economics***: Horizontal multi-frac well technology is delaying the needs for CO_2-EOR in Alberta's mature oil fields.
ULCOS (2012)	🇫🇷	Steel & passive storage Potentially large grant winner	***Economics***: Project withdrew its candidacy for EU NER300 €1.5 B grant scheme despite being the only remaining candidate, amid economic turmoil in Europe's steel sector.
Trailblazer, Taylorville (2013)	🇺🇸	Coal & possibly EOR $400 million tax credit	***Economics***: Regulatory uncertainties, low natural gas prices, and the continuing decline in the cost of renewables.
Mongstadt (2013)	🇳🇴	Refinery, CO_2 fate unknown	***Economics***: Government dropped support due to cost overruns and delays.
Belchatow (2013)	🇵🇱	Coal & passive storage, €180million granted	***Economics***: Lack of funding, lack of interest from oil & gas companies for CO_2 storage contracts, and public opposition to onshore storage.
Porto Tolle (2014)	🇮🇹	Power & passive storage, €100million granted	***Local public opposition*** and difficulties in achieving closure for the financial structure of the project.
Lake Charles (2014)	🇺🇸	Methanol plant & EOR $261million granted	***Economics:*** Methanol market was becoming crowded, and methanol-production costs were uncompetitive, despite government support & EOR.
FutureGen (2015)	🇺🇸	Coal & passive storage $1 billion granted	***Economics***: FutureGen1.0 cancelled in 2004 due to rising costs. FutureGen2.0 funding from DOE cancelled in 2015 due to delays and inability to raise private financing.
White Rose CCUS, Peterhead (2015)	🇬🇧	Power generation & passive storage	***Economics***: Projects cancelled after the UK announced the suspension of the $1bn UK CCUS Competition
E.ON Ruhrgas Killingholme IGCC (2015)	🇬🇧	Large-scale IGCC Plant with storage under North Sea.	***Economics :*** In March 2015 E.ON announced the cancellation of the project because gas-fired power stations market is extremely difficult and without support from the Supplemental Balancing Reserve (SBR) contract
AEP Mountaineer (2015)	🇺🇸	Power generation & geological storage	***Climate policy*** *:* Phase II of the project has been cancelled due to unknown climate policy.
HECA (2016)	🇺🇸	Power generation & EOR, $800m grants & tax credits	***Project delays*** led to the ***expiration of funds*** granted by the US. DOE. While the company hopes to resurrect HECA, it remains unclear when that might happen.
Liaohe EOR Project (2016)	🇨🇳	EOR Project with capture facility	***Economics*** *:* The project was abandoned because due to oil prices decrease, it is expected not to be economical and sustainable for the company.

Source: Kearney Energy Transition Institute

Capture usually represents the largest cost in CCUS, while transport and storage share the remaining 25% equally

Cost range for capture, compression & dehydration, transport, storage and monitoring & verification of CO_2[1, 2, 3, 4]

$\$_{2020}$ per t CO_2



- Capture cost represent about 75% of the total cost for CCUS but can **drastically decrease for applications with high concentrations of CO_2** (95–100%) where only a compression step is needed. Cost of CO_2 capture is expected to decline by 50% from 2010 to 2025 for some applications.

- Transport and storage costs represent about 25% of the total CCUS cost. **Transport cost** is influenced by the **technology used** (pipelines, ship, trucks, rails) and by the **volume transported** (pilot-scale vs. large scale). **Storage cost** is driven by **the nature of the reservoir** (saline aquifer vs. depleted oil and gas field), its **accessibility** (onshore vs. offshore), the **existence of legacies** (wells, infrastructures) and its **physical characteristics** (size, porosity, permeability, pressure).

CCUS Costs

[1] The capture cost is adjusted according to the prices of feedstock in the United States. All costs (except capture) have been converted to US Gulf Coast basis.

[2] Transport costs include liquefaction costs.

[3] Typical range of capture cost: 10 (natural gas processing) – 300 (aluminium smelting) $/t

[4] Low estimates are the sum of low values of range and high estimates are the sum of high values of range and are indicative.

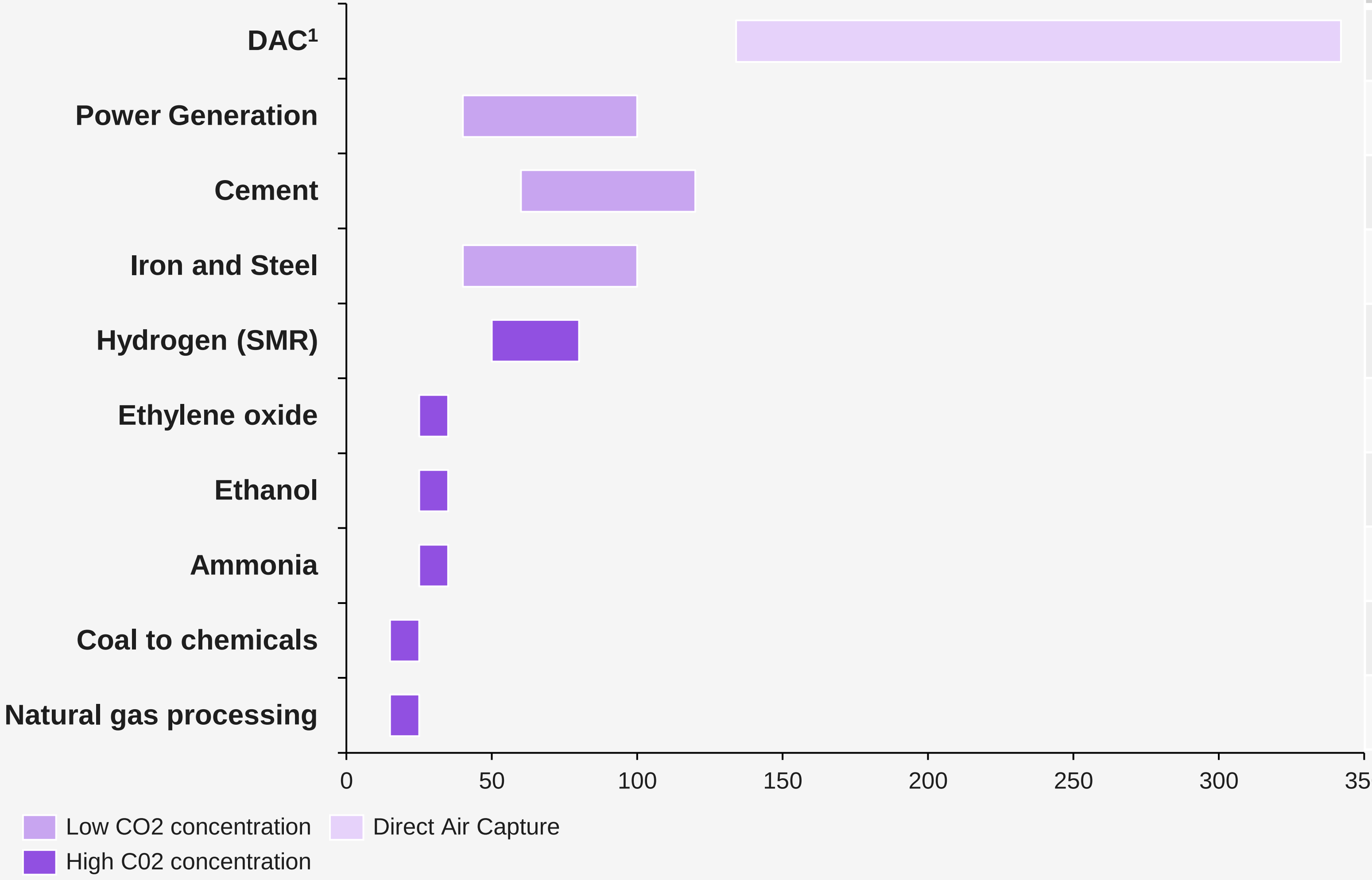
Source: Kearney Energy Transition Institute, , Zero Emission Platform, IEAGHG, The Costs of CO_2 Capture, Transport and Storage, 2011, GCCSI - Technology Readiness and Costs of CCS (March 2021)

CO_2 capture cost depends on the industry and the CO_2 concentration of the stream or flue gas

Cost depends on CO_2 partial pressure in the flue gas (and therefore to its CO_2 concentration assuming atmospheric pressure): high concentration enables direct separation and cheap capture whereas low concentrations require an additional expensive concentration step.

Levelized cost of CO_2 capture for key sectors

$ per ton, 2019



	CO_2 concentration
DAC[1]	0,04%
Power Generation	4-13%
Cement	14-33%
Iron and Steel	26%
Hydrogen (SMR)	~45%
Ethylene oxide	95-100%
Ethanol	95-100%
Ammonia	95-100%
Coal to chemicals	NA
Natural gas processing	95-100%

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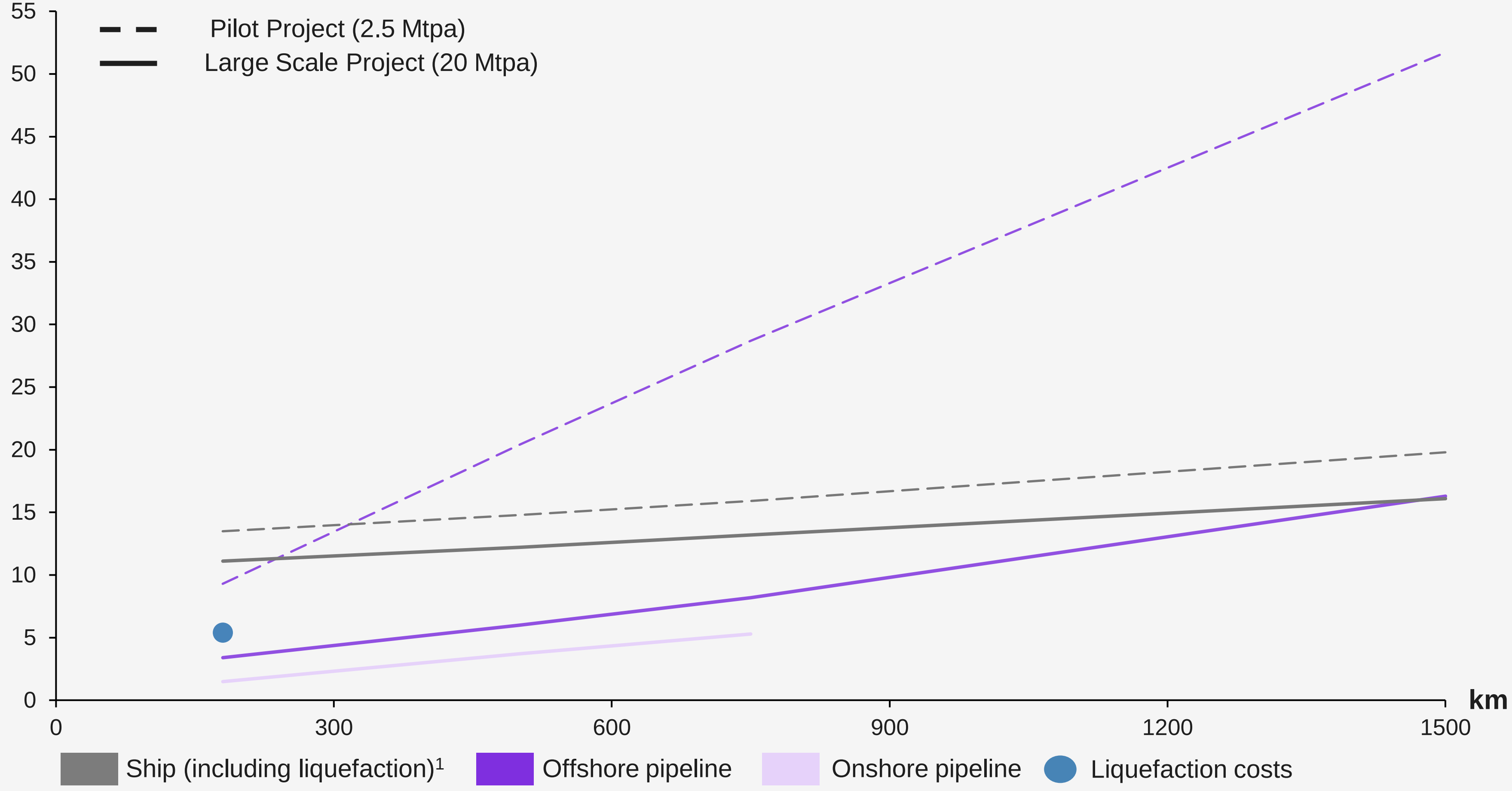
1. DAC = Direct Air Capture, negative technology

Source: Kearney Energy Transition Institute, IEA Levelized cost of CO_2 capture by sector and initial CO_2 concentration, 2019, Meeting the dual challenge: A Roadmap to At-Scale Deployment of CCUS, Ch. 2 – CCUS SUPPLY CHAINS AND ECONOMICS, Energy Futures Initiative and Stanford University, 2020

Offshore pipelines are competitive for large volumes and relatively short distances, while shipping is preferred for pilot projects and very long distances

Cost estimates for long-distance CO_2 transport

€ per t of CO_2, 2011



CCUS Costs

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1. Liquefaction costs are evaluated at 5.3€/ ton of CO_2

Source: Kearney Energy Transition Institute, The Costs of CO_2 Transport : Post-demonstration CCUS in the EU, Zero Emission Platform 2011

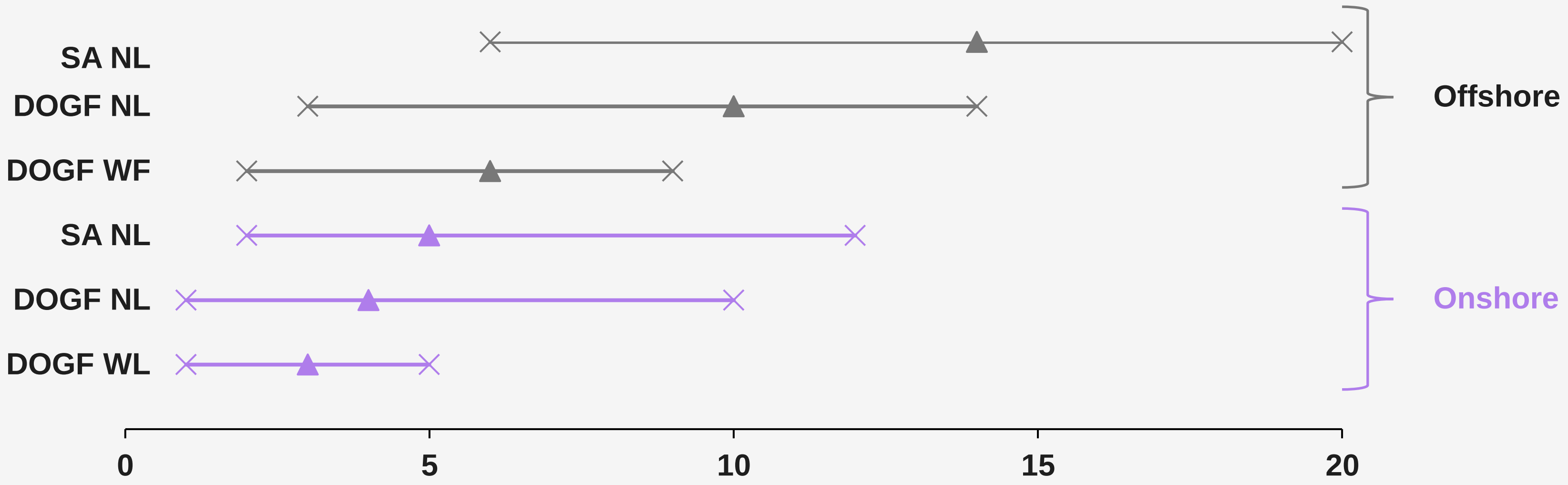
Storage in onshore depleted oil and gas fields is the cheapest, especially if existing wells are reusable but their storage capacity is limited

The variability in the price range depends on local parameters such as the available knowledge on the reservoir, its capacity, and quality.

CCUS Costs

Geological storage cost comparison with uncertainty range[1]

€ per ton of CO_2 stored, EU, 2011



DOGF = Depleted Oil and Gas Fields
SA = Saline Aquifers

WL = With Legacies[2]
NL = No Legacy

- **Onshore storage is cheaper than offshore storage** (for both depleted oil and gas fields and saline aquifers).
- **Depleted oil and gas fields** are cheaper than deep saline aquifers.
- **Larger reservoirs are cheaper** than smaller ones; **high injectivity is cheaper** than poor injectivity.
- **Cheapest storage reservoirs (large onshore DOGF) are also the least available.**

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[1] Does not include any fee (such as tax) for storage from host government.

2. "With Legacies" means existing wells that are re-usable for the storage process

Source: Kearney Energy Transition institute, Zero Emission Platform, IEAGHG, The Costs of CO_2 Storage, 2011

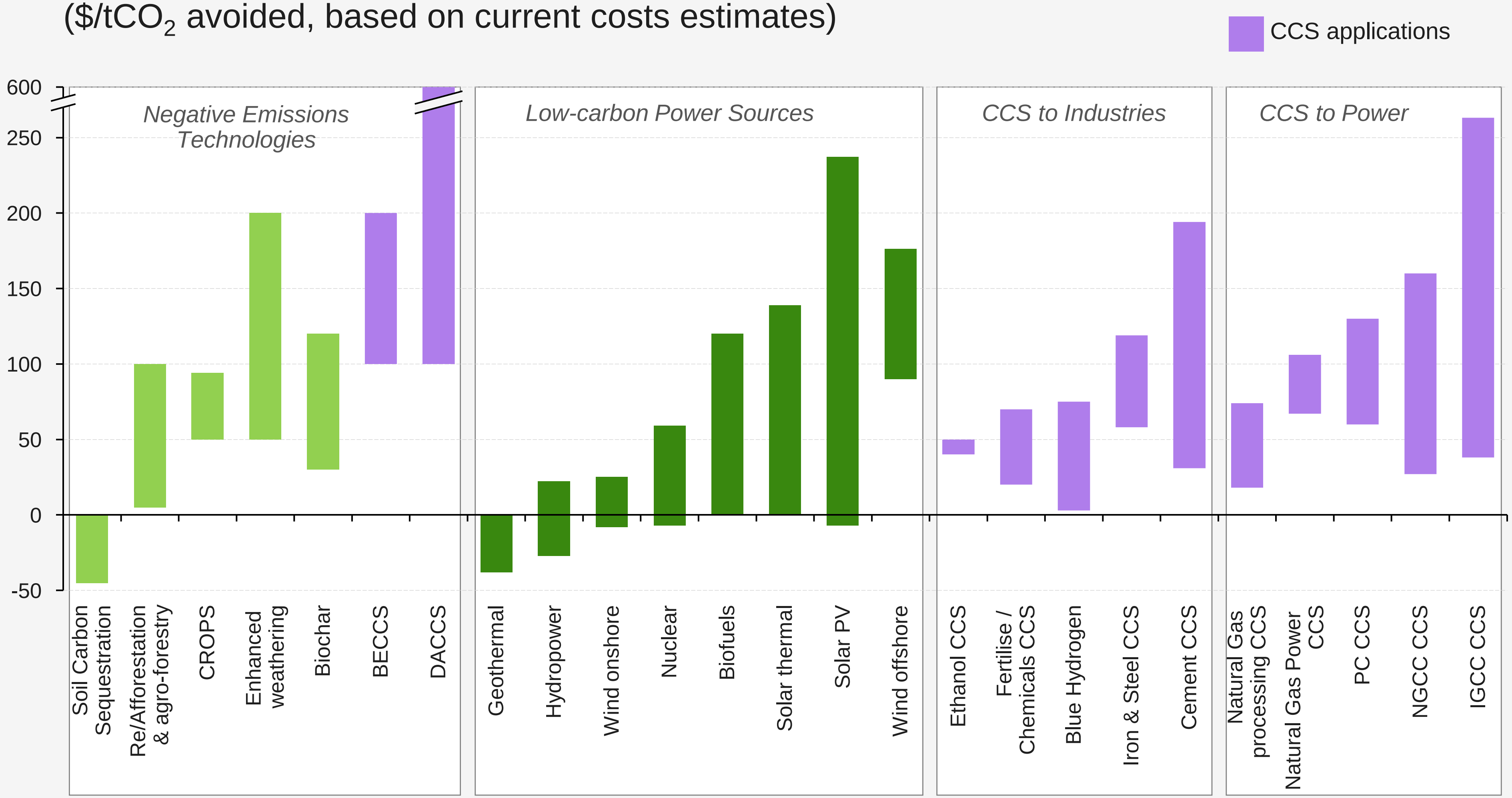
CCUS offers opportunities for CO_2-abatement at a moderate cost, especially in industrial applications where CO_2 separation is already inherent to the process

Local conditions (e.g. wind, solar sources, geological storage, transport…) significantly impact the overall cost of the decarbonisation solution, which explains high range of costs.

CCUS costs

Costs of CO_2 abatement by CCUS for different sectors

($/t$CO_2$ avoided, based on current costs estimates)



CROPS: Crop Residue Ocean Permanent Sequestration; BECCS: Bioenergy with CCS; DACCS: Direct Air Capture combined with CCS; PC: Pulverized Coal Power; IGCC: Integrated Coal Gasification Combined Cycle Power; NGCC: Natural Gas Combined Cycle Power; Integrated Gasification Combined Cycle

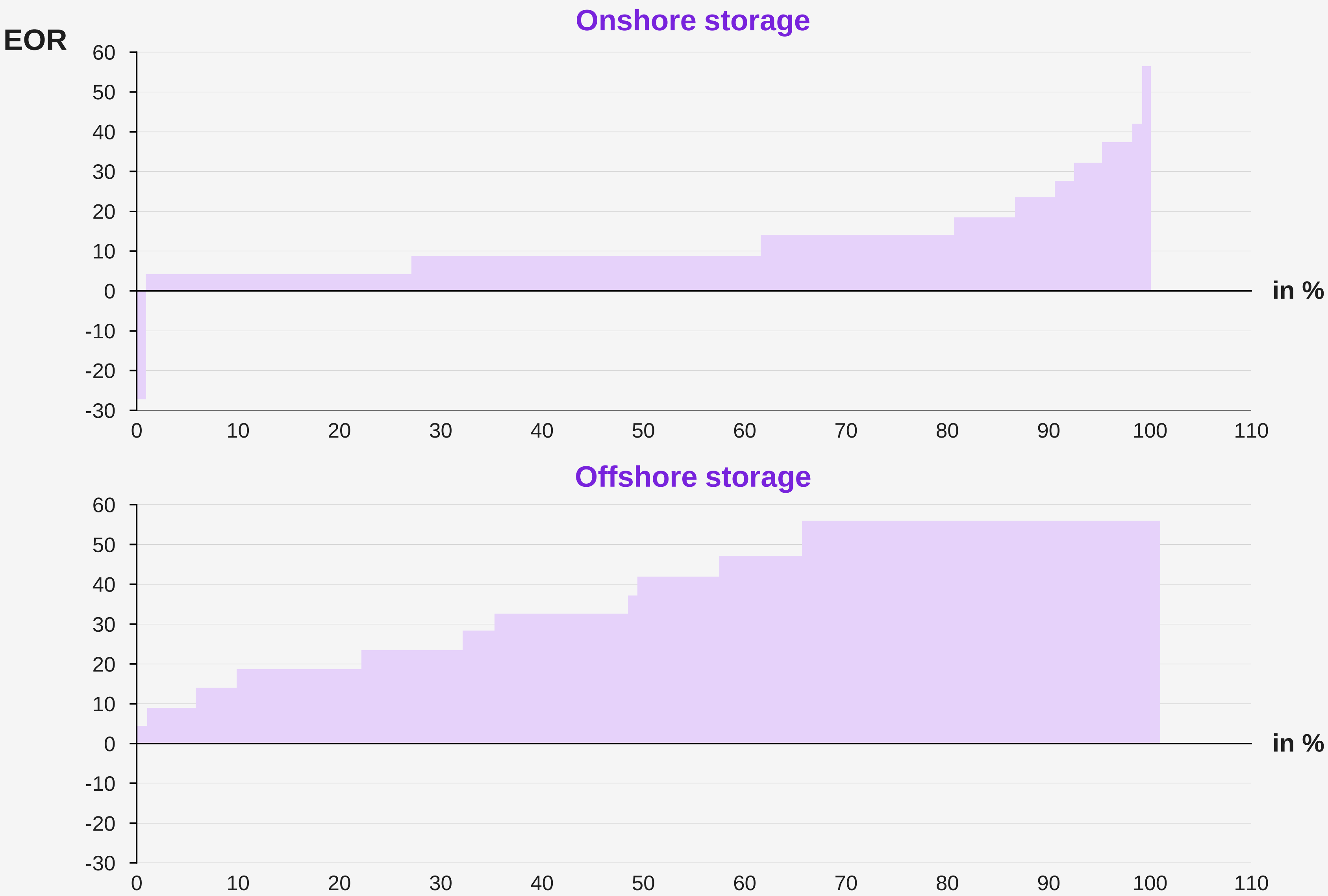
The Coal, IGCC and Natural Gas Power are for Post-Combustion Capture, Fertilizer is the production of ammonia, Hydrogen cover Steam Methane Reforming, Autothermal Reforming and Coal Combustion, Cement covers Calcium Looping, partial and full Oxy-Fuel as well as Post-Combustion for Coal and Natural Gas. The cost for transport and storage when not included was set to 11$/t CO_2 according to the GCCSI study from 2017.

Source: GCCSI Global Costs of Carbon Capture and Storage (2017); IEA Transforming Industry through CCUS (2019); Grantham Institute, A Systematic Review of Current Technology and Cost for Industrial Carbon Capture (2014); Columbia, Levelized Cost of Carbon Abatement: An Improved Cost-Assessment Methodology for a Net-Zero Emissions World (2020); NBER, The Cost of reducing Greenhouse Gas Emissions (2018); IPCC Special Report on Carbon Dioxide Capture and Storage (2005) (https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_chapter8-1.pdf); National Petroleum Council, Meeting the dual challenge - A roadmap to At-Scale Deployment of Carbone Capture, Use, and Storage (2019); Goldman Sachs, Carbonomics - 10 key themes from the inaugural conference (2020); K. Gillingham and T. H. Stock, The Cost of Reducing Greenhouse Gas Emissions (2018); Kearney Energy Transition Institute

CO_2 for EOR is at negative costs, and most of the onshore storage capacity in the United States is available for less than \$10 per tCO_2

Storage cost curve for the US (onshore and offshore)

$/t of CO_2, US, 2017



Source: Kearney Energy Transition, Energy Technology Perspectives 2020 Chapter 3. CCUS technology innovations, 2020, IEA, US EPA 2018, Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2017

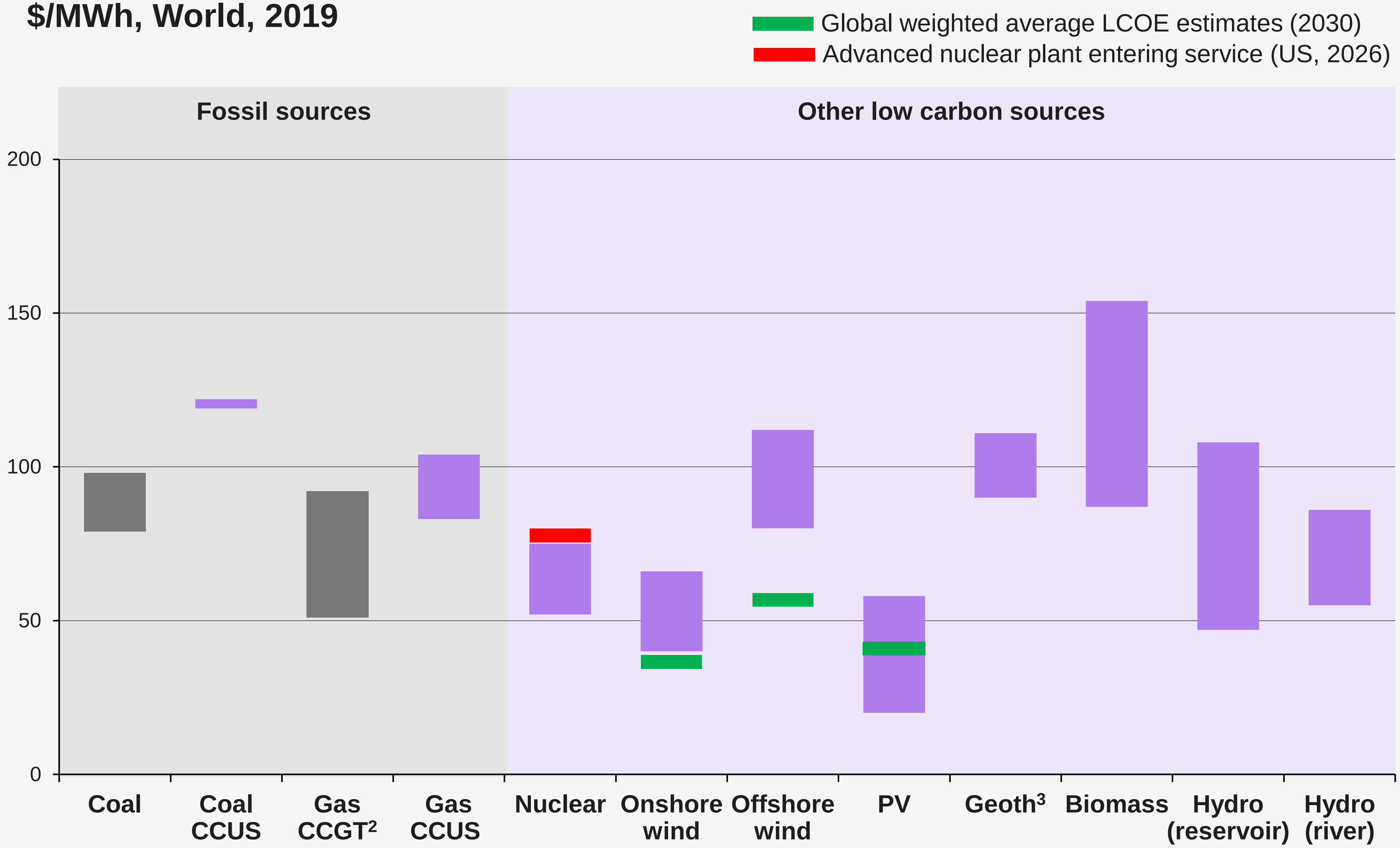
Gas combined with CCUS is within the range of other low carbon electricity sources and has an advantage to be dispatchable

Lower range of the current estimates cover LCOE drop

CCUS costs

LCOE of electricity for different sources[1]

$/MWh, World, 2019



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1. Boxes indicate the central 50% of values i.e. the second and third quartile
2. CCGT = Combined Cycle Gas Turbine, Onshore wind (for > 1MW plants), PV (utility scale)
3. Geothermal

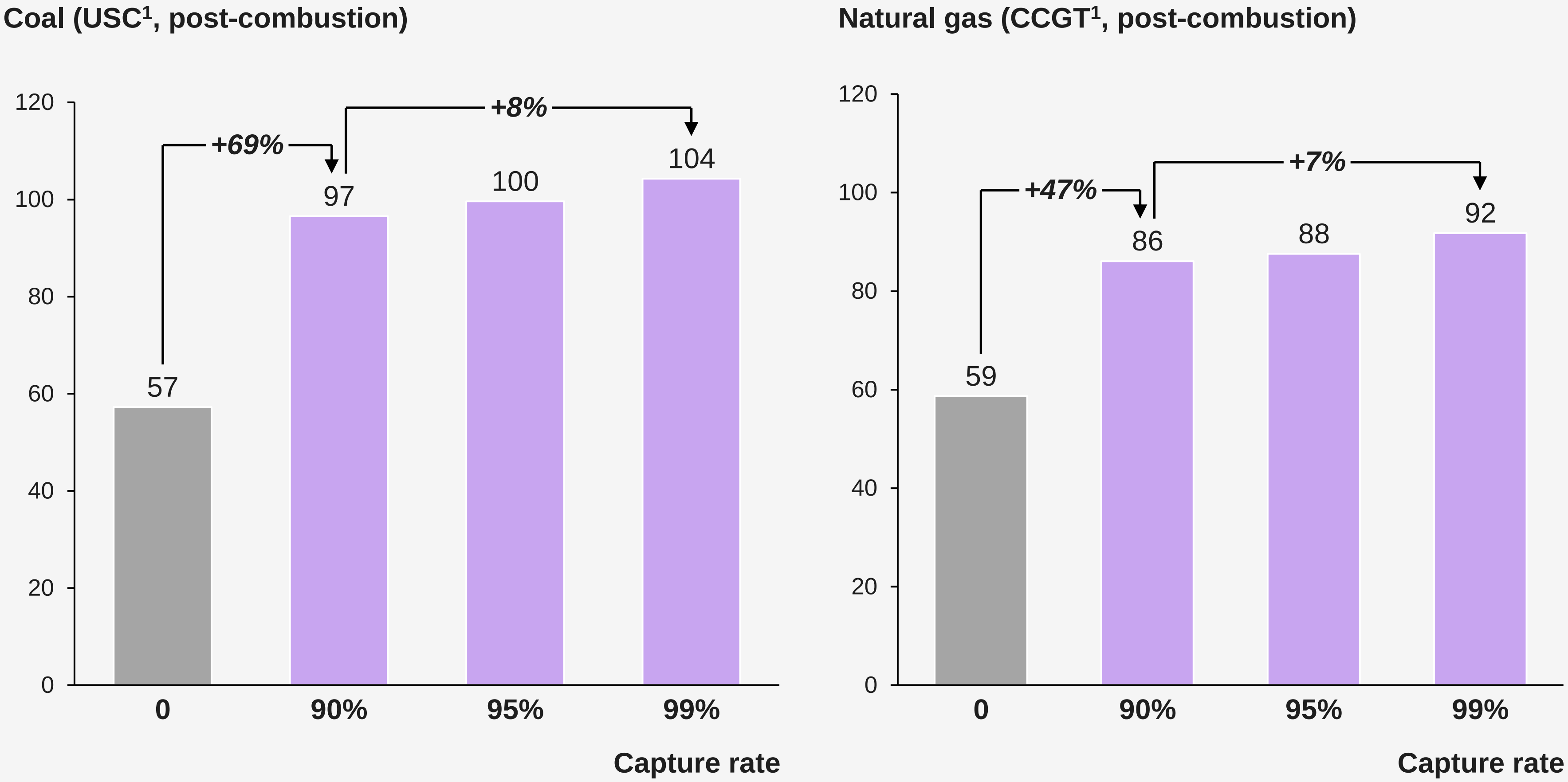
Source: Kearney Energy Transition Institute, Projected Cost of Generating Electricity 2020, IEA, Global renewables outlook 2020 (IRENA), Levelized Costs of New Generation Resources in the Annual Energy Outlook 2021 (EIA)

Applying CCUS to power plants greatly increases the levelized cost of production, but an increase in the capture rate has a moderate impact on the cost

Increase in levelized cost of production for CCUS power plants

Levelized cost of energy production for different CO_2 capture rate

$/MWh, 2019



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1. USC = Ultra Super Critical; CCGT = Combined Cycle Gas Turbine
2. BF-BOF = blast furnace basic oxygen furnace; ISR = innovative smelting reduction; Gas DRI = natural gas-based direct reduced iron/electric arc furnace (EAF) route; H2 DRI = 100% electrolytic hydrogen-based
3. NG = natural gas; Elec = electrolytic;

Source: Kearney Energy Transition Institute, Energy Technology Perspectives 2020 Chapter 2. CCUS in the transition to net-zero emissions, 2020, IEA, The role of CCUS in low-carbon power systems, IEA, 2020

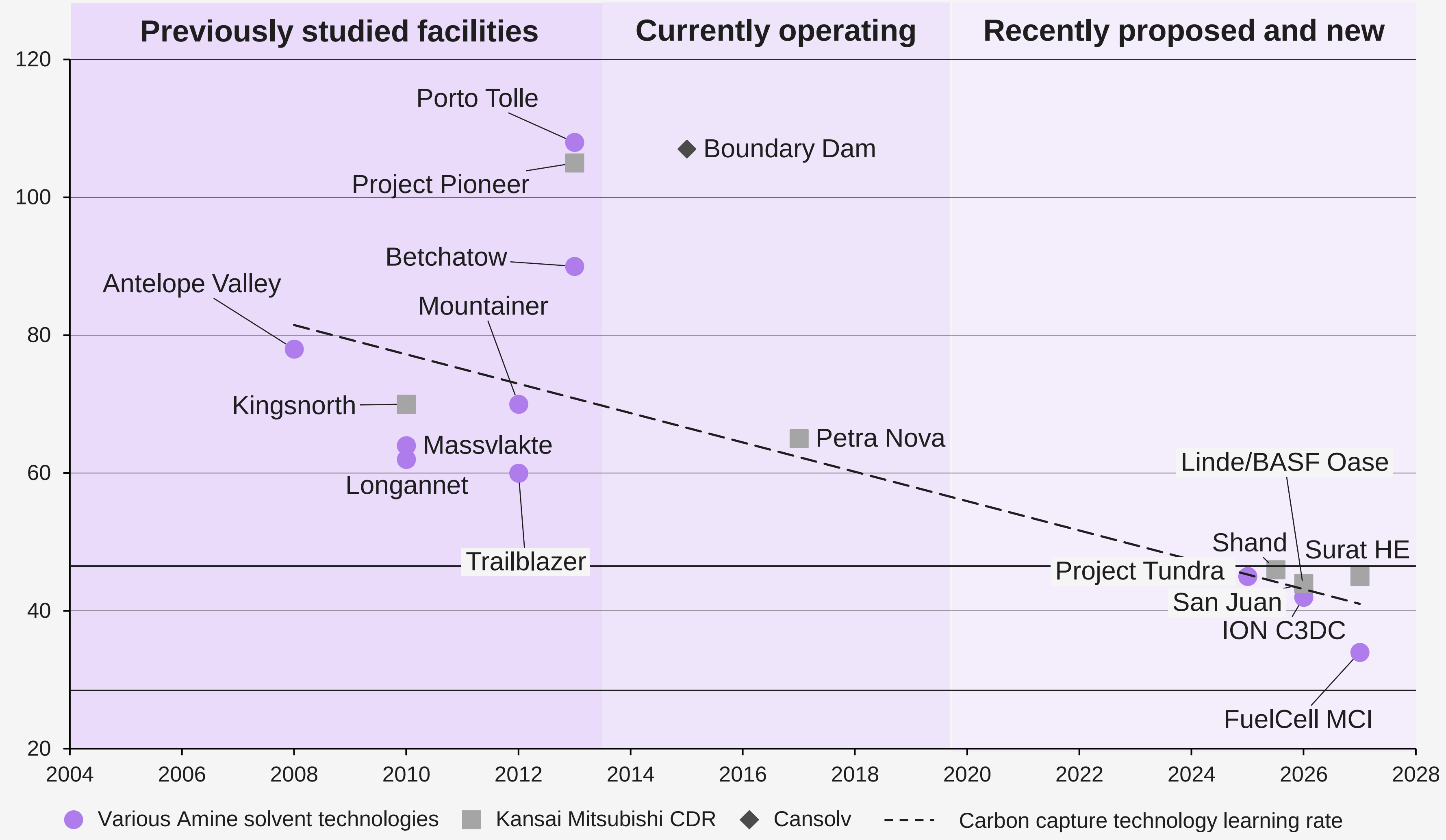
CCUS technology can expect cost reductions from learnings and gains accrued in technology deployment

The cost reduction comes from solvent improvements (lower energy use, lower degradation), new non-solvent based capture technologies, improved CO_2 compression strategies, economies of scale, and standardization of the process.

CCUS costs

Levelized cost of CO_2 capture for large-scale post-combustion at coal-fired power plant

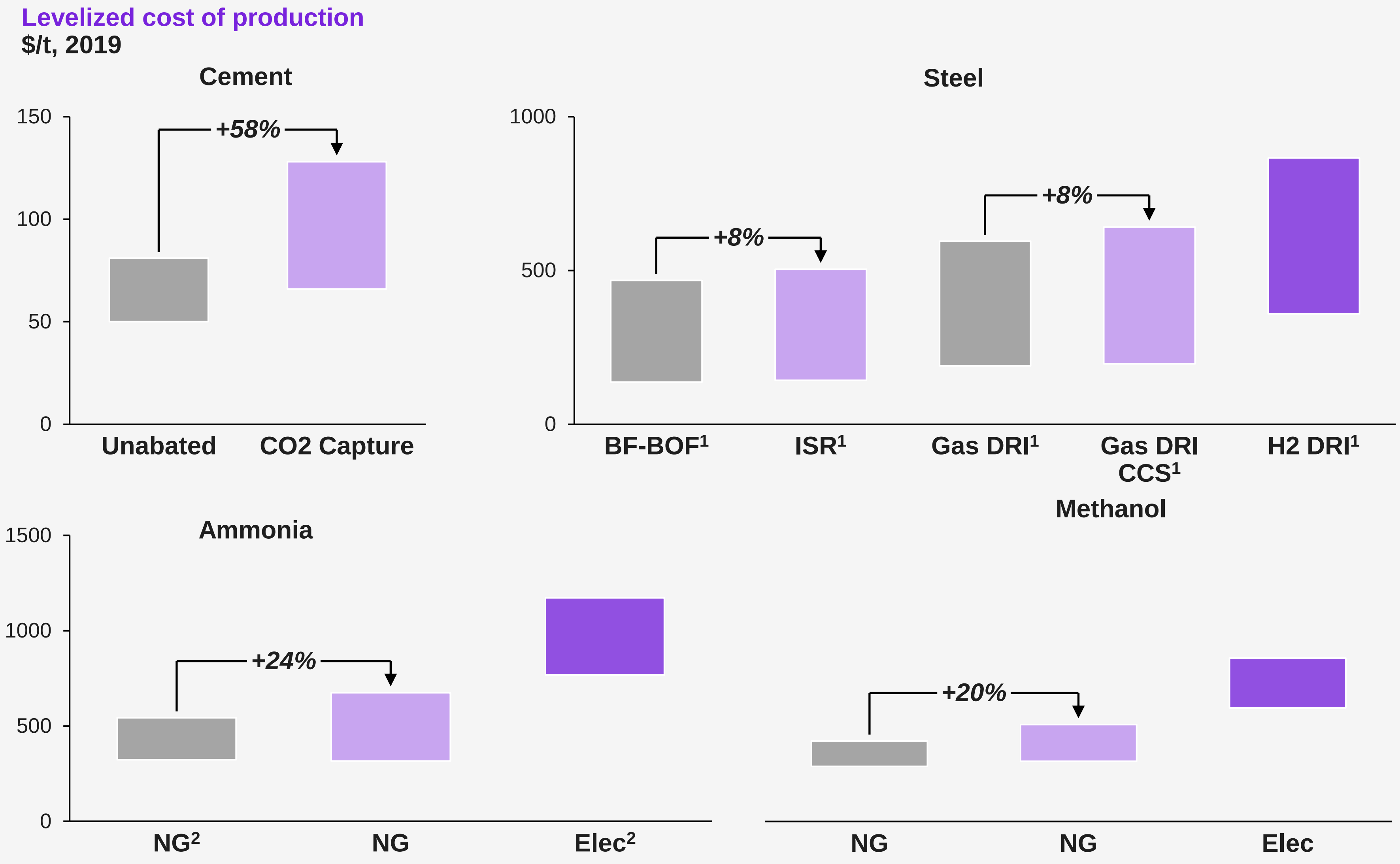
$2017/ t of CO_2



Source: Kearney Energy Transition Institute, CCUS Talks: The Technology Cost Curve, GCCSI, 2020, Is CCUS Expensive ? : Decarbonization costs in the net-zero context, GCCSI, 2020

Applying CCUS to industrial processes increases the levelized cost of production

Increase in levelized cost of production for industrial processes combined with CCUS.



- ⬛ Normal process
- ▨ Process with CCUS
- 🟪 Other low carbon process

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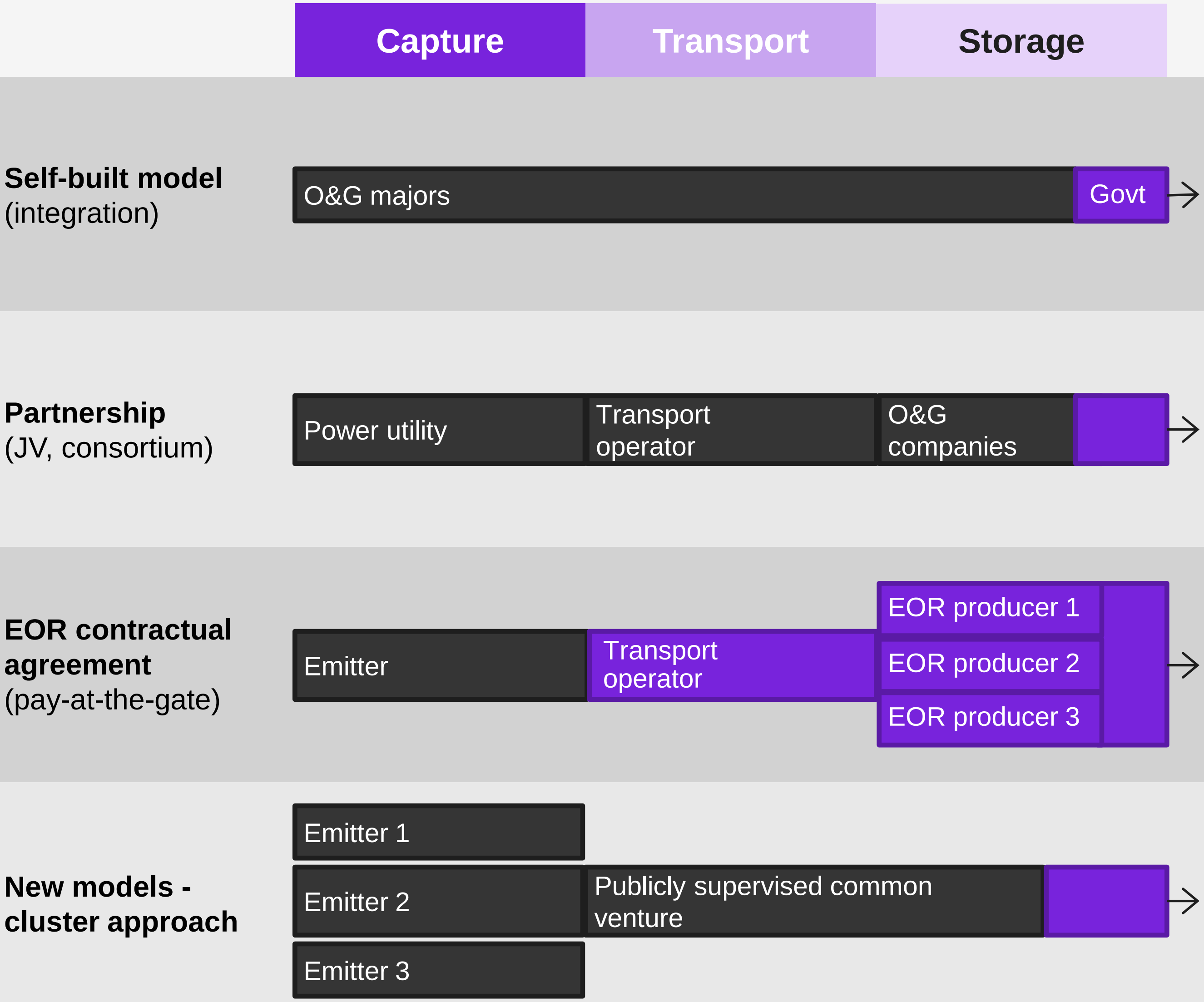
1. BF-BOF = blast furnace basic oxygen furnace; ISR = innovative smelting reduction; Gas DRI = natural gas-based direct reduced iron/electric arc furnace (EAF) route; H2 DRI = 100% electrolytic hydrogen-based
2. NG = natural gas; Elec = electrolytic;

Source: Kearney Energy Transition Institute, Energy Technology Perspectives 2020 Chapter 2. CCUS in the transition to net-zero emissions, 2020, IEA, The role of CCUS in low-carbon power systems, IEA, 2020

Such integrated projects also face planning and coordination difficulties that do not affect CCUS projects related to oil and gas

Business models for integrated projects



Capture | Transport | Storage

Self-built model (integration)

O&G majors | Govt

- Single integrated project owner: high level of control, no coordination issues
- Limited to oil and gas majors or very large utilities only

Partnership (JV, consortium)

Power utility | Transport operator | O&G companies

- Several project owners sharing costs and risks
- Risk of cancellation if a partner pulls out
- Difficulties in managing differing industrial cultures and paperwork

EOR contractual agreement (pay-at-the-gate)

Emitter | Transport operator | EOR producer 1, EOR producer 2, EOR producer 3

- Business model easy to implement
- Shields storage risks from public opposition or long-term liabilities
- Limited to EOR

New models - cluster approach

Emitter 1, Emitter 2, Emitter 3 | Publicly supervised common venture

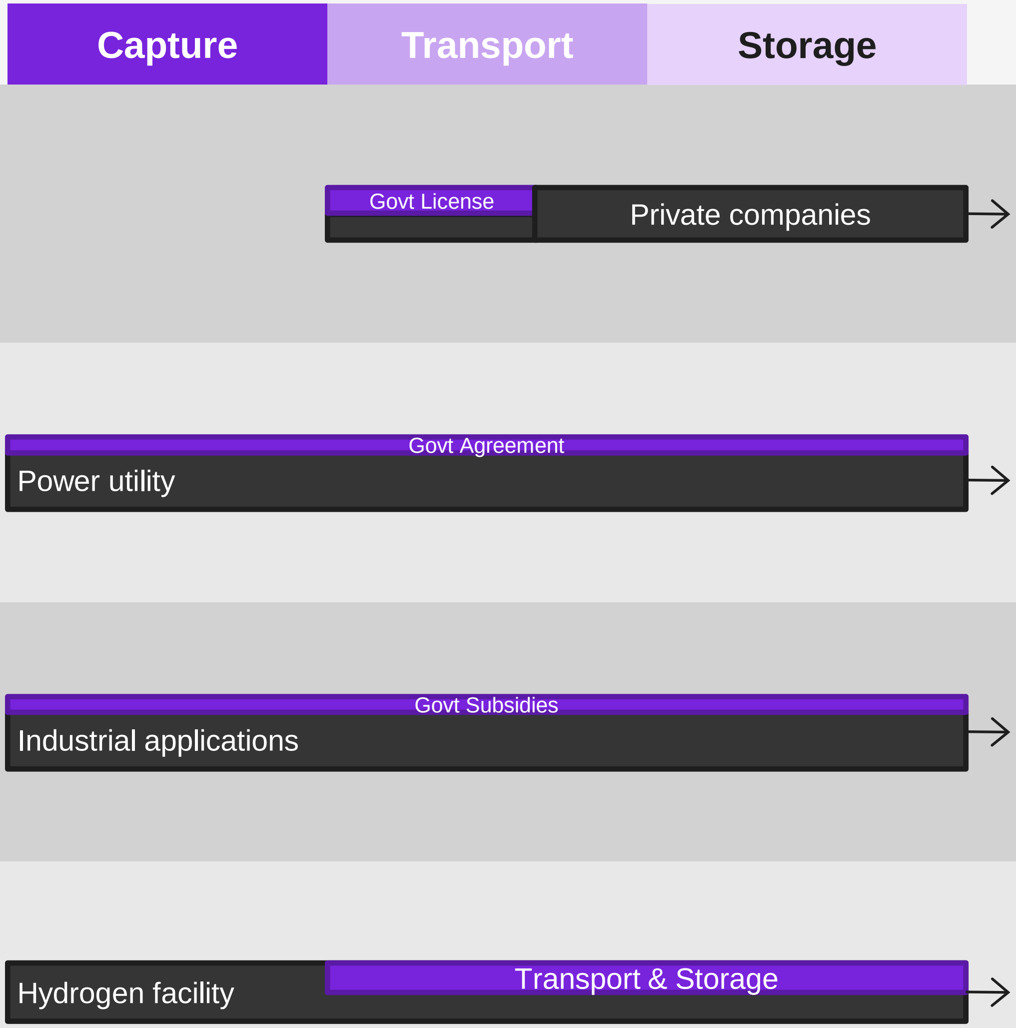
- Shared infrastructure for transport and storage reduces up-front capex
- Involvement of public authorities facilitates public acceptance
- Not for early demonstration phase

Source: Kearney Energy Transition Institute

⬛ Project owner (potentially eligible for emissions reductions) 🟪 Secondary stakeholder

New business models for CCUS clusters have been proposed in the United Kingdom

Business models for projects



Transport and Storage Fee
(Regulated Asset Base Model)

- Give more certainties to investors (governmental subsidies and secured ROI).
- Final customers will pay the price set by the company.

Contract For Difference (CFD)

- Strike price: generator costs and transportation and storage fee
- Transportation and storage fee payable regardless of generation
- Strike price to come down for individual projects as they link up

Carbon Tax
(based on US 45Q)

- No funding required until the operationalization of the project
- Tax credit when carbon is either used or stored

Hydrogen Production

Total cost of hydrogen to include :

- CO_2 capture and separation costs
- CO_2 transport and storage fees
- The link up with transmission or distribution networks for hydrogen

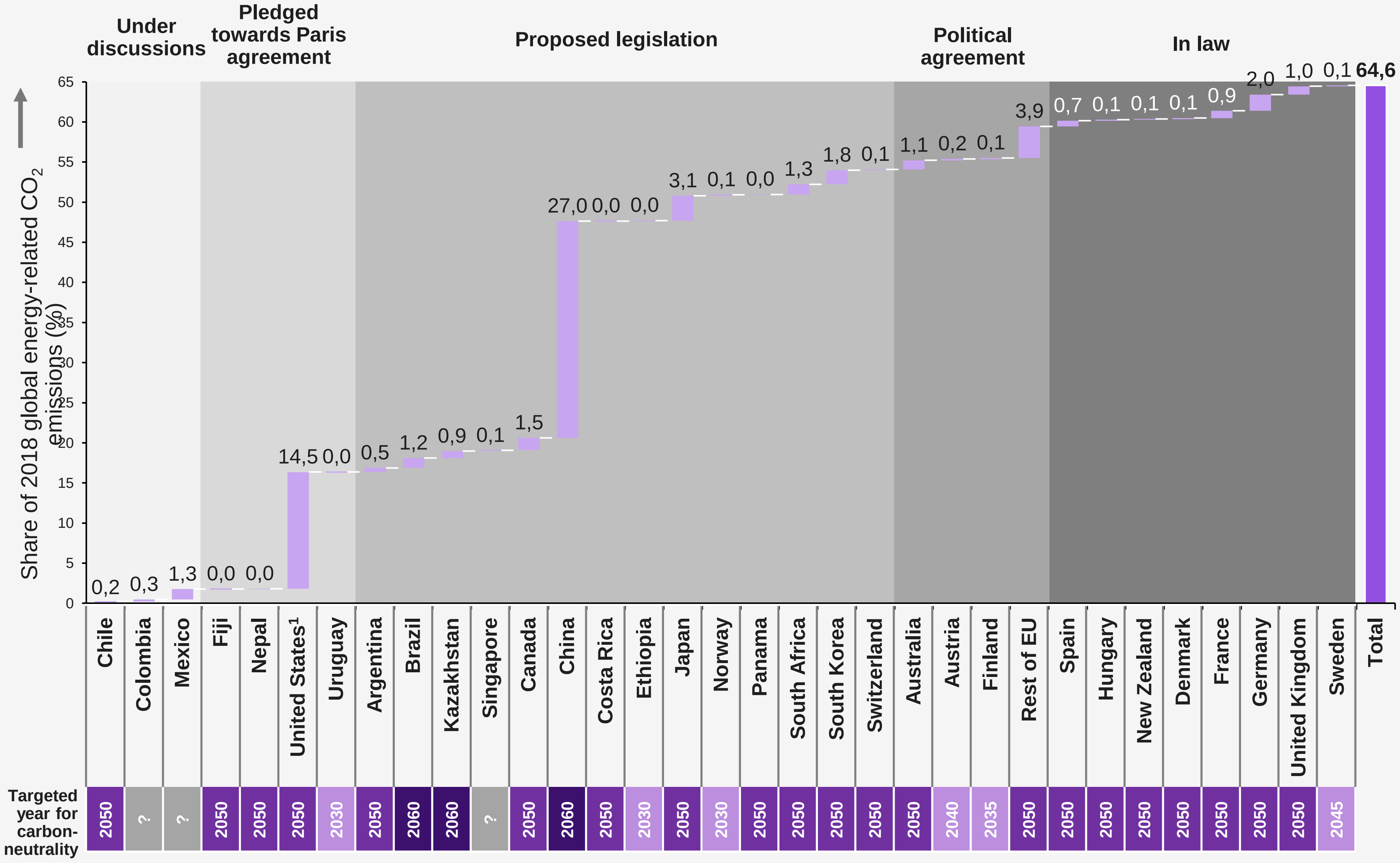
1. Transport & Storage
Source: Kearney Energy Transition Institute – UK CCUS Cost Challenge Taskforce Report (2018)

⬛ Project owner (potentially eligible for emissions reductions)
🟪 Secondary stakeholder

As of August 2020, more than 125 countries have committed to or were considering implementing net-zero targets

Some countries include all GHG emissions in their targets; others only include a subset of GHG emissions.

Status of net-zero CO_2 policy implementations and relative share of global carbon emissions



1. Unites States have withdrawn from the Paris Agreement but new President-Elect J.Biden announced that the USA will join back the agreement once in charge.

Sources: Our World in Data - Annual CO_2 emissions ; Climate Home News - Which countries have a net zero carbon goal? (last update : Jan 8th 2021)

Most key countries have announced plans to become carbon neutral by at least 2060

Emission reduction targets

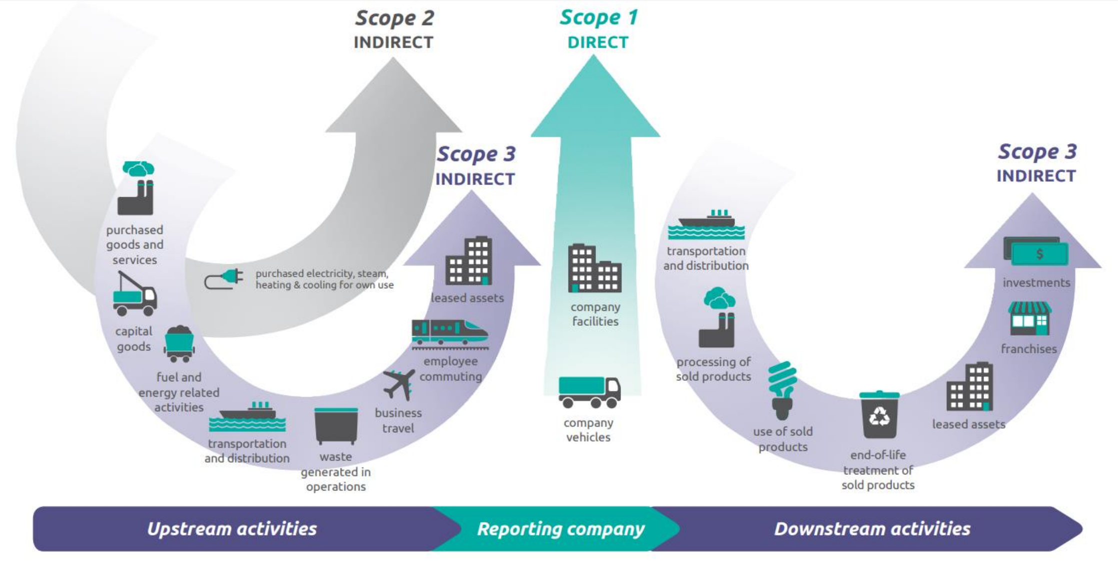
	2018 CO_2 emissions (% of global)	RES[1] Target		GHG reduction vs 2005		Carbon neutrality objective	Carbon policies
		2030	2050	2030	2050		
United States	5,42 $GtCO_2$ (14,5%)	24%	30%	-11% to -14%[2]	-68 %to -76%[3]	Soon back to Paris Agreement at national level California aims to be carbon neutral by 2045	Carbon tax and/or ETS at state level
EU + UK	3,44 $GtCO_2$ (9,2%)	40 to 50%	40 to 100%[4]	-55%	-71% to -94%	Carbon neutral by 2050 Countries like Finland, Austria, Sweden have set the objective sooner (2035 – 2040 – 2045)	EU ETS and several carbon taxes among the countries
China	10,06 $GtCO_2$ (27,0%)	35%	-	-65%	-	Zero carbon footprint objective for 2060	Local ETS pilots undergoing
Australia	0,42 $GtCO_2$ (1,13%)	50%	-	-26% to -28%	-	No national objective But states aims to be carbon neutral by 2050	ETS at national level
Japan	1,92 $GtCO_2$ (5,2%)	24%	-	-22%	-81%	Carbon neutral by 2050	ETS and carbon tax at national level

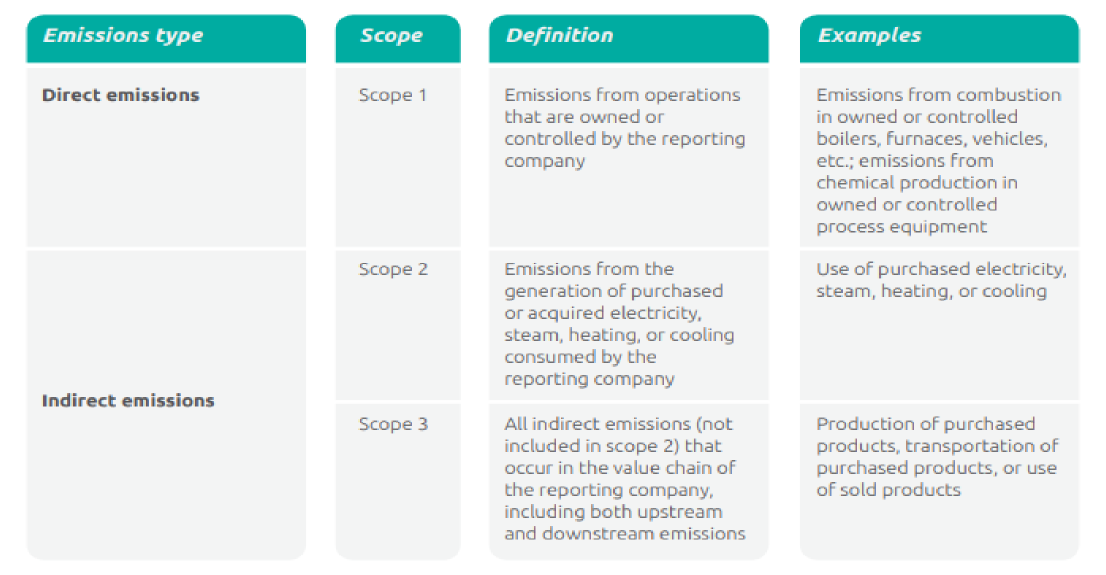
[1] Renewable Energy Sources ; [2] Current policies projections ; [3] Obama Administration Mid-Century Strategy ; [4] Range of all scenarios
Sources: Kearney Energy Transition Institute ; World Bank – State and Trends of Carbon Pricing (2020) ; Our World in Data - Annual CO_2 emissions

GHG emissions reduction pressure on corporations has been increasing with the development of corporate GHG emissions disclosure covering scopes 1, 2, and 3

Overview of GHG disclosure and scopes

- Under certain conditions, which vary per country, companies are now required to ensure that their subsidiaries and suppliers respect human rights and the environment, including their carbon footprint across the value chain.
- In 2016, at least **92% of Fortune 500** companies responding to the CDP used the GHG Protocol directly or indirectly through a program based on the GHG Protocol.
- **Upstream and downstream** (scope 3 emissions) **can constitute up to 90% of large corporations' overall emissions,** with variable distribution across the sources. For example, in the automotive industry, about **98%** of scope 3 emissions are downstream (see next slide). The most emitting category is the fuel combustion during usage, representing almost all downstream emissions.



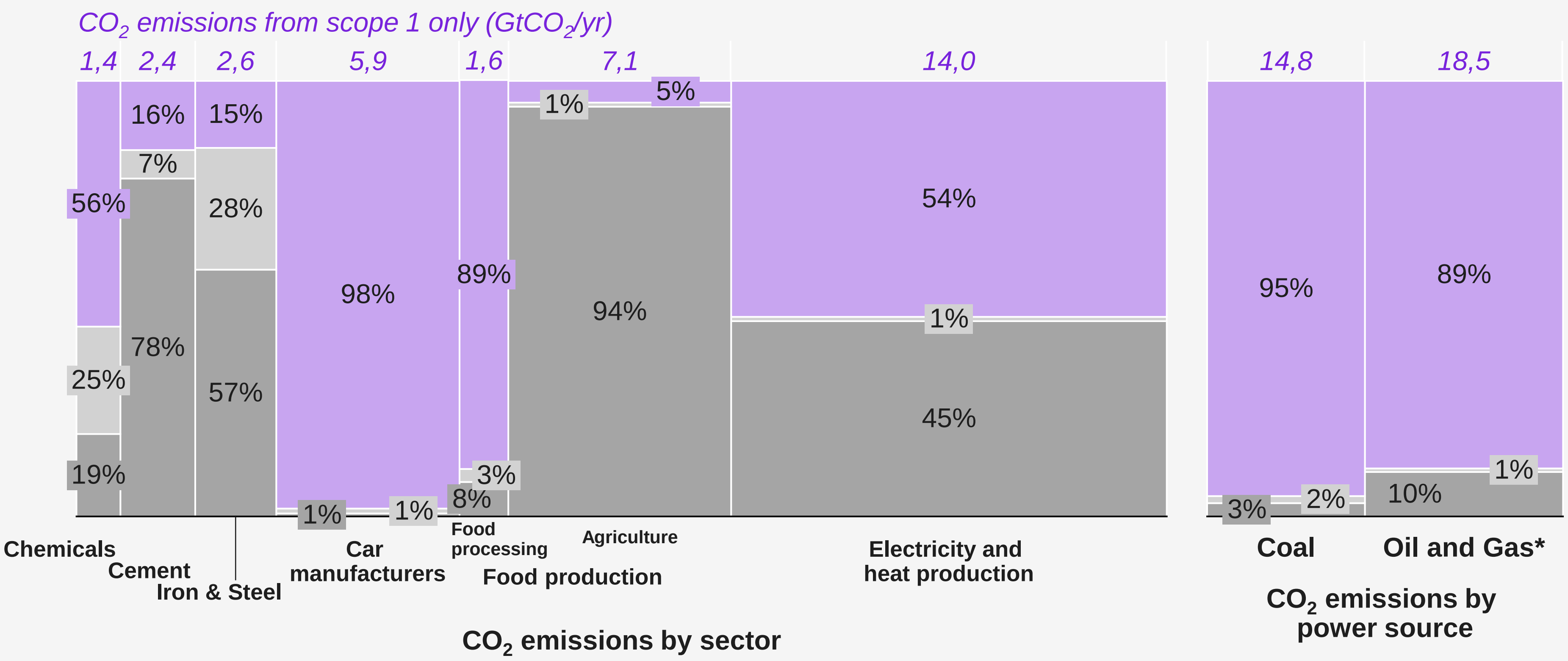


Emissions type	Scope	Definition	Examples
Direct emissions	Scope 1	Emissions from operations that are owned or controlled by the reporting company	Emissions from combustion in owned or controlled boilers, furnaces, vehicles, etc.; emissions from chemical production in owned or controlled process equipment
Indirect emissions	Scope 2	Emissions from the generation of purchased or acquired electricity, steam, heating, or cooling consumed by the reporting company	Use of purchased electricity, steam, heating, or cooling
	Scope 3	All indirect emissions (not included in scope 2) that occur in the value chain of the reporting company, including both upstream and downstream emissions	Production of purchased products, transportation of purchased products, or use of sold products

Sources: GHG Protocol, Kearney Energy Transition Institute

Scope 3 emissions are the most important ones even if they are not always considered in CO_2 emissions reduction objectives

Estimated ratio of scope 1, 2 and 3 per sector (%$GtCO_2$, $GtCO_2$)



▨ Scope 1 (direct emissions from owned or controlled sources)

▨ Scope 2 (indirect emissions from the generation of purchased electricity, steam, heating and cooling consumed)

▨ Scope 3 (other indirect emissions occurring in downstream or upstream in value chain)

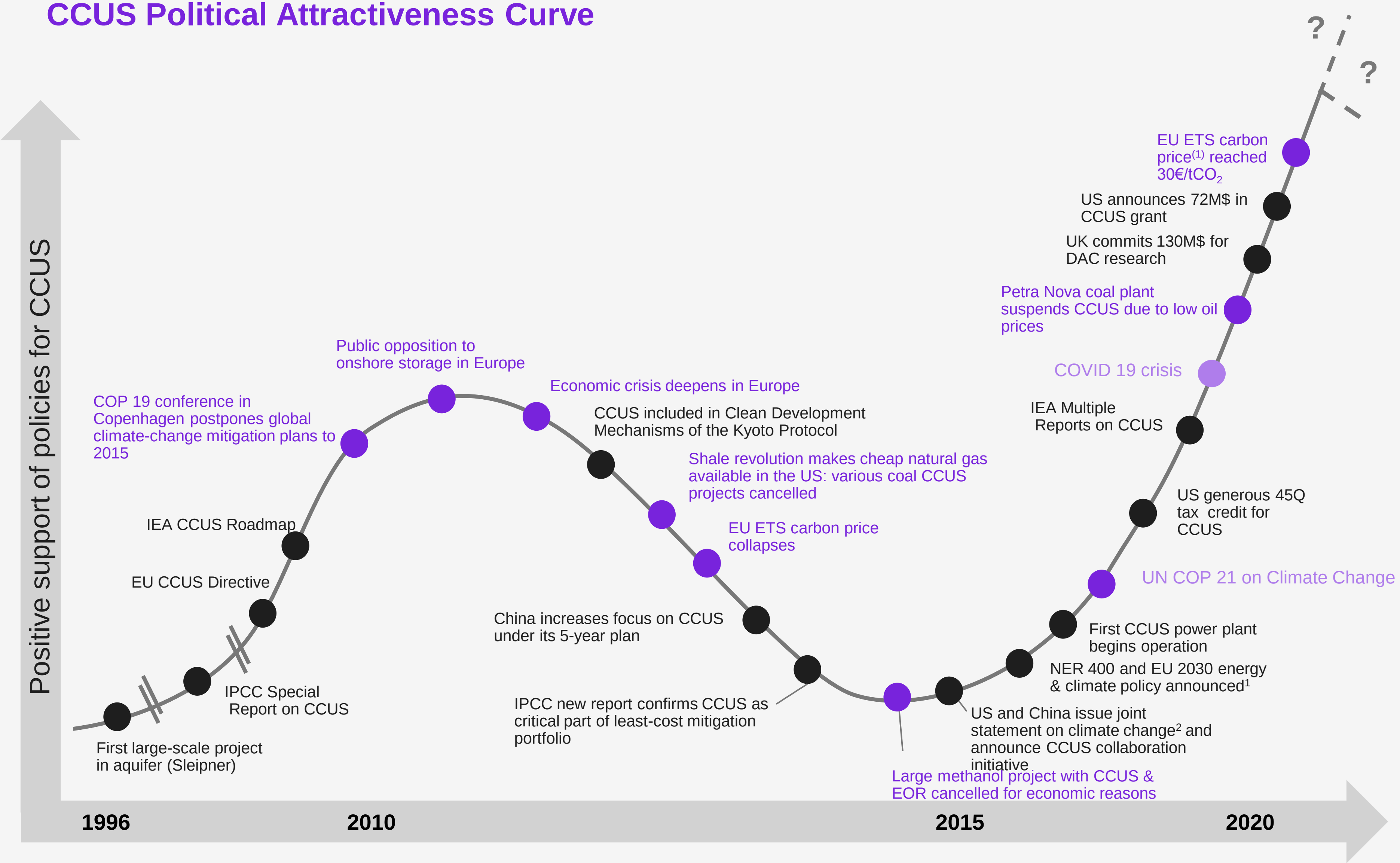
In most industries, scope 3 CO_2 emissions are the most important ones because of the pollutive characteristic of sold products, especially for automotive or oil and gas companies. Sectors that belong to heavy industries have bigger scopes 1 and 2 because of the CO_2 emissions in their process of fabrication.

Note: This graph has been made by averaging the distribution of CO_2 emissions among the scopes 1-2-3 of the five biggest companies of each sector. However, there is no consensus on the definition of each scope.

Some emissions can be counted twice by being in several sectors e.g : the electricity generated by plant (scope 3) used to produce cement (scope 2)
*Global CO_2 emissions related to Oil and Natural Gas from IEA - *CO_2 emissions by energy source, World 1990-2018* (2020)
Sources: Kearney Energy Transition Institute ; Carbon Disclosure Project ; Companies websites and CSR report ; Our World in Data ; FAOSTAT - *CO_2 emissions from agriculture* (2020); IEA ETP 2020

Policies supporting CCUS development are gaining momentum

CCUS Political Attractiveness Curve



First large-scale project in aquifer (Sleipner)

IPCC Special Report on CCUS

EU CCUS Directive

IEA CCUS Roadmap

COP 19 conference in Copenhagen postpones global climate-change mitigation plans to 2015

Public opposition to onshore storage in Europe

Economic crisis deepens in Europe

CCUS included in Clean Development Mechanisms of the Kyoto Protocol

Shale revolution makes cheap natural gas available in the US: various coal CCUS projects cancelled

EU ETS carbon price collapses

China increases focus on CCUS under its 5-year plan

IPCC new report confirms CCUS as critical part of least-cost mitigation portfolio

Large methanol project with CCUS & EOR cancelled for economic reasons

US and China issue joint statement on climate change[2] and announce CCUS collaboration initiative

NER 400 and EU 2030 energy & climate policy announced[1]

First CCUS power plant begins operation

UN COP 21 on Climate Change

US generous 45Q tax credit for CCUS

IEA Multiple Reports on CCUS

COVID 19 crisis

Petra Nova coal plant suspends CCUS due to low oil prices

UK commits 130M$ for DAC research

US announces 72M$ in CCUS grant

EU ETS carbon price(1) reached 30€/tCO_2

(1) In 2020, carbon price fluctuated between ~16 to ~30€/tCO_2 on the EU ETS market, and further increased in 2021, exceeding 50€/tCO2 in May 2021
COP: United Nation Conference of the Parties. NER: New Entrant Reserve fund for climate mitigation in Europe. EU ETS: European Emission Trading Scheme; 1. EU GHG reduction goal: 40% by 2030; 2. US GHG reduction goal: 26-28% by 2030. China's reduction goal: from 2030 onwards.
Source: Kearney Energy Transition Institute, IEA CCUS in clean energy transition, 2020

Carbon policies are not new - key countries have enacted regulatory frameworks to enable the CCUS development at both regional and federal levels

Non-Exhaustive

Name of the program	Description of the program	Date of implementation	Carbon price*	CO_2 emissions covered
US 45Q Tax Credit	Tax credit for the first 12 years following opening for new: – Power plants capturing at least 500,000 t – Industrial facilities not emitting more than 500,000 t and capturing at least 25,000 t – Direct Air Capture and other facilities that capture 100,000 t	Start in 2008 Review in 2018	By 2026, tax credit of (per t) : – $20 → $50 for storage – $10 → $35 for EOR – $10 → $35 for other uses	Total of 63 $MtCO_2$ concerned by May 2019 Some facilities also benefits from the California low-carbon fuel standard (LCFS)
Canada GGPPA *(for provinces that doesn't have their own regulation)*	The Greenhouse Gas Pollution Pricing Act is divided in two parts : – Fuel charge for fuel producers and distributors – Output-Based Pricing System for facilities emitting more than 50,000 t of CO_2	Start in 2018 Review in 2020	2020 : $30/t 2023 : $50/t 2030 : $170/t	*N/A*
China National ETS	Trade system of emissions allowances covering coal- and gas-fired power plants.	Phases 1 & 2 (2017-2020) Phase 3 (2021 – 2025)	Launch price of ¥30/t (around $4,6/t)	CO_2 emissions from power plants (about 3,5 $GtCO_2$ in 2017)
EU ETS Investment Fund NextGen EU	Cap and trade system of emissions allowances covering heavy energy-using installations (power stations & industrial plants) and all airlines operating in Europe. Clean H_2 and CCS (funding)	Phases 1 & 2 (2005-2012) Phase 3 (2013 – 2020) Phase 4 (2021 – 2030) EU framework for carbon removal	Price determined by trading : $30,65/t as of Aug. 1st	Around 45% of global EU CO_2 emissions (about 1,7 $GtCO_2$ in 2018)
Swedish Carbon Tax	Emissions from power units, motor and heat fuels that are not covered by EU ETS (both industry and general level).	Start in 1991	Price increase year by year $137/t as of Aug. 1st	87% of Sweden emissions are covered by either EU ETS or national carbon tax (about 30,4 $MtCO_2$ in 2018)
Norwegian Carbon Tax	To meet Paris commitment of emissions reductions of 50–55% by 2030, the Norwegian government proposes a gradual increase in carbon tax on GHG emissions – Carbon tax raise will be offset by reducing other taxes correspondingly	Start in 1991 (new stricter proposal in 2021)	Proposal to raise carbon tax to about 2000 NOK (ca. € 190) per tonne CO_2 equivalent by 2030 from the current NOK 590 per tonne CO_2-equivalents (ca. € 55)	This proposal covers emissions under EU-ETS as well as non-ETS emissions (for example, transport, waste, agriculture, and certain other sources)
UK ETS	System to replace EU ETS and based on it with allowances of CO_2 emissions. Same emissions as EU ETS are covered plus domestic flight inside the UK	Start in 2021 (following the Brexit)	TBD Minimum of £15/t (around $20/t)	5% below UK former ETS cap Forecast of 155 $MtCO_2$ in 2021

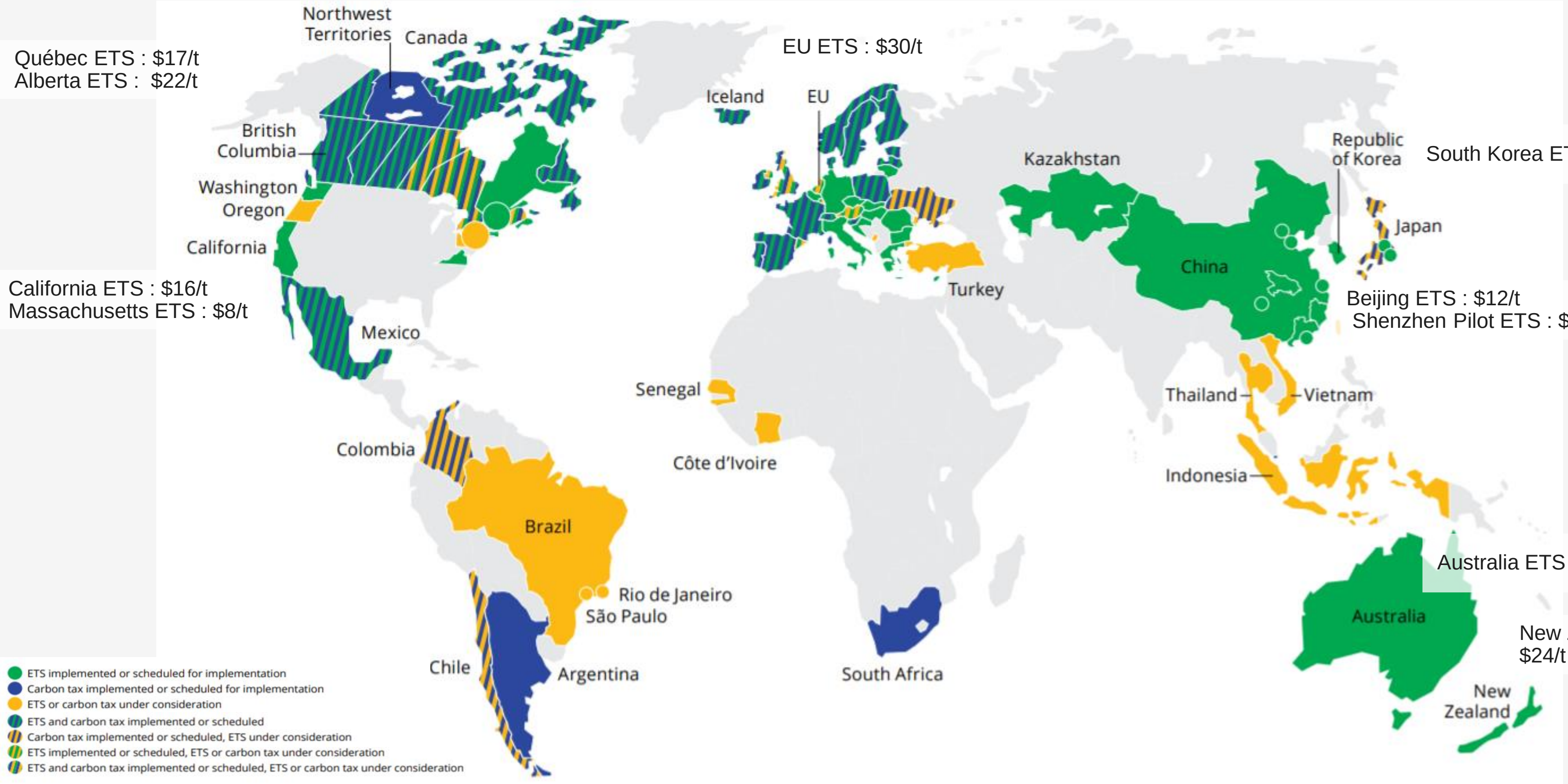
*As of August, 1st 2020 from the World Bank

Source: European Commission - *EU Emissions Trading System (EU ETS)* ; Eurostats – *Greenhouse gas emissions statistics* (2020) ; Government Offices of Sweden – *Carbon Taxation in Sweden* (2020) ; Global CCUS Institute - *The US Section 45Q Tax Credit for Carbon Oxide Sequestration* (2020) ; The Tax Credit for Carbon Sequestration (Section 45Q)

Regulating carbon prices has gained more acceptance in OECD countries

More and more countries are adopting a carbon tax or an ETS or even both. Europe has had it own ETS system since 2005. The United States and China, the two major carbon emitters, don’t yet have a national ETS or carbon tax. Only 16 US states have started something.

World ETS map (2020) – illustrative carbon prices



Québec ETS : $17/t
Alberta ETS : $22/t

California ETS : $16/t
Massachusetts ETS : $8/t

EU ETS : $30/t

South Korea ETS : $33/t

Beijing ETS : $12/t
Shenzhen Pilot ETS : $2/t

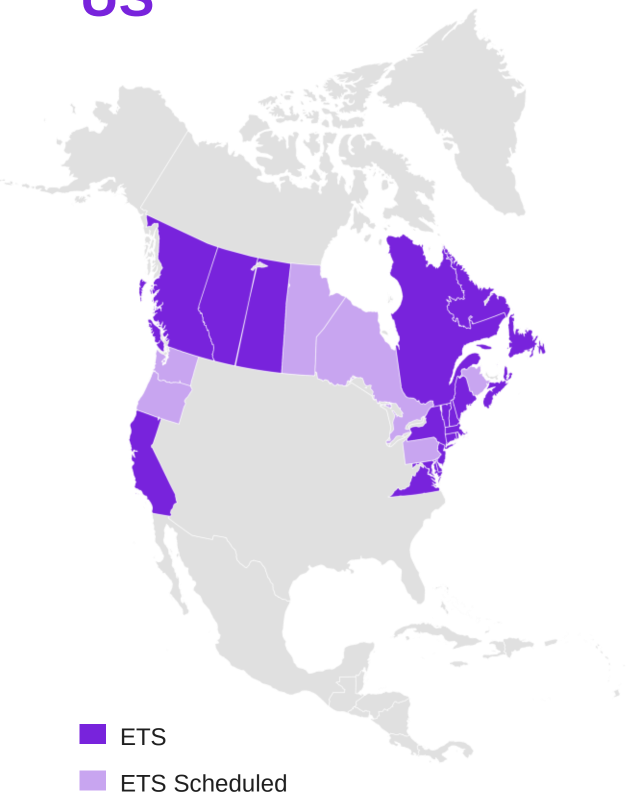
Australia ETS : $8-9/t

New Zealand ETS : $24/t

	Operational ETS	Scheduled ETS
Number of countries	38	11
Sum of CO_2 emissions from countries	6,01 $GtCO_2$	18,58 $GtCO_2$
% of global CO_2 emissions	16,1%	49,9%
World CO_2 emissions covered by ETS	10,7%	8,0%

Note: in February 2021, the carbon price reached 40€/t as a result of cold weather and recent announcement of new carbon reduction emission target in the EU (-55% objective by 2030)
Source: World Bank (2020) - State and Trends of Carbon Pricing 2020 (2020) & Carbon Pricing Dashboard

ETS policies remain a state-level decision in Canada and in the US



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ETS policies in Canadian provinces

Name of the initiative	Provinces	Status of ETS	Year	Price ($/t)*
Alberta TIER	Alberta	Operational	2007	22,38
BC GGIRCA	British Columbia	Operational	2016	Unknown
Manitoba ETS	Manitoba	Scheduled	TBC	TBD
New Brunswick ETS	New Brunswick	Scheduled	TBC	TBD
Newfoundland and Labrador PSS	Newfoundland and Labrador	Operational	2019	± 20
Nova Scotia CaT	Nova Scotia	Operational	2019	Unknown
Ontario CaT	Ontario	Stopped in 2018	2017	14,65
Ontario ETS		Scheduled	TBC	TBD
Quebec CaT	Quebec	Operational	2013	16,89
Saskatchewan OBPS	Saskatchewan	Operational	2019	Unknown

ETS policies in US states

Name of the initiative	States	Status of ETS	Year	Price ($/t)*
California CaT	California	Operational	2012	16,89
Massachusetts ETS	Massachusetts	Operational	2018	8,26
Oregon ETS	Oregon	Scheduled	TBC	TBD
Pennsylvania ETS	Pennsylvania	Scheduled	TBC	TBD
Regional Greenhouse Gas Initiative (RGGI)	Connecticut	Operational	2009	5,94
	Delaware			
	Maine			
	Maryland			
	Massachusetts			
	New Hampshire			
	New Jersey			
	New York			
	Rhode Island			
	Vermont			
	Virginia			
	Pennsylvania	Scheduled	2022	
Virginia ETS	Virginia	Operational	2020	10,77
Washington CAR	Washington	Suspended	2017	Unknown

*Carbon prices from World Bank – Carbon Pricing Dashboard (as of Aug. 1st 2020)
Source: World Bank (2020) - State and Trends of Carbon Pricing 2020 (2020) & Carbon Pricing Dashboard

The new US administration is eager to leverage CCUS in reaching their low carbon objectives

Climate change plan

– Creation of a new cross-agency focused on climate: Advanced Research Projects Agency (ARPA-C)

– Decarbonizing industrial sectors such as steel, concrete, and chemicals

– Decarbonizing food production sector and use agriculture to remove CO_2 from the air and store under the ground

Clean energy plan

– Achieve “largest-ever investment in clean energy research and innovation” by investing $400 billion over 10 years.

– Use CCUS in existing power plants and either store or use the CO_2.

– Aim to double research investments and tax incentives for technologies that capture CO_2 and to lower cost of CCS retrofits on existing power plants.

Energy and climate policy outlook

– Already rejoined the Paris Agreement

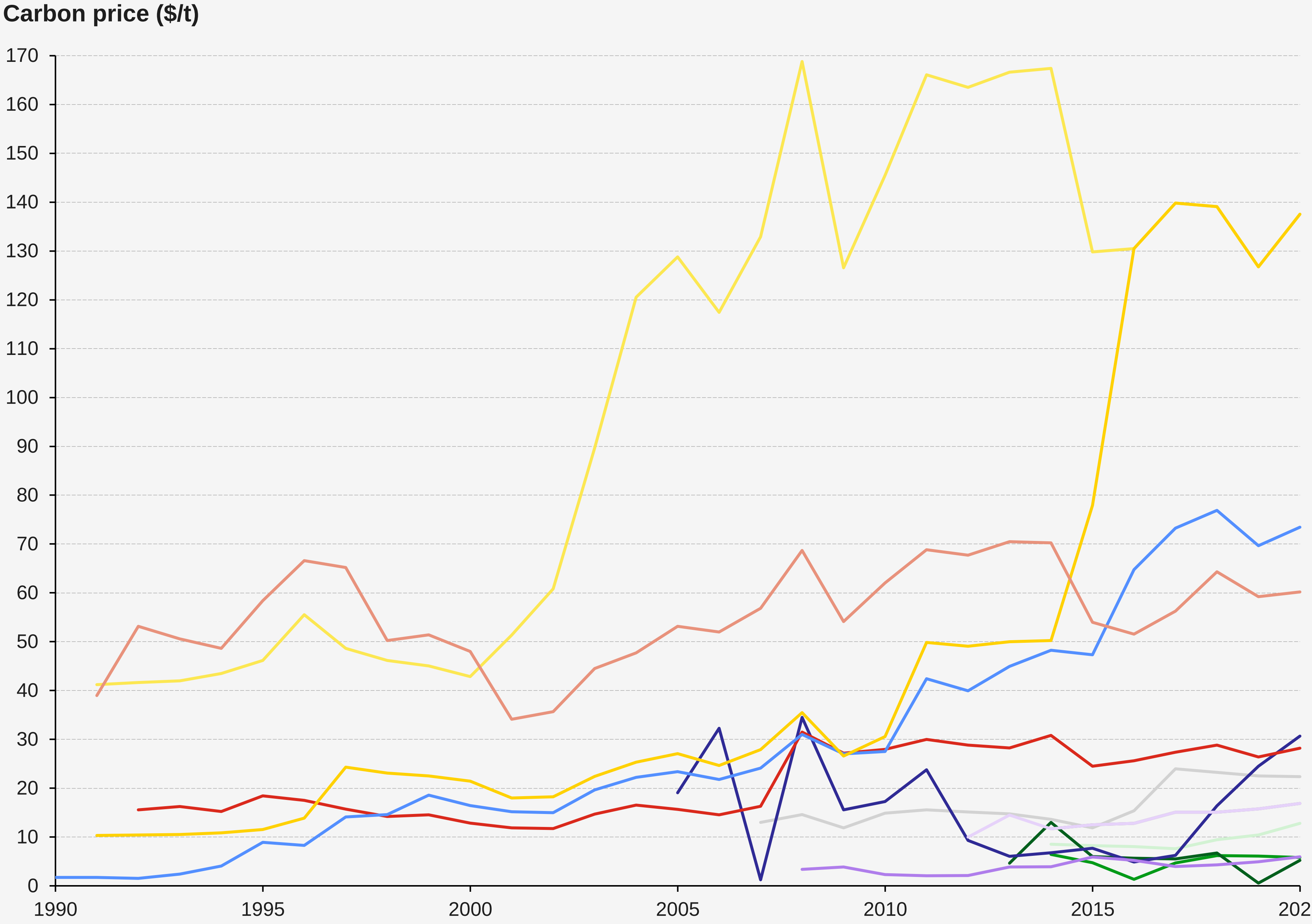
– Ambitious plan to transition away from fossil fuels in favor of clean energies

– Aiming to eliminate emissions from power plants by 2035 and be net-zero emissions by 2050

Source: Joe Biden electoral program : *Plan for Climate Change and Environmental Justice* (2020) & *The Biden Plan to Build a Modern, Sustainable Infrastructure and an Equitable Clean Energy Future* (2020) ; Forbes - *Biden’s Energy Policy Outlook* (2020)

Nordic countries were the first ones to have a carbon price, with Sweden having the highest carbon tax

- Alberta TIER
- Quebec CaT
- Beijing pilot ETS
- Shanghai pilot ETS
- Shenzhen pilot ETS
- EU ETS
- Denmark carbon tax
- Finland carbon tax
- Sweden carbon tax (general)
- Sweden carbon tax (industry)
- Norway Carbon tax
- California CaT
- Massachusetts ETS
- RGGI

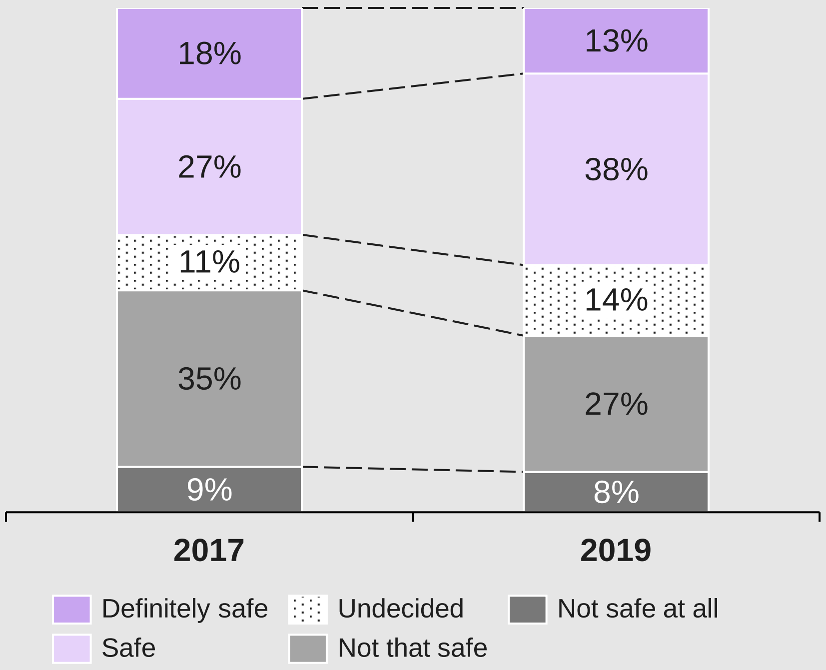


Source: World Bank – *Carbon Pricing Dashboard* ;

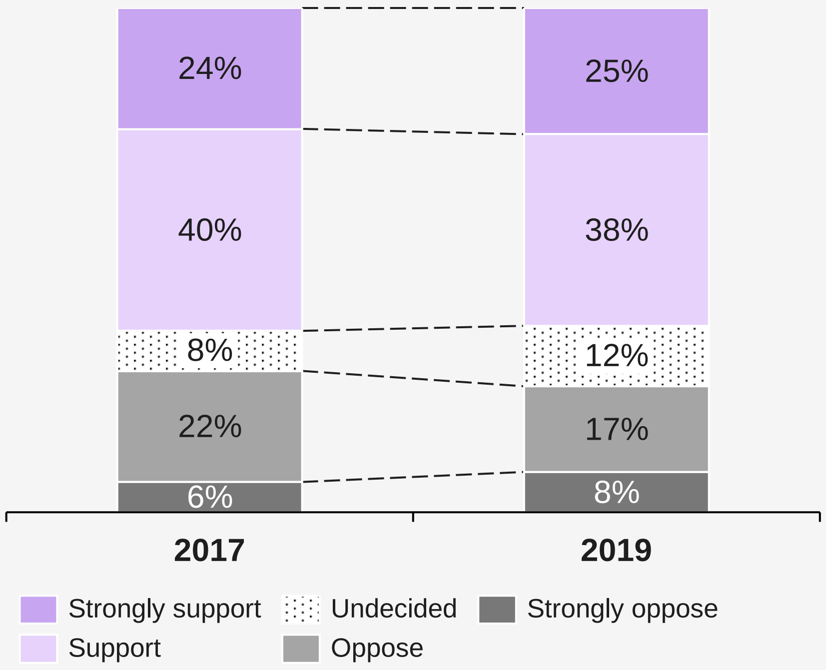
Policies & Regulations

The Global CCS Institute survey recommends stronger public outreach to sensitize the stakeholders about benefits to increase support

Do you believe CCS is safe ?



Do you support the US action to develop CCS ?



The GCCSI surveyed 100 US federal policy influencers (50 from private and 50 from public sector) about CCS in January–February 2019:

- Key findings reveals that CCS is only seen as related to fossil fuels but having some benefits for the environment. Moreover, most of the federal policy influencers agreed that government carbon policies and increasing R&D funding are the best ways to support and develop carbon capture and storage.
- Finally, to increase public support and knowledge on CCS, the survey reports that there is a need to explain "how CCS fits in to the set of tools and approaches to address climate change" and "the importance of CCS in reaching carbon reduction goals."

Source: Global CCS Institute - *Federal Policy Influencers 2019 Survey (2019)*

CCUS have limited awareness and favorable public opinion compared with other low emission technologies

Unknown and misunderstood

- Less awareness about CCUS and the technology is misunderstood by them whereas its potential benefits for climate change are substantial.
- Less experience with CCUS and a strong fear of a tragic failure in the storage process even though offshore storage appears less dangerous than onshore for local populations.
- However, communities with an industrial history are eager to welcome CCS projects.

Unfavourable perception

- CCUS is usually linked with fossil fuels but barely with industry
- BECCS (Bioenergy with CCS) is starting to be recognized but the public opinion prefer wind and solar electricity despite BECCS's strong credentials in achieving negative emissions
- CCUS included in coal or gas plants is also not as appreciate as renewable energy and even lower than natural gas or nuclear

Key challenges

- High capex and opex in whole value chain
- No long-term knowledge about potential effects
- Increase the use of fossil fuels
- CCUS should have been done long time ago and the focus need to be on renewable and clean energies options.

Need to focus on advantages

- Necessary tool to limit temperature rise to 1.5°C
- A way to safely store large amount of CO_2
- Opportunities to transform CO_2 through EOR and other activities (biofuels and urea etc.)
- Only technology to reduce CO_2 emissions in some industrial sectors (cement, iron, and steel)

Source: National Petroleum Council - *Meeting the Dual Challenge a Roadmap To At-scale Deployment Of CARBON CAPTURE, USE, AND STORAGE* (2020) ; Energy Procedia - *Local acceptance and communication as crucial elements for realizing CCS in the Nordic region* (2016)

Despite lack of awareness about CCUS, public opinions differ from country to country within Europe

France

- CCUS features prominently in debates as a solution to reduce CO_2 emissions.
- ADEME assesses that CCS would represent 15 $MtCO_2$ captured in France per year.
- The main challenge is the lack of confidence about the safety of the onshore storage of CO_2.

Germany

- Under public pressure, federal states prohibited carbon storage in certain regions, and many German states have effectively introduced a complete ban
- For Acatech, CCS is seen as a technology with uncontrollable risks

"Germany's citizens assess CCS as a high-risk technology and do not perceive its benefits."

Fraunhofer ISI institute

Nordic countries

- Norway is more familiar with CCS than Denmark or Sweden
- Offshore storage in the North Sea can avoid possible controversies

"Low public awareness and acceptance have been identified as one of the most important barriers for CCS deployment"

J.K Haug & P. Stigson

United Kingdom

- There is a huge lack of awareness of CCS in the UK, but more than half of the population wouldn't be worried
- High level of acceptance and low level of opposition.

"CCS is a necessity not an option"

UK Committee on Climate Change

Sources : France : ADEME - *Le Captage et Stockage géologique du CO_2 (CSC) en France* (2020) ; Germany : Fraunhofer ISI - *Chancen für und Grenzen der Akzeptanz von CCS in Deutschland „CCS-Chancen"* (2015) & Acatech - *CCU und CCS – Bausteine für den Klimaschutz in der Industrie* (2018) ; Nordic Countries : Energy Procedia - *Local acceptance and communication as crucial elements for realizing CCS in the Nordic region* (2016) ; UK : The University of Manchester Research - *Public awareness and acceptance of carbon capture and utilisation in the UK* (2017)

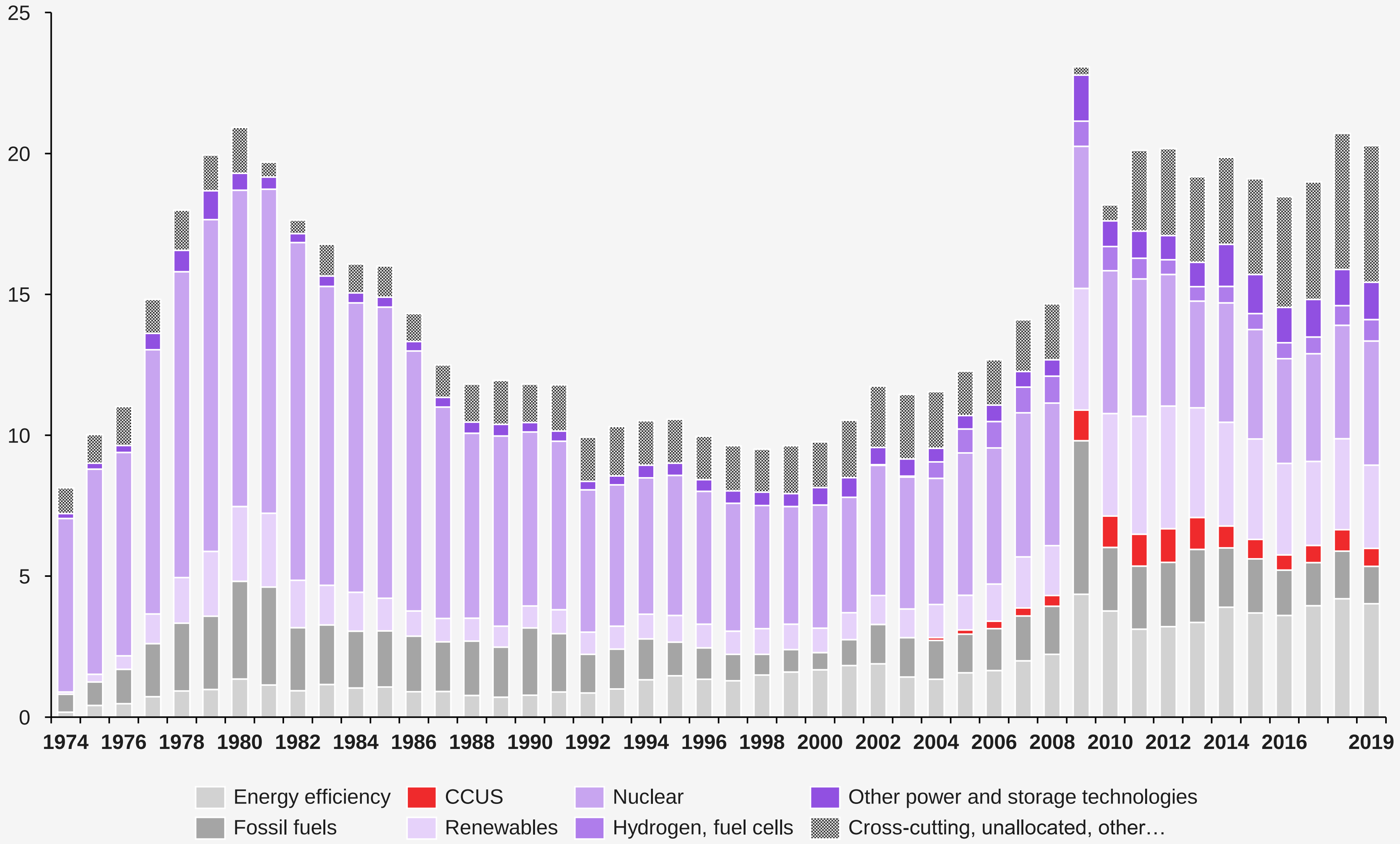
7. Financing and key players

Image by Itung01

CCUS accounts for a small portion of the total public R&D spend

After an increase following the 2009 economical crisis, total R&D budgets slightly decrease until 2017. The total level of R&D spend has stabilized around $20 billion. Renewables increased through the years while fossil fuels budgets have been divided by four between 2009 and 2019. CCUS only appeared in 2003, and after being above $1 billion in 2009–2013, the budget has declined to less than $650 million today.

Total public energy-related R&D spend
($ billion)

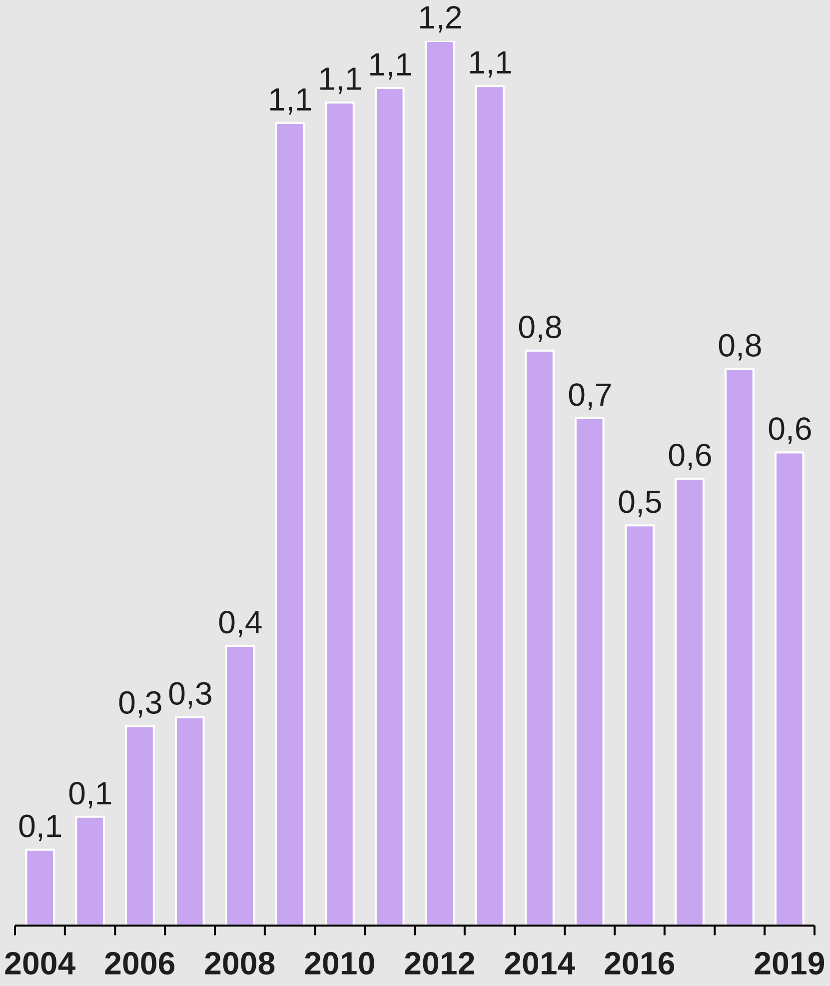


¹Estimated
Sources : IEA - *Energy Technology RD&D Budgets 2020* (2020)

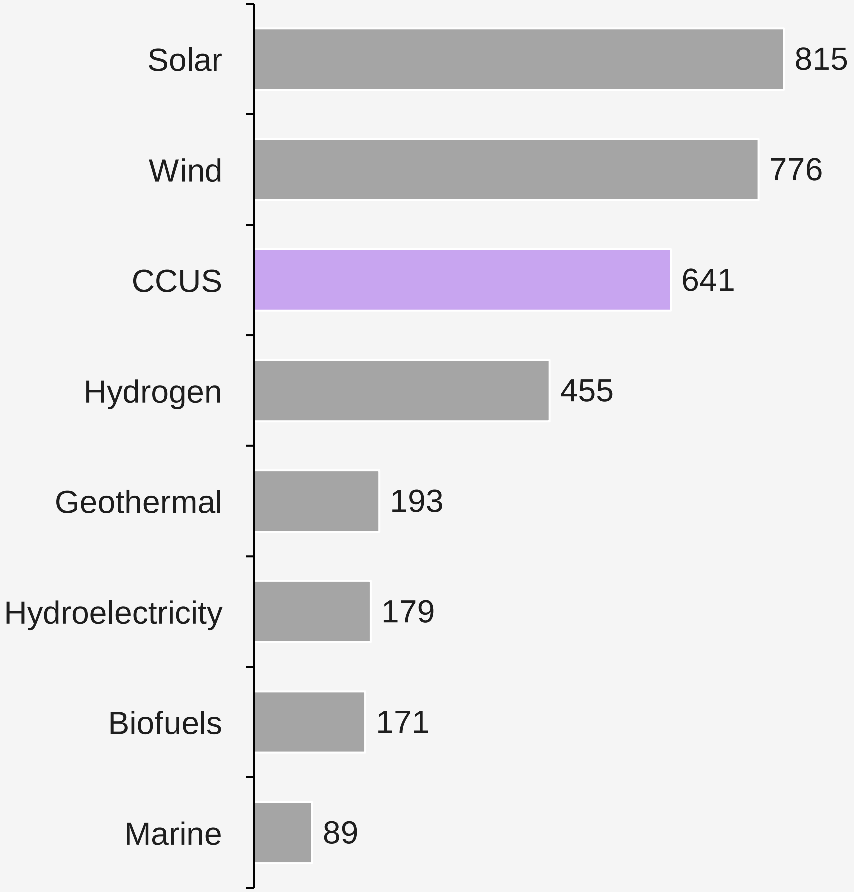
R&D budgets allocated to CCUS rose until 2012-13 post which a decline was witnessed

However, they are still greater than most of the spend on the new emerging renewables technologies

Annual public R&D spending in CCUS (2005-2019) $ billion



2019 public R&D spending in CCUS and renewables $ million



Financing

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1. Public R&D refers to IEA member country only. CCUS R&D is defined in this report as all CCUS investments except those for Large Projects (integrated projects above 0.6 Mt/CO_2year).

Source: IEA - *Energy Technology RD&D Budgets 2020* (2020) & *Energy Technology Perspective* (2020) ; OECDiLibrary - *IEA Energy Technology RD&D Statistics* (data extracted on Jan. 6th 2021)

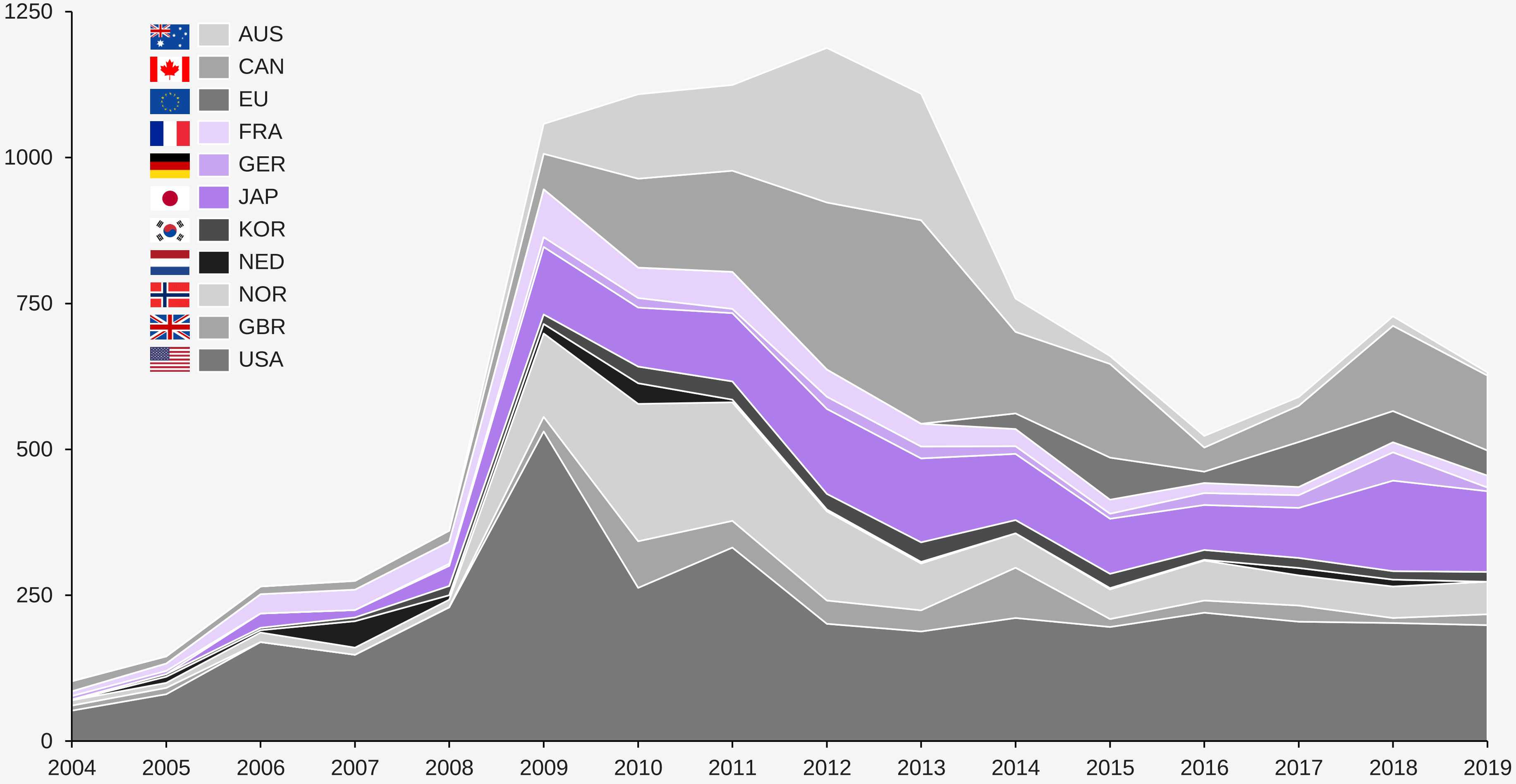
Since 2004, the United States has been a key contributor to CCUS funding

The United States has been a huge contributor to CCUS development, but its envelope has decreased to stabilize around $200 million (30% of the total). Japan and Norway are among the few countries that have increased their budgets since 2016 and have become the second and third highest contributors

Financing

Top 11 CCUS financial contribution[1] from OECD countries

2004-2019, in $ million



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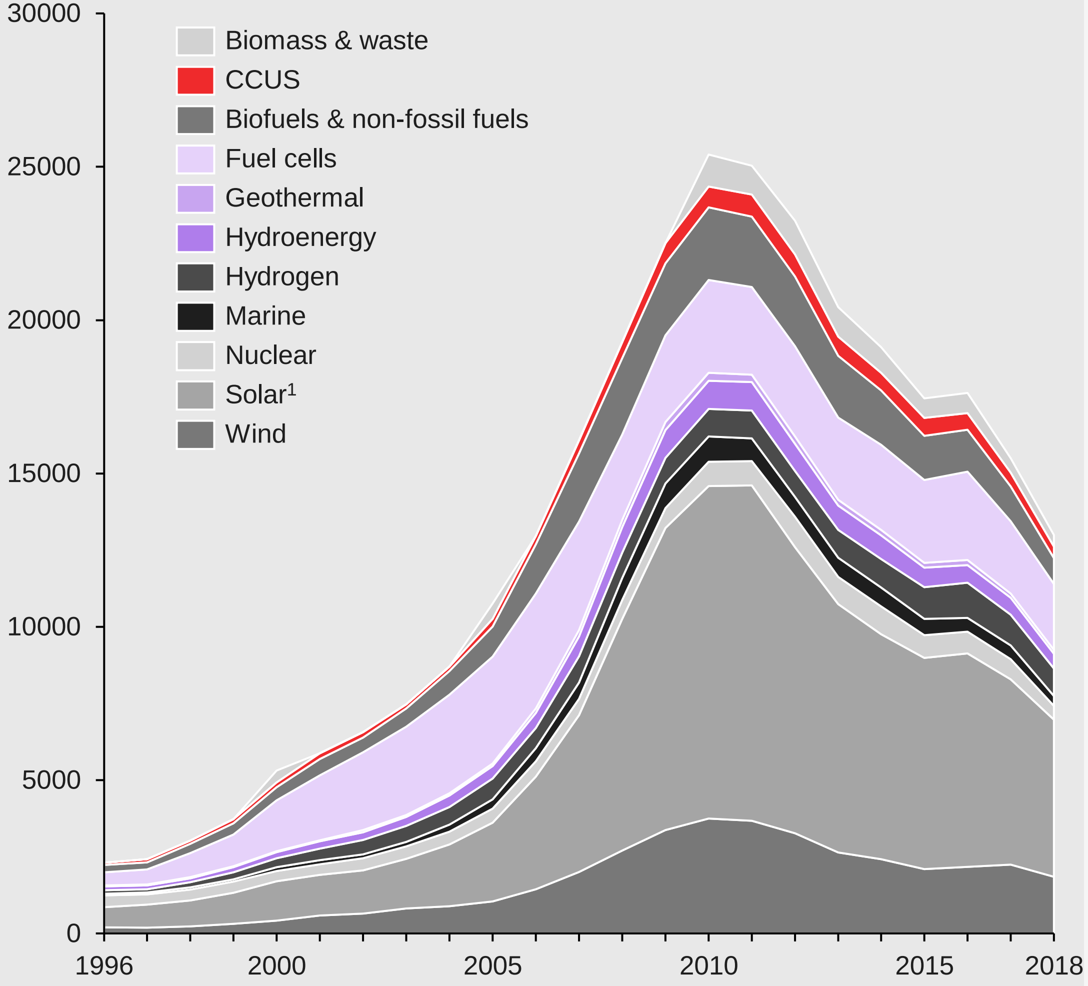
1. only data labelled as "Capture or disposal of CO_2 " were taken into account
2. EU budget is given by the European Union itself and it is not the sum of the budgets from EU members

Source: OECD.Stat – *Innovation in environment-related technologies* (data extracted on Jan. 6th 2021)

The period of 2004–2012 saw an acceleration in R&D efforts, but CCUS never claimed a top spot among low-carbon technologies in terms of patents

Annual number of patents filed for various low-carbon technologies
(in absolute numbers of patents)



Between 1996 and 2006, fuel cells and solar photovoltaic panels were the two technologies with the biggest numbers of patents filed each year.

Solar thermal energy, wind energy and biofuels have accelerated their development from 2005 to 2010.

Patents about CCUS technologies also have known a wave of increase between 2004 and 2012 (to reach more than 700 patents in 2012), before a decrease since that time.

In 2018, solar panels technologies remain the top patent producer with fuel cells and wind at the second and third ranks.

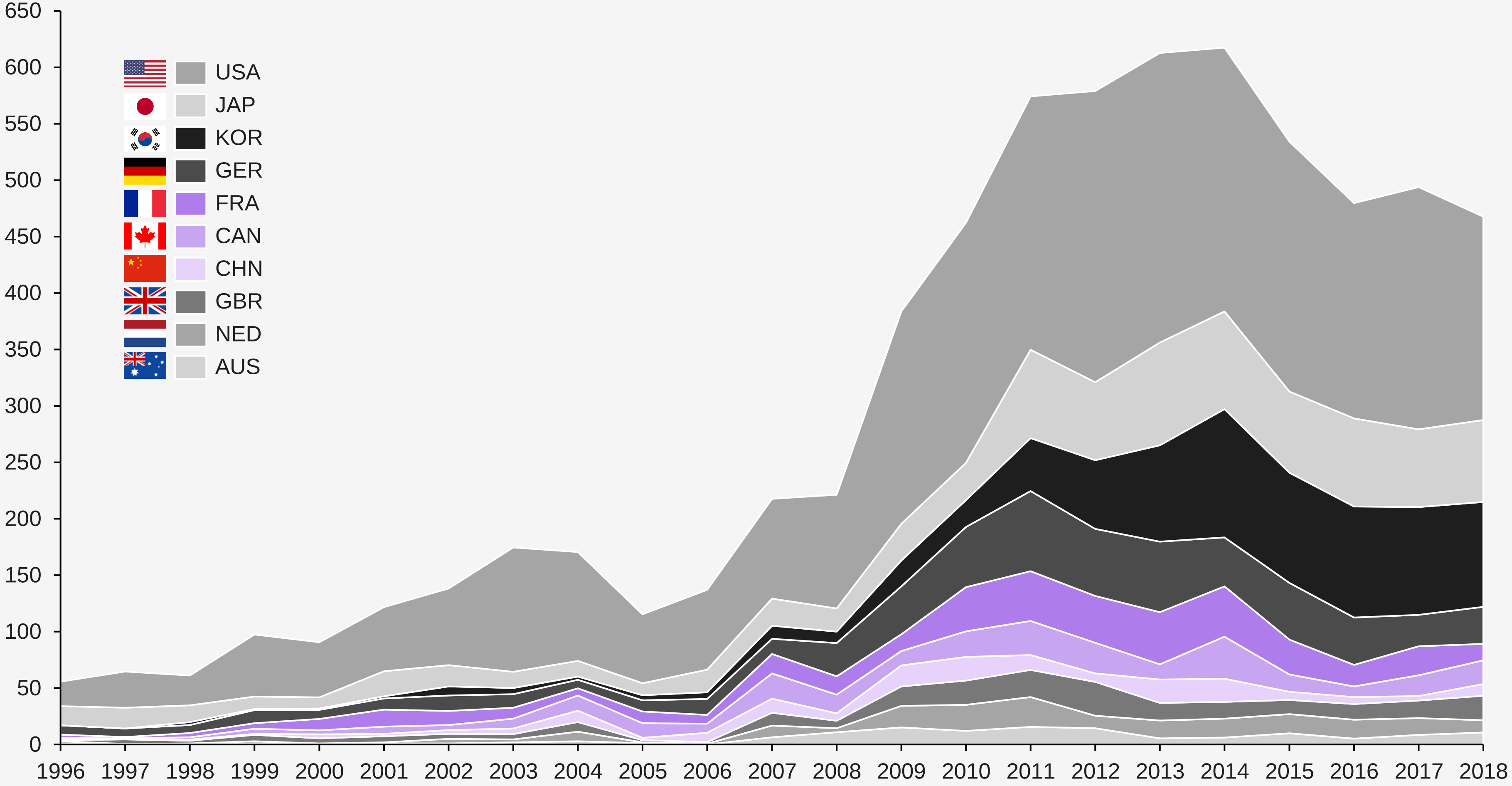
[1] Solar includes : “Solar Photovoltaic (PV)”, “Solar thermal” and “Solar hybrid PV + thermal”
Source: OECD.Stat – *Innovation in environment-related technologies* (data extracted on Jan. 6th 2021)

The United States leads in filing the most patents in CCUS

The United States had a head start of five years in working on CCUS R&D over other countries and regions and has become the reference since 2000. Japan and South Korea only started to research in 2008, while European countries struggle to file patents.

Top 10 CCUS patents OECD country producer

1996-2018, in absolute numbers of patents



Note : only data labelled as “Capture or disposal of CO_2 “ were taken into account.
Source: OECD.Stat – *Innovation in environment-related technologies* (data extracted on Jan. 6th 2021)

Major global and national utilities or oil and gas companies are important in the development of CCUS

	Separation & Capture	Transport	Utilisation and Storage
Key service providers	**Equipment manufacturers**: Alstom, MHI,GE, Siemens, Babcock & Wilcox, Pall Corp **Industrial gas producers**: Air Liquide, Air Product, Linde, Praxair, Aker **Chemicals producers**: UOP, Lurgi, Dow, BASF, YARA **Utilities and O&G companies**: ConocoPhillips, ExxonMobil, Equinor, Vattenfall, **Start-ups**: Climeworks	National Grid Gassco Maersk Tankers Kinder Morgan Larvik Shipping Nippon Gases Europe AS	**EOR producers:** Denbury Resources, Chaparral Energy, Enhance Energy, Chevron **Passive storage service providers**: Schlumberger, Halliburton, Petrofac, C12 company, Pond Technologies, Shell, TAQA **Utilisation technologies :** LanzaTech, Carbon Cure, CarbonFree (Skyonic)
Key project owners	**European utilities:** Engie, Drax Power, E.ON, Enel, Endesa, Scottish and Southern Energy, Vattenfall, Veolia **American utilities:** AES, Capital Power, SCS Energy, Southern Company, NRG Energy, SaskPower, Tenaska, TransAlta **Asia-Pacific utilities**: Dongguan Power, GreenGen, Huaneng Group (China); KEPCO (South Korea) ; Masdar (Middle East) **Major O&G companies:** Shell, BP, ExxonMobil, Total, Eni, Chevron, Equinor **National Oil Companies:** Equinor, Kuwait Petroleum Corporation, Saudi Aramco, Sabic, ADNOC, Petrobras, Pemex, China National Petroleum Corporation, Sinopec **Coal:** Consol Energy, Peabody Energy, Rio Tinto, Xstrata Coal **Chemicals, fertilizers, synfuels:** Archer Daniels Midland, Air Products, Koch Fertilizer, Shenhua Group, Sasol **Steel :** Arcelormittal, Thyssenkrupp, Emirate Steel		

Source: Press search, Kearney Energy Transition Institute

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Picture credit - Peschke, Kevin

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Acronyms.

BECCUS: Bioenergy with Carbon Capture and Storage (CCUS)

CAPEX: capital expenditure

CDR: Carbon dioxide removal, also called “negative emissions technologies” (pls refer to the Negative Emissions Technologies FactBook) are anthropogenic activities removing CO2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage but excludes natural CO2 uptake not directly caused by human activities (IPCC).

CCUS: carbon capture utilization and storage

EOR: enhanced oil recovery

ETP: Energy Technology Perspectives

ETS: Emissions Trading Scheme

EUA: European Union Allowance

FID: final investment decision

IGCC: integrated gasification combined cycle

JV: joint venture

LCOE: levelized cost of electricity

Large Project: integrated CCUS projects of demonstration or commercial scale (above 0.6 MtCO$_2$/year)

MtCO$_2$/yr: million tonnes CO$_2$ per year

MVA: monitoring, verification and accounting

NER300: new entrants reserve

NGCC: natural gas combined cycle

OXY: oxy-combustion capture

PCC: post-combustion capture

R&D: research & development

SNG: synthetic natural gas

Subcritical coal power plants: Subcritical (SUBC) coal-fired power plants work by boiling water to generate steam that activates a turbine. Supercritical (SC) and ultra-supercritical (USC) power plants operate at temperatures and pressures above the critical point of water, i.e. above the temperature and pressure at which the liquid and gas phases of water coexist leading to higher efficiency. Subcritical power plants achieve thermal efficiency in the range between 34% - 40% with the global average efficiency around 36%, whereas supercritical power plants reach efficiencies between 42% - 45%. Ultra-supercritical power plants employ advanced metal alloys to withstand extreme steam conditions and achieve even higher efficiencies (47.5%)

US DOE: US Department of Energy

WEO: World Energy Outlook

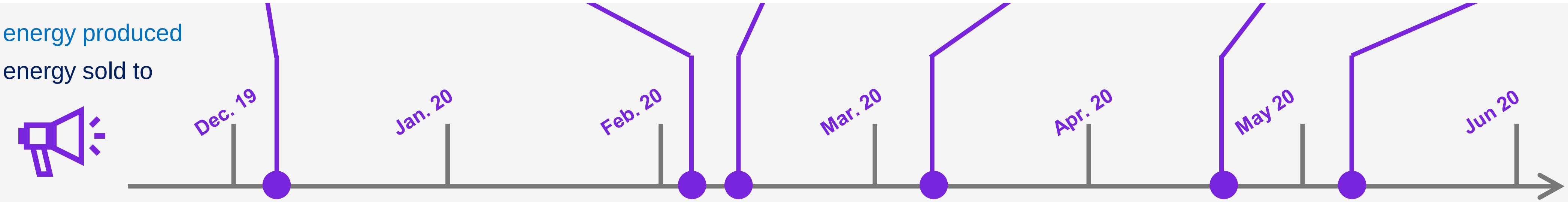
O&G Majors and IOCs in Europe have announced carbon neutrality targets, including scope 3 emissions

Carbon neutrality on scope 3 implies almost no gasoline or fuels sold in some countries by 2050

		REPSOL	equinor	bp	eni		TOTAL
2030	Scope 1 + 2	-20%	Net Zero	-30% to -35%	Net Zero (Upstream)	-	-
	Scope 3	-	-	-35% to -40%	-	-	-
	Scope 3	-20%	-	>-15%	-30% (Absolute[1]) -15% (Intensity[2])	-30%	-15%
2040	Scope 1 + 2	-40%	Net Zero	-	Net Zero	-	-
	Scope 3	-	-	-	-	-	-
	Scope 3	-40%	-	-	-	-	-35%
2050	Scope 1 + 2	Net Zero	Net Zero	Net Zero	Net Zero	Net Zero	Net Zero
	Scope 3	-	Near Zero in Norway	Net Zero	-	-	Net Zero in Europe
	Scope 3	Net Zero	Net zero	-50%	-80% (Absolute[1]) -55% (Intensity[2])	-65%	-60% globally Net zero (EU)

Scope 3 of energy produced

Scope 3 of energy sold to costumers



Note : [1]Absolute: reduction in net emissions from the entire life cycle of sold energy products – [2]Intensity :X% of the emission intensity

The main aim of R&D in storage is to find suitable reservoirs and understand the behaviour of CO_2 underground, for which field demonstration is essential

See the Sleipner case slide 32

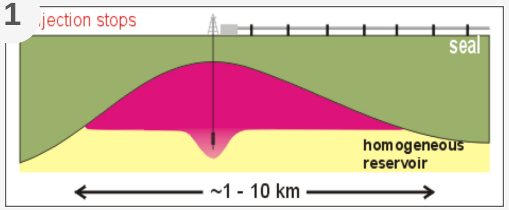
Main storage R&D axis

1. Assess country-wide storage space:
   - Early results seem to indicate massive theoretical storage potential globally;
   - most of the potential lies within deep saline aquifers, which are geographically widespread;
   - Pore space in depleted oil and gas reservoirs is suitable but has limited availability;
   - According to the GCCSI, “the importance of undertaking storage-related actions this decade to prepare for widespread CCUS deployment post-2020 cannot be overstated”.
2. Understand CO_2 behaviour, through:
   - Large-scale field demonstrations in aquifers;
   - Software modelling tools of key trapping mechanisms:
     - ① Physical trapping of mobile CO_2 plume
     - ② Residual trapping of immobile CO_2 bubbles
     - ③ Solubility trapping of dissolved immobile CO_2
   - Reservoir engineering to manage risk of leakage;
   - Monitoring, verification and accounting (MVA);
   - International standards for MVA and risk assessments;

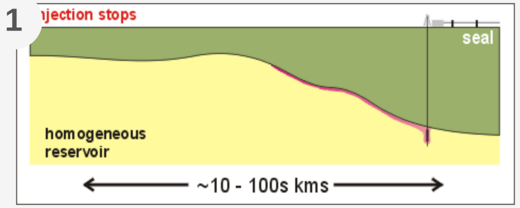
Source: GCCSI (2014), “Global Status of CCUS”; Picture credits: CO2CRC; CAGS

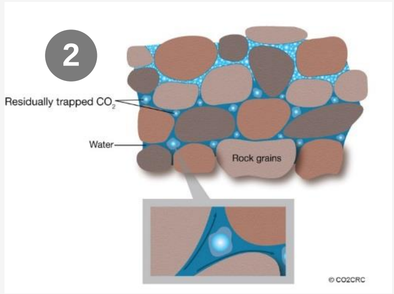
Simplified behaviour of CO_2 after injection

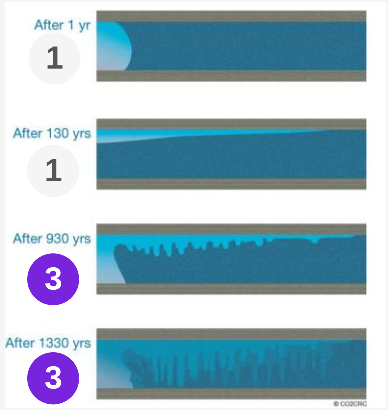
PETROLEUM RESERVOIR
Closed structure



AQUIFER
Open Structure







CCUS can help decarbonize electricity when combined with thermal power generation

Name of the project	Country	Capture capacity ($MtCO_2$)	Description
Calc Capture Elk Hills Power Plant	🇺🇸	1.4	550 MWe natural gas combined cycle plant in California, United States with CO_2 captured and stored through EOR for 2024
Caledonia Clean Energy	🇬🇧	3.1	Natural gas-fired plant provides flexibility without scarifying CO_2 capture for 2024
CarbFix Project Hellisheidi	🇮🇸	0.01	Geothermal power plant capturing 12,000 tons CO_2 per year since 2014
Haifeng	🇨🇳	0.02	2.1 MW coal-fired power plant
Chongqing	🇨🇳	0.01	Post-combustion capture from coal-fired power plant
Drax BECCS Plant	🇬🇧	4.0	Planned for 2027, bio-energy combined with CCUS technology, part of the Zero Carbon Humber Project
Dry Fork	🇺🇸	3.0	Coal-based electric generation power plant plans to capture 3 Mtpa for 2025
Project Tundra	🇺🇸	3.1	Retrofit of the coal-fired Milton R. Young plant unit 2 for 2025
Eemshaven Power Plant	🇺🇸	0.2	Coal and biomass fired 1.6GW plant equipped with CCUS since 2018
Gerald Gentleman Station	🇺🇸	0.8	One of the two coaled fired unit of Gerald Gentleman Station (700 Mwe) is equipped with carbon capture with DOE funding's for 2025

[1] Scope 1 vs 184 gCO_2/kWh for methane

[2] Vacuum swing absorption

Sources: H21 Leeds City Gate Report, HyNet Technical Report August 2017, HyNet North Wet From Vision to Reality 2018, Status of Port-Jérôme Cryocap Plant 2017, The Carbon Capture Project at Air Products' Port Arthur Hydrogen Production facility, Hydrogen Energy California Final Topical Report 2017, Quest CCUS Project Annual Summary Report 2018, How Humber Zero Works, H-Vision Feasibility Report 2019; Kearney Energy Transition Institute analysis

CCUS can help decarbonize electricity when combined with thermal power generation

Name of the project	Country	Capture capacity (MtCO$_2$)	Description
GreenGen IGCC	🇨🇳	2.0	Coal-fueled plant of 650 MW progressively equipped with carbon capture from 2009 to 2020
Korea CCUS 1 & 2	🇰🇷	1.2	Project to demonstrate post-combustion capture technology, which would capture up to 1.2 Mtpa of CO$_2$ from a 300 MW coal power plant.
Petra Nova	🇺🇸	1.4	Texas power plant retrofitted with post-combustion CO$_2$ capture facility, transportation near Houston for EOR
Boundary Dam CCS	🇺🇸	1.0	Combines post-combustion CCUS with coal-fired power generation, some captured CO$_2$ goes for EOR, a portion of the CO$_2$ is stored geologically
Prairie State	🇺🇸	5.0	816 MWe coal-fired unit of Prairie State Energy Campus under study to capture 5 Mtpa by 2021
ZEROS Projects	🇺🇸	1.5	Low-cost waste to energy by oxy-combustion with carbon capture
Ireland Gas Network	🇮🇪	2.5	Plan to decarbonize Ireland activities involving abated natural gas and CCUS technology for 2030
Sinopec Shengli	🇨🇳	1.0	Carbon capture from a coal-fired power plant in China from 0.04 Mtpa from a pilot to 1Mtpa objective in 2025

[1] Scope 1 vs 184 gCO$_2$/kWh for methane
[2] Vacuum swing absorption
Sources: H21 Leeds City Gate Report, HyNet Technical Report August 2017, HyNet North Wet From Vision to Reality 2018, Status of Port-Jérôme Cryocap Plant 2017, The Carbon Capture Project at Air Products' Port Arthur Hydrogen Production facility, Hydrogen Energy California Final Topical Report 2017, Quest CCUS Project Annual Summary Report 2018, How Humber Zero Works, H-Vision Feasibility Report 2019; Kearney Energy Transition Institute analysis

CCUS projects to decarbonize cement industries

Name of the project	Country	Capture capacity ($MtCO_2$)	Description
CO2MENT Project	🇨🇦	1 t per day	Pilot project to capture $1tCO_2$ per day. CO_2 captured would be used for the coal mill fire suppression system and for water treatment. Phase III has begun in 2020.
Leilac Project	🇧🇪	TBD	Project to capture 95% of CO_2 produced during the process thanks to a direct separation calcining technology
Longship CCUS	🇳🇴	0.8	Project to capture 0,8 Mtpa of CO_2 and then stored in the offshore Smeaheia area, total cost of $2.73 billion (67% financed by the country). To be operational by 2024
Lehig's Edmonton plant	🇨🇦	1.4	Project to capture the major of CO_2 from flue gas. To be operational by 2021–2022
LafargeHolcim Cement Carbon Capture	🇺🇸	0.7	Consortium (including Total) to conduct a study to assess the viability of a CO_2 capture facility at LafargeHolcim's cement plant in Colorado. No operational date announced yet

[1] Scope 1 vs 184 gCO_2/kWh for methane

[2] Vacuum swing absorption

Sources: H21 Leeds City Gate Report, HyNet Technical Report August 2017, HyNet North Wet From Vision to Reality 2018, Status of Port-Jérôme Cryocap Plant 2017, The Carbon Capture Project at Air Products' Port Arthur Hydrogen Production facility, Hydrogen Energy California Final Topical Report 2017, Quest CCUS Project Annual Summary Report 2018, How Humber Zero Works, H-Vision Feasibility Report 2019; Kearney Energy Transition Institute analysis

CCUS projects to decarbonize iron and steel production industries

Name of the project	Country	Capture capacity ($MtCO_2$)	Description
Abu Dhabi CCS	🇦🇪	0.8	Built a compression facility to capture 90% of CO_2 from steel factory and to use for EOR; project started in 2016
Beijing Shougang	🇨🇳	0.2	Started in May 2018, converts CO_2 generated at Shougang Steel's Caofeidian facility into fuel grade ethanol thanks to LanzaTech's technology
Swayana Mpumalanga	🇿🇦	0.2 to 0.7	Project to capture CO_2 emissions from a ferroalloy plant and convert them into fuel ethanol thanks to LanzaTech's technology. Started in 2019
3D Project	🇫🇷	1.0	Assesses IFPEN's capture solvent reducing the CO_2 captured cost by 30% and the energy consumption during the capture process at the ArcelorMittal steelworks site. Pilot in 2021, expected to be fully operational by 2025
Steelanol	🇧🇪	0,35	Project aims to produce bioethanol from CO_2 emissions from blast furnaces in a steel mill in Ghent thanks to LanzaTech's technology. Starting in 2022
Athos	🇳🇱	7.5	Project to capture CO_2 from TATA Steel and other industries of the region and then to use for horticulture, mineralization or other future CO_2 industry usages or to be stored in the North Sea. To be operational in 2027
COURSE 50	🇯🇵	6t per day	Project to enable a 20% reduction in CO_2 from blast furnaces in the steel industry. Phase ongoing and industrialization expected for 2030
Net Zero Teesside	🇬🇧	10	Building the first European CCUS equipped industrial zone. First operational steps by mid-2020 and expected to be fully operational by 2030

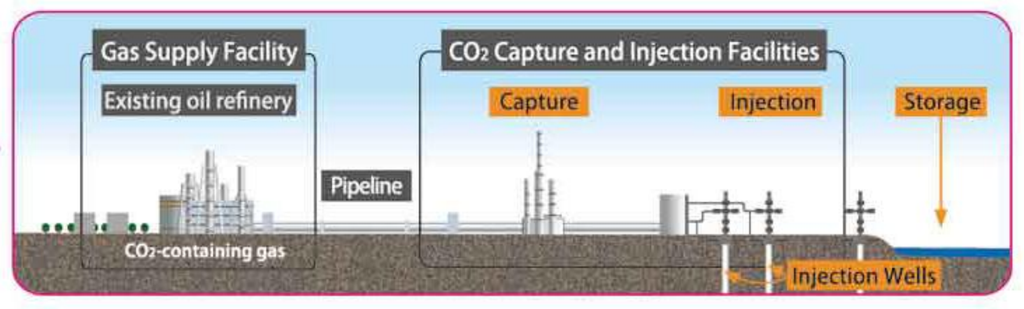
[1] Scope 1 vs 184 gCO_2/kWh for methane

[2] Vacuum swing absorption

Sources: H21 Leeds City Gate Report, HyNet Technical Report August 2017, HyNet North Wet From Vision to Reality 2018, Status of Port-Jérôme Cryocap Plant 2017, The Carbon Capture Project at Air Products' Port Arthur Hydrogen Production facility, Hydrogen Energy California Final Topical Report 2017, Quest CCUS Project Annual Summary Report 2018, How Humber Zero Works, H-Vision Feasibility Report 2019; Kearney Energy Transition Institute analysis

Hydrogen as an industrial resource

Tomakomai



Country: Japan

Capex: $284 million

Opex: $18 million per year

CO_2 savings: 0.1 Mt per year

Project leader: Japan CCUS Co. Ltd

Project characteristics	Details
Production technology	
CCUS	99% of CO_2 is captured
Government funding	
CO_2 storage capacity	Total of 300 000 t
Business type	
Planning	Demonstration phase : 2012–2016 CO_2 injections : 2016–2019 Monitoring : 2016–2020
Capture type	Amine type solvent
Transport type	Pipeline
Storage type	Offshore geological storage

Source: CCUS Technologies@ MIT, Japan CCUS Co.; Kearney Energy Transition Institute analysis

Other sectors: refining

Carbon capture from hydrogen production for a refinery

North West Redwater Refinery (ACTL)

Country: Canada

Capacity: 13 000 m^3 per day

Capex: $6.5 billion

CO_2 savings: 1.2 Mt per year

Partnerships: North West Redwater Partnership and Canadian Natural Resources

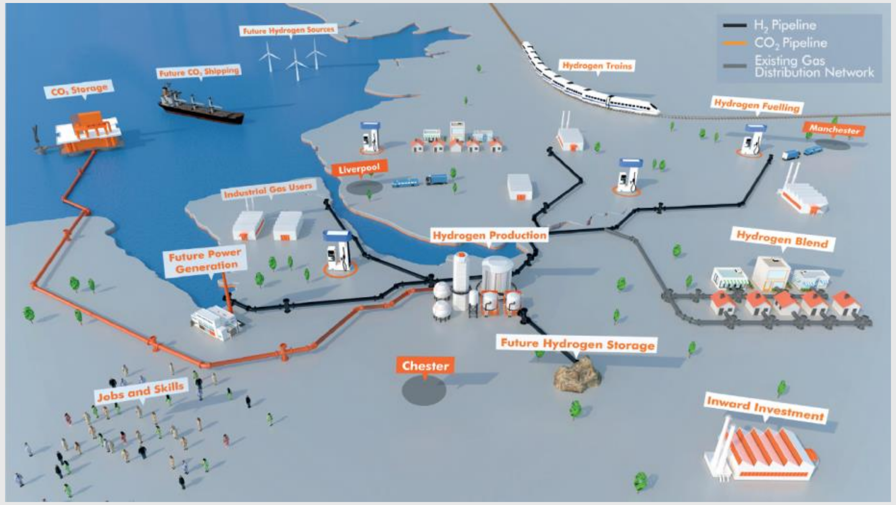
Project characteristics	Details
Production technology	
CCUS	95% of CO_2 is captured (at least 99% pure)
Government funding	$495 million by the Alberta Government for the ACTL $63.3 million by Canadian Government
CO_2 storage capacity	Between 1.2 and 1.4 MtCO_2 per year
Business type	Oil refinery where H_2 is used in the upgrading bitumen process. CO_2 is captured and then transported to central and southern Alberta for EOR purposes.
Planning	2005: Start of the project May 2020: Project operational
Capture type	
Transport type	Alberta Carbon Trunk Line System
Storage type	EOR

Source: Kearney Energy Transition Institute analysis

Other sectors: refining

Produce hydrogen combined with CCUS and blend it with natural gas for supply homes or use it as transport fuel

HyNet North West



Country: UK

Capacity: 890 MW of H_2
Capex: £0.92 billion

Opex: £85 million per year

CoA: £114 per tCO_2

CO_2 savings: 1.1 Mt per year

Project characteristics	Details
Production technology	Low carbon hydrogen from natural gas via two autothermal reforming units
CCUS	93% CO_2 emissions captured, CO_2 savings 1.1 $MtCO_2$/year
Government funding	£12.8 million
CO_2 storage capacity	130 million tons
Business type	Hydrogen production, distribution and blending with natural gas for supply to homes, CCUS, switching industry from natural gas to hydrogen
Planning	Start 2018 Government funding February/October 2020 Construction Spring 2021Deliverable 2026
Capture type	Pre-combustion
Transport type	Pipeline (built)
Storage type	Geological storage sites

Sources: Report: Cadent Your Gas Network, HyNet North West Delivering Clean Growth, HyNet North West from Vision to Reality; Kearney Energy Transition Institute analysis

Produce low carbon hydrogen from natural gas with CCUS to fully supply industries and blend it for home supply

H21 North of England

Country: UK

Capacity: 12.15 GW of H_2
Capex: £1.34 billion
Opex: £24 million per year
CoA:
CO_2 savings:
CO_2 footprint: 14.4g/kWh
Partnerships: Cadent, Equinor, Northern Gas Network

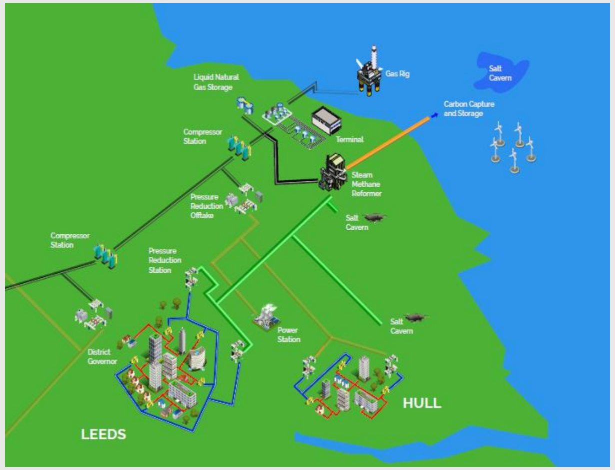
Project characteristics	Details
Production technology	Low carbon hydrogen from natural gas via nine autothermal reforming units
CCUS	94.2% CO_2 emissions captured
Government funding	
CO_2 storage capacity	20 Mtpa CO_2 by 2035
Business type	Hydrogen production, distribution and blending with natural gas for supply to homes, CCUS, switching industry from natural gas to hydrogen
Planning	2028-2034 Delivery
Capture type	Pre-combustion
Transport type	Pipeline
Storage type	Geological storage sites

Sources: H21 NoE Report 2018; Kearney Energy Transition Institute analysis

Other sectors: hydrogen

Power Leeds urban area with hydrogen and replace natural gas

H21 Leeds City Gate



Country: UK

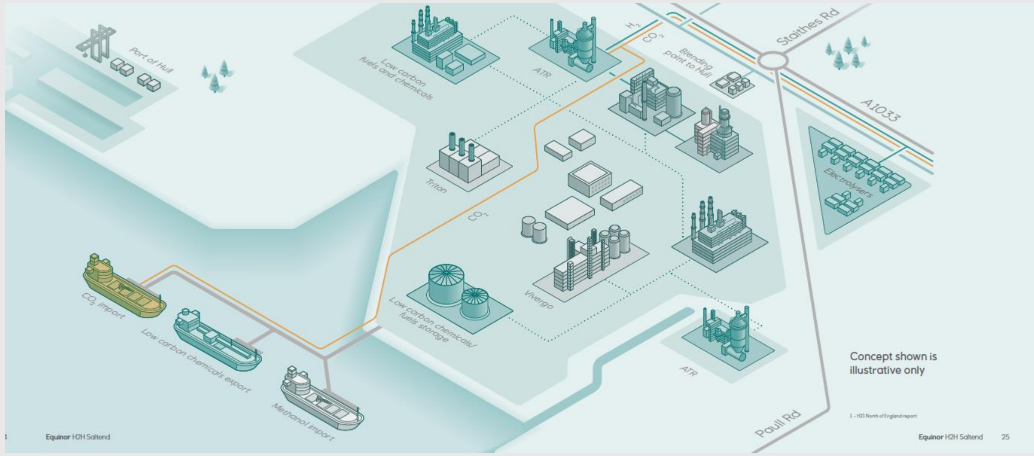
Capacity: 1 GW of H_2
Capex: £2 billion
Opex: £139 million per year
CO_2 savings: 1.5 Mt CO2 per year
CO_2 footprint: 27gCO_2/kWh
Partnerships: Northern Gas Network, Wales and West Utilities

Project characteristics	Details
Production technology	Low carbon hydrogen from natural gas, by four SMR 305,000Sm3/h 1,025 MW
CCUS	90% CO_2 emissions captured
Government funding	
CO_2 storage capacity	
Business type	
Planning	2016 Establishment of H21 program, 2018 Provision of funding to begin the FEED,
Capture type	Pre-combustion
Transport type	Pipeline
Storage type	Geological storage sites

Sources: H2H Saltend; Kearney Energy Transition Institute analysis

Fuel switching from natural gas to hydrogen combined with CCUS to power industries and decarbonize domestic heat

H2H Saltend



Country: UK
Capacity: 600 MW, 3GW by 2030
Capex:
Opex:
CoA:
CO_2 savings: 0.9Mt CO2 per year
CO_2 footprint:
Partnerships: Equinor

Project characteristics	**Details**
Production technology	Produce hydrogen by ATR to be blended with natural gas in the beginning (30%)
CCUS	95% efficiency in carbon capture
Government funding	
CO_2 storage capacity	
Business type	
Planning	2021–2023 project matured to final investment, 2024–2026 engineering and construction, 2026–2027 production
Capture type	Pre-combustion
Transport type	Pipeline
Storage type	Geological storage sites

Sources: H2H Saltend; Kearney Energy Transition Institute analysis

Other sectors: hydrogen

Kearney Energy Transition Institute

The Kearney Energy Transition Institute is a nonprofit organization. It provides leading insights on global trends in energy transition, technologies, and strategic implications for private sector businesses and public sector institutions. The Institute is dedicated to combining objective technological insights with economical perspectives to define the consequences and opportunities for decision makers in a rapidly changing energy landscape. The independence of the Institute fosters unbiased primary insights and the ability to co-create new ideas with interested sponsors and relevant stakeholders.

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