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Technology Scouting - Carbon Capture: From Today's to Novel Technologies

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Technology Scouting - Carbon Capture: From Today's to Novel Technologies

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Thanks for their contribution to the report.

ABSTRACT

The EU Commission has recently published its long-term strategic vision exploring different scenarios leading to an EU low-carbon economy by 2050. In all these scenarios, the Carbon Capture and Storage (CCS) has been identified as a key technology to achieve this ambitious target, playing a crucial role to reduce emission levels required to limit global warming to 2°C and pursuit efforts to limit the temperature increase even further to 1.5°C.

This study, conducted by Future Bridge at the request of Concawe, provides an overview of the carbon capture technologies state-of-art, with focus not only on the commercial but also on the near-term technologies, which are likely to be commercialized in the 2025-2030 timeframe, and on the several new emerging technologies.

For this mapping exercise, FutureBridge has considered various techno-economic factors such as carbon capture efficiency/rates, purity, cost of CO_2 capture per ton, levelised cost of electricity, risks and barriers to assess the near-term and emerging carbon capture technologies. It has collected information from patents, scientific literature, published techno-commercial reports, white papers, annual reports and sustainability reports to assess the overall available technologies around carbon capture. In addition to this, FutureBridge has also analyzed the published front-end engineering and design reports, integrated assessment models, and techno-economic analysis report for pilot and demonstration plants to gauge the near-term commercial carbon capture technologies.

KEYWORDS

Carbon Capture and Storage, CCS, post-combustion, pre-combustion, oxy-fuel, direct air capture, CO_2 storage, emerging CCS technologies

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SUMMARY

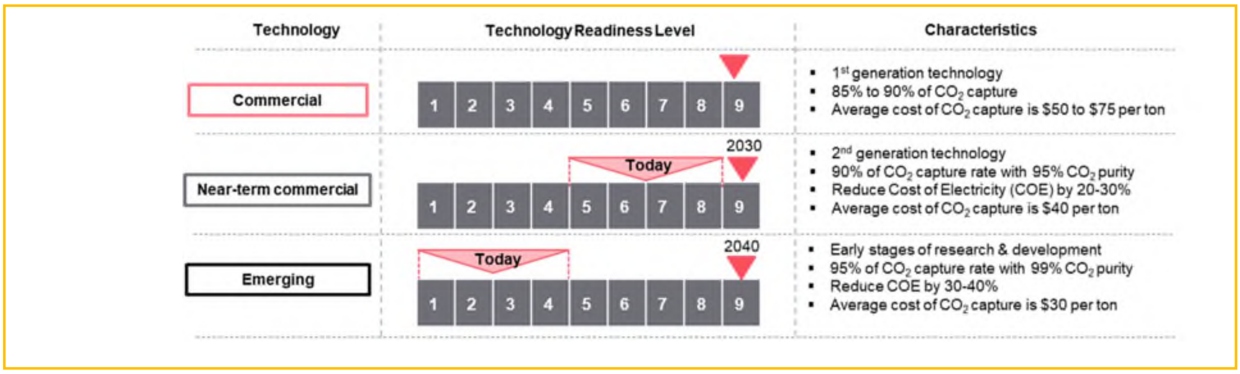
CO_2 emission is a global concern as it is primarily responsible for climate change and global warming. The industry sector is responsible for around 20% of the current greenhouse gas emissions. Technologies for ramping down CO_2 emission already exist; these include swapping fossil fuels for renewable sources, boosting production & energy efficiency, implementing Carbon Capture and Storage (CCS) technologies, and discouraging carbon emissions by putting a price on them. Over the last three decades, several CO_2 capture technologies have been developed owing to the increasing awareness regarding the importance of reducing carbon emissions. A few of these technologies such as amine-based CO_2 capture are implemented at the industrial level.

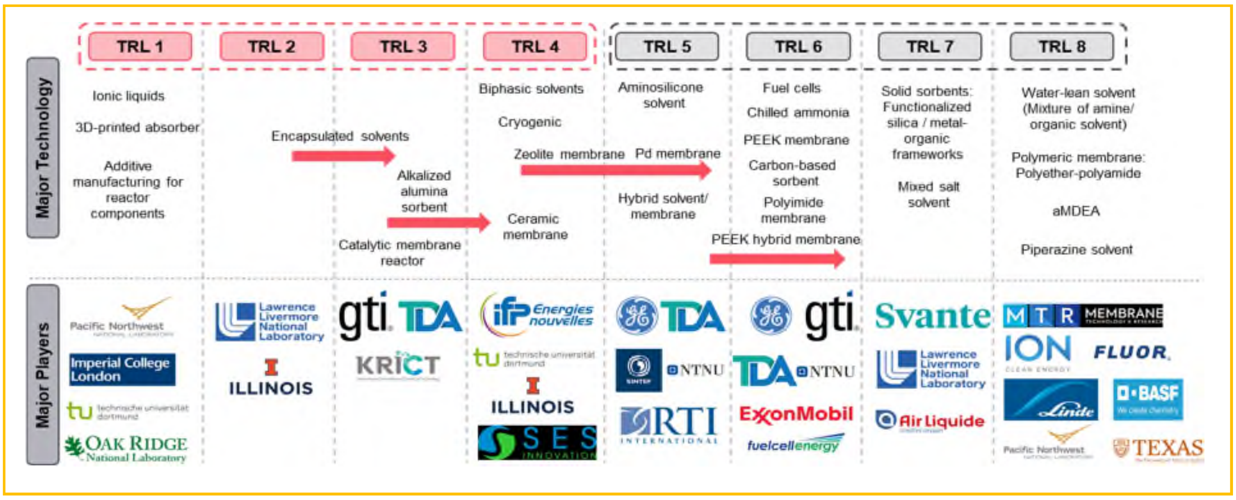
CCS can play a significant role in mitigating climate change. It involves capturing carbon dioxide at stationary point sources, which is a single localized emitter, such as fossil fuel power plants, refineries, industrial manufacturing plants, and heavy industrial (iron & steel and cement) plants as well as mobile sources, such as automobiles, ships, aircraft, etc, or directly from the air (Direct Air Capture) The captured CO_2 is compressed and transported for its storage in geological formations or for direct (non-conversion of CO_2, such as enhanced oil recovery, food & beverage, heat transfer fluids, etc.) and indirect (conversion of CO_2 into chemicals, fuels, and building materials) use.

This study focuses on near-term opportunities in carbon capture technologies, which are likely to be commercialized in the 2025-2030 timeframe, and the several emerging carbon capture technologies for power plants, and industrial process applications as well. FutureBridge has considered the various techno-economical factors such as carbon capture efficiency/rates, purity, cost of CO_2 capture per ton, levelised cost of electricity, risks and barriers to assess the near-term and emerging carbon capture technologies. It has collated information from patents, scientific literature, published techno-commercial reports, white papers, annual reports and sustainability reports to assess the overall available technologies around carbon capture. In addition to this, FutureBridge has also analyzed the published front-end engineering and design reports, integrated assessment models, and techno-economic analysis report for pilot and demonstration plants to gauge the near-term commercial carbon capture technologies.

Currently, the carbon capture technology developers are largely focused on designing facilities to capture rates of 85% to 90%, leaving 10-15% of the carbon emissions uncaptured (technically unfeasible), which are usually referred to as residual emissions.

Technology Categorization: FutureBridge has bucketed the carbon capture technologies into the following categories:





Commercial technology: 1st generation technology (TRL9) with 85% to 90% of CO_2 capture with 95% purity.

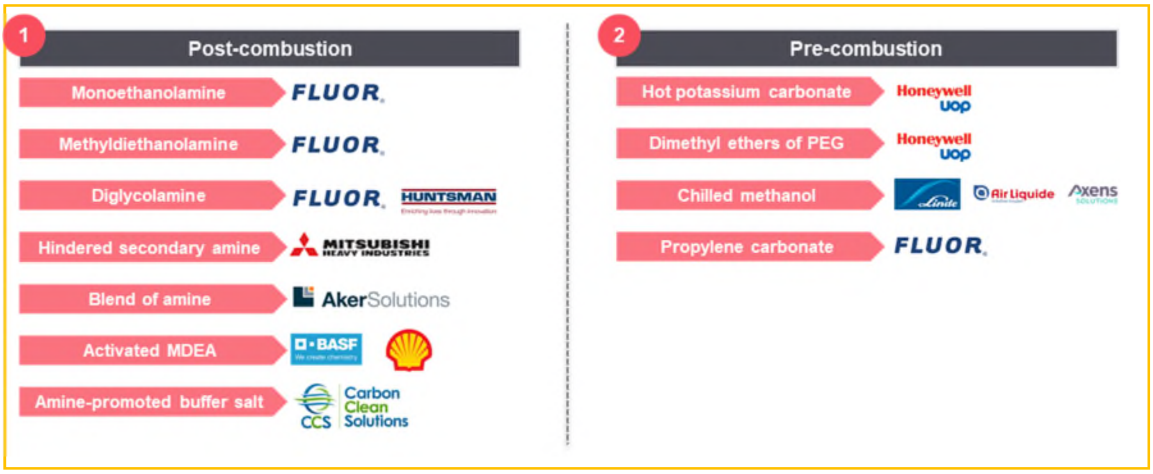
The source characteristics such as quantity, continuity and CO_2 concentration influence the carbon capture cost; generally, it's cheaper to capture CO_2 when its concentration in the emissions is high, hence, in industries where the CO_2 emissions are relatively high (ethanol, natural gas processing, ethylene oxide), the avoided cost of CO_2 is lower than in power plants where the CO_2 concentration in the flue gas is relatively low.

- Post-combustion carbon capture technology consists of treating exhaust gases on the output side of the various industries such as power, fertilizer, paper, hydrogen, etc. is based on chemical absorption which appears to be best suited to CO_2 capture.

  Post-combustion capture technique with chemical absorption is the most proven technology for CO_2 removal from combustion flue gases and it is mostly based on chemical absorption/desorption with the use of liquid absorbent, such as MonoEthanolAmine (MEA) at 30 wt.% in water. The chemical absorption is commercialized and used in petroleum, natural gas, and coal-based power plants for separating acid gas (such as CO_2 or H_2S) from natural gas streams. This technique focuses on the reaction (largely exothermic) between the chemical absorbents and CO_2.

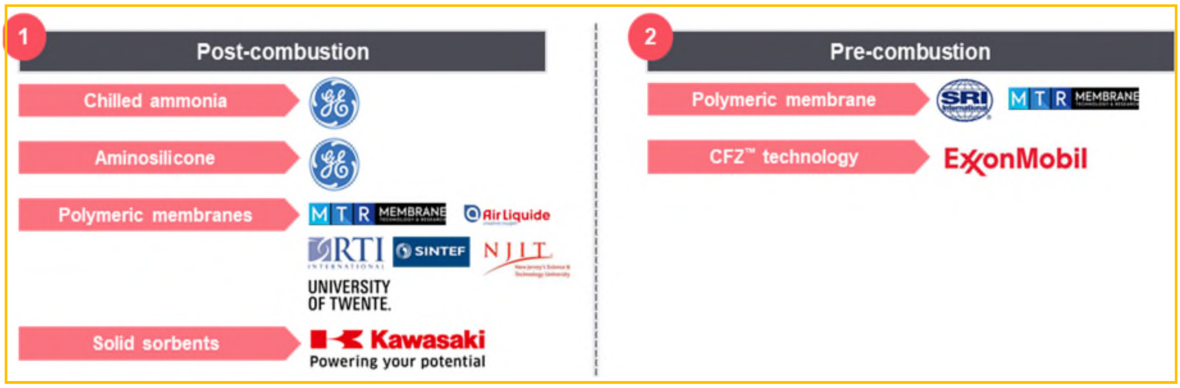
- Pre-combustion carbon capture technology consists of the near-complete capture of CO_2 before fuel combustion or before venting out the exhaust gas or flue gases and is usually implemented in conjunction with gasification of coal, coke, waste biomass, and or residual oil or steam reforming/partial oxidation of natural gas to produce syngas. Further, the water-gas shift reaction produces CO_2 from the CO, resulting in H_2-rich syngas that (syngas) can be combusted in gas turbines, boilers, and furnaces, while when H_2 is sufficiently purified, it can be used in fuel cells and used in refinery operations such as hydrotreatment, hydroprocessing, etc.

  Currently, pre-combustion physical solvent-based technology is used in industrial manufacturing processes, such as syngas, hydrogen, and natural gas production. A few facilities, such as Enid Fertilizer CCS plant, utilize chemical solvents via the implementation of the hot potassium carbonate (Benfield process, Honeywell UOP), which is a high temperature and high-pressure chemical absorption process. Below chart shows the representation of commercial technologies for post and pre-combustion technologies.



Near-term commercial technology: 2nd generation technology: Technologies currently in the **advanced phase (>TRL 5)** which are scheduled to become available for demonstration-scale testing around 2020-25 and expected to become available for commercial deployment in 2025-30. **These technologies can offer overall low carbon capture cost (~$40 per tonne of CO_2), 90% of CO_2 capture rate with 95% CO_2 purity compared to currently available first-generation technologies.**

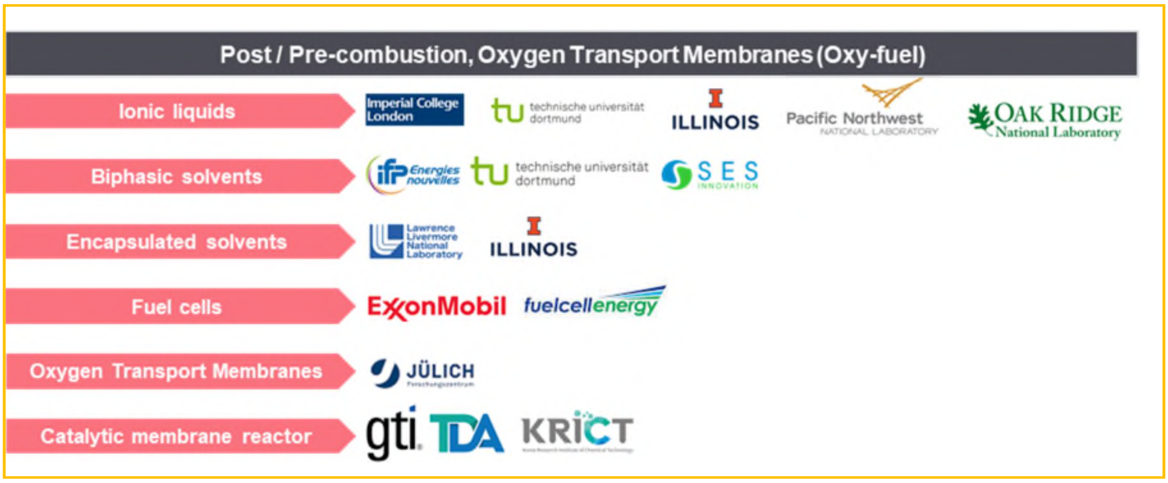
Mentioned below are some of the near-term carbon capture technologies that are likely to be commercialized for coal-fired and natural-gas-fired power plants.



- A lot of research and development work has been conducted around improvements in membranes for pre and post-combustion CO_2 capture technology. Several groups are developing polymeric membrane technology for post-combustion carbon capture, for example, Norwegian University of Science and Technology patented polyvinyl amine membrane[1] together with fixed amine groups, is evaluated at a pilot plant at an EDP power plant in Portugal.
- Membrane Technology Research Inc. is testing its innovative Polaris™ membranes at the various testing centre since 2006. MTR is also evaluating a hybrid membrane-absorption process system based on a combination of Polaris™ membranes and an amine solvent-based capture system. Other organizations such as Air Liquide S.A., SRI International, SINTEF Norway, Twente University, Research Triangle Institute, and New Jersey Institute of Technology are active in this area.

Emerging technology: Transformational technology (<TRL 5) which are in early stages of research & development that offer the potential for game-changing improvements in cost and performance (30-40% COE reduction), carbon capture cost at ~\$30 per tonne of CO_2, and 95% of CO_2 capture rate with 99% CO_2 purity. These technologies would be available for demonstration-scale testing around 2030-35, and for commercial deployment in the 2035-40 timeframe.

These emerging technologies will outperform current technologies for pre-combustion and post-combustion carbon capture in power plants and refineries including H_2 generation.



Status of CCS Technologies: Stakeholders such as federal government, public / private investors, etc., are pursuing a set of concrete initiatives to speed the commercial development of CCS technologies worldwide. FutureBridge concludes that international collaboration and substantial investment in innovation will drive down the cost and accelerate deployment of CCS.

[1] https://patents.google.com/patent/US8764881B2/en

1. NEED FOR CCUS

Global climate change has become an issue of major international concern, as it has been observed that over the years. The 2018 IPCC report (Special Report on Global Warming of 1.5°C) concluded that human-induced global warming reached approximately 1°C above pre-industrial levels in 2017, and is currently increasing at around 0.2°C per decade [ACP4A 2018][2]. An increase in global temperature is harming the environment and ecology, such as loss of sea ice, accelerated sea-level rise, frequent wildfires, more intense heat waves, high intensity of tropical storms, and longer periods of drought in certain regions. The emission of greenhouse gases such as carbon dioxide, nitrous oxide, and methane is primarily responsible for global climate change.

CO_2 emission is a global concern as it is primarily responsible for climate change and global warming. **The Global Carbon Project**, a research partner of the World Climate Research Program, reported that six countries are responsible for at least 67% of the world's CO_2 emissions, with China (28%), the United States (15%), and India (7%) leading the way. In 2019, the United States (-0.09%) and the European Union (-0.06%) managed to cut their CO_2 output, while China grew CO_2 emission by +0.26% and CO_2 emission in India grew far more slowly (+0.05%) than expected[3]. Globally, the decline in CO_2 emission in 2019 is mainly attributed to the unexpected decline in coal usage worldwide, with softening demand for coal in China and India.

Technologies for ramping down CO_2 emission already exist, and these include swapping fossil fuels for renewable sources, boosting production & energy efficiency, implementing Carbon Capture and Storage (CCS) technologies, and discouraging carbon emissions by putting a price on them. Over the last three decades, several CO_2 capture technologies have been developed owing to the increasing awareness regarding the importance of reducing carbon emissions. A few of these technologies such as amine-based CO_2 capture is implemented at the industrial level due to its acceptance by corporates.

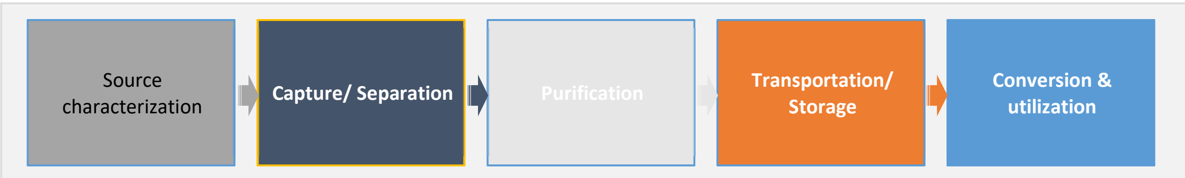
Undoubtedly, the momentum around CCS has surged since the Paris Agreement (signed and implemented in 2016), with increased funding & investment and public-private partnership in carbon capture technologies. CCS provides a platform to produce low-carbon electricity from fossil fuels, thereby reducing carbon emissions from industrial processes, such as cement, iron & steel, and gas processing, wherein decarbonisation options are limited. Although, the commercial implementation of CCS technologies requires high capital and operating costs, advanced carbon capture technology, and carbon conversion & utilization can reduce the cost of the carbon capture process and translate captured CO_2 into a value-added product, which could significantly improve the economics of the CCS system.

CCS can play a significant role in mitigating climate change. It involves capturing carbon dioxide at stationary point sources, which is a single localized emitter, such as fossil fuel power plants, refineries, industrial manufacturing plants, and heavy industrial (iron & steel and cement) plants as well as mobile sources, such as automobiles, ships, aircraft, etc. The captured CO_2 is compressed and transported for its storage in geological formations or for direct (non-conversion of CO_2, such as enhanced oil recovery, food & beverage, heat transfer fluids, etc.) and indirect (conversion of CO_2 into chemicals, fuels, and building materials) use.

[2] https://ec.europa.eu/clima/policies/strategies/2050_en
[3] https://www.globalcarbonproject.org/carbonbudget/19/presentation.htm

The indirect application (conversion & utilization) of CO_2 as feedstock for chemicals, fuels, and building materials allows dealing with the carbon emission problem more effectively by recycling of CO_2 into value-added products, such as polymers, monomers, synthetic fuels, etc. The holistic value chain approach covers all aspects of CCUS, including source characterization, capture, transport, storage, conversion, and utilization of CO_2.

Figure 1. CCUS value chain



Here is an international consensus that Carbon, Capture, Utilization, and Storage (CCUS) will play a crucial role as part of an economically sustainable route to reduce emission levels required to limit global warming to 2°C. Under the Paris Agreement, Parties (Nations) to the United Nations Framework Convention on Climate Change (UNFCCC) reached a landmark agreement to combat climate change by keeping a global temperature rise below 2°C (above pre-industrial levels) and undertake ambitious efforts to limit the temperature increase even further to 1.5°C. Thus, achieving the 1.5-2°C global temperature moderation target implies a massive scaling of carbon dioxide removal technologies. It is also stated in the EU Commission "Long-term Strategic Vision: A Clean Planet for All" document that reduction in CO_2 emission is quintessential to achieve the goals of the Paris Agreement and contribute to the delivery of the UN Sustainable Development Goals. Under this, the EU Commission sets out the following strategic areas for action: Energy efficiency, carbon capture and storage, expansion in renewables, clean mobility, industrial competitiveness, circular economy, smart infrastructure, and bio-economy.

In 2014, the Intergovernmental Panel on Climate Change (IPCC) stated in its report that without CCUS, the costs of climate change mitigation could increase by ~138%, thereby realizing that a 2°C scenario may not be possible without CCUS technologies. The Paris Agreement holds special significance as it highlights efforts made over the past two decades to achieve a certain degree of substantial progress in emission reduction, by bringing together both, emerging and developed nations (~196 parties) at a single platform. All parties had to mandatorily come forward with their Nationally Determined Contributions (NDCs) on how they would strengthen their efforts in the coming years.

According to the International Energy Agency (IEA), ~14% of cumulative reductions should come from CCS driven initiatives by 2060 to achieve the ambitious target set under the Paris Agreement. Furthermore, Beyond the 2°C Scenario (B2DS), IEA predicts a ~32% share of CCS for industrial decarburization. However, for large-scale decarburization, it is imperative to explore other options/technologies beyond CCS to meet the pre-decided goals. Alternatives to CCS include demand-side measures, energy efficiency improvements, electrification of heat, use of green hydrogen (made with renewable electricity) or blue hydrogen (H_2 made from natural gas but coupled with CCS) as feedstock or fuel, and use of sustainable biomass such as agriculture residues, forestry residues, wastes, plastics, algae, etc., as feedstock or fuel.

The global population remained stable during the period, 2000-10; in contrast, the level of economic activity witnessed exponential growth. The industrial sector is vital for the economic prosperity of nations, contributing to approximately one-third of the global GDP. According to IPCC's report on Climate Change, 2014, electricity and heat production (25%), followed by the industrial sector (21%) and the mass transportation (14%) sector are the major contributors of overall GHG emissions[4].

1.1. INTRODUCTION TO CARBON CAPTURE TECHNOLOGIES

Carbon Capture and Storage (CCS) is a process that involves capturing carbon dioxide, at its source or from the air, and storing it underground to avoid its release into the atmosphere. The CCS process includes three main steps:

- **Source Characterization:** It involves identification of source location, CO_2 output flow rate, CO_2 purity, and the type of output stream. There are no nationally or internationally agreed on definition around sources classification. The Centre for Low Carbon Futures has classified CO_2 sources into four categories, based on the impact of CO_2 concentration on energy requirements and the corresponding cost for separating CO_2 from the gas stream. These categories are as follows: high > 90%, secondary highest: 50-90%, moderate: 20-50%, low < 20%[5].

  The table below shows the CO_2 partial pressure and CO_2 concentration for selected industrial and power plant applications.

Table 1. CO_2 partial pressure and concentration for selected industrial and power plant applications

Industrial process	Gas pressure (Bar)	CO_2 concentration (Mol%)	CO_2 partial pressure (Bar)
Aluminium production	~1	1-2	0.01-0.02
Natural gas combined cycle	~1	3-4	0.03-0.04
Conventional coal fired power generation	~1	13-15	0.13-0.15
Cement production	~1	14-33	0.14-0.33
Steel production (Blast furnace)	1-3	20-27	0.2-0.6
Hydrogen production	22-27	15-20	3-5
Integrated gasification combined cycle	20-70	8-20	1.6-14
Natural gas processing	9-80	2-65	0.5-44

[4] https://www.ipcc.ch/site/assets/uploads/2018/03/WGIIIAR5_SPM_TS_Volume-3.pdf
[5] https://www.ctc-n.org/resources/supporting-early-carbon-capture-utilisation-and-storage-development-non-power-industrial

- **Capture/Separation:** CO_2 is separated from the output stream using appropriate technology (chemical solvents, membranes, etc.) based on the type of stream. It is also separated from other gases or air (Direct Air Capture) or a concentrated source. It is to be noted that sources have distinctive characteristics in the way that CO_2 is produced and it could be further categorized into:

  a) High purity CO_2 streams production (from bioethanol, beer, hydrogen, etc.) that directly produce an output stream of 96-100% CO_2 purity

  b) Medium purity CO_2 streams production (from iron & steel, cement, etc.) that directly produce an output stream of 20-50%. Hydrogen production (Syngas, refinery) is considered to be within the 30-45% purity range

  c) Low purity CO_2 streams production (paper & pulp, glass, etc.) that directly produce an output stream of <20%. In refineries, process heating and FCC unit produce low purity (3-20%) streams of CO_2.

- **Purification:** Depending on the carbon emissions source, the type of fuel, and the capture method used, CO_2 stream contains several impurities, such as SO_x, NO_x, O_2, N_2, Ar, H_2, CH_4, CO, H_2S, H_2O, and mercaptans, which may have a negative impact like corrosion and liquid slugs in the pipeline during transportation. The purification requirements of the captured CO_2 vary depending on the final use of the CO_2 stream. For example, the pipeline transport system of CO_2 would mainly require the removal of H_2O and O_2 to prevent corrosion and liquid slug defects in the pipelines. Whereas, for EOR application, very low O_2 contents are permitted as they could react with hydrocarbons within the oil field that could generate overheating at the injection point and reproduction of toxic components at the pumping well. Impurities like O_2 are largely removed by using cryogenic distillation and catalytic oxidation techniques, while H_2O is removed via refrigeration & condensation and adsorption using silica gel. Scrubbing and drying techniques are also used to remove impurities from the captured CO_2. The minimum of 96% CO_2 purity is required for pipeline transportation because CO_2 pipelines are susceptible to propagating ductile fractures[6]. CO_2 exhibits highly non-linear thermodynamic properties, and, it departs significantly from ideal gas behavior due to the presence of impurities, and the pressure increases as well.

- **Transportation:** Captured CO_2 is compressed to a pressure range of 8 to 17 MPa at ambient temperature (286 K to 316 K) to reach the supercritical form, and the compressed CO_2 is then transported via pipelines, truck tankers, railroad tankers (inland transportation), ships, and rail. Each type of transportation system has its advantages and disadvantages, although, pipelines are considered as the most attractive mode of transportation, as they can handle large flow rates effectively. On the contrary, railroad tankers and truck tankers are more useful for handling small quantities.

- **Storage:** Captured CO_2 is stored via injecting CO_2 into the deep underground where it stays permanently. The captured CO_2 is stored into reservoirs, through geological storage, and oceanic storage route, wherein CO_2 is directly injected deep into the saline formations aquifers, and depleted oil/gas wells. There are three types of geological formations that are eligible for storing CO_2: a) depleted oil and gas reservoirs, b) deep saline formations and c) unminable coal beds. It is reported that the injection of CO_2 needs to occur at depths > 0.8 km below ground level to maintain super criticality.

[6] http://pdf.wri.org/ccs_guidelines.pdf

- **Carbon Dioxide Conversion & Utilization**: It is contributing in the reduction of greenhouse gas emissions, such as CO_2, water vapour, nitrous oxide, etc., in two ways: a) by sequestering CO_2 in the production process, i.e. direct emissions reduction, and b) by substituting fossil inputs as feedstock, and thereby reducing the need for fossil resources, i.e., indirect-emission reduction. Although, when fossil inputs as feedstock with a large carbon footprint are substituted with CO_2, the indirect-emission reduction can even outweigh the direct-emission reduction. For example, polyols production, wherein epoxides are partially substituted with CO_2 (40-50%)7. There has been an increasing trend observed for the conversion of carbon dioxide to fuels (i.e. E-fuels). E-fuel is currently pursued with great interest as a mechanism to recycle carbon dioxide produced through the burning of fossil fuels. Due to the substitution of fossil resources and enhancement in production & energy efficiencies, CCU represents a concrete concept for climate change mitigation. Hence, this double functionality makes CCU an important decarbonization concept for highly industrialized geographies with the availability of large emission sources and existing chemicals/intermediates and materials production.

The most technologically challenging and costly step in the process is the capture step. The purification, transportation, and storage components of CCS are not nearly as technology-dependent as the capture component. Currently, approaches available to capture CO_2 are listed as follows:

- **Post-combustion capture:** Post-combustion carbon capture technology, consists of treating exhaust gases on the output side of the various industries such as power, fertilizer, paper, hydrogen, etc. This is based on chemical absorption which appears to be best suited for capturing CO_2. The post-combustion carbon capture system is economically feasible in power plants and not in other industrial processes, mainly for the following reasons:
  1. A much lower partial pressure (<8 bar) of CO_2 is required for post-combustion exhaust gases than in pre-combustion synthesis gas, originating from a gasifier or a reformer (> 8 bar)
  2. The choice of the absorbent (Physical/chemical) is guided by the partial pressure of CO_2 in the gas to be treated. Chemical solvents are more appropriate for post-combustion CO_2 capture method due to it possess partial pressure of less than 8 bars. The chemical solvents based on primary amines such as Monoethanolamine (MEA) are more preferred when the partial pressure of CO_2 is less than 1 bar, while chemical solvents based on tertiary amines such as Methyldiethanolamine (MDEA) are preferred when the partial pressure of CO_2 is slightly higher than 1 bar but lower than 8 bar.
- **Pre-combustion capture**: Physical solvents are more appropriate for pre-combustion CO_2 capture system because it possesses greater than 8 bars partial pressure. The performance of physical absorption improves beyond partial pressure of 8 bars and increases linearly with the partial pressure of CO_2, hence, the Integrated Gasification Combined Cycle (IGCC) system can only be envisaged with the pre-combustion CO_2 capture method. The pre-combustion carbon capture system is economically feasible in IGCC based power plants and industrial processes such as fertilizer manufacturing units, hydrogen production, and refinery, etc., mainly for the following reasons:

[7] https://www.novomer.com/novomer-announces-first-commercial-adoption-converge%C2%AE-polyols-polyurethane-adhesives

1. Pre-combustion CO_2 capture, reforming of methane and then capture of CO_2 on synthesis gas after conversion of CO into CO_2, is based on IGCC system
2. Fertilizer industry containing very clean gas mixtures or few impurities such as dust, SO_x, and NO_x, hence the high pressure is used to capture CO_2 by physical absorption

- **Oxy-fuel combustion**: **Oxy-fuel combustion** is not technically a carbon capture technology but rather it is a process in which coal combustion occurs in an oxygen-enriched environment, hence, producing a flue gas that comprised mainly of CO_2 (~89% by volume) and water[8]. Oxy-combustion capture technology initially referred to as oxy-fired circulating fluidized bed and pulverized coal boilers schemes. Recently, the gas turbine system has also been developed, which can operate in an oxygen/flue gas oxidant environment. In oxy-fuel combustion technology, pure oxygen is used as an oxidant instead of air, which eliminates the huge amounts of N_2 in the flue gas stream. The high capital cost, high energy consumption, and operational challenges of oxygen separation are the main challenge for cost-competitive oxy-combustion systems. However, these challenges can be improved by lowering the cost of oxygen supplied to the system and by increasing the overall system efficiency.
- **Direct air capture:** Commercially active technology in which CO_2 is removed directly from the atmosphere and the current technique uses large fans that move ambient air through a filter, using a chemical adsorbent to produce a pure CO_2 stream. It can be used for EOR, which would incur significant energy costs and divert resources from alternative energy sources.

Currently, post-combustion and pre-combustion capture technologies are commercial and used for gas stream purification in a variety of industrial processes (such as natural gas processing, ammonia production, etc.). Post-combustion capture of CO_2 in power plants is economically feasible, and it is used to capture CO_2 from part of the flue gases from several existing power plants. The technology required for pre-combustion capture is applied in fertilizer manufacturing and hydrogen production.

Hydrogen is produced either through the Steam Methane Reforming (SMR) of natural gas or through the gasification of heavy residues and fuel oil which accounts 5% to 20% of CO_2 emissions from a refinery, and, it produces concentrated streams of CO_2 often at high pressure, hence, it offers a low-cost option for CO_2 capture deployment. Gasification plants for hydrogen production are generally larger than SMR and operate at high pressures of 50-70 bar, thus, the gasification route is more suitable for the use of physical absorption solvents over chemical absorption solvents because they have higher loadings, require less energy input and produce dry CO_2 under these conditions. In addition to this, with gasification, CO_2 emissions associated with conversion end up in the flue gas stream, and therefore, the rate of carbon capture is higher over the SMR route. Physical absorption solvents (pre-combustion) produces very high purity hydrogen which is driven by the market need of high purity hydrogen.

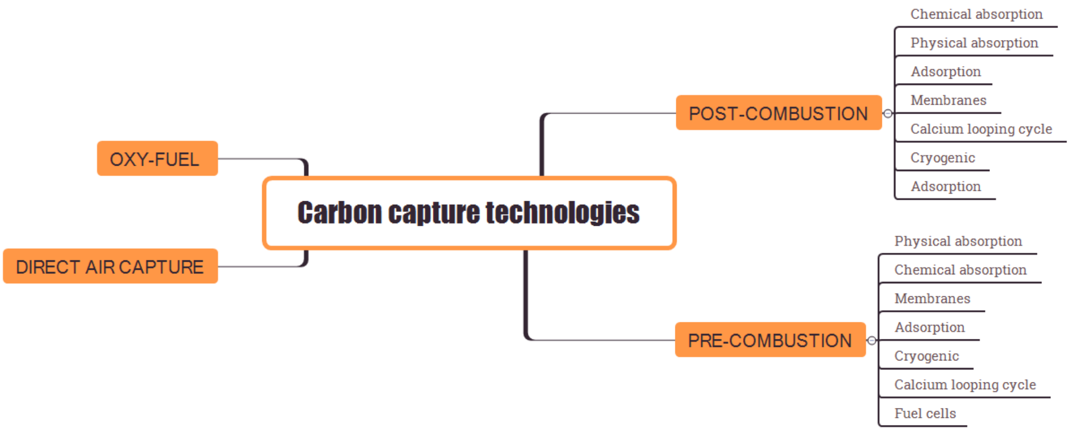
The chemical absorption process is facing largely two challenges; a) related to its strong energy demand for the regeneration of the absorbent, and b) degradation of the absorbent by impurities that contained in the exhaust gases to be treated. It also increases CAPEX and OPEX. Therefore, research and development efforts are focused on development of novel materials such as novel solvents, novel

[8] https://www.sciencedirect.com/topics/engineering/oxyfuel-combustion

membranes, and solid sorbents. The technology developers are targeting to achieve the cost of CO_2 capture to an estimated $40 per metric ton, and a 40% life-cycle cost reduction compared to conventional CO_2 capture technologies.

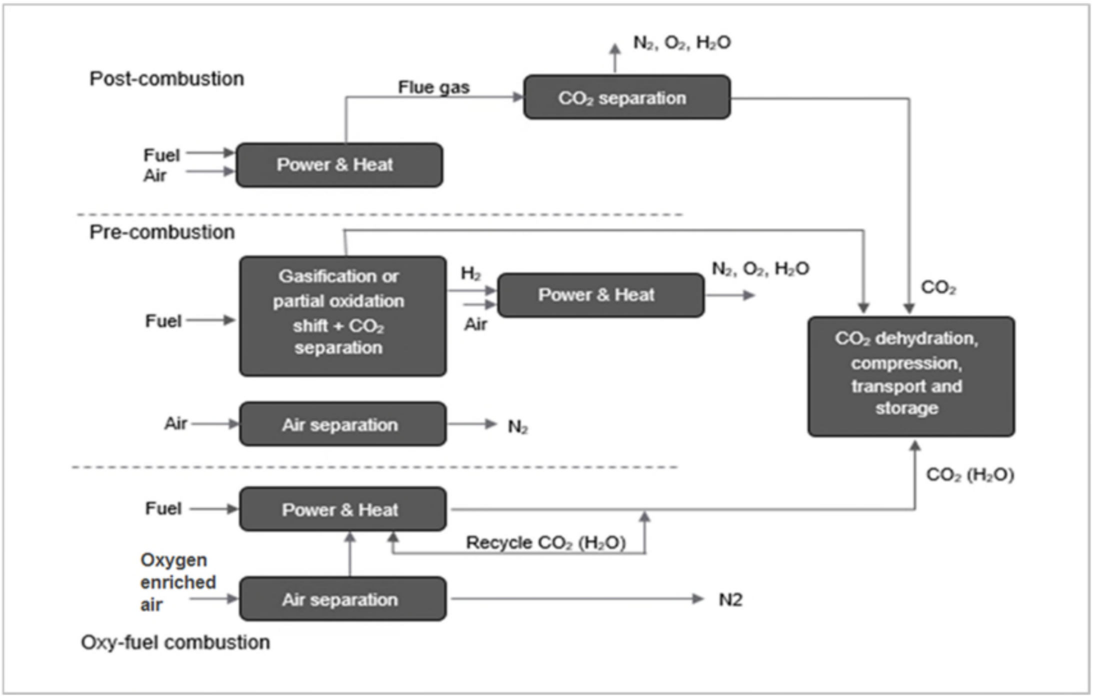
Oxy-combustion capture, however, is still under development and is not currently commercial. Huazhong University of Science and Technology collaborated with industry partners to establish the world's largest operational oxy-fuel combustion demonstration facility of a 35 MWth oxy-fuel unit at the Jiuda Salt Company's captive power plant in Hubei Province, China. It is likely to be operational in 2020 with an estimated capturing of 100,000 tonnes of CO_2 per annum[9].

Figure 2. Carbon Capture Technologies



The detailed description of these carbon capture technologies is mentioned in the next section.

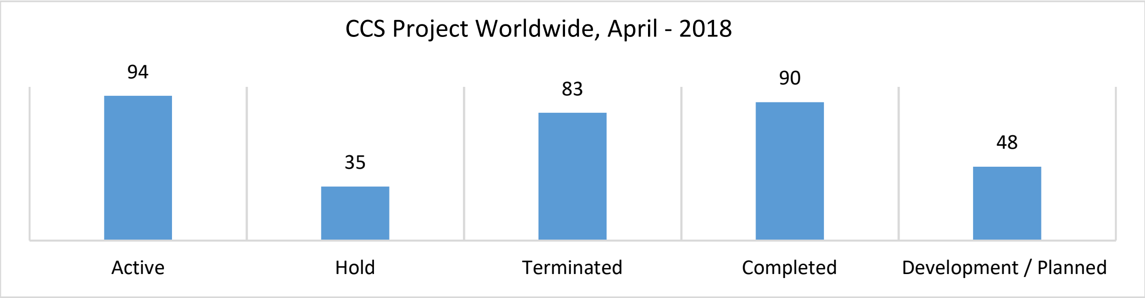
Figure 3. Process flow diagram for carbon capture technologies



9 https://co2re.co/FacilityData

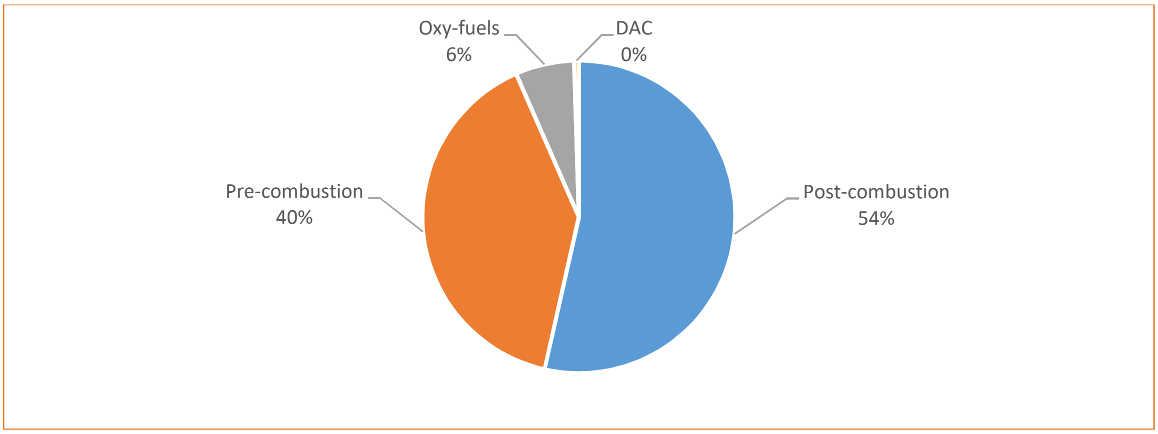
As in April 2018, there are approximately 150 planned or active CCS facilities worldwide[10]; 118 CCS projects are either on hold or terminated and 90 pilot projects have been realized. Overall, the status of these CCS facilities is presented in the charts below.

Figure 4. CCS facilities worldwide



Definition:
Active: CCS facilities where the plant is in operation
Hold: CCS projects announced but hold due to legal, technical and commercial issues
Terminated: Cancelled CCS projects
Completed: Not a full capture project, pilot testing has been done
Development/planned: Announced CCS projects which are not put on hold or cancelled

Figure 5. Distribution of CCS project worldwide



According to the Global Carbon Capture and Storage (CCS) Institute, large-scale integrated CCS facilities comprise the capture, transport, and storage of CO_2 at a scale of at least 800,000 tons of CO_2 annually for a coal-based power plant and at least 400,000 tons of CO_2 annually for industrial facilities, such as natural-gas based power generation[11].

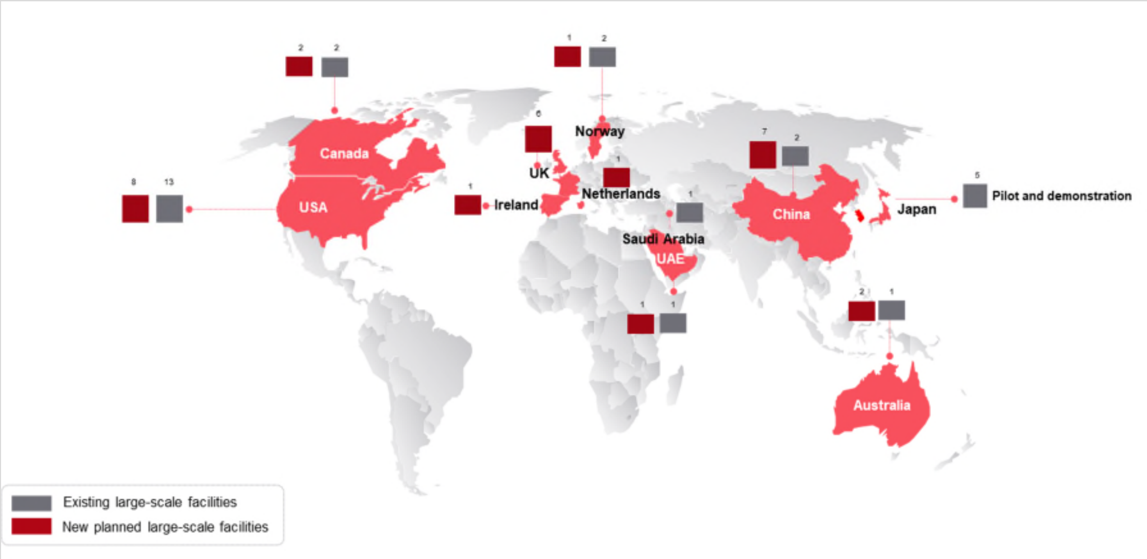
A list of large-scale integrated CCS facilities with solvents and technology providers currently in the operation stage is provided in **Table 2**. This table includes pertinent information concerning solvent technology, technology providers, and the operational period.

[10] https://www.netl.doe.gov/node/7633
[11] https://co2re.co/FacilityData

Geographical Spread

The figure below illustrates the existing and new planned large-scale CCS facilities worldwide.

Figure 6. Existing and new planned large-scale ccs facilities worldwide



Investment in CCS is slowly gathering momentum. Major large-scale CCS projects announced recently are listed below[12]:

- **Abu Dhabi phase 2 natural gas processing plant**: Abu Dhabi National Oil Company is developing its second CCS facility in the United Arab Emirates. It will capture 1.9 to 2.3 Mtpa of CO_2 from its gas processing plant for EOR. It is expected to be operational by 2025.
- **Wabash CO_2 sequestration project:** Wabash Valley Resources LLC announces to develop an ammonia plant with near-zero CO_2 emissions using IGCC plant in Indiana, US. The facility will capture 1.5 to 1.75 Mtpa CO_2 for dedicated geological storage in the Wabash CarbonSAFE CO_2 storage hub. It is expected to be operational by 2022.
- **Tundra project:** Minnkota Power Cooperative is planning to retrofit a 3.1-3.6 Mtpa CO_2 coal-fired power station in North Dakota, US. CO_2 will be captured from Unit 2 of the power station that generates 455 megawatts of electricity. The project targets to utilize CO_2 for EOR application. It is expected to be operational by 2025-26.
- **Dry Fork project:** Basin Electric Power Cooperative aims to capture 3.0 Mtpa CO_2 from the 385 MW Dry Fork coal-fired power station in Wyoming, US for EOR application. It is expected to be operational by 2025-26.
- **Norway Full Chain CCS project:** Oil & gas majors such as Shell, Statoil, and Total are collaborating on the transport and storage elements of CCS demonstration, of which, the Norwegian government has progressed to the FEED stage. CO_2 will be captured at Norcem's cement plant in Brevik. The Norwegian government is expected to make an investment decision on its demonstration project by 2020-21. It is expected to be operational by 2023-24.

[12] https://co2re.co/FacilityData

- **Lake Charles Methanol, US, project** is expected to be operational by 2024.

Note: Numbers for 2018 and 2019 indicate patents published till date. These numbers might change due to a lag of up to eighteen months in the publication of patents since its filing.

In terms of implementation of CCS facilities per regions of the world:

United States of America

In terms of implementation of CCS facilities, the US is leading with a total of 13 of the world's large-scale operating CCS facilities. This is primarily due to abundant geological storage, diverse stakeholder support, and supportive government policy frameworks. The amended Section 45Q of the Internal Revenue Code establishes tax credits for the storage of CO_2 (the US government increased these in 2018). The amount of tax credit would range from $20 to $50 per ton of CO_2 for permanent sequestration (stored geologically) if projects commence construction by 2024[13]. In 2019, Oxy Low Carbon Ventures, LLC (a subsidiary of Occidental Petroleum) and Carbon Engineering Ltd. announced the first large-scale direct air capture with carbon storage project with a capacity of 500,000 tons, to an expected one million tons of CO_2[14]; this project results from the policy confidence offered by the federal 45Q tax credit and a CCS-Amendment to California's Low Carbon Fuel Standard (LCFS) Program. California's LCFS is a credit-based trading mechanism that is aiming for a 20% reduction in the intensity of the state's transportation fuels by 2030. Since January 2019, it has also included a CCS protocol[15]. The Oil and Gas Climate Initiative (OGCI), an international industry-led organization which includes 13 member companies from the oil & gas sector, indicated that it will invest in the largest dedicated geologic storage project of the US, ammonia production facility by Wabash Valley Resources, storing 1.5 Mtpa of CO_2[16].

The US government passed the zero-carbon electricity mandate and carbon-neutrality goal, which needs to be fulfilled by 2050; under this, nine states across the country have enacted policies towards a 100% carbon-free energy goals[17]. States in the US such as Louisiana, Texas, Montana, and North Dakota provide tax incentives for CCS deployment, while others state such as Wyoming, are aiming to substantially progress CCS.

Canada

Canada has agreed to reduce emissions to 30% or approximately 200 Mtpa of CO_2 equivalent below current levels by 2030, under the United Nations Framework Convention on Climate Change (UNFCCC). The combined capacity of four major CCS projects in Canada, two operational till date and two in the development stage which will be operating from 2020, is likely to capture 6.4 Mtpa of CO_2, representing 3% of the reduction needed to meet the 2030 target[18].

In 2019, the Canadian government joined hands with the BHP, Occidental Petroleum, and Chevron, by investing $25 million in Carbon Engineering Ltd., a Canada-based clean energy company, through Canada's Strategic Innovation Fund[19].

[13] https://fas.org/sgp/crs/misc/R44902.pdf
[14] https://carbonengineering.com/news-updates/worlds-largest-direct-air-capture-and-sequestration-plant/
[15] https://ww3.arb.ca.gov/fuels/lcfs/lcfs.htm
[16] https://oilandgasclimateinitiative.com/2019-ccus-day
[17] https://www.americanprogress.org/issues/green/reports/2019/10/16/475863/state-fact-sheet-100-percent-clean-future/
[18] https://www.cer-rec.gc.ca/nrg/ntgrtd/mrkt/snpsht/2016/09-01cndncrbncptr-eng.html
[19] https://carbonengineering.com/news-updates/government-of-canada-invests-25m/

EU

The European Union (EU) aims to be climate-neutral by 2050, and thus, in this direction, in November 2018, the European Commission published its vision for a climate-neutral Europe by 2050 in "A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive, and climate neutral economy"[20]. CCS is one of the seven building blocks in the strategy, which relies mainly on industrial decarbonization, delivering negative emissions through Bio-Energy with Carbon Capture and Storage (BECCS) and producing hydrogen by water electrolysis using carbon-free electricity or natural gas steam reforming CCS. The EU's long-term strategy around climate-neutrality is likely to be submitted to the UNFCCC in early 2020, as requested under the Paris Agreement.

The Innovation Fund, the largest funding programs available for financing CCS in Europe, finances innovative low-carbon technologies and processes in energy-intensive industries, CCUS, renewable energy, and energy storage projects. It is expected that €10 billion to be made available, depending on a €22 carbon price when 450 million EU Emissions Trading System (ETS) allowances are auctioned in 2020-30[21]. It is also expected that Innovation Fund grants can be combined with other funding sources, such as Horizon Europe or Connecting Europe Facility, with national programs, or with private capital. The first call for proposals would be made available in 2020, with regular calls expected thereafter, and it is expected that several planned CCS facilities will already be well-positioned to submit proposals.

China

As part of the 2015 Paris Agreement, China has committed to reducing the carbon intensity of its economy by 60-65% by 2030, as compared to 2005 levels. China is home to one large-scale facility of CCS in operation, two in construction, and five in early development. China has limited experience in large-scale CCS facilities, and thus, the country has signed several memorandums with Europe, the UK, Australia, the US, and Canada to exchange experience in standard design for environmental protection, project deployment, the establishment of policy frameworks, and financing schemes. China is presently on its way to launch its integrated large-scale CCS demonstration projects (Sinopec Qilu Petrochemical, Sinopec Eastern China, and Yanchang Integrated CCS facilities) by 2020-21[22].

To date, China has not promulgated any laws to regulate CCS; laws are mainly based around national sub-five year plans in terms of climate change mitigation, energy-related development, and technical innovation. In May 2019, China published the latest Roadmap around CCS, clarified the strategic position of CCS, and proposed mid- to long-term targets and priorities for achieving low carbon transition through affordable, feasible, and reliable CCS technologies.

The development of CCS facilities in China has also been impeded by limited subsidies for new projects. China does not have a direct tax stimulus policy for CCS as of now, hence, the high capital cost becomes the most substantial barrier for CCS implementation. The approval guideline of CCS projects in China is unavailable at present[23].

[20] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52018DC0773

[21] https://ec.europa.eu/clima/policies/innovation-fund_en

[22] https://co2re.co/FacilityData

[23] https://www.sciencedirect.com/science/article/abs/pii/S1364032119308093

Japan

In Japan, the Ministry of Economy, Trade, and Industry and the Ministry of Environment are driving the country's comprehensive CCS program[24]. This program comprises the full-scale CCS development, demonstration of carbon capture technologies, investigation of the effective regulatory framework, and exploration of policy options for commercial deployment. For instance, the 'Hydrogen Energy Supply Chain' project[25] is a significant example of the Japanese government collaboration with the private sector and other governments to commercialize CCS. This project is being developed by Kawasaki Heavy Industries, Marubeni Corporation, Sumitomo Corporation, Electric Power Development Co., Iwatani Corporation, and the Australian company, AGL Energy Limited, with the support of governments of Japan, Australia, and the State of Victoria. It will demonstrate the production of hydrogen with CCS from coal in the Latrobe Valley of Victoria and the transport of hydrogen by ship from Australia to Japan.

Table 2 shows a list of large-scale operational CCS facilities, as of today.

[24] https://www.meti.go.jp/english/press/2019/1125_004.html
[25] https://hydrogenenergysupplychain.com/hydrogen-energy

Table 2. List of large-scale CCS facilities in the stage of operation[26]

S. No.	Facility/Plant	Location	Industry	Company	Volume of CO_2/Mtpa	CO_2 Capture Technology	Solvent	Technology Provider (Solvent)	Operation Date
1	Century Plant	Texas, USA	Natural gas processing	Occidental Petroleum & Sandridge Energy	8.4	Pre-combustion	Selexol	UOP	2010
2	Boundary Dam	Saskatchewan, Canada	Power	SaskPower	1	Post-combustion	Amine	Shell Global Cansolv	2014
3	Coffeyville Gasification Plant	Kansas, USA	Fertiliser	Chaparral Energy	1	Pre-combustion	Selexol	UOP	2013
4	Enid Fertilizer	Oklahoma, USA	Fertiliser	Chaparral Energy & Merit Energy	0.68	Pre-combustion	Hot potassium carbonate	UOP	1982
5	Great Plains Synfuel Plant and Weyburn-Midale Project	Saskatchewan, Canada	Natural gas processing	Dakota Gasification	3	Pre-combustion	Rectisol	Linde	2000
6	Lost Cabin Gas Plant	Wyoming, USA	Natural gas processing	Denbury Resources	0.9	Pre-combustion	Selexol	UOP	2013
7	Shute Creek Gas Processing Facility	Wyoming, USA	Natural gas processing	ExxonMobil	7	Pre-combustion	Selexol	UOP	1986
8	Sleipner CO_2 Storage Project	North Sea, Norway	Natural gas processing	Statoil, ExxonMobil E&P Norway, Total E&P Norge	0.9	Pre-combustion	45 wt.% MDEA	Aker Solutions	1996
9	Snøhvit CO_2 Storage Project	Barents Sea, Norway	Natural gas processing	Statoil, Petoro, Total E&P Norge, GDF Suez E&P Norge, RWE DEA Norge	0.7	Pre-combustion	Activated MDEA	BASF	2008
10	Val Verde Natural Gas Plants	Texas, USA	Natural gas processing	Sandridge Energy & Occidential Petroleum	1.3	Pre-combustion	Selexol	UOP	1972

[26] https://co2re.co/FacilityData

S. No.	Facility/Plant	Location	Industry	Company	Volume of CO_2/Mtpa	CO_2 Capture Technology	Solvent	Technology Provider (Solvent)	Operation Date
11	Quest CCS Project	Alberta, Canada	Refinery (hydrogen production)	Shell Canada Energy, Chevron Canada Limited, Marathon Oil Canada Corp.	1.08	Pre-combustion	Activated MDEA	Shell	2015
12	Abu Dhabi CCS Project (Formerly Emirates Steel Industries CCS Project)	Abu Dhabi, United Arab Emirates	Iron and steel	Abu Dhabi National Oil Company, Abu Dhabi Future Energy Company	0.8	Pre-combustion	Amine	-	2016
13	Petra Nova	Texas, USA	Power	NRG Energy, JX Nippon Oil & Gas Exploration	1.4	Post-combustion	KM-CDR	Mitsubishi Heavy Industries	2017
14	Uthmaniyah CO_2 EOR Demonstration Project	Eastern Province,	Natural gas processing	Saudi Aramco	0.8	Pre-combustion	Diglycolamine	Fluor	2015
15	Illinois Industrial Carbon Capture and Storage	Illinois, USA	Ethanol	Archer Daniels Midland	1	Pre-combustion	Amine	-	2017
16	Gorgon Carbon Dioxide Injection Project	Western Australia, Australia	Natural gas	Chevron, Shell, ExxonMobil, Osaka Gas, Tokyo Gas, Chubu Electric Power	3.4 - 4.0	Pre-combustion	Activated MDEA	Shell	2019
17	Jilin Oil Field EOR	Songyuan, Jilin Province, China	Natural gas	China National Petroleum Company	0.6	Pre-combustion	Amine	-	2018
18	Petrobras Santos Basin Pre-Salt Oil Field CCS	Brazil	Natural gas	Petrobras	3	Pre-combustion		-	2013
19	Valero Port Arthur Refinery's Methane Steam Reformer Waste Streams	Texas, USA	Refinery	Air Products and Chemicals	1	Pre-combustion		Air Products and Chemicals	2013

Figure 7. Large-scale and pilot & demonstration CCS facilities in the stage of construction, advanced and early development

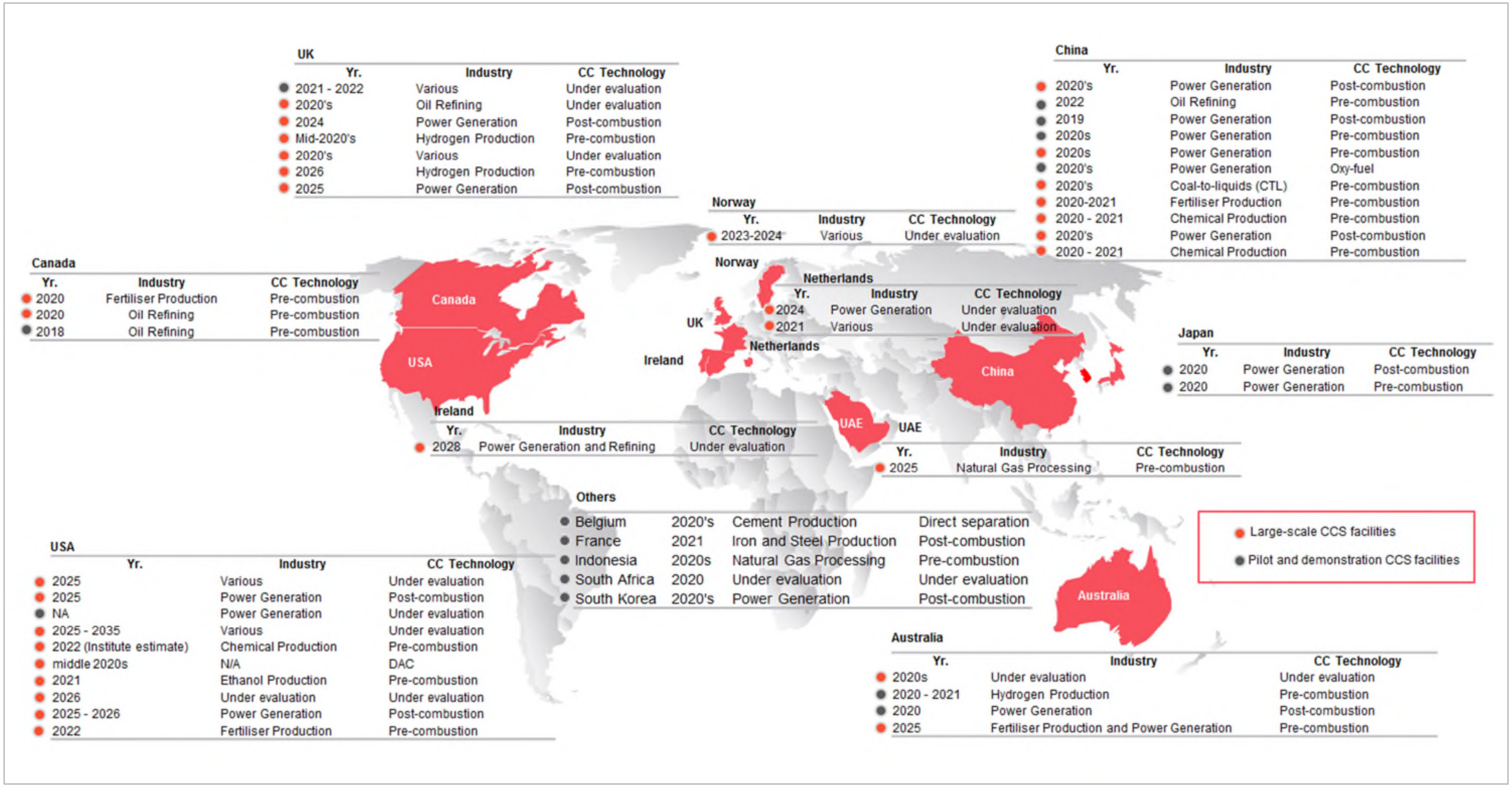


Table 3. List of large-scale and pilot & demonstration CCS facilities in the stage of construction, advanced and early development[27]

S. No.	Project Name	Project Category	Project Status	Country	Capture Capacity (Mtpa)	Operational Year	Industry	Carbon Capture Technology
1	Abu Dhabi CCS Phase 2: Natural gas processing plant	Large-scale CCS facilities	Advanced Development	United Arab Emirates	1.9-2.3	2025	Natural Gas Processing	Pre-combustion
2	Acorn (Minimum Viable CCS Development)	Pilot and demonstration CCS facilities	Advanced Development	United Kingdom	3-4	2021 - 2022	Various	Under evaluation
3	Acorn Scalable CCS Development	Large-scale CCS facilities	Early Development	United Kingdom	-	2020's	Oil Refining	Under evaluation
4	Alberta Carbon Trunk Line (ACTL) with Agrium CO_2 Stream	Large-scale CCS facilities	In Construction	Canada	1.2-1.4	2020	Fertiliser Production	Pre-combustion
5	Alberta Carbon Trunk Line (ACTL) with North West Redwater Partnership's Sturgeon Refinery CO_2 Stream	Large-scale CCS facilities	In Construction	Canada	0.3-0.6	2020	Oil Refining	Pre-combustion
6	Australia-China Post Combustion Capture (PCC) Feasibility Study Project	Pilot and demonstration CCS facilities	Advanced Development	China	1	NA	Power Generation	Post-combustion
7	Caledonia Clean Energy	Large-scale CCS facilities	Early Development	United Kingdom	3	2024	Power Generation	Post-combustion
8	CarbonNet	Large-scale CCS facilities	Advanced Development	Australia	3	2020s	Under evaluation	Under evaluation
9	CarbonSAFE Illinois – Macon County	Large-scale CCS facilities	Advanced Development	USA	2-5	2025	Various	Under evaluation
10	China Resources Power (Haifeng) Integrated Carbon Capture and Sequestration Demonstration	Large-scale CCS facilities	Early Development	China	1	2020's	Power Generation	Post-combustion
11	Chinese-European Emission-Reducing Solutions (CHEERS)	Pilot and demonstration CCS facilities	Advanced Development	China	1	2022	Oil Refining	Pre-combustion
12	DMX™ Demonstration in Dunkirk	Pilot and demonstration CCS facilities	Advanced Development	France	0.3	2021	Iron and Steel Production	Post-combustion
13	Dry Fork Integrated Commercial Carbon Capture and Storage (CCS)	Large-scale CCS facilities	Advanced Development	USA	3	2025	Power Generation	Post-combustion

[27] https://co2re.co/FacilityData

S. No.	Project Name	Project Category	Project Status	Country	Capture Capacity (Mtpa)	Operational Year	Industry	Carbon Capture Technology
14	Ervia Cork CCS	Large-scale CCS facilities	Early Development	Ireland	2.5	2028	Power Generation and Refining	Under evaluation
15	Fuel Cell Carbon Capture Pilot Plant	Pilot and demonstration CCS facilities	Advanced Development	USA	NA	NA	Power Generation	Under evaluation
16	Gundih CCS Pilot	Pilot and demonstration CCS facilities	Advanced Development	Indonesia	0.7	2020s	Natural Gas Processing	Pre-combustion
17	Guohua Jinjie CCS Full Chain Demonstration	Pilot and demonstration CCS facilities	Advanced Development	China	0.15	2019	Power Generation	Post-combustion
18	Huaneng GreenGen IGCC Demonstration-scale System (Phase 2)	Pilot and demonstration CCS facilities	In Construction	China	0.4	2020s	Power Generation	Pre-combustion
19	Huaneng GreenGen IGCC Large-scale System (Phase 3)	Large-scale CCS facilities	Early Development	China	0.41	2020s	Power Generation	Pre-combustion
20	Huazhong University of Science and Technology Oxy-fuel Project	Pilot and demonstration CCS facilities	In Construction	China	0.41	2020's	Power Generation	Oxy-fuel
21	Hydrogen 2 Magnum (H2M)	Large-scale CCS facilities	Early Development	Netherlands	2	2024	Power Generation	Under evaluation
22	Hydrogen Energy Supply Chain (HESC) project	Pilot and demonstration CCS facilities	Advanced Development	Australia		2020 - 2021	Hydrogen Production	Pre-combustion
23	HyNet North West	Large-scale CCS facilities	Early Development	United Kingdom	2	Mid-2020's	Hydrogen Production	Pre-combustion
24	Integrated Midcontinent Stacked Carbon Storage Hub	Large-scale CCS facilities	Advanced Development	USA	NA	2025 - 2035	Various	Under evaluation
25	Integrated Surat Basin CCS Project	Pilot and demonstration CCS facilities	Advanced Development	Australia	0.1-1	2020	Power Generation	Post-combustion
26	Inventys and Husky Energy VeloxoTherm Capture Process Test	Pilot and demonstration CCS facilities	Advanced Development	Canada	NA	2018	Oil Refining	Pre-combustion
27	Korea-CCS 1 & 2	Large-scale CCS facilities	Early Development	South Korea	1	2020's	Power Generation	Post-combustion
28	Lake Charles Methanol	Large-scale CCS facilities	Advanced Development	USA	4.2	2022 (Institute estimate)	Chemical Production	Pre-combustion

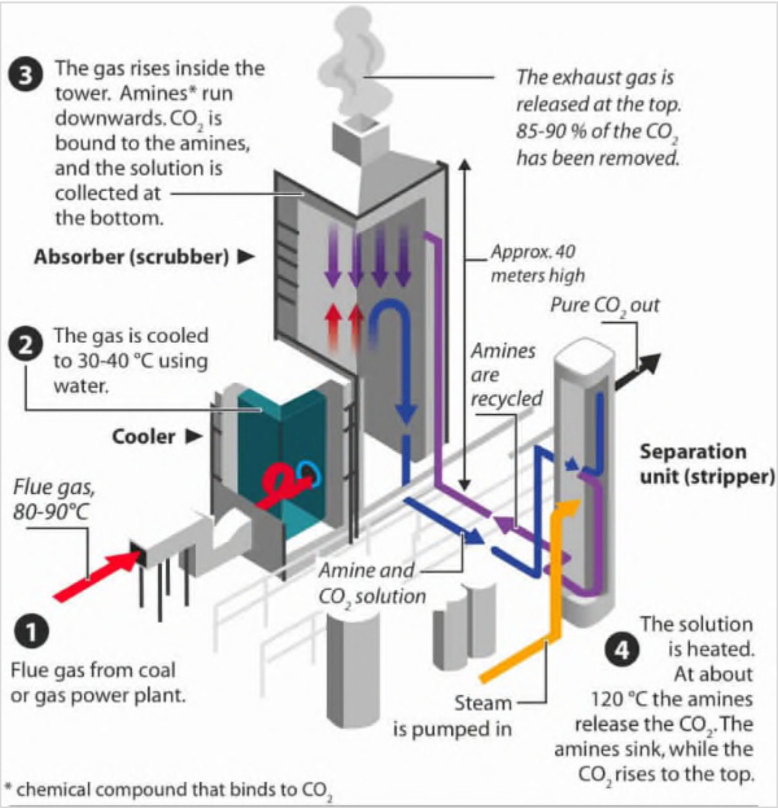
S. No.	Project Name	Project Category	Project Status	Country	Capture Capacity (Mtpa)	Operational Year	Industry	Carbon Capture Technology
29	LEILAC	Pilot and demonstration CCS facilities	In Construction	Belgium	NA	2020's	Cement Production	Direct separation
30	Mikawa Post Combustion Capture Demonstration Plant	Pilot and demonstration CCS facilities	In Construction	Japan	0.3	2020	Power Generation	Post-combustion
31	Net Zero Teesside	Large-scale CCS facilities	Early Development	United Kingdom	0.8-10	2020's	Various	Under evaluation
32	Northern Gas Network H21 North of England	Large-scale CCS facilities	Early Development	United Kingdom	NA	2026	Hydrogen Production	Pre-combustion
33	Norway Full Chain CCS	Large-scale CCS facilities	Advanced Development	Norway	0.8	2023-2024	Various	Under evaluation
34	Osaki CoolGen Project	Pilot and demonstration CCS facilities	In Construction	Japan	NA	2020	Power Generation	Pre-combustion
35	OXY and Carbon Engineering Direct Air Capture and EOR Facility	Large-scale CCS facilities	Early Development	USA	1.0	Middle 2020s	N/A	DAC
36	OXY and White Energy Ethanol EOR Facility	Large-scale CCS facilities	Early Development	USA	0.6-0.7	2021	Ethanol Production	Pre-combustion
37	Pilot Carbon Storage Project (PCSP) - Zululand Basin, South Africa	Pilot and demonstration CCS facilities	Advanced Development	South Africa	NA	2020	Under evaluation	Under evaluation
38	Port of Rotterdam CCUS Backbone Initiative (Porthos)	Large-scale CCS facilities	Advanced Development	Netherlands	2-5	2021	Various	Under evaluation
39	Project ECO2S: Early CO2 Storage Complex in Kemper County	Large-scale CCS facilities	Early Development	USA	3	2026	Under evaluation	Under evaluation
40	Project Tundra	Large-scale CCS facilities	Advanced Development	USA	3.1-3.6	2025 - 2026	Power Generation	Post-combustion
41	Shenhua Ningxia CTL	Large-scale CCS facilities	Early Development	China	0.4	2020's	Coal-to-liquids (CTL)	Pre-combustion
42	Sinopec Eastern China CCS	Large-scale CCS facilities	Early Development	China	0.5	2020-2021	Fertiliser Production	Pre-combustion
43	Sinopec Qilu Petrochemical CCS	Large-scale CCS facilities	In Construction	China	0.4	2020 - 2021	Chemical Production	Pre-combustion
44	Sinopec Shengli Power Plant CCS	Large-scale CCS facilities	Early Development	China	1.0	2020's	Power Generation	Post-combustion

S. No.	Project Name	Project Category	Project Status	Country	Capture Capacity (Mtpa)	Operational Year	Industry	Carbon Capture Technology
45	South West Hub	Large-scale CCS facilities	Early Development	Australia	2.5	2025	Fertiliser Production and Power Generation	Pre-combustion
46	The Clean Gas Project	Large-scale CCS facilities	Early Development	United Kingdom	1.7-2	2025	Power Generation	Post-combustion
47	Wabash CO_2 Sequestration	Large-scale CCS facilities	Advanced Development	USA	1.5-1.75	2022	Fertiliser Production	Pre-combustion
48	Yanchang Integrated Carbon Capture and Storage Demonstration	Large-scale CCS facilities	In Construction	China	0.41	2020 - 2021	Chemical Production	Pre-combustion

1.1.1. Post-combustion Carbon Capture Process

Post-combustion capture technology involves the removal of CO_2 from flue gas produced after the combustion of fossil fuels or other carbonaceous materials (such as biomass)[28]. The combustion results in a flue gas mixture consisting of N_2, CO_2, H_2O, O_2, and a host of compounds, such as SO_x, NO_x. Some of these are removed using existing technologies, such as Selective Catalytic Reduction (SCR), Electrostatic Precipitation (ESP), and Flue-gas Desulphurization (FGD), before carbon dioxide capture. CO_2 is removed from low-pressure (<2 PSIG), and low-CO_2 concentration (<15 vol. %) flue gas, followed by other pollution control devices. Post-combustion technologies can be retrofitted to the existing plants without any significant changes. Therefore, it is the preferred technology for carbon capture in industries. Post-combustion technology could be used at iron and steel manufacturing units using blast furnace capture, refining plants using process heater and combined Heat and Power (CHP) capture, chemical plants using process heater, CHP & steam cracker capture, cement plants using rotary kilns, and pulp and paper plants using process heater and CHP capture.

Figure 8. Process flow diagram for post-combustion carbon capture technologies



Steam Methane Reforming (SMR) based hydrogen plants contribute a significant proportion of the overall CO_2 emission source of many refineries. CO_2 emissions from the hydrogen plant have a high partial pressure of CO_2 compared to most flue gases, thus making the SMR process route very attractive for post-combustion CO_2 capture.

[28] http://www.zeroco2.no/introduction/AminesNyhetsgrafikk.jpg

Post-combustion capture can be applied to the SMR reformer flue gas to capture 90% of the CO_2[29] .

The SMR process can be easily modified for pre-combustion carbon capture. The option that was explored involves the placement of pre-combustion capture on HPU syngas between the shift reactor and the PSA unit. By this route, typically only 50% of the CO_2 can be captured.

There are several methods, such as solvent-based absorption, membrane separation, adsorption, cryogenic separation, etc., which can be used to capture CO_2. However, some of these technologies (such as membrane-based) are still yet to be explored at an industrial scale. Of all the post-combustion technologies, the solvent-based absorption technology is being used mainly for capturing carbon dioxide from flue gases in industries.

Although many different solvents are being explored for capturing CO_2, Monoethanolamine (MEA) is undoubtedly the most preferred solvent in the industry. Research efforts are being made to develop alternative solvents. All near-term (5-10 years) technologies are solvent-based, involving either ammonia or proprietary amines.

The post-combustion capture technique with chemical absorption is the most proven technology for CO2 removal from combustion flue gases due to its maturity level, acceptance by industries, substantial funding, and public-private research work carried out so far in this area. It is mostly based on chemical absorption/desorption with the use of liquid sorbents, such as Monoethanolamine (MEA) at 30 wt. % in water. The chemical absorption is commercialized and broadly used in petroleum, natural gas, and coal-based power plants for separating acid gas (such as CO2 or H2S) from natural gas streams. This technique focuses on the reaction (largely exothermic) between the chemical absorbents, usually an aqueous solution of amines, and CO2. The commonly accepted chemical absorbent system for post-combustion technology is 30 wt. % MEA in water. This system has a few drawbacks, such as high regeneration energy requirement (which is about 3.6-4.0 GJ per ton of CO2 capture), absorbent losses from MEA degradation/vaporization, and moderate reaction speed, which leads to a larger contactor/absorber. Different research activities have been focused on the development of advanced single amines and amine blends to overcome the drawbacks of the amine-enabled system.

Some of these advanced amine-based absorbents such as chilled ammonia (TRL 6-7), aqueous amino acid salt solutions (TRL 6-7), etc., are on the path toward commercialization, whereas others such as piperazine and aminopyridine solvents are still in the pilot phase.

Chemical absorption technologies are used in both pre-combustion and post-combustion CO_2 capture. Chemical absorption systems applied at the commercial level for the capture of CO_2 via post-consumption are listed as follows:

- **Amine-based processes:** The most readily available chemical absorption system for flue gas CO_2 capture is amine scrubbing with Monoethanolamine (MEA), a group of amines that includes diethanolamine, diglycolamine, diisopropanolamine, and triethanolamine.

[29] https://www.digitalrefining.com/article/1000271,Carbon_capture_options_for_refiners.html#.Xk1KCmgzaUk

- **The Econamine FG and Econamine FG Plus** capture systems were developed by the Fluor Corporation after it acquired these technologies from Dow Chemical. The company uses the MEA (wt. 30%)-based amine to capture CO_2 from flue gas, and technologies apply to gas streams containing 3% to 20% CO_2, with oxygen concentrations as high as 15% by volume. Proprietary corrosion and oxidation inhibitors are also added to the MEA solvent to prevent degradation. The Econamine FG technology, an advanced **version** of the Econamine FG technology, provides a faster reaction rate and higher CO_2 loading capacity.
- **Lummus MEA absorption process (part of McDermott) uses** a 15-20 wt. % of aqueous MEA solution with corrosion and oxidation inhibitors.
- **Kansi Mitsubishi Carbon Dioxide Recovery (KM CDR) Process** - KS-1 **proprietary** (hindered secondary) amine
- **Cansolv Technologies Inc. (acquired by Shell Global Solutions International B.V. in 2008)** offers two different amine-based systems (DC-103 and DC-103B) that are capable of capturing CO_2. DC-103 is a fairly standard absorber-stripper arrangement designed for CO_2 capture alone, while DC-103B is an integrated SO_2 control **and** CO_2 capture system. The contribution of Shell Cansolv to SaskPower Boundary Dam ICCS Project is quite diverse. Above and beyond being the process licensor, technology provider and amine supplier for both the flue gas desulphurization and CO_2 capture processes, Shell Cansolv has provided a multitude of products and services such as process licensor, technology provider, and amine supplier for both flue gas desulphurization and CO_2 capture processes to SaskPower Boundary Dam ICCS Project

• **Alkali carbonate:** An Activated Potassium Carbonate Process (AHPC) has been used for CO_2 absorption from natural gas and ammonia synthesis since the 1960s. In this process, inorganic and organic catalysts are commonly used (for high reaction kinetics) with metal carbonate processes. CO_2 is captured at high pressures and the concentration of the potassium carbonate is limited to 20-30 wt.% to prevent solid precipitation. The most widely used commercial hot potassium carbonate process was licensed by Universal Oil Products (UOP) and is known as the Benfield™ Process". Other commercial AHPC processes are the ExxonMobil's Flexsorb HP process, which uses a hindered-amine activator, Eickmeyer & Associates' Catacarb, and GiammarcoVetrocoke's process, which uses an organic activator.

• **Other chemical solvent processes** have been demonstrated at the pilot scale (TRL 6-7) and are in the process of moving to the pilot-scale demonstration in the near term (5-10 years).

  - **Chilled ammonia process**: It is a solvent-based regenerable process that utilizes the low-temperature, low-energy reaction of an aqueous ammonium carbonate solution with CO_2 to form ammonium bicarbonate. This process captures CO_2 from flue gas by directly contacting it with a CO_2 solution at temperatures below 20°C. It was developed by Alstom and acquired by GE. The field **validation** tests (TRL 6-7) have successfully demonstrated, at American Electric Power, Mongstad Cogeneration Plant with CO_2 Storage and We Energies Pleasant Prairie Field Pilot project, >99.9% pure CO_2 product quality at 90% capture rates on combustion flue gas originating from oil, gas, and coal fuels[30].

[30] https://www.ge.com/power/steam/co2-capture/post-combustion-cap

– **Advanced amine solvents**: Aker Clean Carbon, now a part of Aker Solutions, has developed advanced amine solvents (TRL 6-7), a mixture of water and organic amine solvents. The test campaigns are executed using a slipstream of flue gas from the combined heat and power plant at Mongstad, which has a **relatively** low (~3.5-4.0 vol. %) CO_2 content.

– **Amino acid salt solutions**: Siemens developed a post-combustion CO_2 capture "POSTCAP" process (TRL 6-7) that is based on the use of an amino acid–salt solution as the chemical absorbent. This technology was jointly developed by Siemens and utilities company, E.ON, through the German Federal Ministry of Economics and Technology-funded POSTCAP project. The solvent features include the production of a high-purity CO_2 stream, high CO_2 capture rate, low-energy demand, and low rate of solvent degradation. Siemens and E.ON started a pilot CO_2 capture facility in late September 2009 at the E.ON Staudinger power plant, which is still operational.

Table 4. Technical advantages and barriers for post-combustion solven***ts***

Description	Advantages	Barriers
Solvents react reversibly with CO_2, often forming a salt; it is regenerated by heating (temperature swing), which reverses the absorption reaction (normally exothermic)	It provides fast kinetics to allow capture from streams with low CO_2 partial pressure	▪ A large amount of steam required for solvent regeneration that de-rates the power plant significantly ▪ The energy required to heat, cool, and pump non-reactive carrier liquid (usual water) is often high

Table 5. Technical advantages and barriers for solid sorbent for post-combustion capture

Description	Advantages	Barriers
CO_2 is absorbed onto chemically reactive sites on the sorbent pellet, and pellets are then regenerated by a temperature swing, which reverses the absorption reaction	▪ It provides large capacities and fast kinetics that enable capture from streams with low CO_2 partial pressure ▪ Lower heating requirements than wet-scrubbing in many cases	▪ Heat management in solid systems is difficult, and thus, it can limit capacity and/or create operational issues for exothermic absorption reactions ▪ Pressure drop can be large in flue gas applications

Post-combustion capture of carbon dioxide using solvent absorption is an energy-intensive and expensive process. It requires significant energy for the regeneration of CO_2 laden solvent. Besides, the price and quality of solvents also play an important role in the selection of process.

The membrane-based separation process involves passing the flue gas through the membrane for carbon dioxide capture. Key parameters that affect the separation of carbon dioxide using membrane are selectivity and permeability. Therefore, membrane material plays a significant role in CO_2 separation. Although the membrane technology is simpler and requires fewer components as compared to chemical absorption, its application at an industrial scale is still being constrained by several practical problems.

One of the main problems associated with membrane technology is that the pressure difference created by the compressor or vacuum pump is within a certain range, and therefore, a large membrane area is required for CO_2 separation.

Table 6. Technical advantages and challenges for membrane for post-combustion captur***e***

Description	Advantages	Barriers
Use of permeable or semi-permeable materials that allow for the selective transport and separation of CO_2 from flue gas	▪ No steam load ▪ No chemicals needed	▪ Requires high selectivity (due to CO_2 concentration and low-pressure ratio) ▪ Multiple stages and recycle streams may be required

Post-combustion capture is a technological route for capturing low concentration CO_2 (typically 3-15%) from flue gas and manufacturing of a relatively pure CO_2 stream (>99%) for applications, such as EOR[31]. Currently, this carbon capture technology is considered the most feasible measure to retrofit to existing power plants, due to its high CO_2 selectivity, maturity level, and limited impact on the power station operation. Presently, the cost of implementation of this technology is relatively high due to the characteristically low pressure and low CO_2 concentration of the flue gas stream. **Table 2** reveals that out of 19 large-scale integrated CCS facilities, only 2 CCS facilities, such as Boundary Dam Project and Petra Nova Carbon Capture Project (Pulverised coal combustion plant) are served by post-combustion technology. The Boundary Dam Project, operated by SaskPower in Saskatchwan, Canada, is the first commercial-scale CCS project worldwide, which integrated post-combustion CCS with coal-fired power generation[32]. It captures ~1 million ton of CO_2 per year, which is up to 90% of CO_2 emissions from one production unit of the power plant[33].

Capital costs associated with this project are high, estimated ~ $1.5 billion[34]. Shell Global Solutions International B.V. is the technology provider (a chemical solvent) for the Boundary Dam CCS facility. The advanced amine composition comprises a blend of secondary amines, with at least one type of tertiary amine (10-50 wt.%) and an oxidative inhibitor, which also acts as a rate promoter {0-8 wt.% piperazine, 1–30 wt-% *N*-(2-hydroxyethyl) piperazine} with the remaining volume comprising water[35].

The technology of choice for the Petra Nova Carbon Capture Project, the world's largest post-combustion carbon capture retrofit project, is Mitsubishi Heavy Industries, Ltd.'s KM CDR Process™ (KS-1™ solvent, hindered amine-based)36. It captures around 1.4 million tons of CO_2 per year, which is up to 90% of CO_2 emissions from the power plant[37]. The capital costs associated with this project are $1 billion[38]. It is expected that the substantial reduction in operational costs, as well as water and heat energy of post-combustion capture technology, can be achieved from the development of more effective chemical solvents.

[31] https://pdfs.semanticscholar.org/7b8b/88a8ef20fc78a3e24ed2700994f9d821c67f.pdf
[32] https://www.sciencedirect.com/science/article/pii/S1876610214024576
[33] https://www.saskpower.com/Our-Power-Future/Infrastructure-Projects/Carbon-Capture-and-Storage/Boundary-Dam-Carbon-Capture-Project
[34] https://sequestration.mit.edu/tools/projects/boundary_dam.html
[35] https://www.globalccsinstitute.com/archive/hub/publications/108811/evaluation-novel-post-combustion-co2-capture-solvent-concepts.pdf
[36] http://www.mhi.co.jp/technology/review/pdf/e551/e551032.pdf
[37] https://www.globalccsinstitute.com/wp-content/uploads/2019/12/GCC_GLOBAL_STATUS_REPORT_2019.pdf
[38] https://sequestration.mit.edu/tools/projects/wa_parish.html

Table 7. Commercial chemical solvent (TRL 9) for post-combustion carbon capture technology

S. No.	Technology Supplier	Product/Solvent
1	Fluor Corporation	▪ Fluor Econamine^{SM}, diglycolamine as the aqueous solvent ▪ Fluor Econamine FG Plus^{SM}, amine-based
2	Mitsubishi Heavy Industries	▪ KS-1 proprietary (hindered secondary) amine
3	Shell Global Solutions International B.V.	▪ Amine, (10-50 wt.%) and an oxidative inhibitor that acts as a rate promoter (0–8 wt.% piperazine, 1–30 wt.% *N*-(2-hydroxyethyl) piperazine) with the remaining volume comprising water ▪ Tertiary amine (activated MDEA), ADIP-X
4	Aker Solution	▪ Amine solvents, a mixture of water and organic amine solvents
5	BASF	▪ OASE®, blue activated MDEA

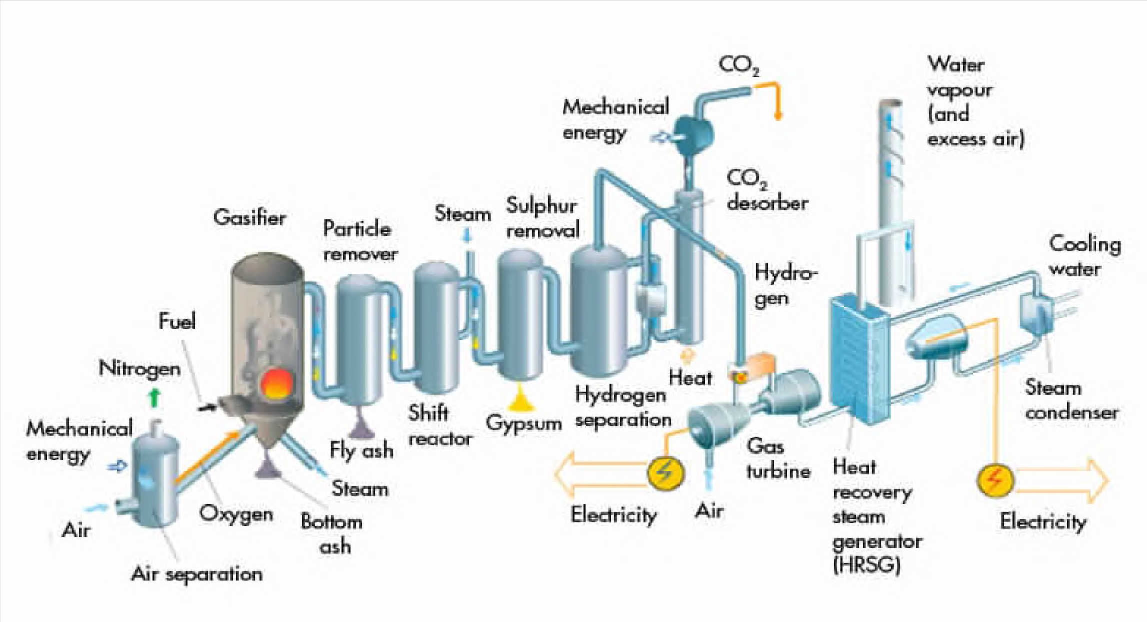
1.1.2. Pre-combustion Carbon Capture Process

Pre-combustion carbon capture process refers to the near-complete capture of CO_2 before fuel combustion or before venting out the exhaust gas or flue gases and is usually implemented in conjunction with gasification of coal, coke, waste biomass, and or residual oil or steam reforming/partial oxidation of natural gas to produce syngas[39]. Further, the water-gas shift reaction produces CO_2 from the CO, resulting in H_2-rich syngas that (syngas) can be combusted in gas turbines, boilers, and furnaces, while when H_2 is sufficiently purified, it can be used in fuel cells and used in refinery operations such as hydrotreatment, hydroprocessing, etc.

Pre-combustion CO_2 capture technology can be used both, in power plants and in other industrial processes, where CO_2 separation is required, such as in synthetic fuel production, ammonia production, etc. It involves the physical absorption onto the surface of a solvent ("synthetic"), followed by the release of CO_2 when the sorbent pressure is dropped.

[39] http://www.zeroco2.no/introduction/PrecombustionVattenfall.jpg

Figure 9. Process flow diagram for pre-combustion carbon capture technologies



In refineries and ammonia production facilities, where a lower-partial-pressure CO_2 (<220 psi), H_2-rich syngas is produced via gas reforming, CO_2 is recovered during acid gas removal using chemical solvents, such as Methyldiethanolamine (MDEA, a tertiary amine) that possess low regenerator heat loads. A majority of the commercial pre-combustion capture technologies, such as Selexol and Rectisol, were developed in the mid-1900s. Physical absorption technologies are often used in pre-combustion CO_2 capture, and it is rarely considered for post-combustion CO_2 capture, whereas chemical absorption technologies are used in both pre-combustion and post-combustion CO_2 capture.

Listed below are physical absorbent systems available for the pre-combustion system at the commercial level that have been used for the capture of CO_2 from gasification fuel and high-pressure natural gas sweetening:

- **Selexol**: Solvent made of dimethyl ethers of polyethylene glycol, developed by Dow Chemical Company and now licensed by UOP, LLC
- **Rectisol**: An organic solvent of methanol, developed by Linde and Lurgi (now part of Air Liquide)

Several CO_2 separation technologies are under development for use in pre-combustion, which include high-temperature, hydrogen-permeable membranes; these technologies are based on the use of magnesium oxide or calcium oxide carbonation with regeneration by calcining the produced magnesium carbonate or calcium carbonate.

Table 8. Key advantages and barriers of physical solvents for pre-combustion capture

Description	Advantages	Barriers
The solubility of solvent is directly proportional to CO_2 partial pressure and inversely proportional to temperature, thus making physical solvents more applicable to low temperature and high-pressure applications (Syngas)	CO_2 recovery does not require heat to reverse a chemical reaction	▪ Low solubility can require circulating large volumes of solvent, which increases energy needs for pumping ▪ CO_2 pressure is lost during flash recovery

Table 9. Key advantages and barrier of solid sorbents for pre-combustion capture

Description	Advantages	Barriers
CO_2 is physically adsorbed onto sites and/or dissolves into the pore structure of the solid sorbent; rate and capacity are directly proportional to CO_2 partial pressure, thus making these sorbents more applicable to high-pressure applications	CO_2 recovery does not require heat to reverse a reaction	Solids handling is more difficult than liquid-gas systems

Table 10. Key advantages and barriers of membrane separation systems for pre-combustion capture

Description	Advantages	Challenges
A membrane material that selectively allows either H_2 or CO_2 to permeate through the material CO2	▪ No steam load or chemical losses ▪ CO_2 can capture at high pressure, thus reducing compression costs	▪ The high capital cost associated with the membrane ▪ Due to decreasing partial pressure differentials, some H_2 will be lost with the CO_2

Pre-combustion carbon capture technology offers several benefits as it captures CO_2 from high pressure, which enables the use of physical solvents as opposed to chemical solvents. It should be noted that the physical solvent-enabled absorption processes exploit Henry's Law, which dictates that gas absorption is preferred under high-pressure conditions, particularly when CO_2 partial pressure is more than 10 bar[40], and solvent regeneration could be occurred through a reduction in pressure as opposed to heat addition.

[40] http://www.mcilvainecompany.com/Decision_Tree/subscriber/CO2DescriptionTextLinks/DOENETL2010UpdateReport.pdf

Table 11. Commercial physical solvent (TRL 9) for pre-combustion carbon capture technology

S. No.	Technology supplier	Product / Solvent
1	Honeywell UOP (Formerly known as UOP LLC or Universal Oil Products)	▪ Hot potassium carbonate ▪ Selexol, Solvent made of dimethyl ethers of polyethylene glycol
2	Linde	▪ Rectisol, an organic solvent of chilled methanol
3	Fluor Corporation	▪ Propylene carbonate

Physical solvents typically have a larger absorption capacity than chemical solvents, thereby enabling them to lower solvent recirculation rates. Physical solvents for acid gas, such as H_2S and CO_2 separation, have been under development since the 1950s. Globally, carbon capture (Pre-combustion) and CO_2-EOR facilities existed since the early 1970s with the Val Verde Natural Gas Plant in Texas, USA, and the Shute Creek Gas Processing Facility, Wyoming, USA, commencing operations in 1972 and 1986, respectively.

Currently, physical solvent-based technology has been broadly used in industrial manufacturing processes (pre-combustion), such as syngas, hydrogen, and natural gas production. A few facilities, such as Enid Fertilizer CCS plant, utilize chemical solvents via the implementation of the hot potassium carbonate (Benfield process, Honeywell UOP), which is a high temperature and high-pressure chemical absorption process.

FutureBridge scanned the various databases and published reports to find out that in which refineries pre-combustion carbon capture is being used.Two large scale CCS demonstration projects integrating CO_2 capture with hydrogen SMR plants have been implemented in North America, i.e., Air Product's SMR plant at Valero refinery at Port Arthur, and the other is Quest SMR at Shell's Scotford Upgrader in Alberta, Canada. These projects are utilizing the pre-combustion integrated with PSA technology[41].

Several studies, particularly Electric Power Research Institute (EPRI) reported that 75% of the produced CO_2 from integrated gasification combined cycle power generation facilities could be captured via using physical solvents, with only a 4% loss in the overall efficiency[42].

The advantages and limitations of the commercial physical solvents are provided in the table below.

[41] https://www.energy.gov/sites/prod/files/2017/11/f46/HPTT%20Roadmap%20FY17%20Final_Nov%202017.pdf

[42] http://citeseerx.ist.psu.edu/viewdoc/download;jsessionid=A6481F95BAAD1A0B4B7C2A02786E3EDE?doi=10.1.1.310.1462&rep=rep1&type=pdf

Table 12. Advantages and limitations of the commercial physical solvents

Physical solvents	Advantages	Limitations
Selexol	▪ Exhibits the highest CO_2 solubility among physical solvents ▪ Able to operate at a broad temperature range: from 0°C to 175°C ▪ No water wash is required due to a very low vapour pressure ▪ Selexol is less costly than Rectisol for CO_2 sequestering	▪ Higher viscosity than most physical solvents, particularly at low temperatures, thus resulting in low mass transfer and high packing requirements
Rectisol	▪ Typical operation temperature is below 0°C because methanol has a relatively high vapour pressure at normal process conditions ▪ Water washing of effluent streams require to prevent high solvent losses	▪ Exhibit higher selectivity for H_2S over CO_2
Fluor Solvent^{SM}	▪ Physical absorption occurs at moderate to high-pressure, ranging between 30 and 80 bar, and at ambient temperature ▪ Non-thermal regeneration	▪ It is not recommended for use if more than trace levels of H2S are present ▪ It reacts irreversibly with water ▪ It is unstable at high temperatures, and thus operating temperature is below 65 °C

Selexol is the most preferred solvent among physical solvents for pre-combustion carbon capture technology, due to the lowest vapour pressure, the highest CO_2 solubility, and the highest operating temperature. It is interesting to note that the two most recently built facilities for pre-combustion carbon technology, Alberta Carbon Trunk Line with Agrium CO_2 stream and Alberta Carbon Trunk Line with North West Sturgeon Refinery CO_2 stream, will commence operations by 2020. These two facilities will be using similar technologies to those implemented in the 1970s, i.e., Rectisol and hot potassium carbonate.

A significant change in solvent selection is witnessed when comparing the end-use of the captured CO_2, i.e., from EOR to dedicated geological storage and pre-combustion gas streams. For example, the dedicated geological storage application[43] does not use traditional physical solvents, although these facilities, such as Quest CCS project, Snøhvit CO_2 storage project, Sleipner CO_2 Storage Project, etc., use chemical solvents, such as Methyldiethanolamine (MDEA) or an activated/accelerated MDEA solvent[44].

MDEA is a tertiary amine with characteristically large CO_2 absorption capacity (required to ensure that the largest volume of CO_2 is captured at the facility); however, it slows reaction kinetics, and thus, activation or acceleration is required through the addition of a rate promoter, such as piperazine, to enhance reaction speeds. Thus, the resultant kinetics of activated MDEA is much faster than conventional amines-based chemical solvents, such as Monoethanolamine (MEA) and Diethanolamine (DEA). The activated MDEA also enables deeper CO_2 removal and improves the purity of the produced CO_2 rich stream.

[43] https://www.globalccsinstitute.com/wp-content/uploads/2019/12/GCC_GLOBAL_STATUS_REPORT_2019.pdf
[44] https://www.netl.doe.gov/node/7633

Chemical solvents, MDEA, have found increased usage in post-combustion carbon capture technology, due to its relatively low regeneration energy requirement for CO_2 liberation, low tendency to form degradation products, low corrosion rates, and substantial reflux recirculation of solvents not required in the regenerator column. MDEA/activated MDEA is being used for natural gas processing on an industrial scale. In addition to this, it is less basic than MEA and DEA, and thus, can be used in significantly higher concentrations.

Several new physical solvents for CO_2 are being developed at TRL 2 to 5, wherein research work is largely focusing on developing physical solvents, such as fluorinated solvents and ionic liquids among others that have high thermal stability, extremely low vapour pressure, and those that are non-flammable and non-toxic. Although these solvents exhibit favourable characteristics, some of them do suffer from high viscosity characteristics, which limits mass transfer rates. Apart from this, the cost of producing novel physical solvents is relatively high, which will also act to increase OPEX.

1.1.3. Oxy-fuel Carbon Capture Combustion

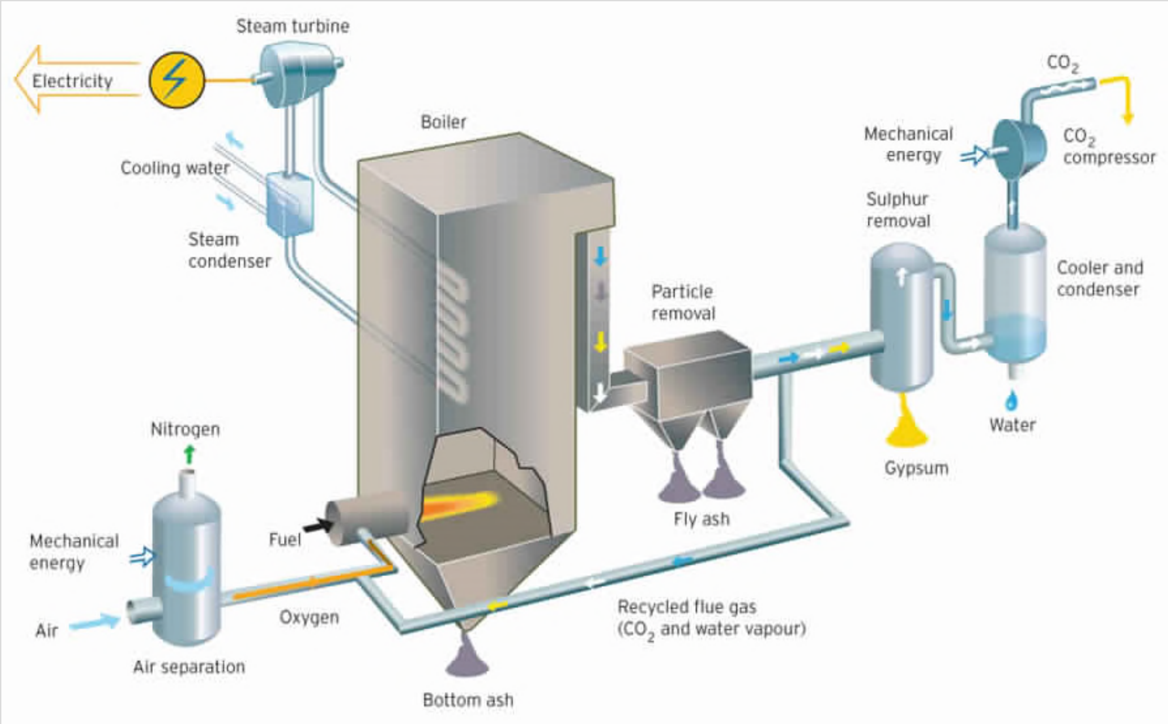
Oxy-combustion system is being developed as an alternative to post-combustion CO_2 capture for various industries such as cement, steel, power plants, etc. This system assists in the separation of oxygen from nitrogen before the combustion process, thereby eliminating a large amount of nitrogen in the flue-gas stream[45]. After the removal of particulate matter, the flue gas consists only of water vapour and CO_2, and smaller amounts of pollutants, such as sulphur dioxide and nitrogen oxides. The water vapour could be easily removed by cooling and compressing the flue gas and the additional removal of other air pollutants leaves a nearly pure CO_2 stream that can be sent directly to storage.

The principal attraction of oxy-combustion system is that it avoids the need for a costly post-combustion CO_2 capture system. However, it requires an Air Separation Unit (ASU) to generate the relatively pure (95%-99%) oxygen needed for combustion such high purity is applicable for carbon capture technologies. It is reported that approximately three times more oxygen is needed for this system than for an IGCC plant of comparable size, and thus, the ASU adds significantly to the cost.

In addition to this, the flue gas processing also is needed to reduce the concentration of conventional air pollutants to prevent the undesirable build-up of a substance in the flue gas recycle loop and to achieve CO_2 purity specifications for the pipeline.

[45] http://www.zeroco2.no/introduction/vattenfalloxyfuel.jpg

Figure 10. Process flow diagram for oxy-combustion carbon capture technologies



In contrast to post-combustion and pre-combustion carbon capture technologies, which are commercial, oxy-combustion carbon capture technology is a potential option that is still under development and not yet commercial.

Key advantages and barriers for the oxy-combustion system is mentioned as below.

Table 13. Advantages and barriers for oxy-combustion system

Description	Advantages	Barriers
Optimization of Air Separation Units (ASU)	▪ Extra equipment consists mainly of conventional equipment and heat exchangers ▪ Boiler and air pollution control devices utilize conventional designs and materials of construction	▪ Energy penalty results from the power needed for ASU air compression and CO_2 compression in the CO_2 purification unit can be reduced net plant output by up to 25% compared to an air-fried power plant of same capacity without CO_2 capture

1.1.4. Direct Air Capture

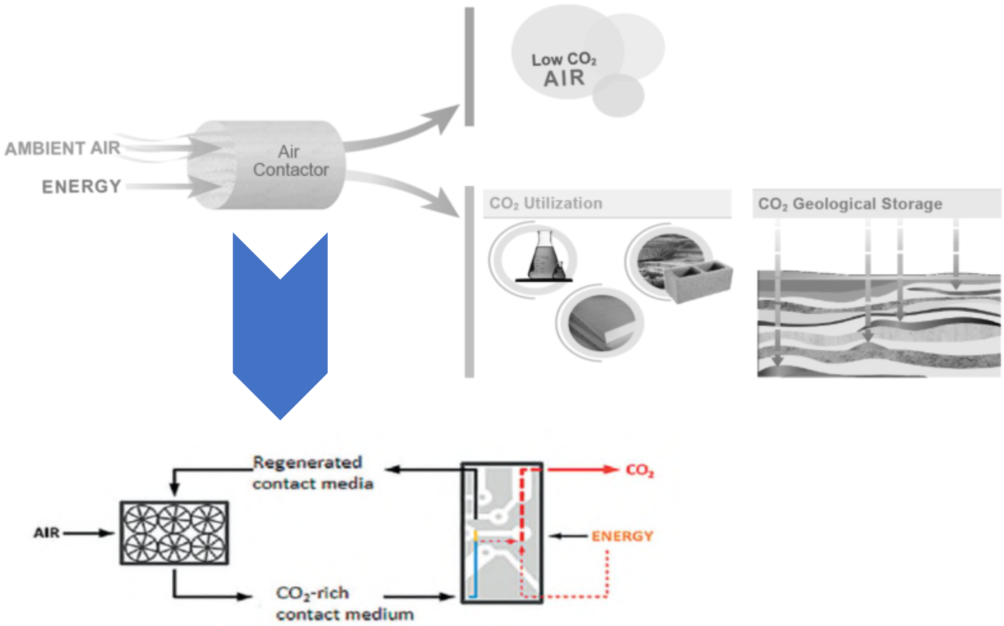
Direct Air Capture (DAC) technology involves capturing carbon dioxide directly from the atmosphere at a concentrated source (low concentration of CO_2 in the air, ~400 ppm) as opposed to the capture at point source itself[46]. DAC as a concept was first introduced for climate change mitigation by Dr. Lackner in 1999. DAC systems can be thought of as artificial trees and can extract CO_2 from the air at a concentration

[46] https://easac.eu/fileadmin/PDF_s/reports_statements/Negative_Carbon/EASAC_Report_on_Negative_Emission_Technologies.pdf

of as low as 400 ppm. DAC systems rely on chemicals capable of selectively binding with CO_2 but not with other chemicals in the air. Once the chemicals become saturated with CO_2, energy is added to the DAC system (in the form of heat, humidity, pressure, etc.) to release the CO_2 in purified form, and regenerate the chemicals to repeat the process. Most of the DAC technologies are currently based on either a liquid solvent or a solid sorbent system. Carbon Engineering's process involves aqueous potassium hydroxide solutions/calcium carbonation that react with CO_2 to precipitate a carbonate salt[47]. Several start-ups or companies are pursuing solid sorbents systems (such as Climeworks, Global Thermostat, Skytree, etc.), and they are developing their unique proprietary process with different design features to commercialize DAC.

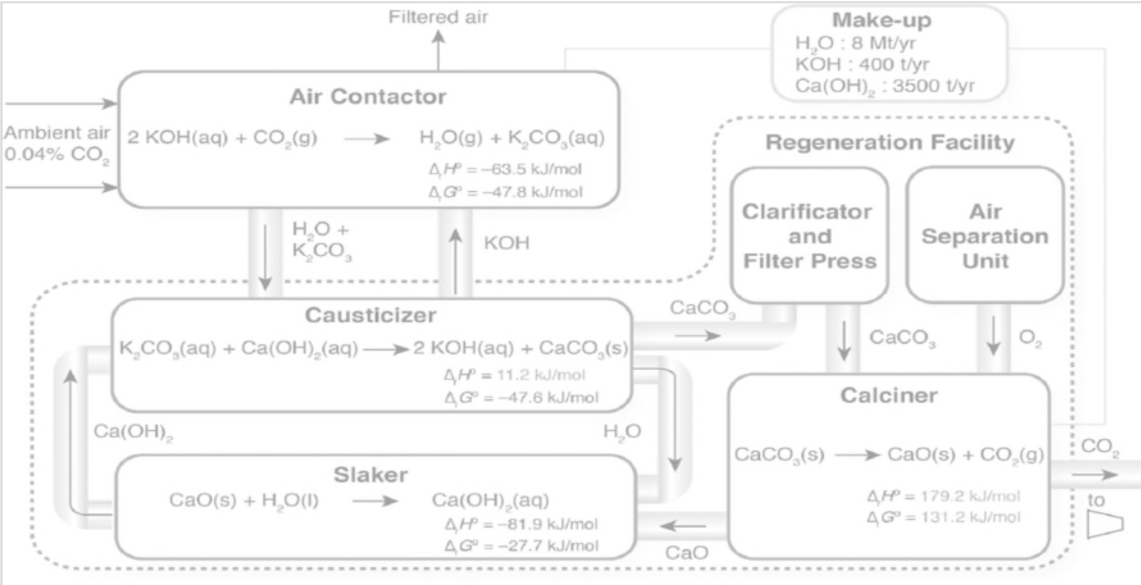
The technology has received immense attention these days; however, to have a significant effect on global CO_2 concentration, it needs to be deployed at a large scale. Though the technology has been commercialized recently by certain start-up companies, there are still concerns regarding energy consumption and the cost of CO_2 capture using this technology.

Figure 11. Overall process flow diagram for DAC system



[47] https://www.nap.edu/read/25259/chapter/7#192

Figure 12. Process flow diagram of a generic liquid solvent-based DAC system



Direct air capture of CO_2 could be revolutionary as the potential capacity for CO_2 removal of DAC is larger than the conventional carbon capture technology. This technology encompasses the potential of sucking massive quantities of carbon dioxide out of the air, anywhere, at any time.

Table 14. Major companies working to commercialize DAC systems[48]

Company	System	Technology	Regeneration	Purity	TRL
Carbon Engineering, Canada	Liquid solvent	Potassium hydroxide solution/calcium carbonation	Temperature	99%	Pilot, 1 t/d
Climeworks AG, Switzerland	Solid sorbent	Amine-functionalized filter	Temperature or vacuum	99% w/dilution depending on application	Demonstration, 900 t/y
Global Thermostat, USA	Solid sorbent	Amine-modified monolith	Temperature and/or vacuum	99%	Demonstration, 1,000 t/y
Infinitree, USA	Solid sorbent	Ion-exchange sorbent	Humidity	NA	Laboratory
Skytree, Netherlands	Solid sorbent	Porous plastic beads functionalized with benzylamines	Temperature	Air purification, greenhouses	Laboratory

Major development by DAC players

- **Carbon Engineering:** In 2019, Oxy Low Carbon Ventures, LLC, and Carbon Engineering announced a joint project of the world's largest DAC and sequestration facility, with a capacity of 0.5 million tonnes per annum of CO_2 capture. The captured CO_2 is planned to be used in Occidental's EOR operations in the Permian Basin[49].

[48] https://www.nap.edu/read/25259/chapter/7#192
[49] https://carbonengineering.com/news-updates/worlds-largest-direct-air-capture-and-sequestration-plant/

- **Climeworks AG:** In 2014, Climeworks in a partnership with Audi and Sunfire launched a pilot plant in Dresden that captures 80% of CO_2 molecules from air passing through the system and converts them into synthetic diesel[50]. In 2017, Climeworks commissioned another commercial-scale DAC plant in Switzerland that provides CO_2 for a nearby-located greenhouse[51]. In 2019, Climeworks acquired Netherlands-based DAC technology developer Antecy[52]. Recently, January 27, 2020, Climeworks and Svante Inc. (formerly Inventys Inc.) announced an agreement to collaborate on the development of carbon capture technology solutions[53].
- **Global Thermostat:** Catalysts technology is licensed from Georgia Institute of Technology and the company already has piloted and commercial demonstration plants operating since 2010 at SRI International in Menlo Park, California[54]. In 2019, Global Thermostat and ExxonMobil have signed a joint development agreement to advance breakthrough technology that can capture and concentrate carbon dioxide emissions from industrial sources, including power plants, and the atmosphere[55].

Other DAC companies such as Skytree and Infinitree have disclosed very limited information in the public domain.

As such the choice of carbon capture technologies depend on the partial pressure of carbon dioxide in the flue gas stream; As such there is not data that directly correlates technology to application areas; it is observed that people are exploring different technologies for same application areas and determining which is best suited for particular applications.

Table 15. Advantages and challenges of the various carbon capture technologies

Capture Process	Advantages	Challenges
Post-combustion	▪ More mature than other alternative technologies ▪ Can easily retrofit into existing plants	▪ Low CO_2 concentration affects the capture efficiency
Pre-combustion	▪ High CO_2 concentration can enhance the sorption efficiency ▪ Can retrofit to existing plants	▪ High energy requirement for sorbent regeneration ▪ High capital and operating costs
Oxyfuel Combustion	▪ Very high CO_2 concentration that enhances absorption efficiency ▪ Reduced volume of gas to be treated, and thus, required smaller boiler and other equipment	▪ High-efficiency drop and energy penalty ▪ Cryogenic O_2 production is costly
DAC	▪ Capture CO_2 from dispersed sources ▪ Portable and easily mounted to existing plants	▪ High manufacturing cost of DAC systems ▪ High energy requirement

50 https://www.audi.com/content/dam/gbp2/company/sustainability/downloads/sustainability-reports/en/Audi_CR-Report%202014_English_Webversion.pdf
51 http://www.climeworks.com/wp-content/uploads/2017/10/PR-Climeworks-CarbFix-Carbon-Removal-1.pdf
52 https://www.climeworks.com/climeworks-ag-and-antecy-b-v-are-joining-forces-thereby-boosting-technology-portfolio-2/
53 https://www.climeworks.com/global-carbon-capture-technology-leaders-svante-and-climeworks-agree-to-collaborate-on-solutions-for-a-net-zero-emissions-world/
54 https://scholar.google.com/scholar_lookup?title=Global%20Thermostat%20low%20cost%20direct%20air%20capture%20technology&publication_year=2018&author=E.%20Ping&author=M.%20Sakwa-Novak&author=P.%20Eisenberger
55 https://globalthermostat.com

Table 16. Cost comparison for different capture processes

Fuel type	Parameter	Capture technology			
		No capture	Post-combustion	Pre-combustion	Oxy-fuel
Coal-fired	Thermal efficiency, (%LHV)	44.0	34.8	31.5	35.4
	Capital cost, ($/kW)	1410	1980	1820	2210
	Electricity cost, (c/kWh)	5.4	7.5	6.9	7.8
	Cost of CO_2 avoided, ($/t$CO_2$)	-	34	23	36
Gas-fired	Thermal efficiency, (%LHV)	55.6	47.4	41.5	44.7
	Capital cost, ($/kW)	500	870	1180	1530
	Electricity cost, (c/kWh)	6.2	8.0	9.7	10
	Cost of CO_2 avoided, ($/t$CO_2$)	-	58	12	102

Costs include CO_2 compression to 11 bar but excluding storage and transportation costs. The cost of DAC reported in the literature is in the range of $27/t$CO_2$ to $136/t$CO_2$[56], recent pilot-scale cost estimates of $94 to $232 per ton CO_2[57], and it predicted to drop below $60 by 2040[58]. It is also reported that minimum costs considering sorbents under various conditions ranged from $29 to $91 per ton CO_2[59].

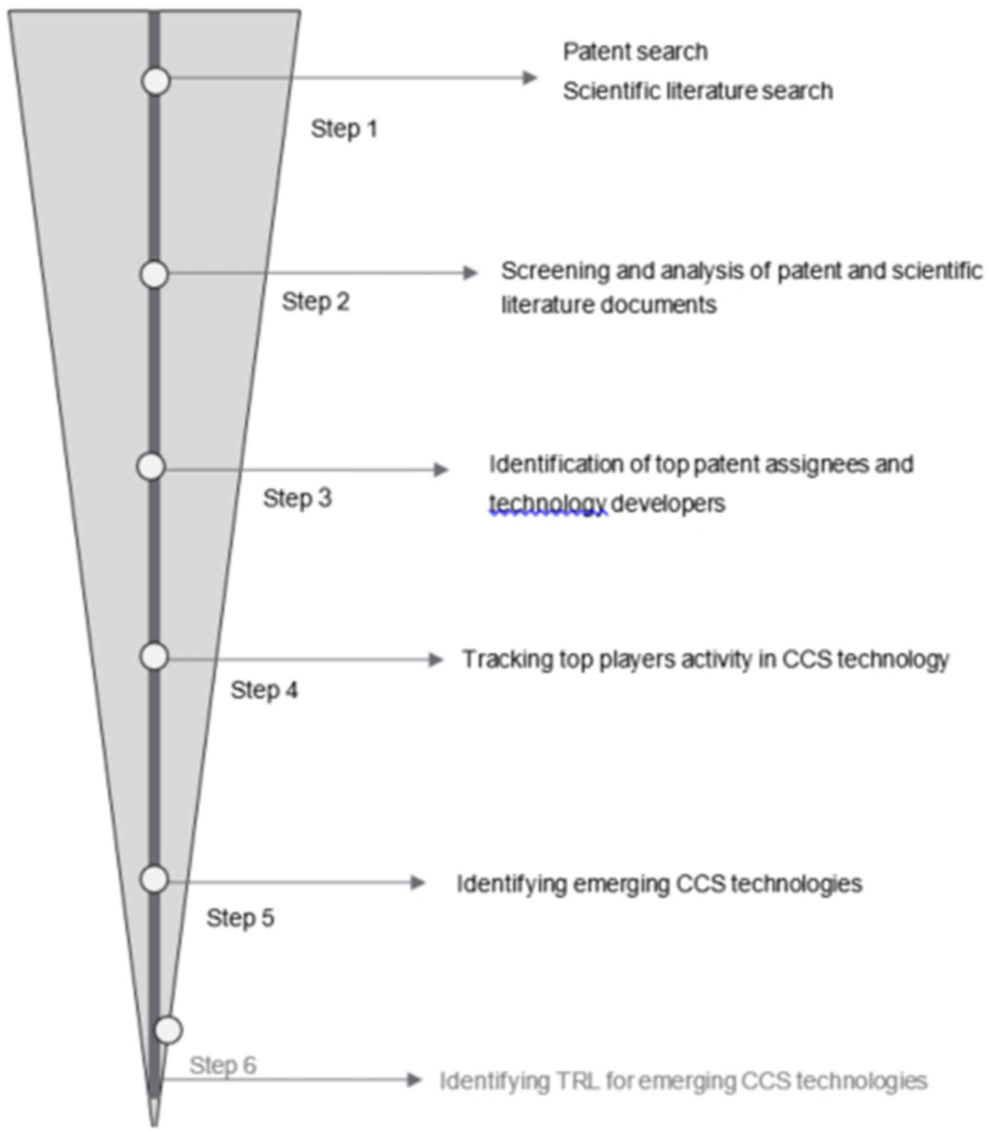
56 https://sequestration.mit.edu/research/aircapture.html
57 https://www.sciencedirect.com/science/article/pii/S2542435118302253
58 https://www.sciencedirect.com/science/article/pii/S0959652619307772
59 https://www.sciencedirect.com/science/article/pii/S0959652619307772

2. TECHNOLOGY SCOUTING: EMERGING TECHNOLOGY

FutureBridge is using a combination of secondary sources and scientometrics analysis to identify emerging technologies for carbon capture. Scientometrics analysis (patent and scientific literature) plays a vital role in assessing the worldwide scientific and technological progress in any particular area of R&D. The analysis can provide valuable insights regarding technology trends, key players from the industry, R&D institutions, and academia, as well as technology innovation. Moreover, patents play a pivotal role in innovation and economic performance as well as in the development of technology transactions from R&D labs to the market place.

2.1. SCOUTING METHODOLOGY

Figure 13. CCS scouting methodology



Scientometrics / Technology Methodology

- FutureBridge has framed search strings based on keywords related to carbon capture technologies
- The search strings run on Questel patent database to retrieve the patents documents for (01.01.2010-31.12.2019)

Table 17. Patent search methodology

Key search string	No. of patent documents retrieved
((Carbon or CO2) 5D (captur+ or separat+ or remov+ or recover+ or collect+ or trap+ or eliminat+ or purif+ or absorp+ or adsorp+ or sorp+ or adsorbent or absorbent or scrub+ or membrane or condensation or cryogenic))/TI/AB/CLMS/OBJ EPRD=2010-01-01:2019-12-23	~ 23,500 (Un-screened)
No. of relevant patents identified	**4993** (Screened)
Relevant patents - patents which are related to, – Carbon capture / separation / removal / elimination, removal, recovery and collection process – Adsorbent manufacturing/modification which is used in carbon capture – Absorbent manufacturing/modification which is used in carbon capture – Sorbent manufacturing/modification which is used in carbon capture – Membranes manufacturing/modification which is used in carbon capture – Carbon capture through the biological process – Cryogenic carbon capture – Apparatus/devices used in carbon capture Exclusion, – Utility models[60] (*In some countries, a utility model system protects so-called “minor inventions” through a system similar to the patent system. Recognizing that minor improvements of existing products, which does not fulfill the patentability requirements, may have an important role in a local innovation system, utility models protect such inventions through granting an exclusive right, which allows the right holder to prevent others from commercially using the protected invention, without his authorization, for a limited period*)	

Patent status	No. of records
Total retrieved patents	23,500
Total relevant patents	4,993
Alive patents	3701
Dead patents	1292
Granted patents	2424
Ratio (%) of granted / total relevant patents	49%

[60] https://www.wipo.int/patents/en/topics/utility_models.html

Figure 14 represents the distribution of patents to carbon capture methods i.e. pre-combustion, post-combustion, oxyfuel combustion, and direct air capture. Patents disclosing carbon capture methods through natural gas processing are considered under pre-combustion methods.

Figure 14. Distribution of patents focused on carbon capture methods

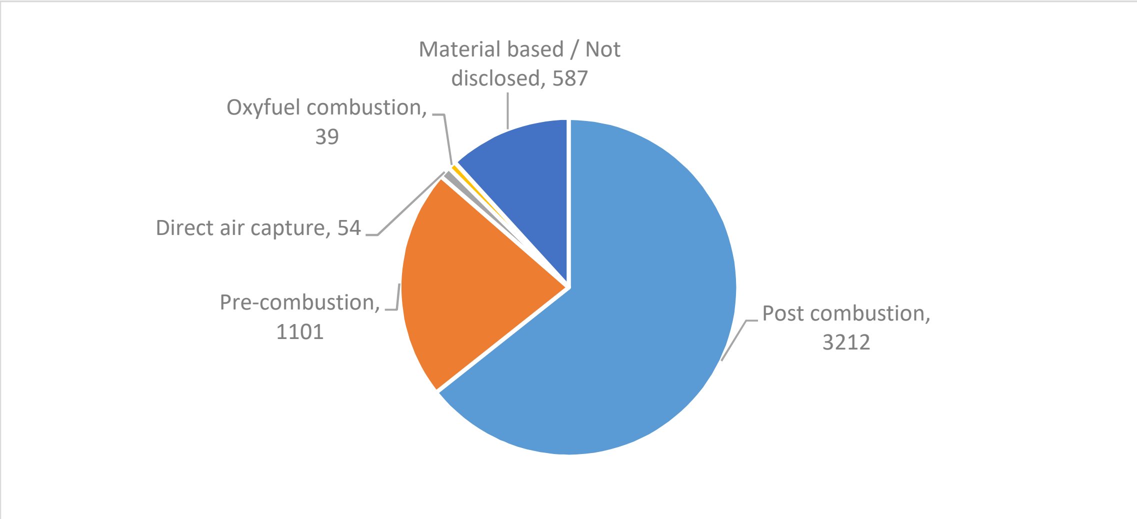
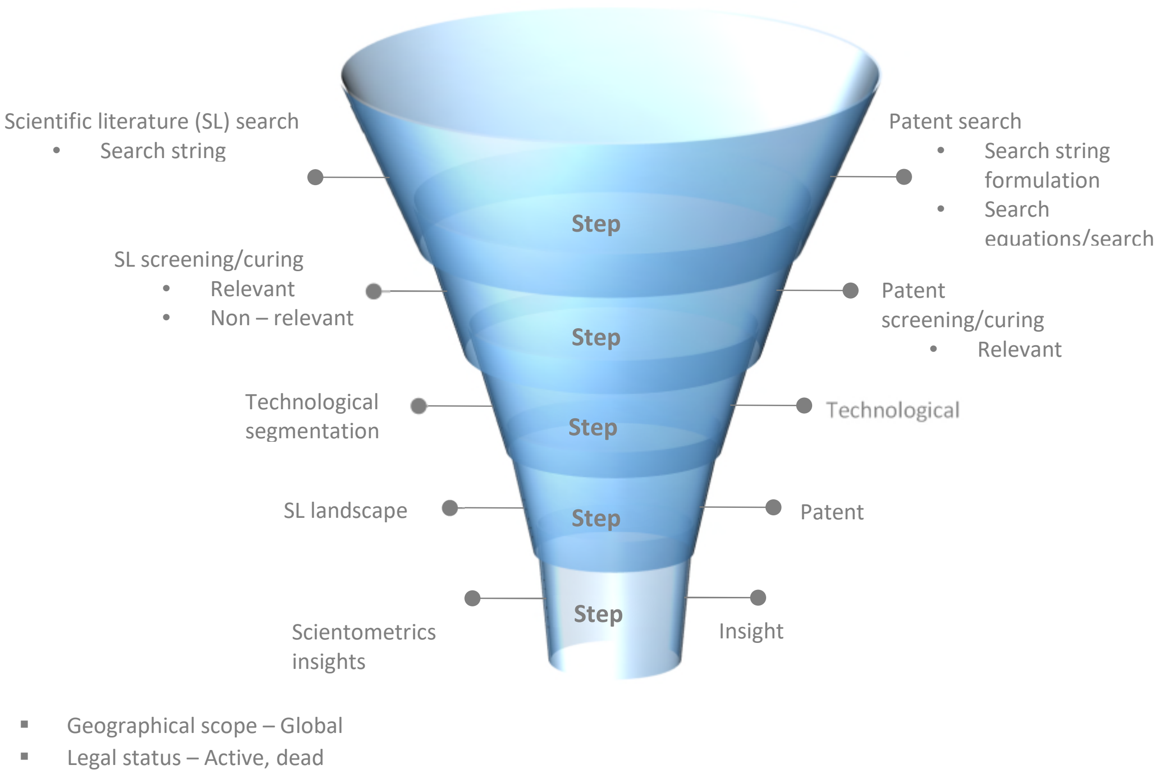


Figure 15 represents the scientometrics approach for technology scouting.

Figure 15. Scientometrics approach for technology scouting



FutureBridge has used a combination of keywords and searched in ‘full-text’ to identify relevant patent

- *FutureBridge also used patent classification codes (CPC - Cooperative patent classification codes and IPC - International patent codes)* to identify relevant patent documents
- FutureBridge has identified 4993 patents focused on carbon capture technologies and these patent are further segregated in the following categories:
  - Post-combustion
  - Pre-combustion
  - Oxy-fuel combustion
  - Direct air capture

Major CPC & IPC patent classification codes for carbon capture technology are provided below:

Table 18. Patent CPC codes and definitions

Patent CPC	Description
Y02C10/00	CO_2 capture or storage
Y02C10/02	Capture by biological separation
Y02C10/04	Capture by chemical separation
Y02C10/06	Capture by absorption
Y02C10/08	Capture by adsorption
Y02C10/10	Capture by membranes or diffusion
Y02C10/12	Capture by rectification and condensation
Y02C10/14	Subterranean or submarine CO_2 storage
Y02E20/344	Oxy-fuel combustion

Table 19. Patent IPC codes and definitions

Patent IPC	Description
B01D 53/00	Separation of gases or vapours
B01D 53/02	by adsorption, e.g. preparative gas chromatography
B01D 53/04	with stationary adsorbents
B01D 53/047	Pressure swing adsorption
B01D 53/053	with storage or buffer vessel
B01D 53/06	with moving adsorbents
B01D 53/08	according to the "moving bed" method
B01D 53/10	with dispersed adsorbents
B01D 53/12	according to the "fluidised technique"
B01D 53/14	by absorption
B01D 53/18	Absorbing units; Liquid distributors therefor
B01D 53/62	Carbon oxides
B01D 53/86	Catalytic processes

Table 20. Database Used for Scouting

For Patent	Scientific Literature	Secondary
Orbit Intelligence	WEB OF SCIENCE	CCSa Carbon Capture & Storage Association
		GLOBAL CCS INSTITUTE
		NETL NATIONAL ENERGY TECHNOLOGY LABORATORY
		iea International Energy Agency
Google Patents		ZEROCO2.NO
		WORLD ECONOMIC FORUM
		SCCS
Other national patent office databases		MIT Technology Review
		ieaghg
		C2ES CENTER FOR CLIMATE AND ENERGY SOLUTIONS

Table 21. Definition of technology readiness level

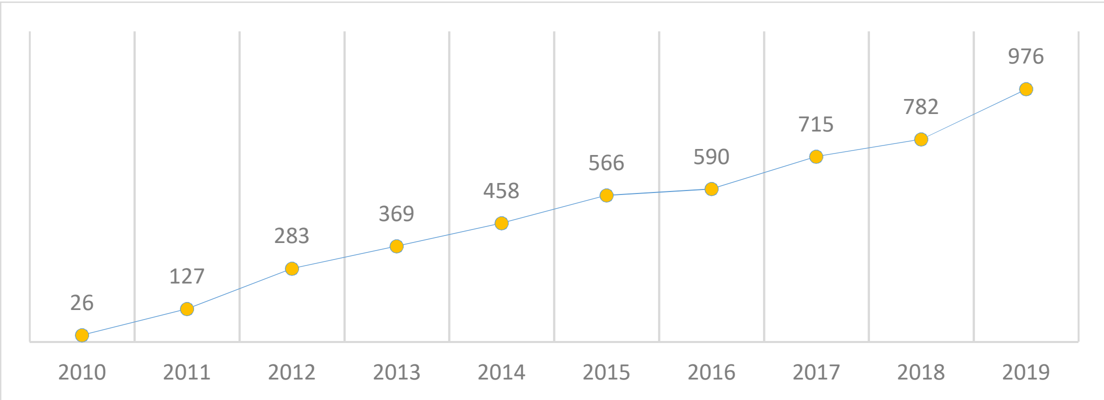
Technology Readiness Levels (TRL)	Definition
TRL 1	Basic principles observed
TRL 2	Technology concept formulated
TRL 3	Experimental proof of concept
TRL 4	Technology validated in lab
TRL 5	Technology validated in a relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 6	Technology demonstrated in a relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 7	System prototype demonstration in an operational environment
TRL 8	System complete and qualified
TRL 9	Actual system is proven in an operational environment (competitive manufacturing in the case of key enabling technologies; or space)

2.2. INSIGHTS FROM PATENT ANALYSIS

Patent analysis provides a snapshot of research activities of a specific technology area, including top patentees, bilateral collaboration, and origin of research. This analysis covers technologies used in carbon capture methods. The patent analysis includes inventions filed between 2010 and 2019. Lists of keywords were developed for carbon capture technology and search conducted to identify relevant result set. There are approximately 5,000 published patent families related to carbon capture methods. Utility patents are not included as they refer only incremental features to parent technology. The analysis was conducted on the patent families' dataset. An assignee is only counted once for each for a patent family observation. Although assignees can sometimes vary through the patent family (for instance, due to patent re-assignment), only the parent patent's assignee as the source of the innovation is included in this analysis. The office of first filing was determined from the priority number of the parent patent in each patent family dataset. The analysis is based on publication year and priority year doesn't provide the real picture, hence, we have provided publication year trends rather than priority year.

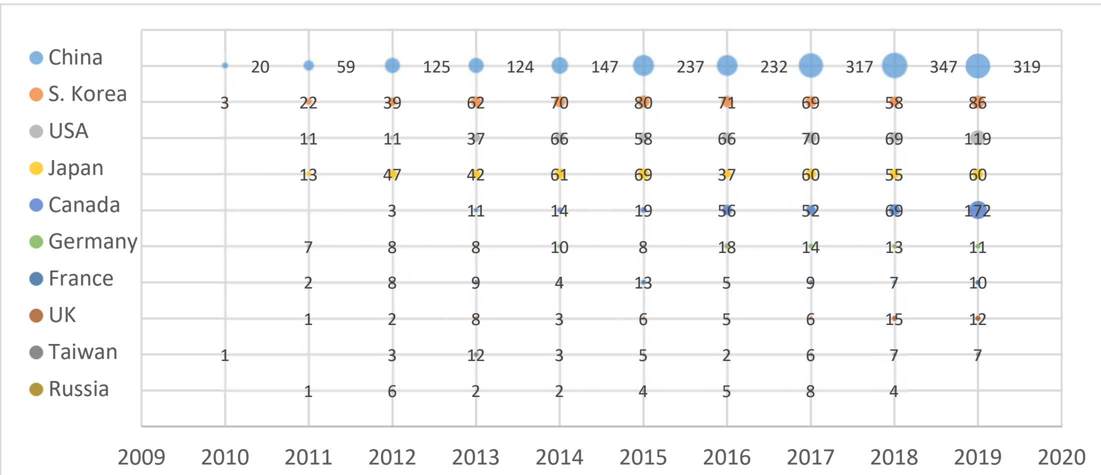
2.2.1. Patent Publication Trend

Figure 16. Patent publication trend worldwide for the last ten years (2010-2019)



2.2.2. Country and Publication Trend

Figure 17. Top 10 countries and their patent filing trends



China is the world's largest carbon emitter, and recently, a push for greener production of goods and energy solutions by the Chinese government and state-owned Chinese companies have propelled the filing of patents around climate change technologies. China recently joined the Coalition Partnership for Market Implementation by the World Bank[61] to acquire technical assistance for the implementation of carbon pricing and market instruments, which could also be one of the drivers for the rapid surge in patent filings.

2.2.3. Top 10 Assignee

FutureBridge has selected the top ten assignees based on the number of most patent populated within the universe of overall patent publications.

Figure 18. Top 10 patent applicant (Academia)

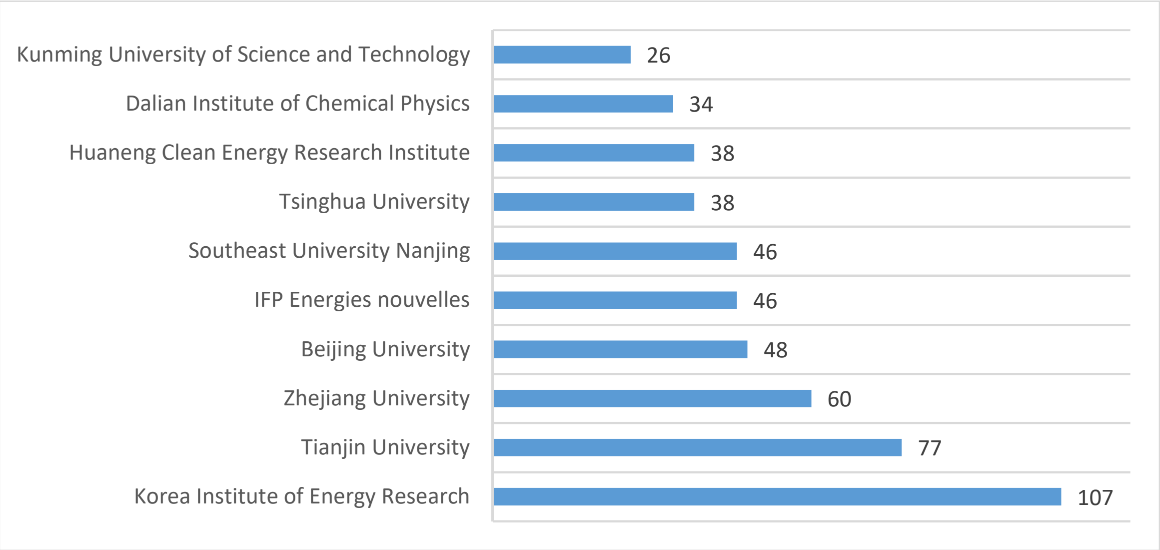
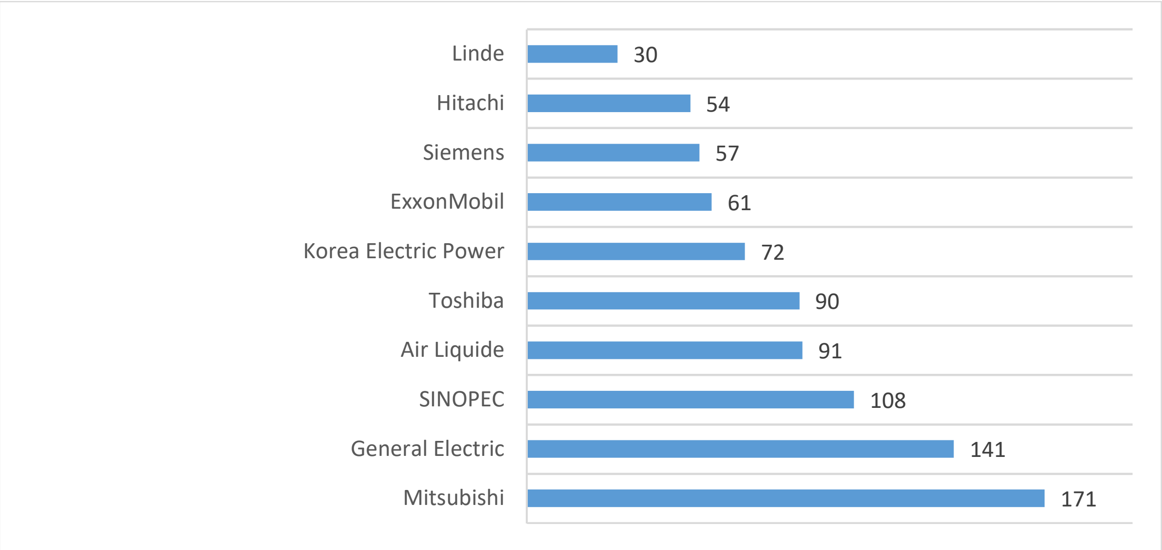
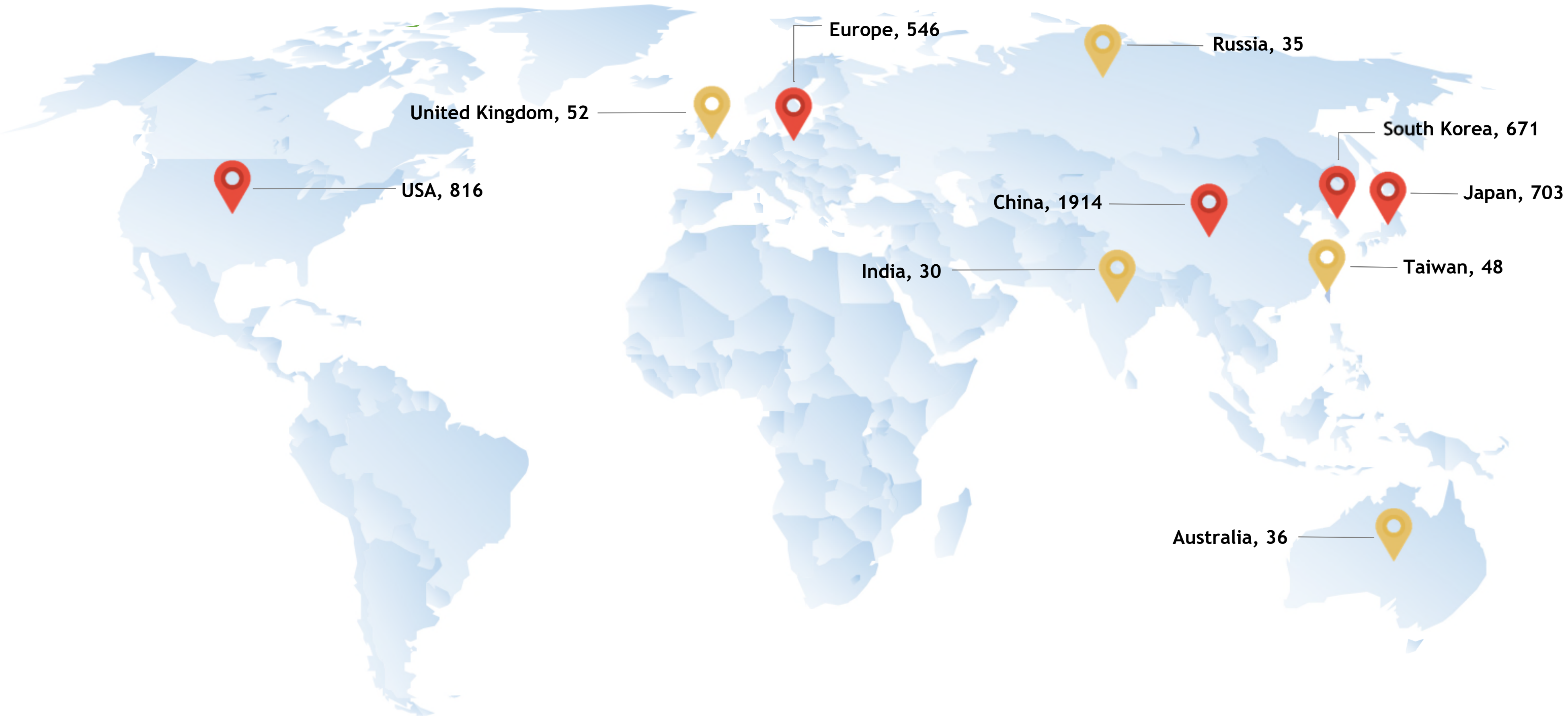


Figure 19. Top 10 patent applicant (Corporate)



[61] https://www.worldbank.org/en/news/press-release/2019/12/10/at-cop25-the-world-bank-announces-global-partnership-for-implementing-carbon-markets

2.2.4. Geographical Distribution of Patents



China patenting activity:

Figure 20. Distribution of patents between academia and corporate and individual inventors

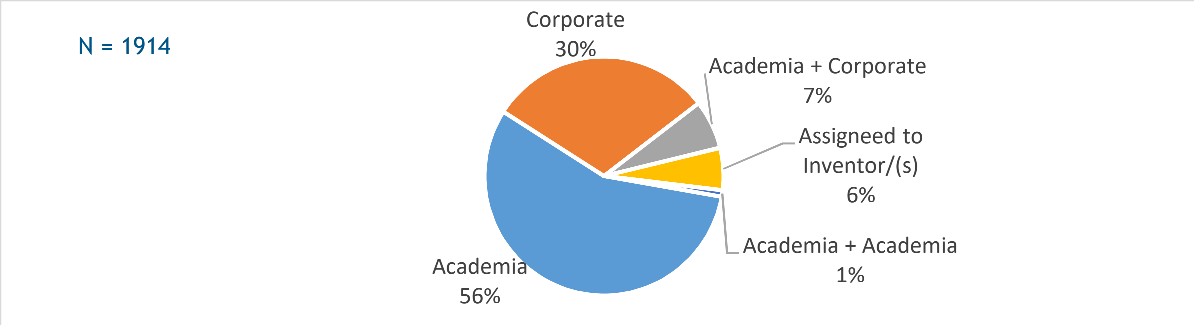


Figure 21. Top 10 patent applicant from China (all, corporate plus academia)

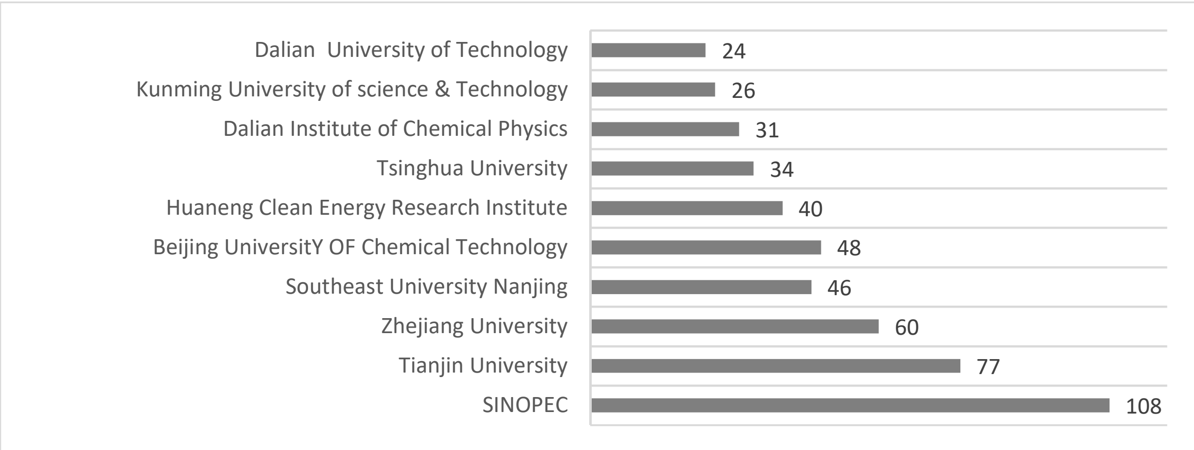
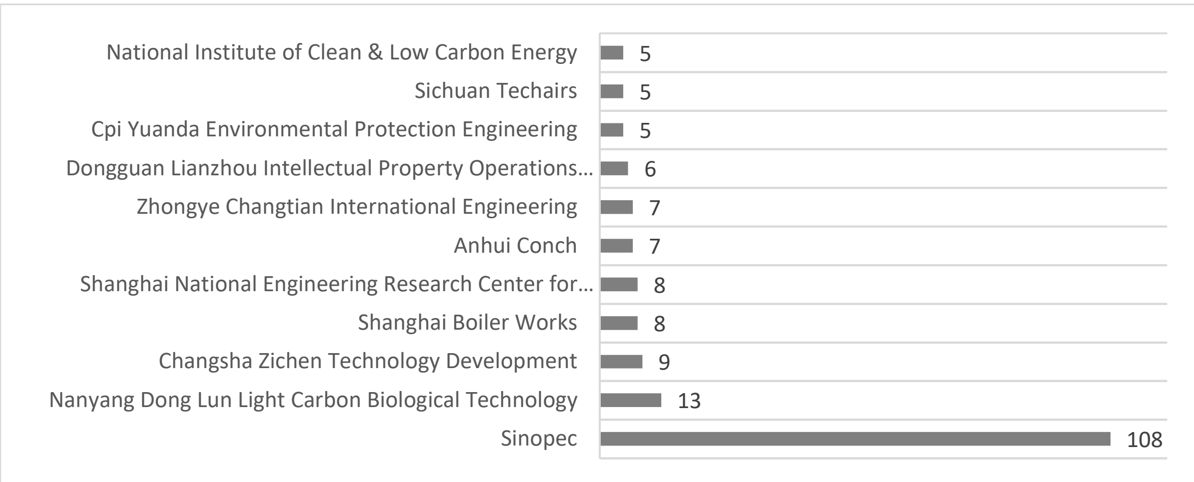


Figure 22. Top 10 patent applicant from China (Corporate only)



2.2.5. Carbon Capture Technology Distribution

2.2.5.1. Post-combustion

Approximately 2,300 patents were identified in the post-combustion category. These patents are further segregated based on the principle of separation of carbon dioxide.

Figure 23. Patent publication trend for post-combustion carbon capture method

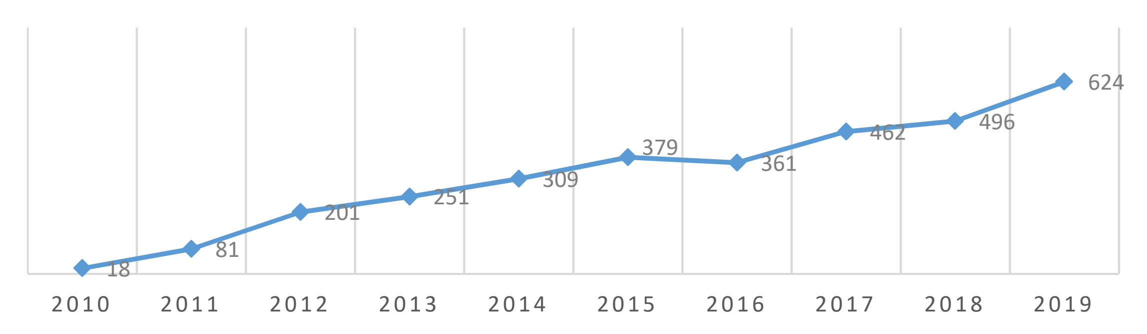
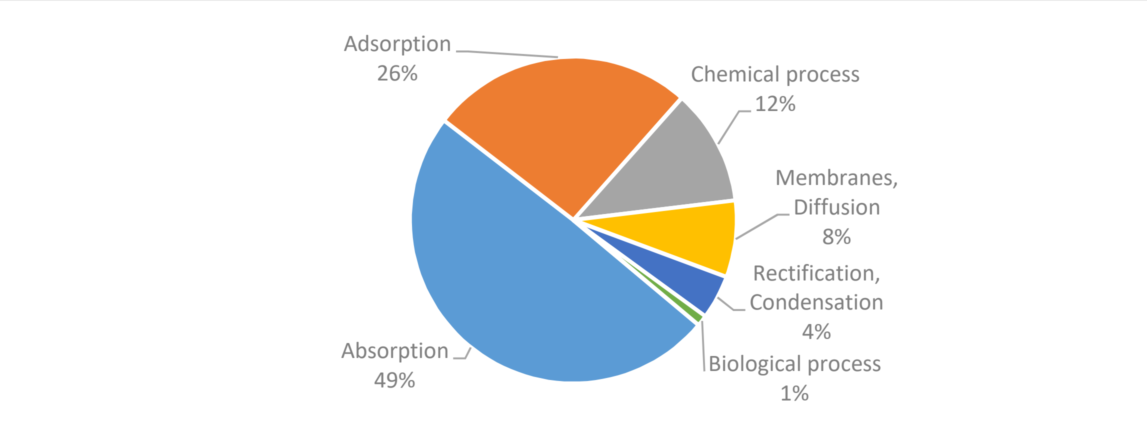


Figure 24. Carbon capture methods distribution in post-combustion technology

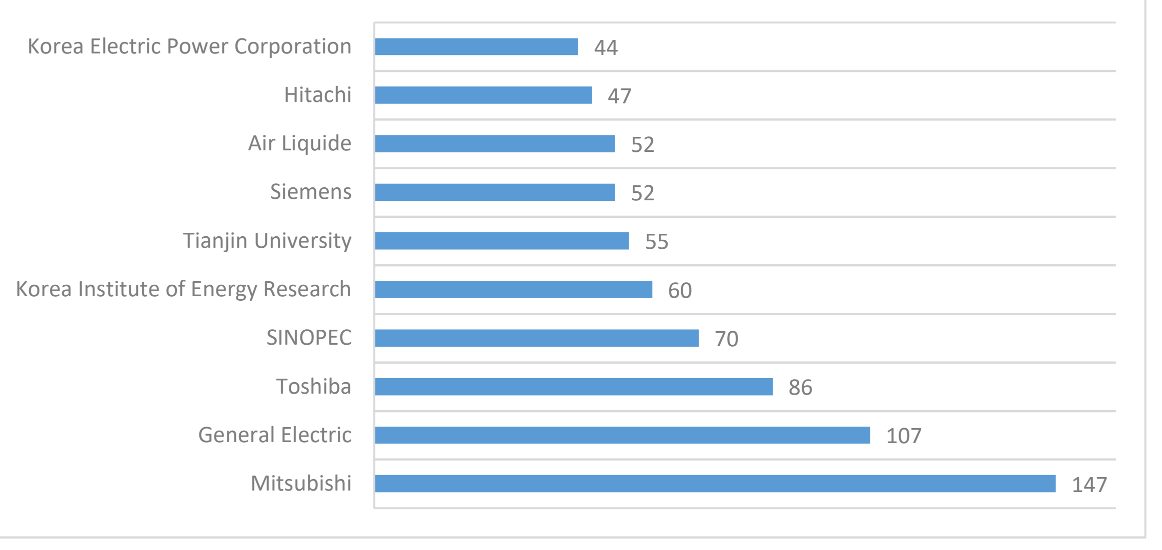


In the post-combustion capture process, absorption is the most preferred route for the carbon capture process. Most patent generation activity is concentrated in capture technologies that use absorption chemical processes. There are several other processes based on this technology. A couple of these processes such as amines and alkali carbonate are considered suitable for the power generation sector.

Companies mainly from the power generation sector, such as Mitsubishi Hitachi Power Systems Europe GmbH and Alstom Technology Ltd., account for major research activity in the absorption domain. Other companies include Toshiba KK, Kansai Electric Power Co. Inc., General Electric Co., Siemens AG, and Kilimanjaro Energy Inc.

The top 10 patent assignee in post-combustion carbon capture process:

Figure 25. Top 10 patent assignee in the post-combustion carbon capture process



FutureBridge has analyzed patents filed by the top 10 players to understand the key research areas in CCS technology. Patent citation data is used to identify the valuable patents for these top 10 players.

Patent citations are of two types, forward patent citations, and backward citation. Here, Non-self forward patent citation (excluding self-citation) are taken to evaluate most referred patent from others.

Mitsubishi's patenting activity is focused on the absorption/absorbent and carbon capture process. It's most preferred patent[62] talks about CO_2 recovery system and a recovery method for moisture containing CO_2 gas that enables recovery of water containing an absorbent, which is generated when CO_2 gas emitted from a regenerator.

GE (Alstom Technology) has a patent focus mainly on absorption/absorbent and carbon capture technology and partially on membrane and condensation technology. It's most referred patent talks about [63] a method and system of washing flue gas after CO_2 absorption to reduce solvent emissions and maintain water neutrality.

Toshiba's main patenting focus is on the absorption/absorbent and carbon capture process. It's most referred patent[64] talks about a carbon-dioxide-recovery-type steam power generation system and a carbon dioxide recovery method, an absorption tower that is supplied with the exhaust gas from the boiler and allows carbon dioxide contained in the exhaust gas to be absorbed into an absorption liquid.

[62] https://patents.google.com/patent/CA2770828C/en?oq=CA2770828
[63] https://patents.google.com/patent/US20110168020A1/en?oq=US20110168020
[64] https://patents.google.com/patent/CA2756157C/en?oq=CA2756157

SINOPEC has a patent focus absorption/absorbent and carbon capture process. It's most referred patent[65] talks about solid absorbent which is made up of porous solid carrier and loaded article two parts; Porous solid carrier comprises activated carbon, molecular sieve, silica gel, aluminium oxide, hydrotalcite and derivative thereof, organometallic skeletal compound.

Korea Institute of Energy Research has filed most of their patent in absorption/absorbent, adsorption/adsorbent, and carbon capture. It's most preferred patent[66] talks about a granular carbon dioxide adsorbent having an amine-based material impregnated into a granular material prepared by including a mesoporous material, an inorganic binder, an organic binder, and a substrate conversion additive.

Siemens has the main patent focus on absorption/absorbent and carbon capture technology. It's most referred patent[67] talks about a fossil-fired power plant with a combustion device and a separator for carbon dioxide.

Air Liquide has filed most of the patents focused on rectification/condensation and carbon capture technology, also a few numbers of patents in absorption and membrane technology. It's most preferred patent[68] talks about a process for efficiently removing carbon dioxide from a hydrocarbon containing feed stream that comprises at least methane and carbon dioxide utilizing a membrane separation unit in conjunction with a heat exchanger. This invention provides a process for treating a hydrocarbon containing feed stream which minimizes the loss of hydrocarbons while at the same time allowing for the recovery of a high-pressure carbon dioxide stream. The various streams (carbon dioxide-rich liquid stream and carbon dioxide lean overhead stream) isolated in the carbon dioxide separation unit which are then used to provide the cooling effect in the heat exchanger and as fuel for the compressors that are utilized in the process.

In Nov 2019, ExxonMobil and FuelCell Energy, Inc., signed a new two-year expanded joint-development agreement to develop carbonate fuel cell technology to capture carbon dioxide from industrial facilities. It is reported that the agreement, worth up to USD60 million, will focus efforts on optimizing the core carbon capture technology, overall process integration, and large-scale deployment of carbon capture solutions. ExxonMobil is exploring options to conduct a pilot test of next-generation carbonate fuel cell technology to capture carbon at one of its operating sites[69]. **ExxonMobil's researchers** have been pursuing this technology, which is based on molten carbonate fuel cells that increase the amount of electricity a power plant produces, while simultaneously delivering significant reductions in CO_2 emissions. It is reported that when natural gas is burned in a gas turbine, the exhaust produced is about 4% of CO_2. Molten carbonate fuel cells can collect that CO_2, and concentrate it into a stream ~70–80% of CO_2. ExxonMobil and FuelCell Energy are planning to test and improve the molten carbonate fuel cell technology to further increase its efficiency and demonstrate it at a larger scale.

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[65] https://patents.google.com/patent/CN105498720A/en?oq=CN105498720

[66] https://patents.google.com/patent/WO2012043942A1/en?oq=WO2012%2f043942

[67] https://patents.google.com/patent/EP2425887A1/en?oq=EP2425887

[68] https://patents.google.com/patent/WO2012048078A1/en?oq=WO2012%2f048078

[69] https://corporate.exxonmobil.com/News/Newsroom/News-releases/2019/1106_ExxonMobil-and-FuelCell-Energy-expand-agreement-for-carbon-capture-technology

The top 10 patent assignee in post-combustion carbon capture process and their carbon capture trend:

Figure 26. Top 10 players and carbon capturing trend

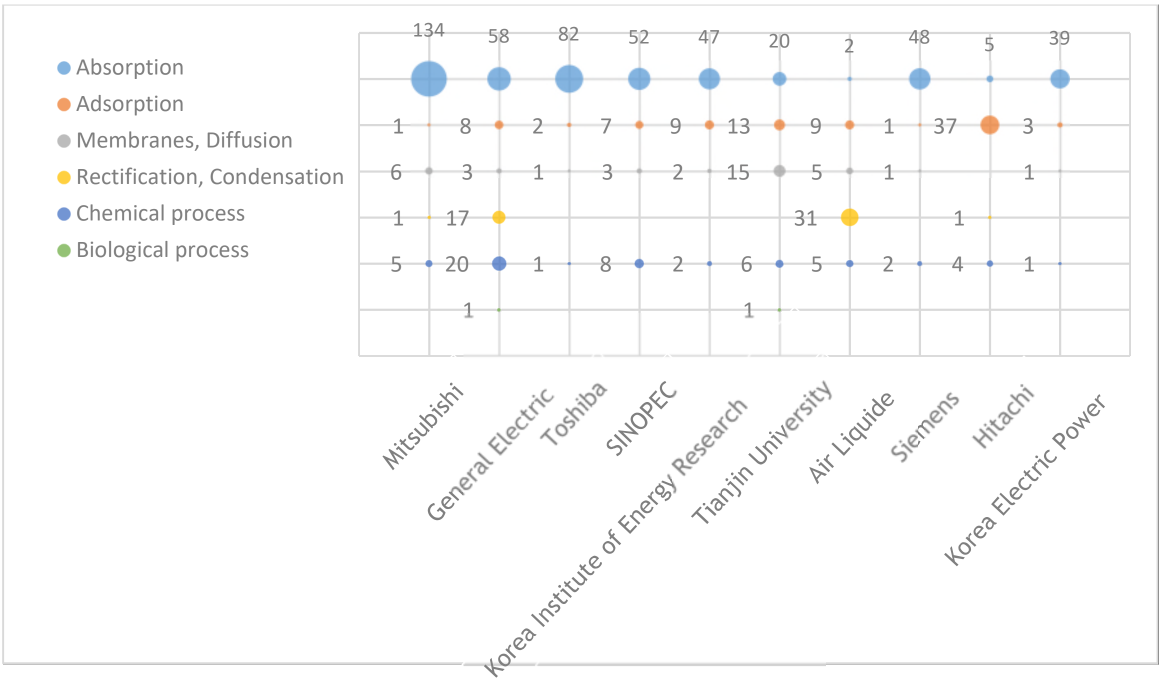
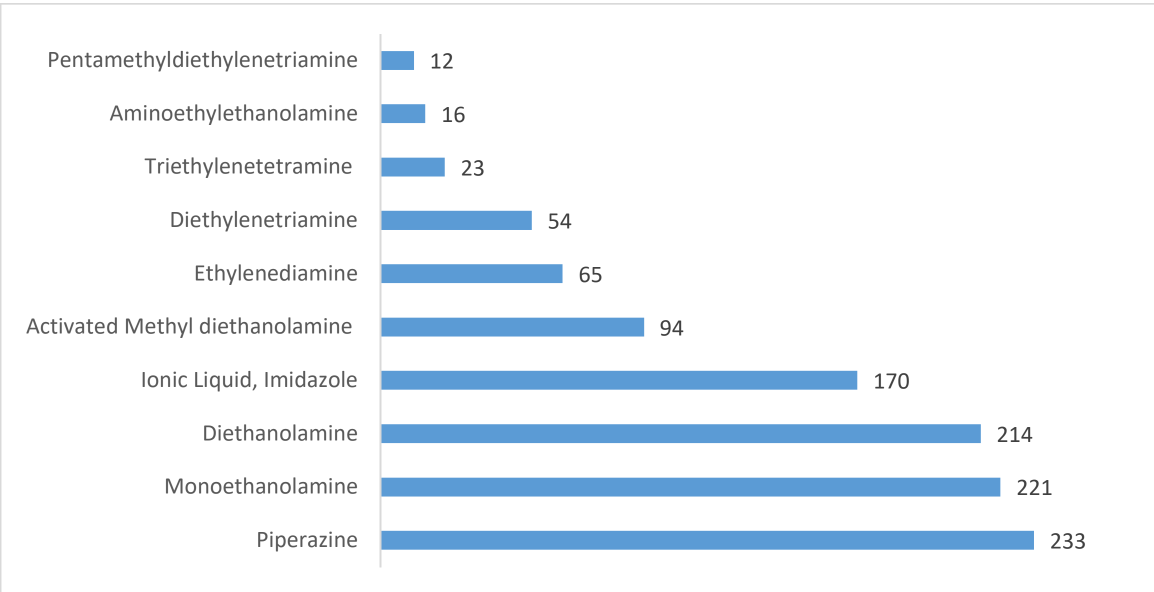


Figure 27 illustrates materials that are being used as an absorbent in post-combustion capture technology.

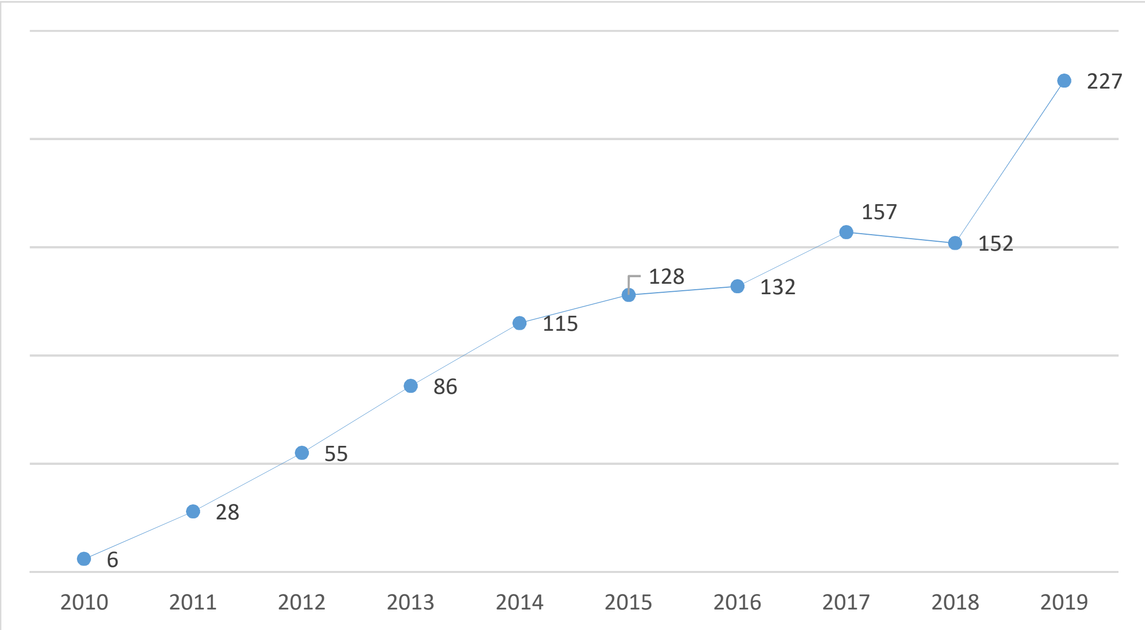
Figure 27. Absorption materials



2.2.5.2. Pre-combustion

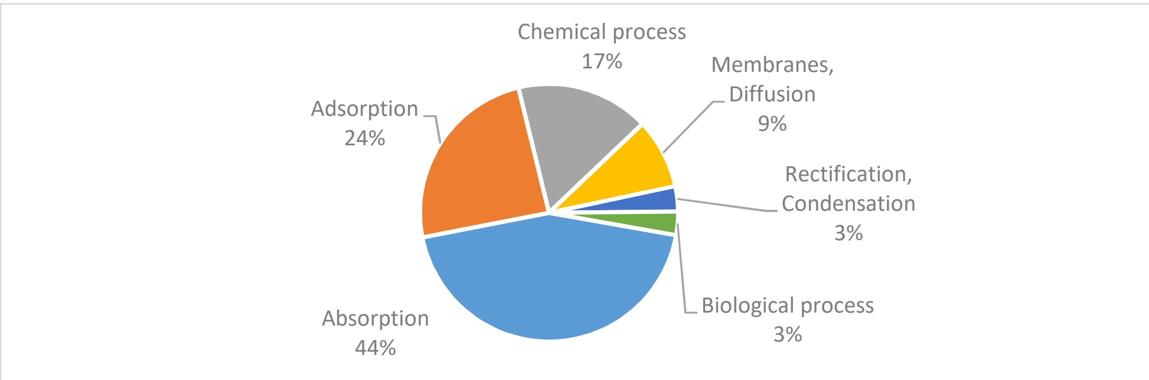
FutureBridge has analyzed 11000 patents related to pre-combustion carbon capture. Image 18 provides the distribution of patents to carbon capture technologies. The absorption and adsorption-based carbon capture technologies account for ~70% of total patents.

Figure 28. Patent publication trend for pre-combustion carbon capture method



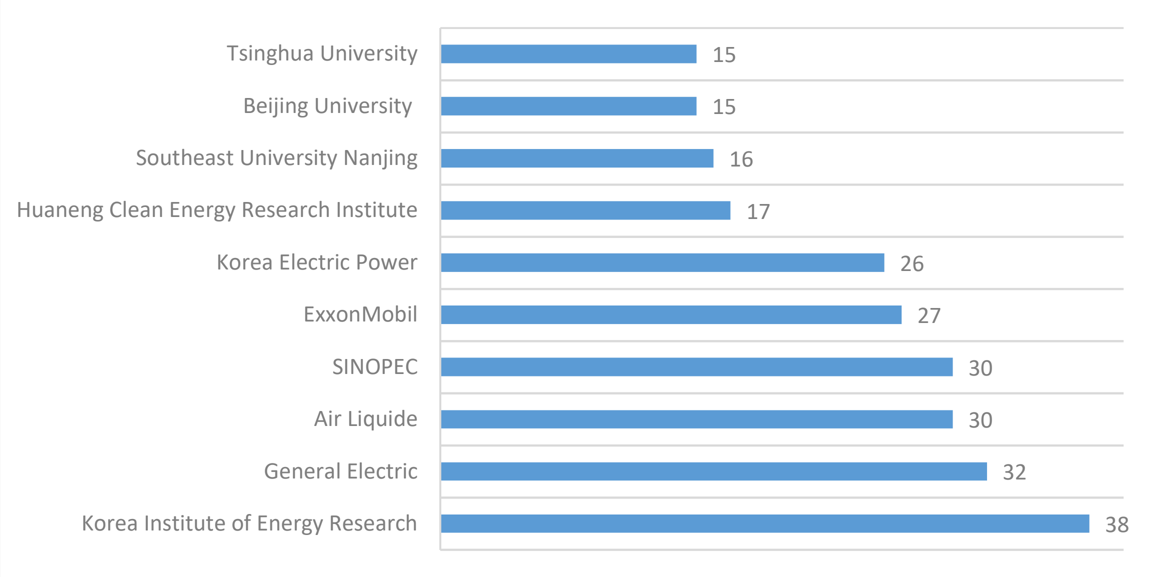
Pre-combustion carbon capture methods:

Figure 29. Carbon capture methods distribution in pre-combustion technology



The top 10 patent assignee in pre-combustion carbon capture process:

Figure 30. Top 10 patent assignee in the pre-combustion carbon capture process



FutureBridge has analysed patent filings by these top 10 players to understand their key research areas related to carbon capture. Patent citation data is used to highlight valuable patents for these top 10 players.

Korea Institute of Energy Research: Most preferred patent filed by KIER related to carbon dioxide absorbent based on natural biomass, alkali metal or alkaline earth metal component such as self-contained for natural plant kind biological material calcium (Ca), magnesium (Mg), potassium (K), apply as carbon dioxide absorber purposes, efficiency is high, the preparation method of the carbon dioxide absorber of low cost.

General Electric: Most of the patent filed by Alstom Technology is related to the use of absorption for CO_2 removal during the combined cycle power plant. These patents disclose the use of amine or chilled ammonia as a solvent for carbon capture.

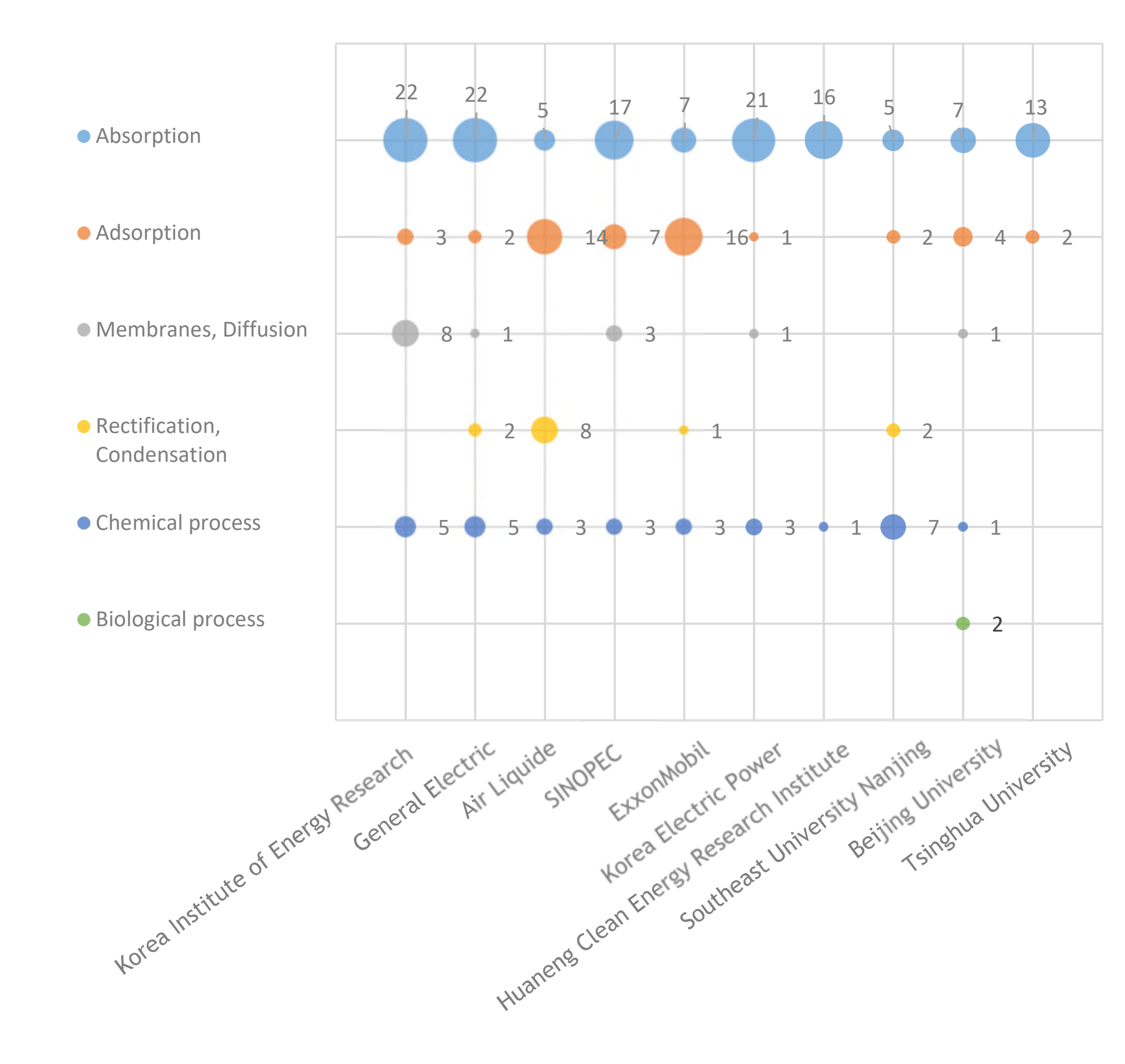
Air Liquide: Most of the patents filed by Air Liquide are related to adsorption and absorption technologies for removal of CO_2 from syngas. The most important patent is focused on hydrogen production with reduced emission of carbon dioxide emissions. It is related to the use of a combination of water gas shift reaction and pressure swing adsorption unit.

SINOPEC: The most preferred patent by SINOPEC discloses solid adsorbent for removing CO_2. The solid adsorbent is composed of a porous solid carrier and a loaded object. The porous solid carrier comprises activated carbon, molecular sieve, silica gel, alumina, hydrotalcite, derivatives of hydrotalcite, and metal-organic framework compounds (MOFs). The loaded object is composed of the main agent and an auxiliary agent.

Korea Electric Power: The major focus area is the use of absorption technology for capture of CO_2 in IGCC power plant. The patent focused on a combined power generation system with CO_2 capture has received maximum attention.

Tsinghua University: All of the patent filings by Tsinghua University are focused on the development of a new solvent for the absorption process. The invention related to the use of organic amine loaded solid porous medium for carbon dioxide removal has received maximum attention.

Figure 31. Top 10 players patent publication trend



2.2.5.3. Oxy-fuel Combustion

Figure 32. Patent publication trend for geography

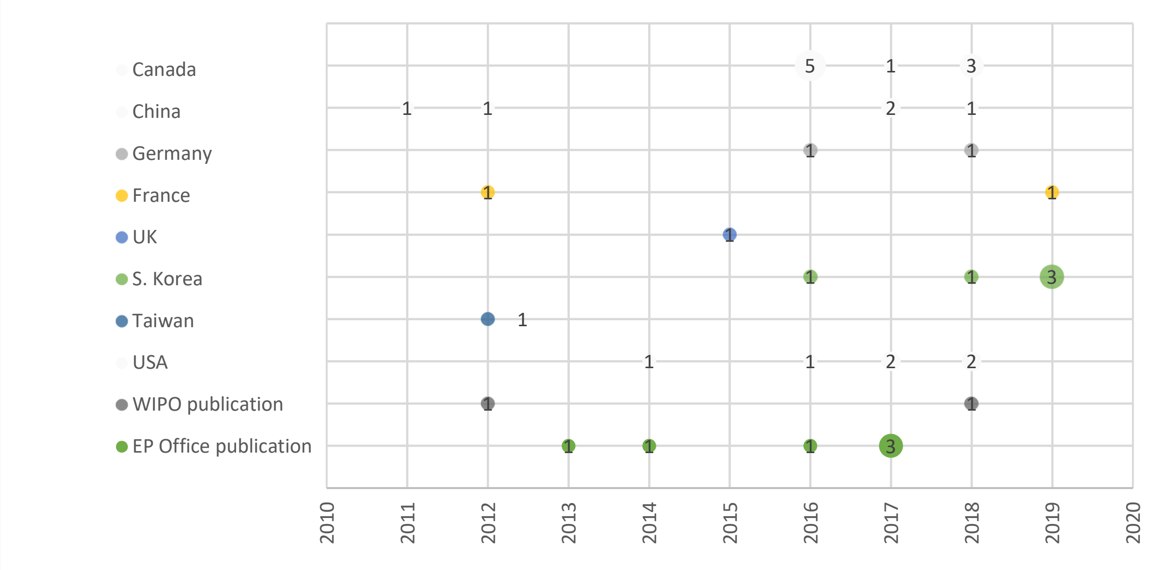
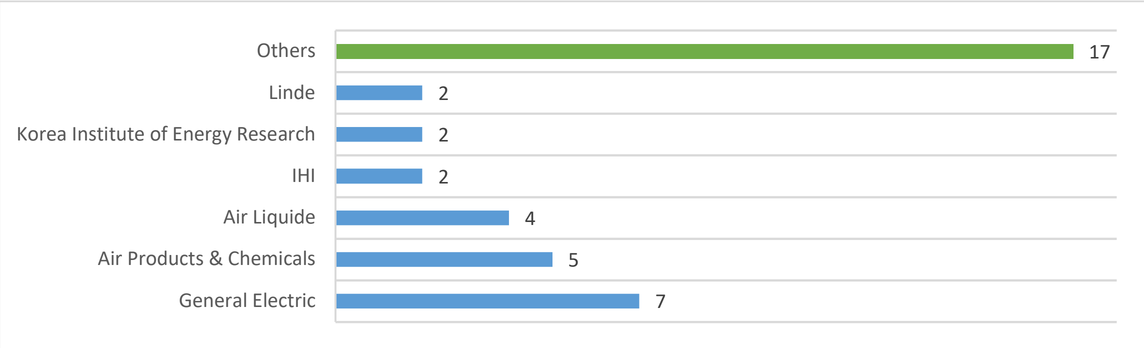


Figure 33. Patent applicants in Oxy-fuel combustion technology



Oxy-fuel combustion is a promising and relatively new technology to facilitate CO_2 capture. In 2001 the Swedish power company Vattenfall AB, Europe's third-largest power company, began a comprehensive RD&D program into oxyfuel combustion, which it had identified as the preferred option for lignite-fueled plants. Vattenfall generates >40% of its power from fossil fuels, and the program aimed to develop oxyfuel technology for full commercial deployment by 2015[70].

The analysis shows that General Electric, Air Products & Chemicals, Air Liquide, Linde are developing technology around oxy-fuel combustion.

[70] https://www.sciencedirect.com/topics/engineering/oxyfuel-combustion

2.3. SCIENTIFIC LITERATURE

Figure 34. Scientific literature publication trend

Figure 35. Top 10 publication country

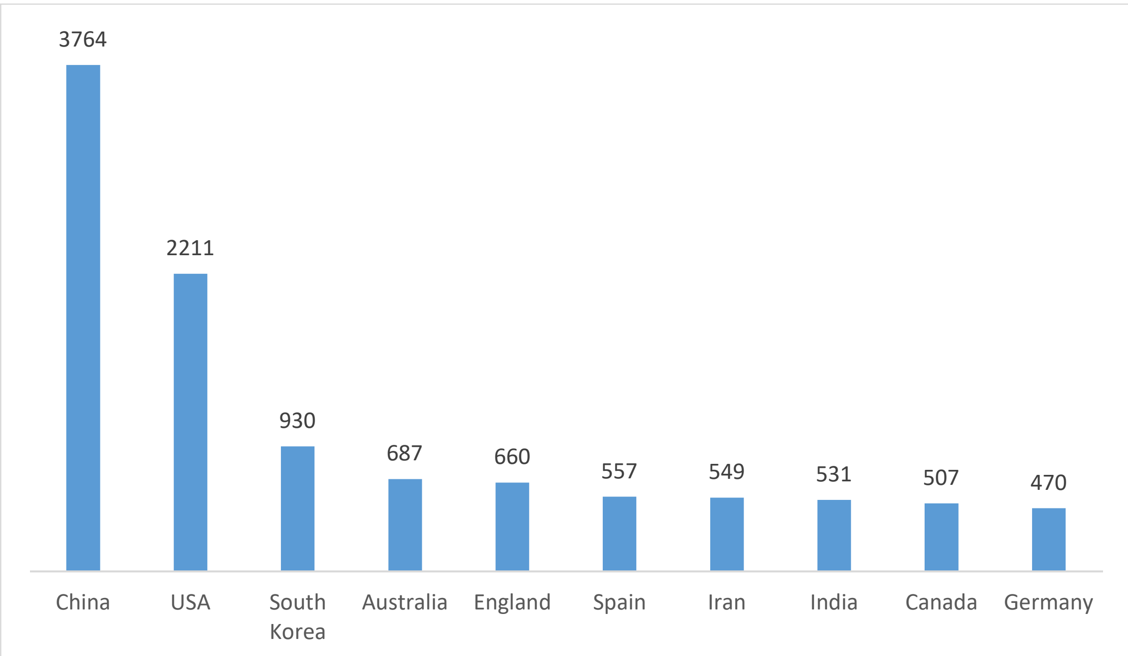


Figure 36. Distribution of scientific literature with respect to capture technology

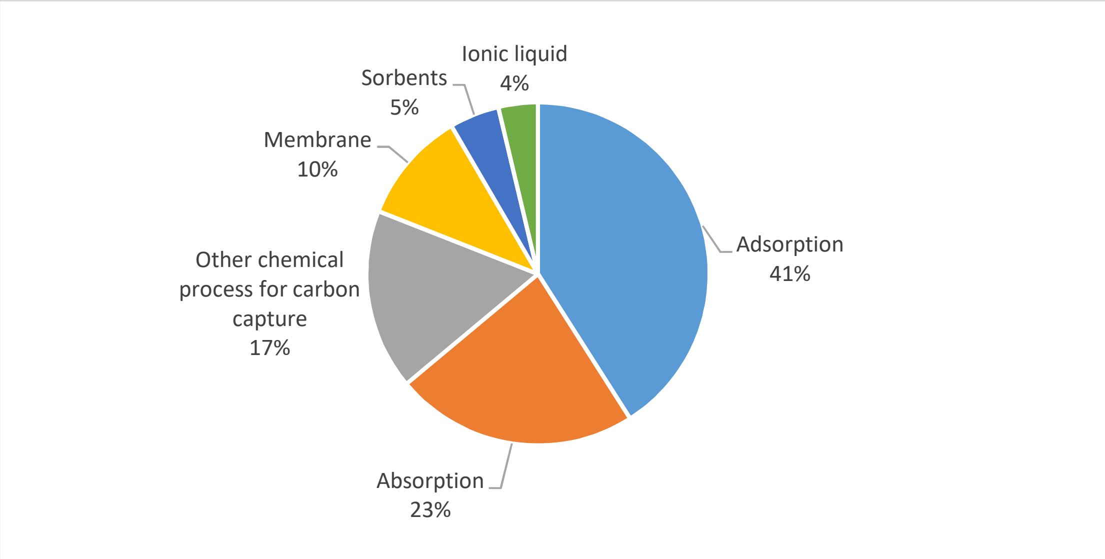
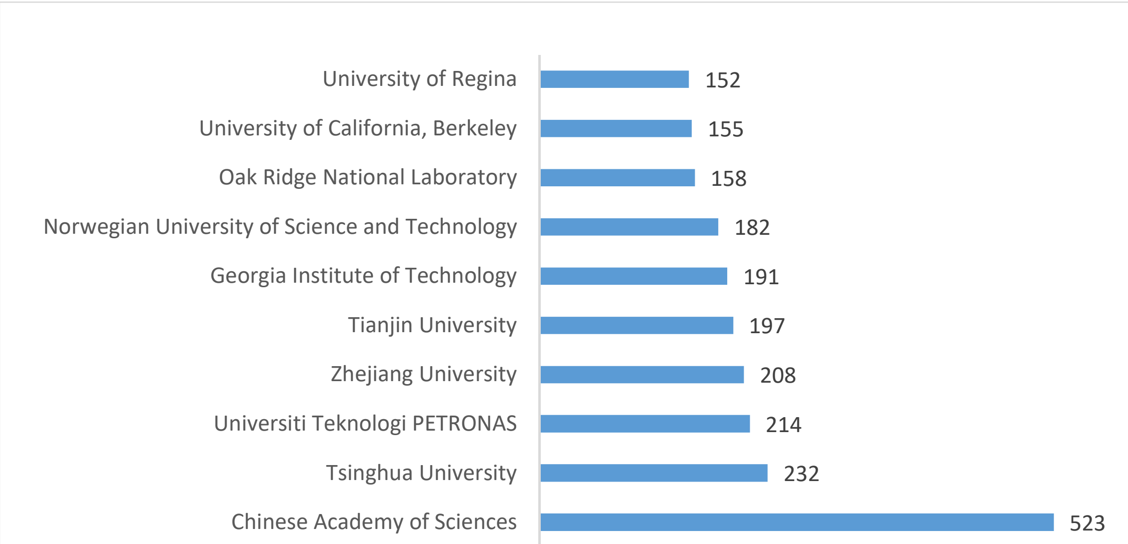


Figure 37. Top 10 publishers

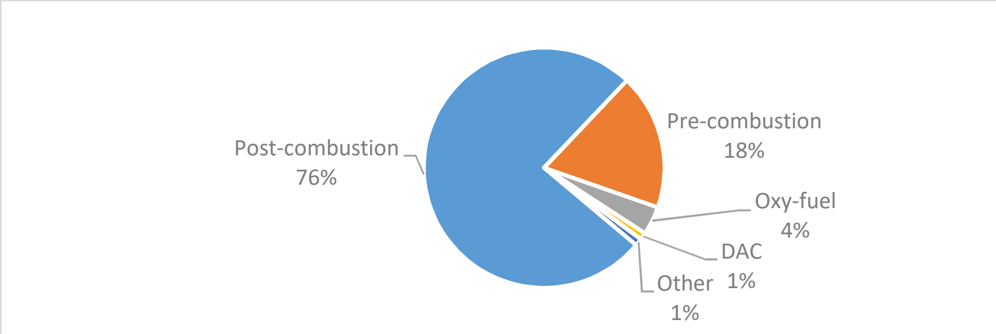


2.4. EMERGING TECHNOLOGIES

This section talks about recent developments and advancements in CCS technology. FutureBridge has referred to various websites, such as Community Research and Development Information Service (CORDIS) and National Energy Technology Laboratory (NETL, USA), in addition to databases to identify emerging carbon capture technologies. FutureBridge has also conducted searches based on patents and scientific literature. The basic objective is to identify technologies that are falling under the Technology Readiness Level (TRL) 5. FutureBridge is following the European standard[71] to assess the technology maturity level.

[71] https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

Figure 38. Carbon capture technology with respect to combustion type



Till now, FutureBridge has identified 100 technologies that are claiming to be innovative carbon capture processes. Further analysis showed that most of the emerging CCS technologies are falling under the post-combustion process, where solvent and sorbent capturing methods are the preferred mode of capturing carbon. For the pre-combustion process, comparatively fewer numbers of technologies are being developed by research organizations.

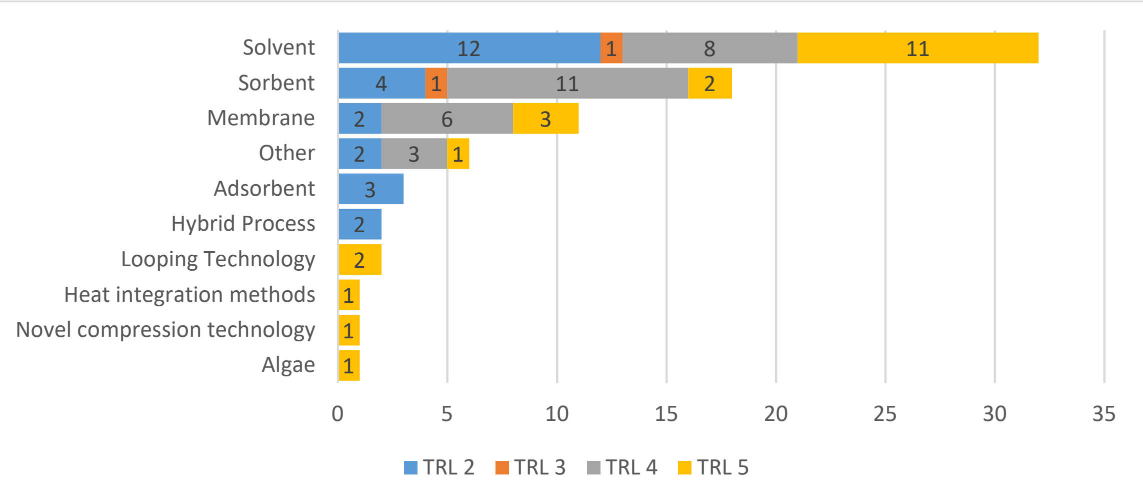
2.4.1. Post-combustion Technology

This section provides a detailed analysis of the innovative post-combustion technologies identified during the study. **Figure 39** highlights the distribution of these innovative technologies as per the separation principle and highlights the technology maturity level of respective technologies. Solvent-based separation accounts for ~50% innovative technologies. Sorbent and membrane-based technologies are also being explored as alternatives to the solvent separation process. It is observed that the solvent-based separation process accounts for a major share of innovative technologies falling under the post-combustion category. Solvent-based technologies are further segregated based on the type of solvent used for carbon dioxide capture as mentioned below:

- **Novel amines/modification to existing amine solvents:** It is based on **Activated Methyl Diethanolamine (aMDEA)** solvent that uses piperazine as a catalyst to increase the speed of the reaction with CO_2. Linde and BASF are designing, building, and operating a 1 MWe pilot plant at the National Carbon Capture Center (NCCC). The post-combustion capture technology aims to reduce the regeneration energy requirements using BASF's OASE® blue technology (aMDEA solvents) that are stable under coal-fired power plant feed gas conditions. The technology developer claims that this technology can address the key drawbacks, such as high-specific energy for regeneration, lack of stability toward thermal and oxidative degradation, and increased corrosiveness with increased carbon dioxide loading in the large-scale application of monoethanolamine for flue gas carbon capture technology.
- **Carbonate solvent:** It is based on **ammonia and potassium carbonate-based mixed-salt** solvent. SRI International has demonstrated this technology with partners, Aqueous Solutions ApS, Politecnico di Milano, Stanford University, OLI Systems, and IHI Corporation, at bench scale. The mixed-salt of ammonia and potassium carbonate maintains the high CO_2 loading and enhanced absorption kinetics, delivering high-pressure CO_2 in a solids-free system.

- **Non-aqueous solvent/phase change solvent:** It is based on amino silicone. GE Global Research is developing an amino silicone-based process for a phase-changing CO_2 capture solvent for use in post-combustion capture in coal-fired power plants.
- **Ionic liquids:** It is based on alkanolguanidine organic liquids, silyl amine-based ionic liquids, amine solvent in ionic liquid, etc. Major technology players in these areas are the University of Notre Dame, Georgia Tech Research Corporation, and ION Engineering, LLC.

Figure 39. Number of carbon capture methods in post-combustion process and respective TRLs



Sorbent-based carbon dioxide capture technologies are also being explored as alternative solvent-based capture technologies. FutureBridge has identified a total of 18 sorbent-based innovative technologies. Sorbent-based technologies are further categorized based on the type of material used for the absorption of carbon dioxide as mentioned below:

- **Amine impregnated sorbent:** It is based on solid sorbents, wherein the carbon-based sorbent is impregnated with an alkali carbonate salt and an active promoter. The University of North Dakota (UND) and Envergex LLC are developing this technology for coal-fired plants. The University of Akron is developing this technology by impregnating porous silica, alumina, zeolite, and carbon with alkyl amine molecules, such as monoethanolamine /tetraethylenepentamine.
- **Alumina or alumina derived material:** It is based on alkalized alumina sorbent for post-combustion capture technology. TDA Research Inc., developed this technology with partners, the University of California at Irvine, Clariant, Babcock and Wilcox, Louisiana State University, and Western Research Institute. The project involves designing and operating a slipstream 0.5-MWe pilot-scale process for post-combustion CO_2 capture at NCCC.
- **Metal-organic framework:** MOFs typically consist of a transition metal that is attached three-dimensionally to other metal vertices by organic linker molecules. They are having an extremely high surface area, microporous, crystalline, and thermally stable materials that have shown exceptional storage capacity for CO_2. It is reported that after removal of the reaction solvent, the resulting porosity can be adjusted by simply changing the length

or composition of the molecules used to link the metal vertices. UOP LLC is developing MOF-based sorbents with partners, such as the University of Edinburgh, University of Michigan, Vanderbilt University, and Northwestern University. MOFs-enabled adsorbents will be utilized in a vacuum pressure swing adsorption process for removal of CO_2 from flue gas.

- **Advanced carbon materials:** It is based on graphene and carbon nanotubes materials.
- **Zeolites:** It is based on solid sorbents.

FutureBridge identified a total of 11 membrane-based innovative technologies. Most of these technologies are focused on the use of polymeric membranes or composite membranes for the separation of carbon dioxide. It is also observed that some of the technologies identified during the study focus on the reduction of cost or energy requirement for conventional post-combustion technologies. Researchers at Southern Company Services and Southwest Research Institute are exploring novel heat integration and compression processes, respectively.

2.4.1.1. TRL for Post-combustion Carbon Capture Technologies

FutureBridge has assessed the TRL for post and pre-combustion carbon capture technologies based on published reports, press releases, announcements, patents, and scientific literature documents. FutureBridge has referred carbon capture and sequestration project database provided by NETL/DoE, Global CCS Institute, MIT, company webpage, and web searches. Comparison for each patent with respect to TRL is not possible; although, FutureBridge have tried to establish the link between the patents by filed by top assignees. We also looked at the patent priority date and current status of technology maturity to link the patent and TRL. FutureBridge's analyst hypothesis is that consistent patent activity indicates follow up research activity and an indication of movement towards commercialization; However, we can look at the European players (both corporate and academia) and see what is their TRL level.

Table 22. Major technology developers in post-combustion carbon capture, developed technology, and respective TRL

Capture Method	Major Technology Developers	Technology Name	TRL
Solvent	▪ Fluor Corporation	Monoethanolamine	9
Solvent	▪ Fluor Corporation ▪ Huntsman Corp.	Methyldiethanolamine	9
Solvent	▪ Fluor Corporation	Diglycolamine	9
Solvent	▪ Mitsubishi Heavy Industries	Hindered secondary amine	9
Solvent	▪ Aker Solution	Blend of amine	9
Solvent	▪ BASF ▪ Shell	Activated MDEA	9
Solvent	▪ Carbon Clean Solutions Limited	APBS-CDRMax™, amine-promoted buffer salt	9
Solvent	▪ GE (Alstom chilled ammonia process)	Chilled ammonia	6
Solvent	▪ GE	Aminosilicone	5

Capture Method	Major Technology Developers	Technology Name	TRL
Solvent	▪ University of Notre Dame ▪ Georgia Tech Research Corporation ▪ Pacific Northwest National Laboratory ▪ University of Dortmund ▪ ION Engineering ▪ Imperial College London	Ionic liquids	1
Solvent	▪ IFPEN ▪ University of Dortmund ▪ The University of Illinois at Urbana-Champaign	Biphasic solvents	4
Solvent	▪ University of Illinois Urbana-Champaign Babcock and Wilcox ▪ Lawrence Livermore National Laboratory	Encapsulated solvents	2 to 3
Membranes	▪ Membrane Technology Research Inc. ▪ Air Liquide S.A. ▪ SINTEF Norway ▪ Research Triangle Institute ▪ Twente University ▪ New Jersey Institute of Technology	Polymeric membranes	6 to 7
Membranes	▪ Honeywell UOP ▪ Grace ▪ Svante	Solid sorbents: Vacuum Pressure Swing Adsorption	3
Solid sorbents	▪ Kawasaki Heavy Industries, Ltd	Amine catalysed adsorption process	6
Solid sorbents	▪ Massachusetts Institute of Technology ▪ Siemens ▪ Topchiev Institute of Petrochemical Synthesis, Russia	Electrochemically Mediated Adsorption	1
Others	▪ CO_2 Solutions ▪ Novozymes	Enzyme catalysed absorption	6
Others	▪ ENI ▪ Idaho National Lab	Algae-based	3
Others	▪ Shell Global Solutions ▪ GE ▪ University of Eindhoven ▪ MINES ParisTech	Cryogenic Capture	4

Biphasic Solvents

In May 2019, the "3D" project (DMX™ demonstration in Dunkirk), a part of Horizon 2020, the European Union's research and innovation program, launched to test the biphasic solvents under real process conditions as part of the OCTAVIUS project (FP7, 2007-2013)[72]. This H2020 project has a €19.2 million budget over 4 years (2019-2023), including a consortium of 11 European stakeholders such as IFPEN, ArcelorMittal, Axens, Total Greenflex, RWTH, DTU, ACP, CMI, Gassco, and Brevik Engineering.

[72] https://cordis.europa.eu/project/id/838031

This project will be demonstrating IFP Energies Nouvelles' DMX^{TM} CO_2 post-combustion capture technology in Arcelor Mittal Atlantique et Lorraine's Dunkirk (FR) steel mill on an industrial pilot plant (0.5 tCO_2/hr.) to achieve the current TRL from 4 to 7.

The DMXTM technology is developed by IFP Energies Nouvelles (IFPEN) and licensed by PROSERNAT, which uses a phase change solvent73. The DMXTM technology is based on the use of specific solvents (a blend of amines) which form two immiscible liquid phases above the critical solubility temperature when CO2 is absorbed. It is interesting to note that the light phase is almost free of CO2, and, only the high capacity heavy phase is sent to the stripper, which makes energy savings possible.

FutureBridge observes that several groups are investigating two-phase liquid solvents, the most prominent is the University of Illinois at Urbana-Champaign[74], USA, and University of Dortmund, Germany, that have been developing their 'Biphasic Solvent' for several years.

FutureBridge observes that the IFP DMXTM technology, the most developed process within biphasic solvents group, did not progress to the planned industrial plant pilot test at Enel's Brindisi pilot plant, Italy, due to cancellation of large scale demonstration plant, and no other pilot references have been identified during the investigation of this study, hence it appears that this technology is at TRL 4. This technology was being tested at a pilot plant under real process conditions as part of the OCTAVIUS project[75].

Ionic Liquids

Ionic liquids, inorganic or organic salts, are considered as a potential solvent for post-combustion CO_2 capture because they have low vapour pressures, high physical and chemical CO_2 solubility, and high stability, thus resulting in low losses and reduced environmental impact, when compared to conventional amine-based solvents. From a commercial perspective, FutureBridge concludes that ionic liquids remain as TRL 1 till now, since ionic liquids can struggle to compete with conventional absorption systems because their absorption capacity is likely to be much lower, and it could also be linked with ION Engineering that has moved away from a pure ionic liquid approach to a blend of amines technology[76]. Several groups that are developing this technology, such as the University of Notre Dame, Imperial College London, University of Dortmund, and several universities in China have been focusing on improving ionic liquids. Interestingly, Georgia Tech Research Corporation has been developing reversible ionic liquids[77] for several years and DowDuPont is also looking at CO_2 solubility and phase behaviour for different ionic liquids.

Amine-promoted Buffer Salt

Carbon Clean Solutions Limited (CCSL) has developed a CDRMax™ process that is based on amine-promoted buffer salt solvent for post-combustion CO_2 capture technology. The UK Department of Energy & Climate Change (DECC) and the US Department of Energy-funded this technology. CCSL's CDRMax™ technology has been demonstrated globally at industrial power plants in the UK, Netherland,

[73] https://hal-ifp.archives-ouvertes.fr/hal-01740300
[74] https://www.netl.doe.gov/sites/default/files/netl-file/Carbon-Capture-Technology-Compendium-2018.pdf
[75] https://www.sciencedirect.com/science/article/pii/S1876610214024771
[76] https://www.osti.gov/servlets/purl/1484045
[77] https://www.netl.doe.gov/sites/default/files/netl-file/Carbon-Capture-Technology-Compendium-2018.pdf

Germany, Norway, India, and the USA[78]. The solvent has also been tested at both the National Carbon Capture Centre, USA, and the Technology Centre Mongstad, Norway, and the results show that CDRMax™ was less corrosive and had a lower specific reboiler duty than 30 wt.% MEA, with low emissions and was resistant to oxidative degradation. CCSL has showcased CDRMax™ technology at the world's largest commercially funded industrial-scale carbon capture and utilisation plant in Tuticorin, India[79].

Encapsulated Solvent

The encapsulated solvent technology is a new concept in which the operating fluid, such as amines or carbonates are enclosed in a thick polymer shell-like silicone shells forming 220- 400 µm beads. The beads then are intended to dramatically increase the surface area of the solvent in contact with the flue gas. A team of researchers from the University of Illinois Urbana-Champaign, Babcock and Wilcox, and Lawrence Livermore National Laboratory are developing this technology[80]. The Lawrence Livermore National Laboratory claims that they have developed two polymer formulations that show promise as shell materials for a range of ionic liquids and CO_2-binding organic liquids. They have made the first demonstration of an encapsulated ionic liquid for carbon capture technology, however, they concede that the current formulation of the encapsulated solvent does not quite meet the required criteria as a good match for shell material and solvent[81].

Precipitating Solvents

Solvents such as potassium carbonate, chilled ammonia, amino silicone, and amino acid salts precipitate out of solution when reacted with CO_2. The precipitating solvents need a lower energy requirement for solvent regeneration and thus makes it possible to regenerate the precipitated solvent at a higher pressure than can result in energy savings from CO_2 compression. FutureBridge observes that the most widely used commercial hot potassium carbonate process was licensed by Universal Oil Products (UOP) to Honeywell (now Honeywell UOP) and is known as the UOP Benfield™ Process and is the most mature technology for precipitating solvents[82]. Apart from this, Alstom (now part of GE) has developed the chilled ammonia process with precipitation but GE is currently operating their pilot plants without precipitation.

General Electric Global Research has developed a non-aqueous amino silicone solvent (GAP-1m) for post-combustion carbon capture technology over the last 8 years. This technology pilot testing results have shown increased CO_2 working capacity, lower volatility, and corrosivity than the benchmark aqueous amine technology. The performance of GAP-1m solvent was demonstrated in a 0.5 MWe pilot at National Carbon Capture Center with real flue gas for over 500 hours of operation using a steam stripper column[83].

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[78] https://www.aiche.org/system/files/aiche-proceedings/conferences/404771/papers/486212/P486212.pdf

[79] https://carboncleansolutions.com/media-center/news/article/2020/02/carbon-clean-solutions-attracts-16-million-growth-capital-from-a-consortium-of-global-investors-

[80] https://www.netl.doe.gov/sites/default/files/netl-file/Carbon-Capture-Technology-Compendium-2018.pdf

[81] https://pubs.rsc.org/en/content/articlelanding/2016/fd/c6fd00049e/unauth#!divAbstract

[82] https://www.uop.com/?document=benfield-process-datasheet&download=1

[83] https://www.osti.gov/servlets/purl/1414342

Enzyme Catalysed Absorption

Enzymes can be used as an activator to accelerate the CO_2 absorption process in potassium carbonate (carbonate/bicarbonate) solvents. However, the pure carbonate/bicarbonate solvent has limitations on the CO_2 absorption rate. In the enzyme-catalyzed absorption process, the enzymes are clustered together in a cross-linked enzyme aggregate and then filtration is used to separate the enzyme from CO_2 rich solvent before the solvent is sent for CO_2 regeneration. **Currently, CO_2 Solutions[84] and Novozymes[85] are developing their proprietary enzymes for CO_2 absorption processes, and CO_2 Solutions technology has reached TRL 6[86].**

Algae Based

FutureBridge assesses that the technology readiness level of algae-based carbon capture technology and it has reached TRL-3. However, challenges such as the large volume of algae required for a commercial power plant still exist.

Italian Oil and Gas Company, Eni is running the first carbon capture and utilization project aimed at capturing carbon dioxide emissions on an industrial scale using algae and also conducted a field experiment of CO_2 uptake by algae in a raceway pond [87]. Duke Energy and partners, with $1.8 million in funding from the Kentucky Energy and Environment Cabinet, have a project to test a pilot-scale algae system at East Bend Station, Kentucky, to demonstrate an algae-based system for CO_2 mitigation from coal-fired power plants[88].

Membrane

A lot of research and development work has conducted around improvements in membranes for post-combustion CO_2 capture technology. Several groups are developing polymeric membrane technology for post-combustion carbon capture, for example, Norwegian University of Science and Technology patented polyvinyl amine membrane[89] together with fixed amine groups, is evaluated at a pilot plant at an EDP power plant in Portugal.

Membrane Technology Research Inc. (MTR) is testing its innovative Polaris™ membranes at the various testing center since 2006[90]. MTR is also evaluating a hybrid membrane-absorption process system based on a combination of Polaris™ membranes and an amine solvent-based capture system. Other organizations such as Air Liquide S.A., SINTEF Norway, Twente University, Research Triangle Institute, and New Jersey Institute of Technology are active in this area. The challenges involved in CO_2 capture via membrane are the low concentrations of CO_2 present in the large volumes of flue gas, and the high purity required as well.

FutureBridge has observed several pilot plant tests at a large scale and the deployment of membranes in other applications, therefore, FutureBridge has assigned TRL 6 to 7 to membranes technology.

[84] https://co2solutions.com/enzyme
[85] https://www.novozymes.com/en/news/news-archive/2011/09/carbon-capture-doe-funding
[86] https://co2solutions.com/historique
[87] https://www.eni.com/en-IT/operations/carbon-dioxide-biofixation.html
[88] https://caer.uky.edu/pilot-scale-algae-system-at-duke-energys-east-bend-station
[89] https://patents.google.com/patent/US8764881B2/en
[90] https://www.netl.doe.gov/sites/default/files/netl-file/MTR-Kickoff-Presentation-Public-FE0031587-FOA1788.pdf

Solid Sorbents

Solid sorbents have been proposed for post-combustion CO_2 capture technology in a large number of different systems, such as in fixed beds, circulating fluid beds, and rotating fixed beds, utilizing pressure or temperature swing adsorption, chemical reaction and as supports for amines or enzymes. Solid sorbents are also used for chemical looping, pre-combustion and oxy-combustion CO_2 capture technologies.

The well-proven pressure and temperature swing adsorption processes have been in use for other industrial applications for many years, such as for hydrogen purification and dehydration of gases. It is mostly made up of multiple fixed beds, with one or more beds operating in adsorption mode, while other beds are being regenerated. When pressure and temperature swing adsorption process is applied to post-combustion CO_2 capture technology, they are inherently challenged by the need for a large volume of hot, and low-pressure flue gas before feeding it to multiple trains of fixed beds, and a large quantity requirement of the adsorbent.

Mostly zeolites are used in the Vacuum Pressure Swing Adsorption Process (VPSA), however, other improved adsorbents such as metal-organic framework, zeolite imidazolate frameworks and carbon-based materials with a higher surface area are being developed. This technology is best suited to flue gases with concentrations greater than 10% to try and limit the necessary bed volumes. **Zeolites based adsorbents have been developed by Honeywell UOP, Grace, and University of Oslo. Major industrial gas companies, such as Linde, Air Products, and Honeywell UOP, are setting up VPSA plants.**

Since the solid sorbents concept has been proven, FutureBridge still believes that many factors are remaining to validate the process for post-capture CO_2 commercial use, hence, this technology will fall under a TRL 3. FutureBridge did not find any recent developments in the public domain related to this.

There is only one large scale CCS pilot plant in operation since 1991, which is a dual pressure and temperature swing adsorption process reported at the Tokyo Electric Power Company[91].

Companies such as Inventys Inc. (changed its name to Svante Inc., in 2019)[92] has patents for a monolith concept, a TSA process, but with very different physical form. The TSA technology uses a rotary bed adsorption system, which is referred to as a “rotary adsorption machine” with the trademark “VeloxoTherm™. Svante is using nano-materials based solid adsorbents with very high storage capacity for CO_2.

On February 6, 2020, Svante Inc. announced that Chevron Technology Ventures commissioned a pre-front end engineering design study that will explore the potential for trialling Svante’s technology in Chevron’s operations. The study will evaluate the feasibility and design of a 10,000 tonne-per-year CO_2 capture in one of Chevron’s California facilities[93].

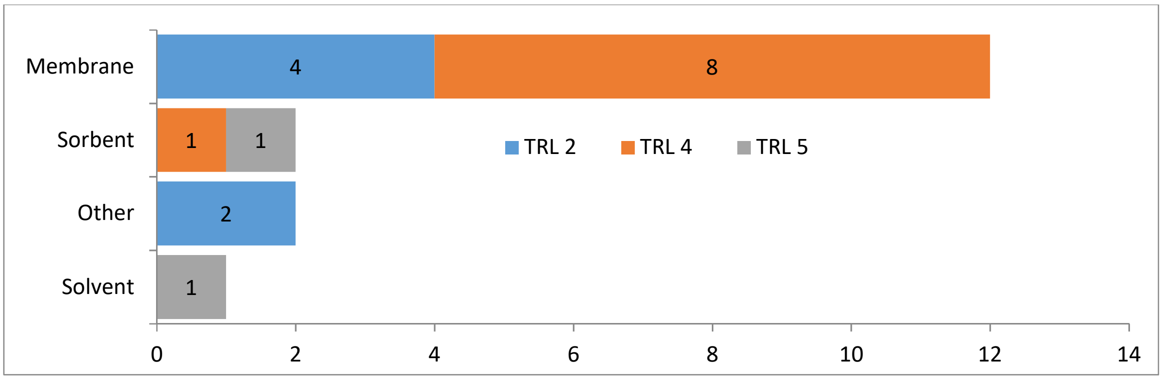
In addition to this, several technology developers are making use of the chemical affinity of amines with CO_2 combined with a solid adsorbent. Kawasaki Heavy Industries, Ltd. has developed a solid adsorbent, based on amine-coated porous

[91] https://pdfs.semanticscholar.org/1858/7751f1ca2a1a03e5ef0448ea190d8cfa050e.pdf
[92] http://svanteinc.com/inventys-a-leading-developer-of-commercially-viable-economically-scalable-carbon-capture-technology-changes-name-to-svante-inc/
[93] http://svanteinc.com/svante-and-chevron-technology-ventures-launch-study-for-carbon-capture-pilot-unit/

material that enables selective CO_2 adsorption for post-combustion technology. This technology called Kawasaki CO_2 Capture (KCC) and tested the technology at a 10 tonne CO_2 per day test plant, on coal-fired flue gas. The test results showed that half the thermal energy is required for its KCC CO_2 capture compared with MEA[94]. Since Kawasaki has been operating a 10 tonne CO_2 per day test plant, FutureBridge concludes that the amine catalyzed based adsorption process has reached at TRL 6.

2.4.2. Pre-combustion

Figure 40. Number of carbon capture methods in pre-combustion process and respective TRLs



FutureBridge identified a total of 17 innovative technologies for pre-combustion capture of carbon dioxide. Membrane-based technologies account for approximately 70% share of the total pre-combustion capture technologies. **Figure 40** highlights the technology maturity level for the identified technologies.

A total of 12 membrane-based innovative technologies has been identified until now for pre-combustion capture of carbon dioxide. The intrinsic trade-off between permeability and selectivity is one of the limitations of using polymer membranes in the post- and pre-combustion CO_2 capture. Barriers for membrane development for CO_2 capture include a) enhanced material permeability and selectivity for CO_2; b) enhanced material performance under operating conditions such as elevated temperature or pressure; c) high resistance to contaminants including water, sulfur species, or particulates; d) better compatibility between composite membrane materials, and e) superior performance for separation.

Technologies classified based on the type of polymer used for manufacturing membranes are listed as follows:

- Polymer membrane
- Pd membranes/Pd incorporated membranes
- Zeolite membranes
- Ceramic membranes

Polymers such as Polybenzimidazole, Polyetheretherketone, and Polytetrafluoroethylene are being used for manufacturing polymeric membranes for carbon dioxide separation.

[94] file:///Y:/1_Live/2019/2019_10387_Technology%20&%20Economic%20Assessment_CCS/3_Operations/2_Searches/Vivek/SSRN-id3365953.pdf

2.4.2.1. TRL for Pre-combustion Carbon Capture Technologies

Table 23. Major technology developers in pre-combustion carbon capture, developed technology, and respective TRL

Capture Method	Major Technology Developers	Technology Name	TRL
Solvent	▪ Honeywell UOP	Hot potassium carbonate	9
Solvent	▪ Honeywell UOP	Dimethyl ethers of polyethylene glycol	9
Solvent	▪ Linde ▪ Air Liquide S.A. ▪ Axens	Chilled methanol	9
Solvent	▪ Fluor Corporation	Propylene carbonate	9
Membranes	▪ SRI ▪ Membrane Technology Research Inc.	Polymeric membrane	8
Solid Sorbents	▪ Air Liquide ▪ Honeywell UOP ▪ Linde ▪ Air Products and Chemicals, Inc.	Solid sorbents, pressure swing adsorption	9
Others	▪ Exxon Mobil Controlled Freeze Zone Technology	Physical separation	7

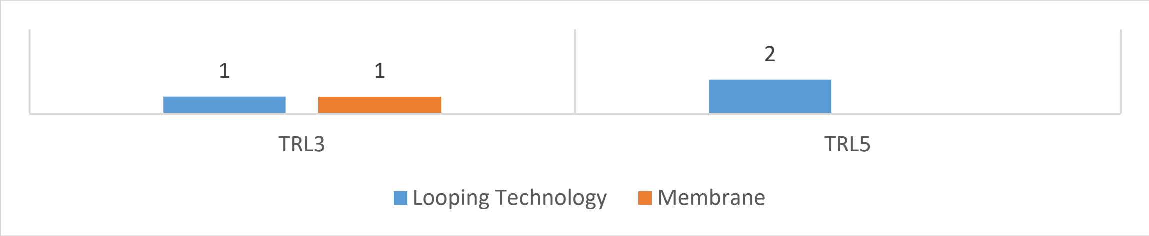
Membranes for CO_2 capture from pre-combustion systems can be placed at several stages in the IGCC or reforming scheme to assist the shift reaction. Such membranes need to withstand high temperatures. Various types of membranes, such as porous inorganic membranes, palladium membranes, polymeric membranes, and zeolites, are currently available for pre-combustion CO_2 capture. **The pilot testing of various membranes has been conducted using a slipstream of a gasifier fuel gas at the National Carbon Capture Center, USA.**

Solid Oxide Fuel Cells (SOFCs) are the emerging CO_2 capture technologies which are having the inherent ability to capture CO_2 while generating electricity. It comprises Integrated Gasification Fuel Cell (IGFC) and Integrated Reforming Fuel Cell (IRFC) systems in which the carbon is removed upstream of a SOFC and does not cover the possibility of using molten carbonate fuel cells' for post-combustion CO_2 capture. The fuel cells themselves are given a technology readiness level of TRL-6 for large scale power generation due to being available at 60 kW scale. FuelCell Energy, Inc. is a pioneer in this field and developing a 200 kW plant system with the support of NETL[95]. The Molten Carbonate Fuel Cells based capture system also looks promising as CO_2 capture systems.

[95] https://netl.doe.gov/sites/default/files/2019-05/2019%20SOFC%20Proceedings/FE1-20th%20Annual%20SOFC%20Workshop%20-%20FCE%20Team.pdf

2.4.3. Oxy-fuel Combustion

Figure 41. Number of Carbon Capture Methods in Oxy-Combustion Process and Respective TRLs



FutureBridge identified four technologies focused on oxy-fuel combustion for **carbon dioxide capture. Chemical looping combustion accounts for 75% of the identified technologies. Most of the identified chemical looping combustion technologies are focused on the use of novel oxygen carriers, such as Cu and Mn metal oxides.** Chemical looping can be applied to capture CO_2, either in post-combustion or pre-combustion systems, where it can be used in combination with a chemical loop to provide oxygen to the gasifier. Oxides of the common transition metals (Fe, Cu, Ni, Mn, and Ba) are possible carriers, with Fe_2O_3/Fe_2O_2, NiO/Ni, and BaO_2/BaO. The fuel oxidation step could be exothermic for Cu, Mn, or Ba carriers or endothermic for Fe and Ni carriers, while the carrier reoxidation step is always exothermic.

Researchers at Forschungszentrum Julich GmbH are exploring the use of Oxygen Transport Membranes (OTM) and the integration of these OTM modules in the power and cement industry. OTMs are commonly made of mixed ionic electronic conductors, such as La0.6Sr0.4Co0.2Fe0.8O3-δ and Ba0.5Sr0.5Co0.8Fe0.2O3-δ, which consist of single-phase membrane materials that have shown exceptional permeability for oxygen. OTM materials are prone to phase instability and carbonate formation on exposure to pure CO_2 under chemical potential gradient at elevated temperatures.

2.5. TECHNO-ECONOMIC ASSESSMENT (TEA) OF IDENTIFIED INNOVATIVE TECHNOLOGIES

Pre-combustion

Research organizations are presently developing new/advanced solvents, including chemical & physical solvents, membranes, and sorbent-based carbon capture technology for integrated gasification combined cycle power plants and industrial manufacturing units, such as hydrogen, chemical, refinery, fertilizers, etc., to meet the **United States Department of Energy (DoE) goals of 90% CO_2 capture and 95% purity[96] at a cost of less than $40/ton (in the 2020-25 horizon) CO_2 captured**[97].

This section provides Techno-economic Assessment (TEA) of various carbon capture technologies. FutureBridge has taken into consideration of the published TEA data sets in the public domain. In some cases, preliminary TEA is published, wherein the availability of data points is limited. **The concentration of CO_2 for each carbon capture technologies are not available in the public domain. It should be noted that no specific mention of the inclusion of CAPEX or OPEX in published documents focused on TEA assessment.**

[96] https://www.osti.gov/servlets/purl/1484045
[97] https://www.energy.gov/fe/science-innovation/carbon-capture-and-storage-research/carbon-capture-rd

Technology Developer: TDA Research, Inc.

Technology: TDA has demonstrated the techno-economic viability of a new sorbent-based (mesoporous carbon with surface functional groups) pre-combustion capture technology for IGCC power plants by conducting field test (slipstream at 0.1 MWe equivalent, 10 kg/hr. CO_2) #1 at National Carbon Capture Center (NCCC): Airblown gasification & field test #2 at Sinopec Nanhua Petrochemical Plant, Nanjing, Jiangsu Province, China: Oxygen blown gasification.

TRL: 5-6

Table 24. Techno-economic analysis of TDA's pre-combustion carbon capture technology[98]

Gasifier	E-Gas		GE	
Case	1	2	3	4
CO_2 Capture Technology	Cold Gas Cleanup Selexol™, TRL above 9	Warm Gas Cleanup TDA's CO_2 Sorbent	Cold Gas Cleanup Selexol™, TRL above 9	Warm Gas Cleanup TDA's CO_2 Sorbent
CO_2 Capture, %	90	90	90	90
Gross Power Generated, kW	710,789	670,056	727,633	674,331
Gas Turbine Power	464,000	425,605	464,000	417,554
Steam Turbine Power	246,789	244,450	257,657	246,746
Syngas Expander Power	-	-	5,977	10,031
Auxiliary Load, kW	194,473	124,138	192,546	120,661
Net Power, kW	516,316	545,917	535,087	553,671
Net Plant Efficiency, % HHV	31.0	34.1	32.0	34.5
Coal Feed Rate, kg/h	220,549	212,265	221,917	213,013
Raw Water Usage, GPM/MW	10.9	10.3	10.7	10.5
Total Plant Cost, $/kW	3,464	3,102	3,359	3,212
Cost of electricity (COE) without CO_2 cost for transportation, storage, and monitoring (TS&M), $/MWh	136.8	122.3	133.0	125.5
COE with CO_2 TS&M, $/MWh	145.7	130.4	141.6	133.4
Cost of CO_2 Capture, $/tonne	43	30	37	31

*GPM: Gallons per minute, *HHV: Higher heating value

[98] https://netl.doe.gov/projects/files/Pilot%20Testing%20of%20a%20Highly%20Effective%20Pre-Combustion%20Sorbent-Based%20Carbon%20Capture%20System%20(FE0013105).pdf

Conclusion: IGCC plant with TDA's CO_2 capture system achieves higher efficiencies (34.5% and 34.1%) than IGCC with Selexol™ (32% and 31%) for E-Gas™ and GE gasifiers.

Technology Developer: SRI International

Technology: Polybenzimidazole (PBI) polymer-based hollow-fibre membrane for pre-combustion CO_2 capture technology. The pilot testing has been conducted at NCCC in April 2017 at 50 kWth scales.

TRL: 5

It is based on the preliminary TEA, whereas, full-scale TEA is likely to happen in 2021.

Table 25. Techno-economic analysis of SRI's membrane-based pre-combustion carbon capture technology[99]

Description	DoE/NETL, Reference case	SRI International, Pilot test
CO_2 Capture Technology	Selexol	PBI membrane
CO_2 Capture Efficiency (%)	92.25	90
CO_2 Stream Purity (%)	99.48	≥ 95.6
Net Plant Efficiency, % HHV	42.1	32.6
COE without TS&M, $/ MWh	135	120
COE with TS&M, $/ MWh	144	130

Post-combustion:

Technology Developer: ION Engineering, LLC

Technology: Ion Engineering developed a novel solvent (blend amine)-based post-combustion carbon capture technology and conducted pilot-scale testing at the National Carbon NCCC's Pilot Solvent Test Unit at 0.6 MWe scale and the Technology Centre Mongstad, Norway at 12 MWe scale.

In the past, ION Engineering developed the ionic liquid-based solvent for CO_2 capture with technology partners and contractors, such as The University of Alabama, Worley Parsons, Energy and Environmental Research Centre (EERC), EPRI, Excel Energy, Evonik, and Elstron R&D. ION Engineering performed pilot plant testing of 0.2 MWe at the EERC in North Dakota in 2012; however, ionic liquids struggle to compete with conventional absorption systems due to their lower absorption capacity. Thus, ION engineering has moved away from an ionic liquid solvent approach to a blend of amines and other constituents.

[99] https://netl.doe.gov/projects/files/Development%20of%20Pre-Combustion%20CO2%20Capture%20Process%20Using%20High-Temperature%20PBI%20(FE0031633).pdf

TRL: 5

Table 26. Techno-economic analysis of ION's solvent-based post-combustion carbon capture technology[100]

Description	DoE/NETL, Reference case	ION, Pilot test
Net Plant Size (MW)	550	550
Annual Capacity Factor (%)	85	85
CO_2 Capture Technology	Aqueous mono-ethanolamine (aq-MEA)	Blend of MEA and water
CO_2 Capture Efficiency (%)	90	90
CO_2 Stream Purity (%)	99.6	≥ 99
Total O&M Cost, $	166,888,000	229,444,000
COE without TS&M, $/ MWh	90	128
COE with TS&M, $/ MWh	90	137
Total Cost of CO_2 Capture with TS&M, $/ton	66	53
CO_2 Capture Cost, $/ton	56	43

Technology Developer: Air Liquide

Technology: Polyimide-based membrane for post-combustion capture combines cold membrane operation with cryogenic separation to reduce the overall cost of capturing CO_2 from flue gas (Power plant). The performance of a polymeric membrane has been validated with > 3,000 hours of testing with real flue gas at NCCC (0.3 MWe scale).

TRL: 5

Table 27. TEA of Air Liquide's membrane-based post-combustion carbon capture technology[101]

Description	DoE/NETL, Reference case	Air Liquide, Pilot test
CO_2 Capture Technology	CO_2 capture with amine adsorption	Polyimide-based membrane
CO_2 Capture Efficiency (%)	90	90
Power Plant Cost (MM$)	1,602	1,440
CO_2 Capture System (MM$)	593	300
COE without TS&M, $/ MWh	111	100
CO_2 Capture Cost ($/ton)	42.2	34

Technology Developer: Linde / BASF

Technology: Activated Methyl diethanolamine (aMDEA) solvent uses piperazine as a catalyst to increase the speed of the reaction with CO_2 for post-combustion carbon capture technology at a coal-fired power plant.

[100] https://www.osti.gov/servlets/purl/1484045
[101] https://netl.doe.gov/projects/files/A-Augustine-AAL-Next-Generation-Hollow-Fiber-Modules.pdf

TRL: 8

Table 28. TEA of Linde's solvent-based post-combustion carbon capture technology[102]

Description	DoE/NETL, Reference case	Linde / BASF, Pilot test
Net Plant Size (MW)	550	550
CO_2 Capture Technology	CO_2 capture with Cansolv amine technology	BASF's OASE® blue technology
CO_2 Capture Efficiency (%)	90	90
Net Plant Efficiency, % HHV	32.5	
COE with TS&M, $/ MWh	143	127
CO_2 Capture Cost ($/ton)	58	43

The carbon capture solution for the cement sector seems to be feasible, and thus, FutureBridge has highlighted the TEA of various carbon capture technologies. The European cement producers are largely involved in CCS activities, mainly as part of a consortium.

Table 29. Key performance indicators[103]

Parameter	Value	Technical KPIs	Economic KPIs
Clinker production	3000 t/day	Emission Abatement • CO_2 capture ratio • CO_2 avoided from flue gas • Equivalent CO_2 avoided	CAPEX (cement plant + CO_2 capture plant)
Clinker/cement factor	0.73	Energy Performance • Specific Primary Energy Consumption for CO_2 Avoided (SPECCA)	CAPEX (CO_2 capture plant)
Raw meal/clinker factor	1.6	Retrofittability • Impact on the cement production process • Equipment and footprint • Utilities and services • Introduction of new chemicals/subsystems • Available operational experiences	Operating costs
Specific CO_2 emissions	850 kg/t_{clk}		Cost of clinker
Specific electric power consumption	97 kWh/tcement		Cost of CO_2 avoided

[102] https://www.netl.doe.gov/project-information?p=FE0031581
[103] https://www.mdpi.com/1996-1073/12/3/542/pdf

Table 30. Technical analysis for capture technologies

	Technology													
	Post-combustion										Oxy-fuel			Other
Parameter	Absorption - MEA		Absorption-AMP-PZ-MEA	Chilled ammonia process (absorption)		Membrane-assisted CO_2 liquefaction	Calcium looping (Tail-end)		Calcium looping (Integrated)		Full oxy fuel		Partial oxy fuel	Direct separation
Carbon capture rate/ capture efficiency (%)	>90	67.2*	>90	90		90	>90		>90		>90	87.1*	65	60**(emission reduction) 85 (with alternate energy sources)
Added equivalent specific primary energy consumption (MJ/t_{clk})	3,959		-	2,401		2,216	3,280		2,528		1,173		-	-
Equivalent specific CO_2 avoided (kg/t_{clk})	559		-	640		687	806		797		719		-	-
Specific primary energy consumption for CO_2avoided - SPECCA (MJ/kg CO_2)	7.08	3.78****	-	3.75	2.43****	3.22	4.07	3.26***	3.17	2.32***	1.63		-	-

Note:

- Energy consumption (MJ/t_{clk}), where clk relates to clinker
- CO_2 concentration in cement kiln flue gases (approximately 15 to 30 mol%), which is higher than the power generation industry (10 to 15% mol%), that provides advantages for capturing CO_2 in cement production

Table 31. TEA of Various Carbon Capture Technologies in the Cement Sector[104]

	Technology							
	Post-combustion					Oxy-fuel		
Parameter	Absorption - MEA	Chilled ammonia process (absorption)	Membrane-assisted CO_2 liquefaction	Calcium looping (Tail-end)	Calcium looping (Integrated)	Full oxy-fuel	Partial oxy-fuel	AMP-PZ-MEA
CAPEX for cement plant + CO_2 capture plant (€$_{million}$)	280 260.25* 440 NB**	353	450	406	424	332 216.6* 291(NB)**	-	
CAPEX for CO_2 capture plant (€$_{million}$)	76 106** (RF-China)	149	247	202	220	128 104(RF)	97-107 (RF)** 113.5*	
Annual OPEX for CO_2 capture plant (€$_{million}$)	76	66	71	59	61	58	-	
Cost of clinker (€/t_{clk})	107.4	104.9	120.0	105.8	110.3	93.0	-	
CO_2 avoided cost (€/t_{CO2})	80.2 51** 107** 143** 86.87*	66.2	83.5	52.4 18** 31** 57.76*	58.6	42.4	49 NB @ DR 8 %**	
Capture cost /tonne of CO_2 (€)	82.97	-	-	-	-	-	-	68.83

104 https://pubs.acs.org/doi/abs/10.1021/acs.est.5b03508

3. CARBON CAPTURE IN REFINERY

The industrial sector represents one-fifth of total global CO_2 emissions. Refining is the fourth largest contributor to CO_2 industrial emissions. Many CO_2 point sources are typically dispersed across each refinery complex. A refinery may contain pure CO_2 sources that allow easy capture at low cost, as well as sources where CO_2 is more diluted. A typical refinery could have between 20 and 30 different interconnected processes around the site. This heating equipment usually uses different types of fuel that are available on-site, thus producing flue gas with a wide-ranging CO_2 composition. The refining sector is responsible for 0.7 $GtCO_2$ out of the 7.1 $GtCO_2$[105].

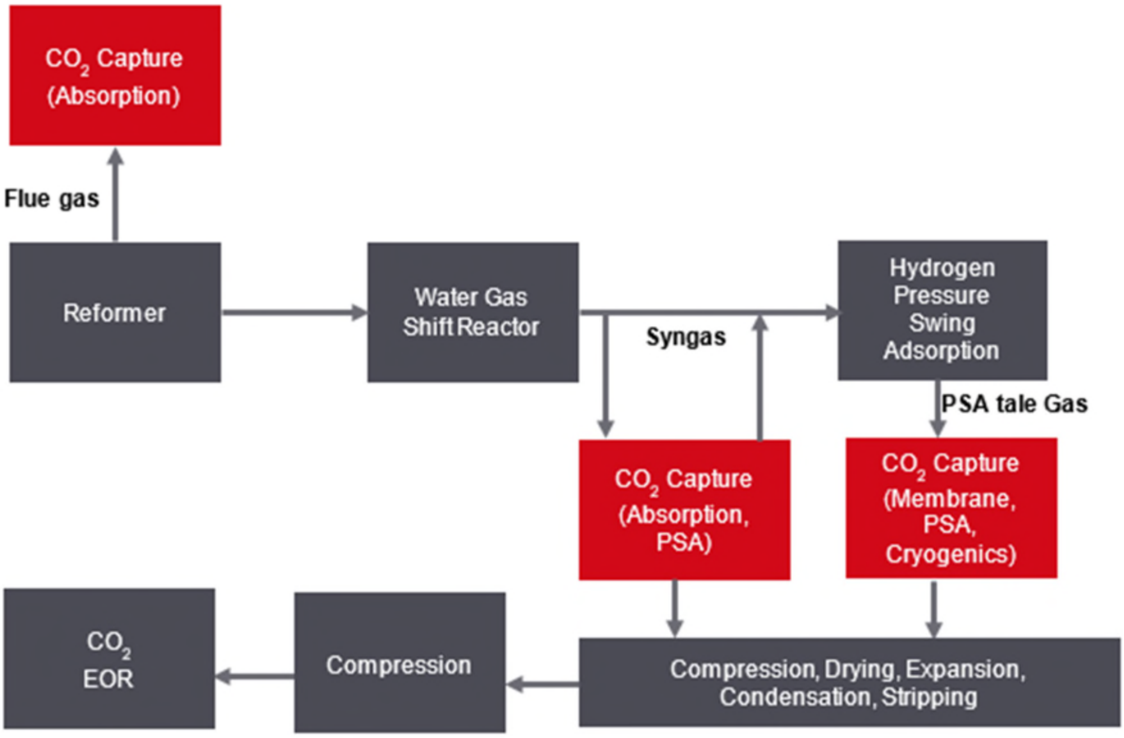
CO_2 emissions from refineries originate from four main sources: Process heaters (30-60%), FCC (20-50%), hydrogen production (5-20%) and utilities (20-50%):

- **Process heaters:** CO_2 capture is a technically feasible option for reducing CO_2 emissions from the refining sector through a range of post-combustion, pre-combustion, and oxy-fuel technologies. It is observed that most of the literatures are focused on the use of post-combustion capture and oxy-fuel combustion for reducing emissions from process heaters in refineries. The adoption of new technologies like chemical looping combustion (CLC) is also being explored with a focus on the development of oxygen carrier and process development. The main barrier to the development of the CLC process is the high cost associated with the process. Oxygen carrier cost also contributes significantly to the total cost of CLC.
- **Fluidized catalytic crackers (FCC):** The literatures identified on carbon capture for fluid catalytic cracking (FCC) unit are also focused on the use of solvent-based post-combustion capture and oxyfuel technologies. Recently, researchers at the University of Nottingham have explored the use of chemical looping combustion for carbon capture from FCC units.
- **Hydrogen production:** Hydrogen production accounts for 5% to 20% of CO_2 emissions from a refinery. Carbon dioxide can be captured from three streams i.e. PSA tail gas, syngas or flue gas. Various technologies are available commercially for capturing the carbon dioxide from these streams as the concentration of carbon dioxide is different in these streams. It is observed that solvent (amine) based post-combustion is preferred for carbon capture from syngas and flue gas stream; and the PSA process is used for carbon capture from syngas and tail gas stream.
- **Utilities:** Post-combustion technologies, being commercially explored for capturing emissions from a power plant, is more suitable to capture carbon dioxide from the utility area.

Table 32 provides an overview of different technologies and their applicability to refinery process units. **Figure 42** highlights pathways for carbon capture for the SMR unit in petroleum refineries.

[105] http://www.enerclub.es/file/39igbUIX1QMuB2ZrJ-Xl7g

Figure 42. Pathways for carbon capture for SMR unit



Pre-combustion technology seems to be applicable only for hydrogen production in refineries at this moment. It can be applied to process heaters and utilities. However, it needs modification in terms of fuels that can be used with these units, and also modification in these units will be required to accommodate the use of hydrogen-rich fuels.

Table 32. Major CO_2 emission sources at a typical refinery complex[106]

Refinery process	Description	Capture methods and conditions		
		Post-combustion	Pre-combustion	Oxyfuel-combustion
Hydrogen production - natural gas SMR (Most refineries produce hydrogen on-site)	SMR hydrogen plants contribute a significant proportion of the overall CO_2 footprint of many refineries and are a major single-point CO_2 emission source.	• Post-combustion capture can be applied to the SMR reformer flue gas to capture 90% of the CO_2.	• The SMR process can be easily modified for pre-combustion carbon capture. The option that was explored involves the placement of pre-combustion capture on HPU syngas between the shift reactor and the PSA unit. By this route, typically only 50% of the CO_2 can be captured.	-
FCC (Process used to upgrade a low valuable feed (as VGO) feed to more valuable products as gasoline)	The FCC unit is another key CO_2 emitter, both post-combustion and oxy-combustion are feasible options for the FCC unit.	• For the post-combustion case, more sulfur removal is likely to be required compared with a coal or natural gas boiler flue gas. • (Energy consumption is higher for the post-combustion case; typically 2.5-3.5 GJ/ton)	-	• Oxyfuel technology could be applied to new FCC, and when large on-site heaters and boilers are replaced. Small-scale testing has shown that it is technically feasible to maintain stable operation of FCC in oxy-firing mode. • (Energy consumption: 1.5 to 2.5 Gj/ton)
Process heat (Furnaces and boilers - Heat required for the separation of liquid feed, to produce steam, and to provide heat of reaction to the refinery processes such as reforming and cracking)	• Most emissions are due to the combustion of hydrocarbon fuels for process heating, while other emissions are waste streams from the unit operation processes, such as sulphur removal unit tail gas treatment. • Large process heaters include the CDU, VDU, CCR, and visbreaker. Units with smaller heaters include the NHT, DHT, and SRU.	• If a process unit's heaters are fired on various fuels or waste streams generated within the unit (if space is available for the capture equipment). • Post-combustion CO_2 capture is often likely to be the simplest capture method to add to an existing unit, as long as its plot and/or surroundings are not too congested.	• When a processing unit contains several small heaters fired on refinery fuel gas in a very congested plot • Use of pre-combustion technology is applicable when all process heaters are run on the same fuel and requires routing of fuel to gasification/reforming unit and allow decarbonizing gas stream from gasification or reforming unit and using the decarbonized stream for process heaters	• If the heaters can be sealed against air ingress and an air separation unit added to the site, oxy-combustion may be a good option. • Applying oxy-combustion to an existing heater requires review and likely modification of the burners and careful checking that the equipment can tolerate safe operation at modified temperatures and pressures without exceeding the design conditions

[106] https://webstore.iea.org/technology-roadmap-carbon-capture-and-storage-in-industrial-applications

	• Post-combustion capture and oxy-fuel combustion currently offer possibilities for reducing emissions from process heaters in refineries. Technologies that could potentially be implemented in the future in new facilities include chemical looping combustion and pre-combustion capture in the production of hydrogen fuel for use in boilers and heaters.	• Applying post-combustion capture requires re-routing the flue gas to cooling and sulphur removal, It is necessary to minimize the distance between the flue gas source, CO_2 absorption, and the stack, as this minimizes pressure drop and hence minimizes the blower power.	• Use of pre-combustion capture will also require retrofitting of boilers and heaters as the fuel produced will be rich in hydrogen content	
Utilities (CO_2 from the production of electricity and steam at a refinery)	• Post-combustion and oxy-fuel combustion are the most promising technology for CHP. • In the case of the Integrated Gasification Combined Cycle (IGCC) pre-combustion would be the most suitable technology for CO_2 capture.	• The current state-of-the-art post-combustion capture technologies can be applied to any flue gas.	• Pre-combustion CO_2 capture can be applied to any steam and power systems that can be fired on a high hydrogen content gas, this is done by decarbonizing the fuel gas upstream of the combustion location. For this capture method, it is not necessary to have the carbon capture equipment located adjacent to the boiler or gas turbine. • Pre-combustion carbon capture can allow either a single fuel to a single unit to be decarbonized, or it could be applied to the whole refinery fuel gas system. • If a site has a large power island fired on a single fuel, such as a natural gas-fired combined heat and power unit, it may be more sensible to add pre-combustion CO_2 capture by reforming the natural gas, shifting the syngas to hydrogen and CO_2, and then removing the CO_2 before feeding the remaining hydrogen-rich gas to the CHP.	• Oxyfuel CO_2 capture can be applied to all of those steam and power systems that can be sealed to air ingress and whose burner systems and design conditions can tolerate switching to operation in a fuel-CO2-water + oxygen regime as opposed to a fuel + air regime.

Table 33[107] summarises studies of CO_2 capture costs for oil refineries found in the literature. The most common approaches that have been explored in the literature are listed here. The cost varies between different studies and different technologies because different studies apply different system boundaries. For example, some studies include CO_2 capture from heat and power production unit, while other does not.

Table 33. Cost comparison of carbon capture technologies in an oil refinery

Author	Capture Process	Process	Energy Source	CO_2 captured (Mt/year)	Cost year	Cost (€/t CO_2 avoided)
(Ho et al., 2011)[a]	Post-combustion	Combined stack	External NGCHP	0.88	2008	59
(Kuramochi et al., 2012)[b]	Post-combustion	Combined stack	On-site NGCHP[c]	1.2-1.6	2007	120
(Kuramochi et al., 2012)[b]	Post-combustion	FCC	Steam import[c]	0.6-0.8	2007	70-110
(Kuramochi et al., 2012)[b]	Oxyfuel combustion	Combined stack	On-site NGCC or NG-CHP or power import[c]	1.6	2007	50
(Kuramochi et al., 2012)[b]	Oxyfuel combustion	FCC	Steam import[c]	0.8	2007	60
(Kuramochi et al., 2012)[b]	Oxyfuel combustion	Combined stack	On-site NGCC or NG-CHP or power import[c]	1.6	2007	30
(Kuramochi et al., 2012)[b]	Pre-combustion	Combined stack	Water gas shift membrane reactor[c]	1.6	2007	80
(Meerman et al., 2012)[d]	Post-combustion	SMR	On-site CHP	0.33	2008	41

[a] Includes CO_2 emissions from the facility that generates the heat but do not consider the saved CO_2 emissions due to saved marginal electricity.
[b] Includes also CO_2 emissions from heat and/or power production plus including CO_2 emissions from exported electricity.
[c] Capture CO_2 from heat and power production.
[d] Does not consider CO_2 capture of emissions from heat and power production.

It is observed that oxyfuel combustion is reported to have a lower avoidance cost than other CO_2 capture technologies. Though the implementation of oxyfuel combustion technology has been explored since 2011, it's not been commercially applied yet because it faces challenges with respect to handling and use of oxygen-rich stream as most of the current equipment (e.g. burners) needs to be modified to handle oxygen-rich gas streams.

As per the information published by Kuramochi et al, capital cost of the carbon dioxide capture depends significantly on whether the energy required for the process is imported or generated onsite. The incremental capital cost per year for post-combustion technology using amine as a solvent for combined stack falls in the range of 100 to 210 € per tonne of captured carbon dioxide if the steam is imported; it goes up to 250 € per tonne of captured carbon dioxide if there is on-site CHP plant. It is not explicitly mentioned that whether both CAPEX and OPEX were considered for CO_2 abatement cost calculations.

107 https://core.ac.uk/download/pdf/70598988.pdf

Some key milestones for carbon capture in the refining sector that are already underway, and planned in near future are provided below

- In Norway, Statoil, Gassnova (which represents the Norwegian Government in matters relating to CCS), Norske Shell, and Sasol have established an agreement to develop, test, and verify solutions for carbon capture, in Statoil's refinery in Mongstad. They have built a center for carbon capture technologies at Mongstad, known as the "CO_2 Technology Centre Mongstad" (TCM). TCM is located at the Mongstad oil refinery and offers testing of carbon dioxide capture technologies. So far, Aker Solutions (Norway), Alstom SA (France), Cansolv Technologies Inc (Canada), Carbon Clean Solutions (UK / India), ION Engineering (USA), and Fluor Corporation have tested their technologies on TCM. It will launch a new testing facility for testing new technologies such as membrane separation or adsorption in 2020
- In Brazil, Petrobras is operating a demonstration project for CO_2 capture by oxy-firing FCC in a refinery
- In Canada, the Alberta government financially supported the North West Upgrading bitumen refinery project, which will capture CO_2 from a gasification process used to produce hydrogen. The technology used for carbon capture is solvent (Rectisol) based pre-combustion technology
- In Rotterdam, CO_2 from Shell's Pernis refinery is captured, transported, and used in nearby greenhouses. Plans to transport more CO_2 from the refinery and store it in the depleted Barendrecht gas field were cancelled because of public resistance to storage
- In France, Total has been testing since 2010 oxy-fuel combustion capture at the countries' largest production site of liquid hydrocarbons, in Lacq
- Aker Solutions will conduct a feasibility study of the technological and economic impact of implementing carbon capture of major emission source at Preemraff Lysekil refinery

4. PLAYER ECOSYSTEM

Post-combustion solvent Technologies

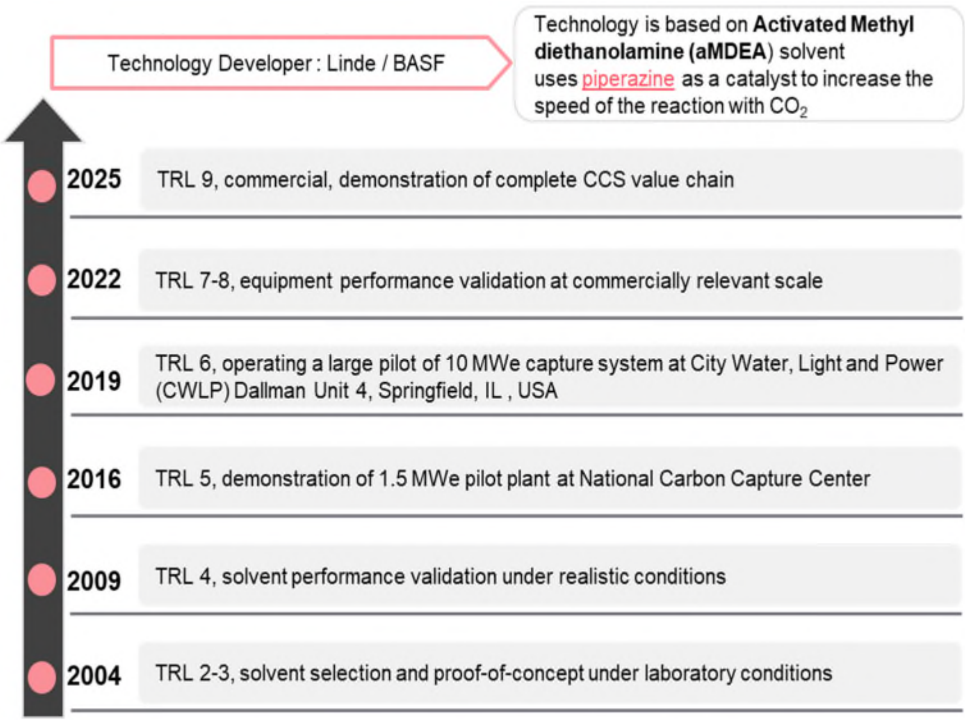
The next-generation carbon capture technologies have unique features either through material innovation, process innovation, and/or equipment innovation, which reduce CAPEX and OPEX costs and improve capture performance.

Some of the technologies already considered in engineering studies for CCS facilities are listed below:

1. Linde/BASF:

Linde Group and BASF Corporation are testing advanced post-combustion CO_2 capture technology of 10 MWe capture system at a coal-fired power plant in the US. They have been jointly developing, optimizing, and demonstrating advanced post-combustion CO_2 capture technology since 2004. Major milestones achieved so far is depicted in the figure below:

Figure 43. Linde Group and BASF Corporation's milestones



Successful reference projects:

- Post-combustion capture (PCC) plant, Niederaussem, Germany, customer: RWE Power AG
- In 2009, Linde completed the installation of a PCC pilot plant connected at a lignite-fired power plant run by RWE in Niederaussem, Germany. The PCC plant was engineered and built by Linde based on BASF's OASE® blue technology with a design capacity of 1,550 Nm^3/h flue gas equal to 7.2 t/d CO_2 captured. The power plant operated ~ 55,000 hours and achieved a carbon capture capacity of 97%[108].

[108] https://www.linde-engineering.com/en/images/Carbon-capture-storage-and-utilisation_tcm19-462558.pdf

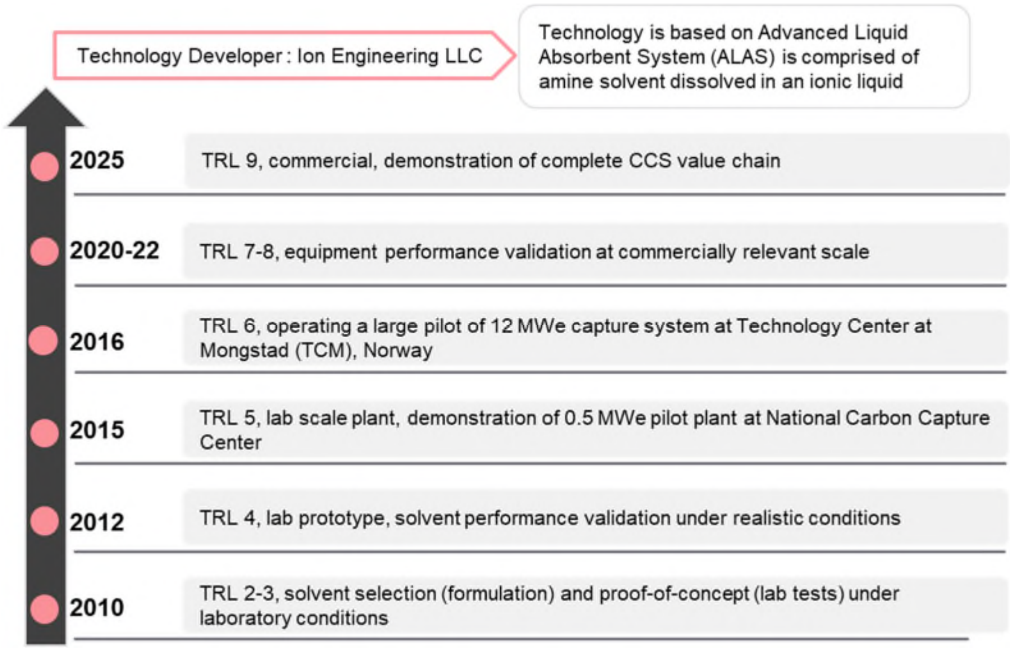
- Post-combustion capture plant, Wilsonville, US, customer: National Carbon Capture Center, a US Department of Energy research facility, which is managed and operated by Southern Company in Wilsonville, Alabama.

Linde and BASF successfully operated this PCC pilot plant (from January 2015 to July 2016) at Southern Company, Wilsonville location. The project combined BASF's OASE® blue technology with a design capacity of 6,500 Nm^3/h flue gas equal to 30 t/d CO_2 captured. The pilot plant demonstrated more than 3,200 operating hours and captured more than 90% of CO_2 from the flue gas at a purity level of ~ 99.9%[109].

2. ION Engineering LLC:

ION's proprietary Advanced Liquid Absorbent System (ALAS) is comprised of amine solvent dissolved in an ionic liquid. This technology is selected for a Front-End Engineering Design (FEED) study, retrofitting to Nebraska Public Power District's Gerald Gentleman Station. The laboratory and pilot-scale testing for ION's (ALAS) demonstrated regeneration energy requirements less than 60% in comparison to traditional aqueous monoethanolamine solvent, with less solvent degradation due to impacts of flue gas impurities, such as sulfur oxides[110].

Figure 44. ION's milestones



3. URS Corporation:

URS Corp., acquired by AECOM in 2014 (now affiliated with AECOM), in collaboration with the University of Texas and Trimeric Corporation, is investigating the use of concentrated piperazine as a solvent for absorbing CO_2 from coal-fired power plant flue gas. The test results showed a faster CO_2 absorption rate, higher CO_2 capacity, lower volatility, and negligible thermal and oxidative degradation compared with conventional amine solvents[111].

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[109] https://www.linde-engineering.com/en/images/Carbon-capture-storage-and-utilisation_tcm19-462558.pdf
[110] https://www.netl.doe.gov/project-information?p=FE0013303
[111] https://www.netl.doe.gov/project-information?p=FE0005654

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4. Hitachi Power Systems America

Hitachi is developing an amine-based advanced solvent (H3-1) for capturing CO_2 in the flue gas for coal-fired power plants, in partnership with the University of Kentucky Center for Applied Energy Research, Electric Power Research Institute, and Smith Management. Hitachi demonstrated H3-1 solvent at pilot scale and slipstream test facilities at Energy and Environmental Research Center (EERC) and the National Carbon Capture Center (NCCC) in the US.

5. University of Kentucky Center for Applied Energy Research, TRL-5 as of now, over 4500 hours of operation

Two-stage Solvent Regeneration: leading to 8% less energy compared to conventional with >10% of regeneration in secondary air stripper

6. The University of Illinois at Urbana-Champaign (UIUC):

The University of Illinois at Urbana-Champaign (UIUC) is developing and evaluating a novel biphasic solvent for post-combustion CO_2 capture. The solvent is a blend of amines and water, which contain a small amount of water (< 30 wt. %) and absorbs CO_2 through a chemical reaction between amines and CO_2. It also undergoes a phase transition to form dual liquid phases based on the difference of hydrophobicity between different species. The experimental results revealed that the oxidative degradation of the biphasic solvent is 10 times slower than the benchmark MEA under similar absorption conditions. The solvent is stable with oxygen at a high temperature of 150°C. TRL 2-3 till date.

7. University of Notre Dame

The University of Notre Dame, in collaboration with Lawrence Livermore National Laboratory, is developing hybrid encapsulated ionic liquid and phase change ionic liquid solvent for post-combustion CO_2 capture. Although ionic liquids have excellent properties as CO_2 absorbing solvents, their high viscosities (due to poor mass transfer rates) prohibit their practicable application in large-scale commercial operation when they are configured in conventional absorption/regeneration systems. Ionic liquid solvents (for example, hexafluorophosphate, tetrafluoroborate, etc.), a class of ionic salts containing nitrogen or phosphorous-bearing cations with alkyl chain substituents, are anhydrous, liquid at ambient temperatures, having low vapour pressures, thermally stable, and relatively non-corrosive as compared to conventional solvents, such as MEA. It is at TRL 2.

8. Carbon Engineering Ltd.

The DAC process is based on the use of a wet scrubbing air contactor, followed by several chemical processing steps. The aqueous potassium hydroxide is used in air contactor, which is converted into aqueous potassium carbonate when reacted with CO_2 from the air. In the pellet reactor, the aqueous potassium carbonate reacts with solid calcium hydroxide from the slaker to regenerate the aqueous hydroxide, which is sent back to the air contactor, and calcium carbonate to be used in the calciner.

9. Research Triangle Institute

Research Triangle Institute (RTI) is developing the non-aqueous solvent, sterically-hindered, carbamate-forming amine, for the post-combustion CO_2 capture process.

RTI is using the bench-scale test unit (up to 60kW) at SINTEF's Tiller plant to experimentally show that its non-aqueous solvent is capable of achieving 90% of CO_2 capture and generating a high-purity CO_2 (>95%). This test is also used to evaluate the effectiveness of the developed NAS recovery/wash section and solvent regenerator design.

TRL: 2

10. GE Global Research

GE Global Research is developing a novel solvent based on phase-changing amino silicone materials for CO_2 capture absorbent for post-combustion capture. The amino silicone-based solvent is a 60 wt. % mixture of 3-aminopropyl end-capped polydimethylsiloxane with 40 wt. % tri-ethylene glycol (TEG) as a co-solvent.

At present, GE and NETL have mutually agreed to terminate the project before the completion of the final task due to internal changes within GE.

5. OVERVIEW OF CO_2 STORAGE POTENTIAL IN EUROPE

Carbon dioxide storage is an essential element of the CCUS value chain. Carbon dioxide storage options are explained below:

- **Underground storage in Sedimentary formation:** Carbon dioxide is stored in underground porous geological formations. The geological formations are located at several kilometers depth and have pressure and temperature conditions that allow carbon dioxide to be either in the supercritical state or liquid state. This is one of the most mature technology for the storage of carbon dioxide and has been in use for now more than two decades. As per the report published by Global CCS Institute (2019), National Academies of Sciences Engineering Medicine (2019), approximately 3.7-4.2 $MtCO_2$/year, for a cumulative total of 30.4 Mt of carbon dioxide is stored in sedimentary formations at the end of 2017. Suitable sedimentary formations for storing carbon dioxide are mentioned below:
- **Saline Aquifers:** Saline Aquifers are porous and permeable reservoir rocks that contain saline fluid in the pore spaces between the rock grains and found at depths greater than aquifers that contain potable water. Usually, due to its high saline proportion and its depth, the water contained cannot be technically and economically exploited for surface uses. Various scientific literature published related to carbon dioxide storage states that the saline aquifers have enormous potential for carbon dioxide storage. A large part of the European storage capacity is found in offshore saline aquifers, especially in the North Sea region, around Britain and Ireland, to some extent in the Barents Sea and likely in the Baltic Sea. The first known industrial CCS project in this domain is Sleipner in the Norwegian sector of the North Sea. **Table 35** provides a list of projects focused on carbon dioxide storage in saline aquifers. The major challenge associated with Saline aquifers is their unknown geology which leads to uncertainties about reservoir integrity and properties.
  - **Depleted Oil and Gas fields:** Depleted oil and gas fields are suitable candidates for geological sequestration of carbon dioxide. The carbon dioxide storage capacity of depleted oil and gas fields is less. This is because of the need to avoid exceeding pressures that can damage the caprock and the significant leakage threat posed by the abandoned wells. The major advantage of this type of storage is its known geology and proven capability to store oil and gas in the formation. Royal Dutch Shell, in strategic partnership with the power station owner Scottish and Southern Energy (SSE), is working on Europe’s first project focused on carbon dioxide storage in depleted Goldeneye gas reservoir. It is expected that this project will be operational by the end of 2020.
  - **Oil and Gas wells - Enhanced Oil Recovery:** Carbon dioxide has been used for enhanced oil recovery since long back. The IEA’s new global database of enhanced oil **recovery** projects shows that around 500 thousand barrels of oil are produced daily using CO_2-EOR today, representing around 20% of total oil production from EOR. **Table 36** provides a list of the current projects focused on carbon capture and storage using EOR.

- **Coal Beds/Seams:** Research on CO_2 storage in coal seams and simultaneously enhanced coal bed methane recovery (ECBM) has been going on for the last two decades. The major **technical** challenges with carbon dioxide storage in coal beds are low injectivity of coal seams and injectivity loss with CO_2 injection. This significantly limits the opportunity for carbon dioxide storage. In Europe, coal seams of the Upper Silesian Coal Basin, Poland has been chosen to understand carbon dioxide storage in coal seams/bed in European conditions.
- **Carbon mineralization of mafic and ultramafic rocks**: This is an emerging storage technology and involves storing carbon dioxide in mafic and ultramafic rocks through mineralization via carbonation reaction. CO_2 mineralization can be used in different settings and include the in situ CO_2 mineralization of basalts or ultramafic **rocks**, ex-situ mineralization of alkaline mine tailings, and reactions that produce other materials that have the potential to be used as mineral resources. Basalt rock has high porosity and permeability which increases its reactivity with CO_2 making it an ideal medium for CO_2 injection and storage. In Europe, the storage of carbon dioxide through carbon mineralization is being explored in Iceland. The aim of the CarbFix project to develop a new technique for the storage of carbon dioxide in Basalt rock. The main advantage of the storage technology is that it eliminates the need of an impermeable caprock or sealing rock for avoiding carbon dioxide leakage.

Table 34. Cost of CO_2 storage for various storage sites[112]

Properties	Storage cost ($2015/t$CO_2$)	
	Min.	Max.
Depleted oil and gas field - reusing wells onshore	1.6	11
Depleted oil and gas field - no reusing wells onshore	1.6	15.7
Saline formations onshore	3.1	18.8
Depleted oil and gas field - reusing wells offshore	3.1	14.1
Depleted oil and gas field - no reusing wells offshore	4.7	22
Saline formations offshore	9.4	31.4

[112] https://www.sciencedirect.com/science/article/pii/S2211467X18300634#sec4

Figure 45. Global storage capacity (Gigatonne CO_2)[113]

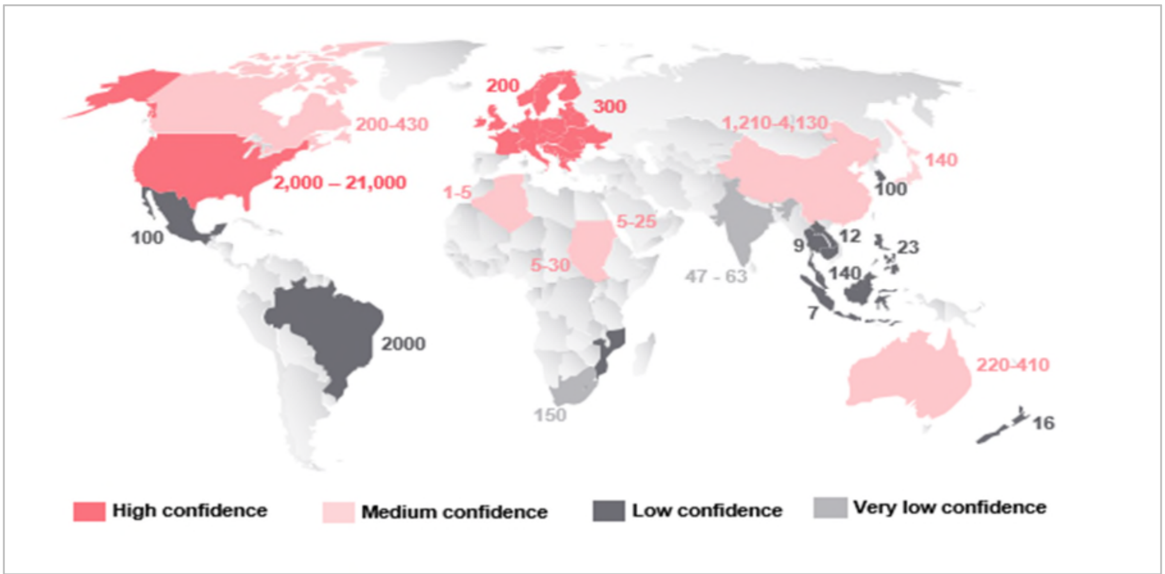
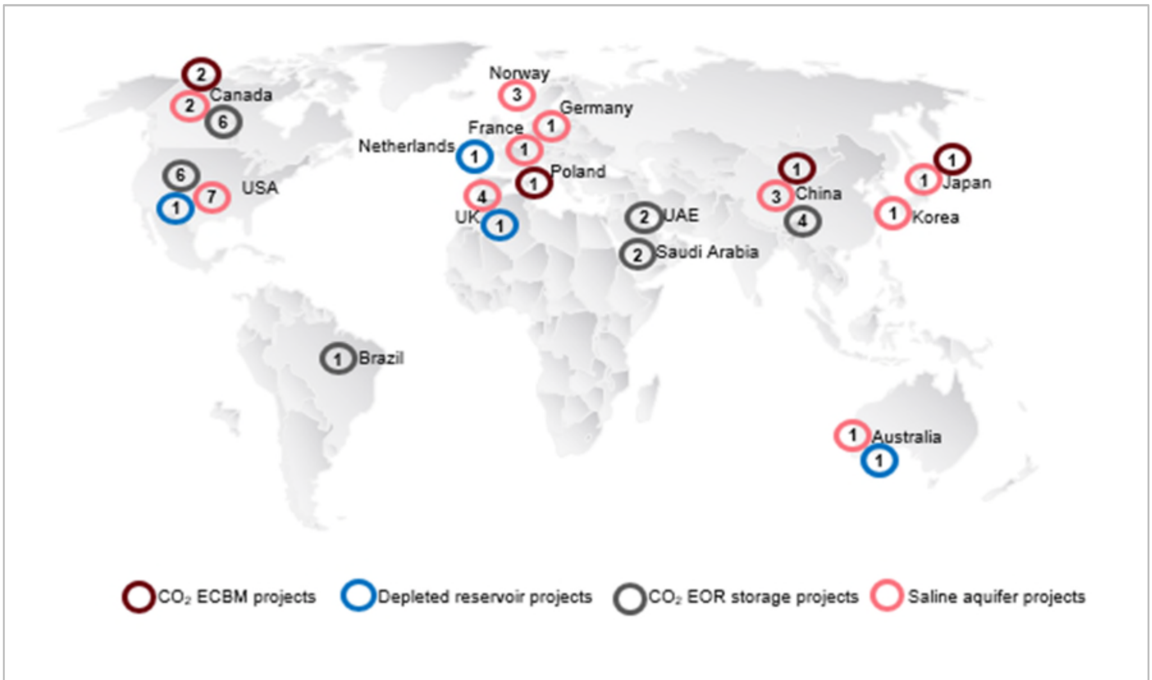


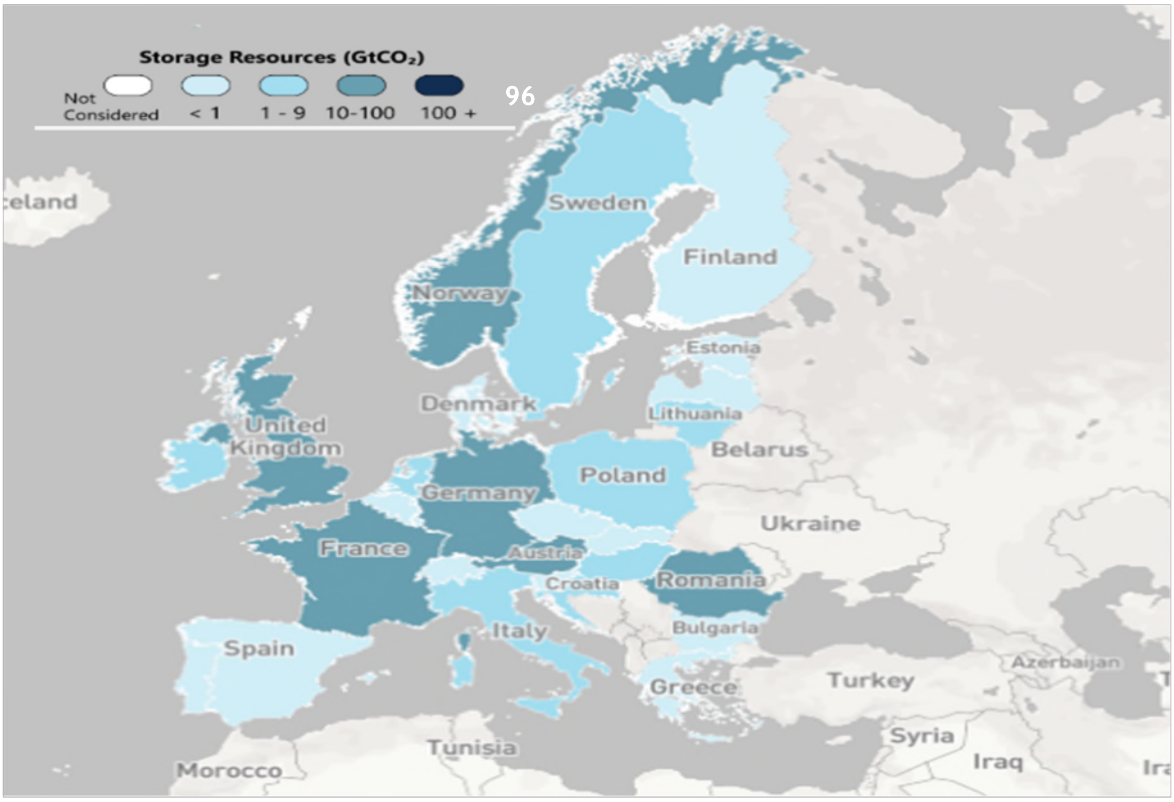
Figure 46. Storage projects across the world[114]



[113] https://www.globalccsinstitute.com/resources/global-status-report/
[114] https://link.springer.com/article/10.1007/s12182-019-0340-8

CCS Storage resource[115]**:** Storage resource map defines the board overview of national storage estimates around the world. Published estimates include deep saline formations, depleted oil and gas fields, and CO_2-EOR estimates.

Figure 47. Storage resources ($GtCO_2$)



[115] https://co2re.co/StorageData

Table 35. Comparative Assessment of Carbon Dioxide Storage Option[116]

	Depleted oil and gas well	CO_2-EOR	Saline Aquifer
Overarching Motivator	Climate change abatement. Containment required by storage-specific regulations (environmental protection and emission abatement)	Hydrocarbon production. Containment required by environmental & air pollution protection regulations. And to avoid loss of purchased CO_2.	Climate change abatement. Containment required by storage-specific regulations (environmental protection and emission abatement)
Regulation maturity	Purpose-designed, relatively recent (EU: 2009, USA: 2011) & not tested in either EU or USA yet	Very mature, but somewhat fragmented and comparably complex in the USA	Purpose-designed, relatively recent (EU: 2009, USA: 2011) & not tested in EU yet
Characterization effort required	**Low:** Well(s) with production history, tested containment of CH4	**Low:** Many wells with production and injection history. High effort may be required to assimilate vast historic datasets	**High:** Few or no wells, no production history, untested trap. Well tests likely needed to reduce uncertainty before permitting/injection
Modelling requirements	To predict behaviour & demonstrate site capacity & containment. Initial predictions submitted to obtain permit. Thereafter, history matched (and long term stability predictions updated) EU: reported annually, USA: no reporting schedule specified.	Typically focus on improving understanding of sweep efficiency and compositional phase behaviour for operator internal use only.	To predict behaviour & demonstrate site capacity & containment. Initial predictions submitted to obtain permit. Thereafter, history matched (and long term stability predictions updated) EU: reported annually, USA: no reporting schedule specified.
Modelling capabilities	May be complex because of residual hydrocarbon saturations, but can be matched to production data to reduce uncertainty. Geomechanical modelling to include site history to ensure wellbore/caprock rock integrity after pressure cycling	May be complex because of residual hydrocarbon saturations. (Potential data 'overload' to match to full-field history. E.g. Pressure cycling may be complex)	Less complex because no residual hydrocarbon saturations (2 phases only), but no production data to match to, to reduce uncertainty.

[116] https://www.sciencedirect.com/science/article/pii/S1876610217319082

	Depleted oil and gas well	CO_2-EOR	Saline Aquifer
Monitoring requirements	Report to regulator typically annually (EU): risk-based monitoring focussing on how results demonstrate containment & conformance with models.	Report to regulator typically monthly (USA): well production and injection volumes, wellhead pressures. Other risk-based monitoring data may be collected but not reported	Report to regulator typically annually (EU): risk-based monitoring focussing on how results demonstrate containment & conformance with models.
Monitoring capabilities	Wells may allow opportunities for well-based monitoring. May be difficult to distinguish CO_2 from residual hydrocarbons using geophysical techniques	Wells almost certainly allow opportunities for well-based monitoring. May be difficult to distinguish CO_2 from residual hydrocarbons using geophysical techniques	Fewer opportunities for well-based monitoring. CO_2 likely to be much more readily distinguishable from brine using geophysical techniques
Irregularity detection and contingency potential	Likely to have continuous well-based monitoring for early warning irregularities, although less spatial coverage than at CO_2-EOR sites (but also consequently reduced wellbore leakage risks)	Many wells - lots of well based continuous monitoring, the potential for early catching of irregularities (but also many more possible leakage paths). Potential for "plume steering" using multiple active wells a way for contingency containment.	Fewer opportunities for continuous well-based monitoring (other than in injection well) (but could represent a lower risk of wellbore leakage). High spatial coverage monitoring (e.g. seismic) likely to be periodic (i.e. less opportunity for early detection of irregularities)
Site closure requirements	In EU operator needs to demonstrate long term stability of the site, potentially monitor for up to 30 years.	No specific requirements for CO_2-EOR compared to other EOR operations.	In EU operator needs to demonstrate long term stability of the site, potentially monitor for up to 30 years.
Costs & economics	May be savings in reusing infrastructure such as wells	Economic benefit from the sale of produced hydrocarbon. Additional costs of equipment and higher operating costs for EOR. May be cost savings by reusing existing wells	Likely to be additional costs for characterisation and infrastructure installation. Long term costs for abandonment might be less (fewer wells)

Table 36. Storage projects across the world: saline aquifer projects[117]

Project name	Country	Company operators	Total planned storage	Status of project
Gorgon	Australia	Gorgon Joint Venture (Chevron Australia, ExxonMobil, Shell, Tokyo Gas, Osaka Gas and Chubu Electric)	3.4-4.0 Mt/year	Under construction
Fort Nelson	Canada	Plains CO2 Reduction Partnership (PCOR), Spectra Energy, British Columbia Ministry of Energy, Mines and Petroleum Resources	2.2 Mt/year	Planning
Quest	Canada	Athabasca Oil Sands Project: Shell Canada, Chevron Canada, and Marathon Oil Sands	1.1 Mt/year	Launched in November 2015
Lianyungang	China	Summit Power, National Grid, CO2 Deep Store	1 Mt/year	Planning
Ordos	China	Shenhua Group	1 Mt/year	In operation since 2010
Yulin	China	Shenhua Group, Dow Chemicals	2-3 Mt/year	Planning
ULCOS Florange	France	ArcelorMittal and ULCOS (Ultra-Low-CO2-Steel)	1.2 Mt/year	On hold
Ketzin	Germany	GFZ German Research Centre for Geosciences and Ketzin partners	0.06 Mt/year	In operation since 2008
Minami-Nagaka	Japan	EnCana, IEA	0.015 Mt/year	In operation since 2002
Korea CCS	Korea	Korea Carbon Capture and Sequestration R&D Center (KCRC)	1 Mt/year	Planning
Longyearbyen	Norway	UNIS CO2 Lab-AS	Not available	Planning
Sleipner	Norway	StatOil	0.9 Mt/year	In operation since 1996
Snohvit	Norway	Statoil ASA, Petoro AS (Norwegian state direct interest), Total E&P Norge AS, GDF Suez E&P Norge AS, Norsk Hydro, Hess Norge	0.7 Mt/year	In operation since 2007
Captain	UK	Captain Clean Energy Limited (CCEL) owned by Summit Power and CO2 Deep Store	3.8 Mt/year	Planning
Don Valley	UK	2Co Energy Ltd, Samsung Construction & Trading, BOC	4.9 Mt/year	Planning
Killing Holme	UK	C.GEN NV and National Grid	2.5 Mt/year	Planning
White Rose	UK	Capture Power Limited, the consortium of Alstom UK Limited, Drax Power Limited and National Grid plc	2 Mt/year	Planning
Cranfield	USA	SECARB	1-1.5 Mt/year	In operation since 2009
Citronelle	USA	SECARB, Denbury, Southern Energy	0.25 Mt/year	In operation since 2011
Decatur	USA	Archer Daniels Midland, MGSC (Led by Illinois State Geological Survey), Schlumberger Carbon Services and Richland Community College	1 Mt/year	In operation since 2011
Kevin Dome	USA	Big Sky Partnership, Schlumberger Carbon Services, Vecta Oil & Gas Ltd, Lawrence Berkeley National Lab, Los Alamos National Lab	0.125 Mt/year	Planning

117 https://link.springer.com/article/10.1007/s12182-019-0340-8

Project name	Country	Company operators	Total planned storage	Status of project
Wasatch Plateau	USA	South West Partnership (SWP), New Mexico Institute of Mining and Technology, University of Utah, Schlumberger and Los Alamos National Laboratory	1 Mt/year	Planning
Frio	USA	Bureau of Economic Geology of the University of Texas	177 t/day	In operation since 2004
Teapot Dome	USA	Rocky Mountain Oilfield Testing Center (RMOTC)	170 t/day	In operation since 2006

Table 37. Storage projects across the world: CO_2 EOR/storage projects[118]

Project name	Country	Company operators	Total planned storage	Status of project
Santos Basin	Brazil	Petrobras, BG E&P Brasil Ltda, Petrogal Brasil	1 Mt/year	In operation since 2013
Boundary Dam	Canada	SaskPower	1 Mt/year	October 2014-date
Bow City	Canada	Bow City Power, Cansolv (Subsidiary of Shell), Luscar, Fluor	1 Mt/year	Planning
Pembina	Canada	Penn West	50 t/day	In operation since 2005
Weyburn-Midale	Canada	Cenovus Energy, Apache Canada, PTRC (Petroleum Technology Research Center)	1 Mt/year	In operation since 2000
Zama	Canada	PCOR, Apache Canada Ltd	0.067 Mt/year	In operation since 2006
Alberta Carbon Trunk Line	Canada	Enhance Energy Inc.	14.7 Mt/year	Planning
Daqing	China	Alstom and China Datang Corporation	1 Mt/year	Planning
Dongguan	China	Dongguan Taiyangzhou Power Corporation, Xinxing Group, Nanjing Harbin Turbine Co, KBR, Southern Company,	1 Mt/year	Planning
GreenGen	China	GreenGen	2 Mt/year	Planning
Shengli	China	Sinopec	1 Mt/year	Planning
Uthmaniyah	Saudi Arabia	Saudi Aramco	0.8 Mt/year.	In operation
Uthmaniyah	Saudi Arabia	Saudi Aramco	0.8 Mt/year.	In operation since 2015
ESI CCS Project	United Arab Emirates (UAE)	Abu Dhabi Future Energy Company (Masdar) and Abu Dhabi National Oil Company (ADNOC)	0.8 Mt/year	Started in 2017
Taweelah	United Arab Emirates (UAE)	Abu Dhabi Future Energy Company (Masdar) and Taweelah Asia Power Company (TAPCO) and Emirates Aluminium (EMAL)	2 Mt/year	Planning
Bell Creek	USA	PCOR, Denbury	1 Mt/year	Planning
Hydrogen Energy California	USA	SCS Energy	3 Mt of CO2 captured annually	Planning

118 https://link.springer.com/article/10.1007/s12182-019-0340-8

Project name	Country	Company operators	Total planned storage	Status of project
Project (HECA)				
Kemper County	USA	Mississippi Power, Southern Energy, KBR	3.5 Mt of CO_2 annually	In construction
Port Arthur	USA	Air Products and Chemicals, Denbury Onshore LLC, University of Texas Bureau of Economic Geology and Valero Energy Corporation	1 Mt/year	In operation since 2013
Texas Clean Energy Project (TCEP)	USA	Summit Power Group Inc, Siemens, Fluor, Linde, R.W. Beck, Blue Source and Texas Bureau of Economic Geology	2-3 Mt/year captured	Planning
Waarish Petra Nova	USA	Petra Nova Holdings: a 50/50 partnership between NRG Energy and JX Nippon Oil & Gas Exploration Corp.	1.4 Mt of CO_2 captured annually	In construction

Table 38. Storage projects across the world: depleted reservoir projects[119]

Project name	Country	Company operators	Total planned storage	Status of project
In Salah	Algeria	BP, Sontrach, and Statoil	1.2 Mt/year	2004-2011 suspended
Otway	Australia	CO_2 CRC (Cooperative Research Center for Greenhouse Gas Technologies)	0.065 Mt/year	In operation since 2008
*ROAD (Rotterdam Opslag en Afvang Demonstrate project)	Netherlands	E.ON Benelux, Electrabel, GDF Suez and Alstom	1.1 Mt/year	Planning
K12B	Netherlands	Gaz de France	0.365 Mt/year	In operation since 2004
Peterhead	UK	Scottish and Southern Energy (SSE) and Shell	1 Mt/year	Planning
Northern Reef Trend	USA	Midwest Regional Carbon Sequestration Partnership (MRCSP). DTE Energy, Core Energy and Batelle	0.365 Mt/year	In operation since 2013

Table 39. Storage projects across the world: CO_2 ECBM projects[120]

Project name	Country	Company operators	Total planned storage	Status of project
Fenn Big Valley	Canada	Alberta Research Council	50 t/day	In operation since 1998
CSEMP	Canada	Suncor Energy	50 t/day	In operation since 2005
Qinshui Basin	China	Alberta Research Council	30 t/day	In operation since 2003
Yubari	Japan	Japanese Ministry of Economy, Trade and Industry	0.004 Mt/year	In operation since 2004
Recopol	Poland	TNO-NITG (Netherlands)	1 t/day	In operation since 2003

[119] https://link.springer.com/article/10.1007/s12182-019-0340-8
[120] https://link.springer.com/article/10.1007/s12182-019-0340-8

6. LIST OF ABBREVIATIONS

AHPC	Activated Potassium Carbonate Process
ALAS	Advanced Liquid Absorbent System
aMDEA	Activated Methyl Diethanolamine
ASU	Air Separation Unit
BECCS	Bio-Energy with Carbon Capture and Storage
CAPEX	CAPital EXpense
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilization, and Storage
CHP	Combined Heat and Power
CORDIS	Community Research and Development Information Service
CPC	Cooperative Patent Classification
DAC	Direct Air Capture
EERC	Environmental Research Center
EOR	Enhanced Oil Recovery
EPRI	Electric Power Research Institute
ESP	Electrostatic Precipitation
ETS	Emissions Trading System
FCC	Fluid Catalytic Cracking
FGD	Flue-gas Desulphurization
GDP	Gross Domestic Product
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
IPC	International Patent Classification
IPCC	Intergovernmental Panel on Climate Change
LCFS	Low Carbon Fuel Standard
LCOE	Levelized Cost of *Energy*
MDEA	MethylDiEthanolAmine
MEA	MonoEthanolAmine
MOF	Metal Organic Framework
NCCC	National Carbon Capture Center
NDCs	Nationally Determined Contributions
NETL	National Energy Technology Laboratory
NGCC	Natural Gas Combined Cycle
OGCI	Oil and Gas Climate Initiative
OPEX	OPerating EXpense

PC	Pulverised Coal
PSA	Pressure Swing Adsorption
SCR	Selective Catalytic Reduction
SMR	Steam Methane Reforming
TRL	Technology Readiness Level

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APPENDIX 1

1.1 LIST OF TECHNOLOGIES DEVELOPERS

S. No.	Capture	Project	Technology	Technology developer	Technology Details	TRL
			University / Research Institute			
1	Post-combustion	Application of a heat integrated post-combustion CO_2 capture system with Hitachi advanced solvent into the existing coal-fired power plant	Solvent	University Of Kentucky Center For Applied Energy Research	H3-1 aqueous amine	5
2	Post-combustion	Large pilot-scale testing of Linde/BASF post-combustion CO_2 capture technology at the Abbott coal-fired power plant	Solvent	The University Of Illinois At Urbana-Champaign	Novel amine-based solvents	5
3	Post-combustion	Metal monolithic amine-grafted silica for CO_2 capture	Sorbent	University Of Akron	Amine-grafted silica	5
4	Post-combustion	Novel inorganic/polymer composite membranes for CO_2 capture	Membrane	Ohio State University	Inorganic/PolymerComposite	5
5	Post-combustion	Novel concepts for the compression of large volumes of carbon dioxide	Novel compression technology	Southwest Research Institute	NA	5
6	Oxy-fuel	Industrial steam generation with 100% carbon capture and insignificant efficiency penalty - scale-up of oxygen carrier for chemical-looping combustion using environmentally sustainable materials	Looping Technology	Technische Universitaet Wien	Fluidized bed reactor	5
7	Post-combustion	Novel algae-based solution for carbon dioxide capture and biomass production	Algae	Wageningen University & Research	PBR reactors	5
8	Other	Innovative carbon dioxide capture	Hybrid Process	Norges Teknisk-Naturvitenskapelige Universitet	DEEA/MAPA, Hybrid or Mixed Matrix (polymer-based + nanoparticles) membranes, currently there is not result published on membrane study	5
9	Post-combustion	Novel ionic liquid and supported ionic liquid solvents for reversible capture of carbon dioxide	Solvent	Wissenschaftliches Gebiet	Ionic Liquids	5
10	Post-combustion	Transformational sorbents	Sorbent	West Virginia University	Amine impregnated polybenzimidazole linked polymer sorbent	4
11	Pre-combustion	Zeolite membrane reactor for pre-combustion carbon dioxide capture	Membrane	Arizona State University	Zeolite membrane	4

S. No.	Capture	Project	Technology	Technology developer	Technology Details	TRL
12	Post-combustion	Combined pressure, temperature contrast and surface-enhanced separation of carbon dioxide for post-combustion carbon capture	Solvent	William Marsh Rice University	Aqueous Diglycolamine	4
13	Post-combustion	Rapid temperature swing adsorption using polymeric/supported amine hollow fibre materials	Sorbent	Georgia Tech Research Corporation	Polymeric/Supported amine hollow fibre materials	4
14	Post-combustion	Evaluation of carbon dioxide capture from existing coal-fired plants by hybrid sorption using solid sorbents	Sorbent	University Of North Dakota	Hybrid	4
15	Pre-combustion	Evaluation of dry sorbent technology for pre-combustion carbon dioxide capture	Sorbent	URS Group And The University of Illinois At Urbana-Champaign	Cao, $CaCO_3$	4
16	Pre-combustion	Hydrogen-selective exfoliated zeolite membranes	Membrane	University Of Minnesota	Zeolite	4
17	Pre-combustion	Pre-combustion carbon capture by a nanoporous, superhydrophobic membrane contactor process	Membrane	Gas Technologies Institute	Polyether ether ketone	4
18	Post-combustion	Development of mixed-salt technology for carbon dioxide capture from coal power plants	Solvent	Sri International	Ammonia and potassium carbonate-based mixed-salt solvent	4
19	Post-combustion	Pilot-scale evaluation of an advanced carbon sorbent-based process for post-combustion carbon capture	Sorbent	Sri International	Advanced carbon	4
20	Post-combustion	Bench-scale development of an advanced solid sorbent-based CO_2 capture process for coal-fired power plants	Sorbent	RTI International	Polyethyleneimine	4
21	Post-combustion	Carbon dioxide capture membrane process for power plant flue gas	Membrane	Research Triangle Institute	Fluorinated polymers (PVDF)	4
22	Pre-combustion	Robust and energy efficient dual-stage membrane-based process for enhanced carbon dioxide recovery	Membrane	The Media And Process Technology Inc.	Dual-stage membrane process	4
23	Pre-combustion	Polymer-based carbon dioxide capture membrane systems	Membrane	Los Alamos National Laboratory	Polybenzimidazole	4
24	DAC	Atmospheric carbon capture	Direct air capture	University Of Edinburgh	Nanoporous sorbents (Zeolites such as Na-ETS4)	3
25	Oxy-fuel	Graded membranes for energy-efficient new generation carbon capture process	Membrane	Forschungszentrum Julich Gmbh	La0.6Sr0.4Co0.2Fe0.8O3-δ (LSCF)	3
26	Post-combustion	Innovative enzymes and polyionic-liquids based membranes as carbon dioxide capture technology	Absorbent	Technische Universitat Dortmund	Ionic liquid	3

S. No.	Capture	Project	Technology	Technology developer	Technology Details	TRL
27	Post-combustion	Energy-efficient go-peek hybrid membrane process for post-combustion carbon dioxide capture	Hybrid Process	Gas Technology Institute	Hybrid process	2
28	Post-combustion	Development of a novel biphasic CO_2 absorption process with multiple stages of liquid-liquid phase separation for post-combustion carbon capture	Absorbent	The University Of Illinois At Urbana-Champaign	Biphasic solvent	2
29	Post-combustion	Hybrid encapsulated ionic liquids for post-combustion carbon dioxide capture	Solvent	University Of Notre Dame | Lawrence Livermore National Laboratory	Hybrid encapsulated ionic liquid (IL) | Phase change ionic liquid (PCIL)	2
30	Post-combustion	A novel process that achieves 10 mol/kg sorbent swing capacity in a rapidly cycled pressure swing adsorption process	Sorbent	Georgia Tech Research Corporation	Polymer/MOF sorbent	2
31	Post-combustion	Evaluation of amine-incorporated porous polymer networks as sorbents for post-combustion CO_2 capture	Sorbent	Texas A&M University	Amine incorporated polymers sorbent	2
32	Post-combustion	Lab-scale development of a hybrid capture system with the advanced membrane, solvent system, and process integration	Hybrid Process	Liquid Ion Solutions | Pennsylvania State University | Carbon Capture Scientific	Hybrid membrane/solvent process	2
33	Post-combustion	Process intensification for carbon capture	Other	Altex Technologies Corporation | Pennsylvania State University	Integrated temperature and pressure swing (ITAPS) carbon capture system	2
34	Post-combustion	Advanced manufacturing to enable enhanced processes and new solvents for carbon capture	Solvent	Lawrence Livermore National Laboratory (Llnl) | Harvard University | Carnegie Mellon University (Cmu)	Microencapsulated solvents	2
35	Pre-combustion	A high efficiency, the ultra-compact process for pre-combustion CO_2 capture	Other	University Of Southern California	Carbon molecular sieve (CMS) membrane reactor (MR) followed by an adsorption reactor	2
36	Post-combustion	Novel carbon dioxide-selective membranes for CO_2 capture from less than 1% CO_2 sources	Membrane	Ohio State University	Amine Polymer Layer on PES Support	2
37	Post-combustion	Electrochemically mediated amine regeneration CO_2 scrubbing processes	Solvent	Massachusetts Institute Of Technology	Amine regeneration	2
38	Post-combustion	Bench-scale development of a hot carbonate absorption process with crystallization-enabled high-pressure stripping for post-combustion CO_2 capture	Solvent	The University Of Illinois At Urbana-Champaign	K2CO3	2

S. No.	Capture	Project	Technology	Technology developer	Technology Details	TRL
39	Post-combustion	Ionic liquids: breakthrough absorption technology for post-combustion CO2 capture	Solvent	University Of Notre Dame	Ionic Liquids	2
40	Post-combustion	Development and evaluation of a novel integrated vacuum carbonate absorption process	Solvent	The University Of Illinois At Urbana-Champaign	Carbonic anhydrase enzyme	2
41	Post-combustion	Reversible ionic liquids as double-action solvents for efficient CO_2 capture	Solvent	Georgia Tech Research Corporation	Ionic Liquids	2
42	Post-combustion	CO_2 capture from flue gas by phase transitional absorption	Solvent	Hampton University	Amine	2
43	Post-combustion	Novel dual function membrane for controlling carbon dioxide from fossil-fueled power plants	Membrane	University Of New Mexico	Silica	2
44	Pre-combustion	Pre-combustion carbon dioxide capture by a new dual-phase ceramic-carbonate membrane reactor	Membrane	Arizona State University	Ceramic-carbonate	2
45	Post-combustion	Biomass-derived microporous carbon adsorbents for CO_2 capture and storage	Adsorbent	Queen Mary University Of London	Pristine and N functionalized carbon nanotubes	2
46	Post-combustion	Robust N-donor ligand-based metal-organic frameworks (MOFs) for capture and degradation of harmful gases and volatile organic compounds (VOCs)	Adsorbent	Universidad De Granada	Metal-Organic Frameworks (Zeolitic imidazolate framework)	2
47	Post-combustion	Novel amide based polymeric ionic liquids: potential candidates for carbon dioxide capture	Absorbent	Universidad Del Pais Vasco/ Euskal Herriko Unibertsitatea	Amide Based Polymeric ionic Liquids	2
48	Post-combustion	Accelerating the development of “transformational” solvents for CO_2 separations	Solvent	Pacific Northwest National Laboratory	Amino pyridine solvents	2
49	Post-combustion	Lab- and bench-scale applications for research and development of transformational carbon dioxide capture	Sorbent	Research Triangle Institute (RTI)	hybrid metal-organic frameworks (MOF) and hybrid phosphorus dendrimers (P-dendrimers)	2
50	Post-combustion	Additively manufactured intensified device for enhanced carbon capture	Other	Oak Ridge National Laboratory	Intensified device	2
51	Pre-combustion	Combined sorbent/WGS-based CO_2 capture process with integrated heat management for IGCC systems	Other	Southern Research Institute	Combined Magnesium oxide sorbent/WGS reactor	2
52	Pre-combustion	Pressure swing adsorption device and process for separating carbon dioxide from shifted syngas and its capture for subsequent storage	Membrane	New Jersey Institute Of Technology	Polyetheretherketone, Polytetrafluoroethylene	2

S. No.	Capture	Project	Technology	Technology developer	Technology Details	TRL
Corporates						
1	Post-combustion	Development and demonstration of waste heat integration with the solvent process for more efficient CO_2 removal from coal-fired flue gas	Heat integration methods	Southern Company Services	Heat integration	5
2	Post-combustion	Evaluation of concentrated piperazine for CO_2 capture from coal-fired flue gas	Solvent	URS Group, Inc.	Piperazine	5
3	Post-combustion	Ion advanced solvent CO_2 capture pilot project	Solvent	Ion Engineering	Amine-organic salt solution	5
4	Post-combustion	Large pilot-scale carbon dioxide capture project using aminosilicone solvent	Solvent	GE Global Research	Non-aqueous phase change aminosilicone based solvent	5
5	Post-combustion	Advanced solvent-based carbon capture technology development	Solvent	Southern Company Services	Advanced hindered amine solvent	5
6	Post-combustion	Sorbent based post-combustion CO_2 slipstream testing	Sorbent	TDA Research Inc	Alkalized alumina solvent	5
7	Post-combustion	Integrated testing of a membrane CO_2 capture process with a coal-fired boiler	Membrane	Membrane Technology And Research	Polaris Membrane	5
8	Post-combustion	The pilot test of a novel electrochemical membrane system for carbon dioxide capture and power generation	Membrane	Fuelcell Energy, Inc.	Electrochemical membrane process	5
9	Post-combustion	Advanced carbon dioxide compression with supersonic technology	Other	Ramgen Power Systems | Dresser-Rand | A Siemens	Supersonic compression	5
10	Pre-combustion	Pilot testing of a highly effective pre-combustion sorbent-based carbon capture system	Sorbent	TDA Research Inc	NA	5
11	Post-combustion	Slipstreampilot-scale demonstration of a novel amine-based post-combustion process technology for CO_2capture from coal-fired power plant flue gas	Solvent	Linde	Novel Amine	5
12	Post-combustion	Carbon absorber retrofit equipment (care)	Solvent	Neumann Systems Group, Inc.	Piperazine	5
13	Post-combustion	Slipstream development and testing of Siemens post-combustion capture and separation technology	Solvent	Siemens	Aqueous amino acid salt	5
14	Pre-combustion	Carbon dioxide capture from IGCC gas streams using the ac-ABC process	Solvent	SRI International	An aqueous ammoniated solution	5

S. No.	Capture	Project	Technology	Technology developer	Technology Details	TRL
15	Post-combustion	Scale-up of calcium carbonate looping technology for efficient carbon dioxide capture from power and industrial plants	Looping Technology	Ethniko Kentro Erevnas Kai Technologikis Anaptyxis | ArcelorMittal Maizieres Research Sa | Steinmuller Babcock Environment Gmbh | Cemex Research Group Ag | SWR Engineering Messtechnik Gmbh | GE Carbon Capture Gmbh | RWE Power Ag | Uniper Technologies Limited | Lhoist Recherche Et Developpement Sa | University Of Ulster	Fluidized bed reactor	5
16	Post-combustion	Design technologies for multi-scale innovation and integration in post-combustion carbon dioxide capture: from molecules to unit operations and integrated plants	Solvent	Ethniko Kentro Erevnas Kai Technologikis Anaptyxis	Not disclosed, claims superior solution than the monoethanolamine (MEA)	5
17	Oxy-fuel	Innovative oxygen carriers uplifting chemical-looping combustion	Looping Technology	Chalmers Tekniska Hoegskola Ab	Fluidized bed reactor	5
18	Post-combustion	Development of post-combustion carbon dioxide capture with CaO in a large testing facility: “CaOling”	Looping Technology	Endesa Generacion Sa	Fluidized bed reactor	5
19	Post-combustion	Bench-scale testing of next-generation hollow fibre membrane modules	Membrane	Air Liquide	Polyimide membrane	4
20	Post-combustion	Supersonic post-combustion inertial CO_2 extraction system	Other	Orbital Atk, Inc.	Supersonic expansion	4
21	Pre-combustion	Membranesdevelopment of a pre-combustion carbon dioxide capture process using high-temperature PBI hollow-fibre membranes	Membrane	SRI	Polybenzimidazole polymer	4
22	Pre-combustion	Robust and energy efficient dual-stage membrane-based process for enhanced carbon dioxide recovery	Membrane	The Media And Process Technology Inc.	Dual-stage membrane process	4
23	Pre-combustion	Membranessorption enhanced mixed matrix membranes for hydrogen purification and carbon dioxide capture	Membrane	Membrane Technology And Research	Pd nanomaterial-based polymer membrane	4
24	Post-combustion	Cryogenic carbon capture development	Other	Sesinnovation	Cryogenic	4
25	Post-combustion	Improvement of GE power’s chilled ammonia process large pilot with the use of membrane technology	Membrane	GE Power	Cellulose acetate, polyamide	4
26	Post-combustion	Novel flow sheet for low energy CO_2 capture enabled by biocatalyst delivery system	Solvent	Akermin	AKM24 solvent, Biocatalyst Delivery System	4

S. No.	Capture	Project	Technology	Technology developer	Technology Details	TRL
27	Post-combustion	Development of a novel gas-pressurized stripping-based technology for CO_2 capture from post-combustion flue gases	Solvent	Carbon Capture Scientific, Llc.	Rotating packed bed	4
28	Post-combustion	Low-energy solvents for CO_2 capture enabled by a combination of enzymes and vacuum regeneration	Solvent	Novozymes	Aqueous potassium carbonate (K2CO3)-based solvent with carbonic anhydrase enzyme catalyst	4
29	Post-combustion	Development of an energy-efficient, environmentally friendly solvent for the capture of CO_2	Solvent	Babcock & Wilcox Power Generation Group, Inc	NA	4
30	Post-combustion	Development of chemical additives for CO_2 capture cost reduction	Solvent	Lawrence Berkeley National Laboratory	Amine, potassium, and ammonia-based solvent	4
31	Post-combustion	Bench-scale development and testing of aerogel sorbents for CO_2 capture	Sorbent	Aspen Aerogels	Amine functionalized aerogel	4
32	Post-combustion	Bench-scale development and testing of rapid pressure swing adsorption for carbon dioxide capture	Sorbent	W.R. Grace	Zeolite	4
33	Post-combustion	Optimizing the costs of solid sorbent-based CO_2 capture process through heat integration	Sorbent	Ada Environmental Solutions	An ion-exchange resin with a primary benzylamine	4
34	Post-combustion	Slow-cost high-capacity regenerable sorbent for carbon dioxide capture from existing coal-fired power plants	Sorbent	TDA Research, Inc.	Alumina	4
35	Post-combustion	Bench-scale development and testing of a novel adsorption process for post-combustion CO_2 capture	Sorbent	Innosepra, LLC	Amine	4
36	Post-combustion	Development of dry sorbent-based post-combustion CO_2 capture technology for retrofit in existing power plant	Sorbent	Na	NA	4
37	Post-combustion	Bench-scale, high-performance, thin-film composite hollow fibre membrane for post-combustion carbon dioxide capture	Membrane	General Electric Global Research	Phosphazene polymer-based composite hollow	4
38	Post-combustion	Low-pressure membrane contactors for carbon dioxide capture	Membrane	Membrane Technology And Research	Not disclosed	4
39	Post-combustion	Development of biometric membranes for near-zero pc power plant emission	Membrane	Na	NA	4
40	Pre-combustion	Novel polymer membrane process for pre-combustion CO_2 capture from coal-fired syngas	Membrane	Membrane Technology & Research, Inc.	Hydrogen-permeable polymeric membranes	4
41	Post-combustion	High-performance capture - Hipercap	Other	SINTEF	A mixture of AMP and piperazine	4

S. No.	Capture	Project	Technology	Technology developer	Technology Details	TRL
42	Post-combustion	NRG CO_2ncept - confirmation of novel cost-effective emerging post-combustion technology	Sorbent	NRG Energy	Reactor	3
43	Oxy-fuel	Novel combustion principle with inherent capture of carbon dioxide	Looping Technology	Chalmers Tekniska Hoegskola Ab	Fluidized bed reactor, Four families of manganese-based combined oxide materials suitable for the application were identified and investigated: I) Mn-Fe-oxides, II) doped and undoped Mn-Si-oxides, III) Mn-Fe-Si-oxides, and IV) doped and undoped Mn-Ca-oxides	3
44	Post-combustion	Post-combustion CO_2 capture for existing pc boilers by self-concentrating amine absorbent	Solvent	Na	NA	2
45	Post-combustion	CO_2 removal from flue gas using the microporous metal-organic framework	Sorbent	UOP	Metal-organic framework	2
46	Pre-combustion	Designing and validating ternary Pd-alloys for optimum sulfur/carbon resistance	Membrane	Pall Corporation	PD alloys	2
47	Pre-combustion	Carbon dioxide capture and hydrogen production with membranes	Membrane	Bp Exploration Operating Company Ltd	Pd / Pd-alloy membrane	2
48	Post-combustion	Advanced materials and electric swing adsorption process for carbon dioxide capture	Adsorbent	SINTEF	ZSM-5 and metal-organic frameworks (CPO-27-Ni and UTSA-16)	2

1.2 LIST OF TECHNOLOGY DEVELOPERS (PATENT HOLDERS HAVING PATENT MORE THAN 5)

Current assignees	Combustion Technology	Route - Separation Process	Country
Agricultural product storage & preservation institute shanxi prov academy of agricultural sciences	Material based/Not disclosed	Absorption	China
Ajou university industry cooperation foundation	Pre combustion	Chemical process	S. Korea
Anhui jianzhu university	Pre combustion	Absorption	China
	Pre combustion	Absorption	China
	Pre combustion	Chemical process	China
	Post combustion	Chemical process	China
	Post combustion	Chemical process	China
Anhui university of science & technology	Pre combustion	Absorption	China
	Pre combustion	Absorption	China
Anhui university of technology	Pre combustion	Chemical process	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Pre combustion	Absorption	China
Arizona state university	Pre combustion	Membranes, Diffusion	USA
	Pre combustion	Adsorption	USA
	Direct air capture	Absorption	USA
	Post combustion	Absorption	USA

Current assignees	Combustion Technology	Route - Separation Process	Country
Av topchiev institute petrochemical	Pre combustion	Absorption	Russia
Battelle memorial institute university of connecticut	Pre combustion	Absorption	USA
Beifang university of nationalities	Post combustion	Chemical process	China
Beihang university of aeronautics & astronautics	Post combustion	Adsorption	China
	Material based/Not disclosed	Biological process	China
Beijing forestry university	Pre combustion	Adsorption	China
	Pre combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Absorption	China
	Pre combustion	Absorption	China
	Post combustion	Adsorption	China
Beijing peking university pioneer technology	Post combustion	Absorption	China
Beijing university of chemical technology	Pre combustion	Absorption	China
	Pre combustion	Adsorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Pre combustion	Absorption	China
	Pre combustion	Absorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Post combustion	Absorption	China
	Pre combustion	Adsorption	China
	Pre combustion	Biological process	China
	Pre combustion	Absorption	China
	Post combustion	Adsorption	China
	Pre combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Pre combustion	Absorption	China
	Pre combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Pre combustion	Biological process	China
	Pre combustion	Chemical process	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Pre combustion	Adsorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Adsorption	China
	Material based/Not disclosed	Absorption	China
	Post combustion	Adsorption	China
	Material based/Not disclosed	Chemical process	China
	Post combustion	Absorption	China
	Material based/Not disclosed	Adsorption	China
Beijing university of civil engineering & architecture	Post combustion	Adsorption	China
Beijing university of technology	Pre combustion	Membranes, Diffusion	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Material based/Not disclosed	Adsorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Post combustion	Adsorption	China
Beijing zhongshida new energy research institute china university of petroleum (beijing)	Post combustion	Membranes, Diffusion	China
Bharath university	Post combustion	Chemical process	India
Board of supervisors of louisisana state university & agricultural & mechanical college louisiana state university	Post combustion	Chemical process	USA
Boreskov institute of catalysis	Post combustion	Absorption	Russia
	Material based/Not disclosed	Absorption	Russia
	Material based/Not disclosed	Absorption	Russia
	Post combustion	Absorption	Russia
California berkeley university of university of california	Pre combustion	Adsorption	USA
California institute of technology	Post combustion	Chemical process	USA
Carnegie mellon university	Pre combustion	Absorption	USA
Catholic university of korea industry academic cooperation foundation	Pre combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Pre combustion	Absorption	S. Korea
Central china normal university	Material based/Not disclosed	Adsorption	China
	Post combustion	Adsorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
Central michigan university sentral michigan juniversiti	Post combustion	Adsorption	WIPO Patent application
Central south university	Post combustion	Adsorption	China
	Pre combustion	Chemical process	China
	Pre combustion	Absorption	China
	Pre combustion	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Adsorption	China
Centre tecnòlogic de la quim de catalunya universitat rovira i virgili	Direct air capture	Absorption	Spain
Chang'an university	Post combustion	Adsorption	China
Changchun university of technology	Post combustion	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Adsorption	China
Changzhou university	Post combustion	Chemical process	China
	Post combustion	Membranes, Diffusion	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Pre combustion	Chemical process	China
	Post combustion	Chemical process	China
	Material based/Not disclosed	Membranes, Diffusion	China
	Post combustion	Absorption	China
Changzhou xianjin material research institute of beijing chemical technology university	Post combustion	Adsorption	China
	Material based/Not disclosed	Adsorption	China
Chengdu university of information technology	Post combustion	Adsorption	China
Chia nan university of pharmacy & science	Post combustion	Absorption	Chinese Taipei
Chiba university	Post combustion	Absorption	Japan
	Material based/Not disclosed	Chemical process	Japan
China coal research institute energy conservation technology	Post combustion	Absorption	China
China coal research institute china coal research institute energy conservation technology	Post combustion	Adsorption	China
China huaneng r & d center huaneng clean energy research institute	Pre combustion	Absorption	China
China university of geosciences	Post combustion	Absorption	China
	Material based/Not disclosed	Adsorption	China
China university of mining & technology	Post combustion	Absorption	China
	Post combustion	Adsorption	China
	Pre combustion	Absorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Post combustion	Adsorption	China
	Post combustion	Membranes, Diffusion	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Pre combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Chemical process	China
China university of petroleum (beijing)	Post combustion	Adsorption	China
	Post combustion	Absorption	China
	Post combustion	Adsorption	China
	Post combustion	Absorption	China
China university of petroleum east china	Post combustion	Membranes, Diffusion	China
	Pre combustion	Absorption	China
	Post combustion	Membranes, Diffusion	China
	Post combustion	Absorption	China
	Material based/Not disclosed	Chemical process	China
	Material based/Not disclosed	Adsorption	China
	Post combustion	Membranes, Diffusion	China
China university of petroleum china university of petroleum (beijing)	Pre combustion	Absorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
Chinese research academy of environmental sciences	Post combustion	Chemical process	China
Chongqing academy of agricultural sciences chongqing kairui agricultural development	Material based/Not disclosed	Membranes, Diffusion	China
Chongqing university	Post combustion	Absorption	China
	Post combustion	Membranes, Diffusion	China
	Pre combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Chemical process	China
	Pre combustion	Absorption	China
	Post combustion	Adsorption	China
Chonnam national university	Post combustion	Absorption	S. Korea
	Post combustion	Adsorption	S. Korea
Chung ang university industry academic cooperation foundation	Material based/Not disclosed	Chemical process	S. Korea
Chung yuan christian university	Post combustion	Membranes, Diffusion	Chinese Taipei
	Material based/Not disclosed	Membranes, Diffusion	USA
Chungnam national university industry academic foundation	Material based/Not disclosed	Adsorption	S. Korea
	Post combustion	Rectification, Condensation	S. Korea
Chuo university	Post combustion	Absorption	Japan

Current assignees	Combustion Technology	Route - Separation Process	Country
Cnrs - centre national de la recherche scientifique ens ifp energies nouvelles ucbl	Pre combustion	Biological process	France
	Pre combustion	Adsorption	France
	Post combustion	Absorption	France
Columbia university	Post combustion	Adsorption	USA
	Post combustion	Absorption	USA
	Pre combustion	Biological process	USA
	Pre combustion	Chemical process	USA
	Direct air capture	Adsorption	USA
	Direct air capture	Adsorption	USA
	Pre combustion	Adsorption	USA
Company of the hebrew university of jerusalem ltd deberopumento issumu research gymsum research development yissum research development	Pre combustion	Absorption	USA
Consiglio nazionale delle ricerche universidad de sevilla universita degli studi di napoli federico ii	Pre combustion	Adsorption	Spain
Cornell university	Post combustion	Adsorption	USA
	Post combustion	Adsorption	USA
Csic - consejo superior de investigaciones cientificas universidad de cadiz universidad de sevilla	Post combustion	Chemical process	Spain

Current assignees	Combustion Technology	Route - Separation Process	Country
Dalian university of technology	Post combustion	Absorption	China
	Pre combustion	Absorption	China
	Pre combustion	Chemical process	China
	Post combustion	Absorption	China
	Post combustion	Absorption	WIPO Patent application
	Post combustion	Absorption	China
	Post combustion	Adsorption	China
	Post combustion	Membranes, Diffusion	China
	Pre combustion	Chemical process	China
	Post combustion	Absorption	China
	Pre combustion	Adsorption	China
	Post combustion	Absorption	China
	Post combustion	Adsorption	China
	Post combustion	Chemical process	China
	Post combustion	Chemical process	China
	Post combustion	Adsorption	China
	Pre combustion	Membranes, Diffusion	China
	Post combustion	Membranes, Diffusion	China
	Post combustion	Membranes, Diffusion	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Chemical process	China
	Material based/Not disclosed	Membranes, Diffusion	China
	Post combustion	Membranes, Diffusion	China
Dalian institute chemical & physics	Post combustion	Adsorption	WIPO Patent application
	Post combustion	Membranes, Diffusion	China
	Post combustion	Membranes, Diffusion	China
	Post combustion	Adsorption	WIPO Patent application
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Membranes, Diffusion	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Adsorption	China
	Post combustion	Membranes, Diffusion	China
	Post combustion	Absorption	China
	Material based/Not disclosed	Membranes, Diffusion	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Material based/Not disclosed	Membranes, Diffusion	China
	Material based/Not disclosed	Membranes, Diffusion	China
	Material based/Not disclosed	Absorption	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Membranes, Diffusion	China
	Material based/Not disclosed	Absorption	China
	Post combustion	Absorption	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Membranes, Diffusion	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Post combustion	Membranes, Diffusion	China

Current assignees	Combustion Technology	Route - Separation Process	Country
Dalian maritime university	Post combustion	Chemical process	China
Dalian polytechnic university	Post combustion	Adsorption	China
Danmarks tekniske universitet	Post combustion	Absorption	Patent filed through European Patent Office
	Post combustion	Absorption	Patent filed through European Patent Office
Danmarks tekniske universitet	Post combustion	Absorption	Patent filed through European Patent Office
Dongguan university of technology	Material based/Not disclosed	Absorption	China
Dongguk university	Pre combustion	Absorption	S. Korea
	Oxyfuel combustion	Membranes, Diffusion	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Chemical process	China
	Post combustion	Absorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Post combustion	Chemical process	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Chemical process	China
	Pre combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
Dongseo university technology headquarters	Material based/Not disclosed	Membranes, Diffusion	S. Korea
Doshisha university	Post combustion	Absorption	Japan
Drdo - defence research & development organization	Material based/Not disclosed	Chemical process	India
Dze quins university of belfast queens university belfast	Pre combustion	Absorption	Great Britain
East china jiaotong university	Post combustion	Absorption	China
East china university of science & technology	Post combustion	Adsorption	China
	Pre combustion	Adsorption	China
	Pre combustion	Chemical process	China
	Post combustion	Adsorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Pre combustion	Absorption	China
	Post combustion	Adsorption	China
	Pre combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
Electric power research institute	Pre combustion	Absorption	China
	Pre combustion	Absorption	China
	Pre combustion	Absorption	China
	Post combustion	Absorption	China
	Material based/Not disclosed	Absorption	China
	Post combustion	Adsorption	China
Electric power research institute of guangdong	Pre combustion	Absorption	China
	Post combustion	Absorption	China
Electric power research institute	Post combustion	Absorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
Epri - electric power research institute	Pre combustion	Adsorption	USA
Ethniko kentro erevnas kai technologikis anaptyxis eketa institouto chimikon diergasion kai energei	Material based/Not disclosed	Chemical process	Greece
Ewha woman university	Material based/Not disclosed	Absorption	S. Korea
Ewha woman university krict korea research institute of chemical technology	Material based/Not disclosed	Adsorption	S. Korea
Federalnoe gosudarstvennoe bjudzhetnoe uchrezhdenie nauki institut organicheskoj khimii im n d zelinskogo rossijskoj akademii nauk	Post combustion	Adsorption	Russia
	Material based/Not disclosed	Adsorption	Russia
	Material based/Not disclosed	Adsorption	Russia
	Material based/Not disclosed	Chemical process	Russia
Foshan university	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Material based/Not disclosed	Adsorption	China
Fujian agriculture & forestry university	Material based/Not disclosed	Adsorption	China
Fujian normal university	Material based/Not disclosed	Adsorption	China
Fujian university of technology	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
Fuzhou university	Post combustion	Chemical process	China
Gas technology institute	Post combustion	Absorption	USA
	Post combustion	Membranes, Diffusion	USA

Current assignees	Combustion Technology	Route - Separation Process	Country
	Pre combustion	Chemical process	USA
	Pre combustion	Chemical process	USA
	Pre combustion	Adsorption	USA
	Post combustion	Absorption	USA
	Pre combustion	Absorption	USA
Georgia tech (georgia institute of technology)	Post combustion	Adsorption	USA
	Direct air capture	Adsorption	USA
	Direct air capture	Adsorption	USA
	Pre combustion	Membranes, Diffusion	USA
	Material based/Not disclosed	Membranes, Diffusion	USA
	Material based/Not disclosed	Membranes, Diffusion	USA
	Post combustion	Adsorption	USA
Guangdong university of technology	Pre combustion	Adsorption	China
	Post combustion	Biological process	China
	Post combustion	Absorption	China
Guangxi normal university	Material based/Not disclosed	Adsorption	China
Guangxi university	Post combustion	Chemical process	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Pre combustion	Adsorption	China
	Post combustion	Adsorption	China
Guangxi university of chinese medicine	Material based/Not disclosed	Chemical process	China
Guangzhou institute energy conversion	Post combustion	Absorption	China
Guangzhou institute of energy conversion chinese academy of sciences	Post combustion	Chemical process	China
	Post combustion	Chemical process	China
	Pre combustion	Biological process	China
	Post combustion	Chemical process	China
Guilin university of electronic technology	Post combustion	Absorption	China
	Post combustion	Absorption	China
Guilin university of technology	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
Gwangju institute of science & technology	Post combustion	Absorption	S. Korea
	Post combustion	Membranes, Diffusion	USA
	Post combustion	Absorption	S. Korea
	Post combustion	Membranes, Diffusion	S. Korea

Current assignees	Combustion Technology	Route - Separation Process	Country
	Post combustion	Absorption	S. Korea
	Post combustion	Membranes, Diffusion	USA
	Post combustion	Membranes, Diffusion	USA
	Post combustion	Absorption	S. Korea
	Material based/Not disclosed	Membranes, Diffusion	USA
Gyeongsang national university industry academic cooperation foundation	Post combustion	Membranes, Diffusion	S. Korea
	Post combustion	Membranes, Diffusion	S. Korea
	Post combustion	Chemical process	S. Korea
	Post combustion	Membranes, Diffusion	S. Korea
	Post combustion	Membranes, Diffusion	S. Korea
Hanseo university academic cooperation foundation	Post combustion	Absorption	S. Korea
Hanyang university industry university cooperation foundation	Material based/Not disclosed	Membranes, Diffusion	S. Korea
	Pre combustion	Absorption	S. Korea
Harbin engineering university	Post combustion	Chemical process	China
Hebei university of engineering	Post combustion	Absorption	China
Hebei university of science & technology	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Post combustion	Adsorption	China
Hebei university of technology	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Chemical process	China
	Post combustion	Adsorption	China
Hechi university	Post combustion	Adsorption	China
Hefei university of technology	Material based/Not disclosed	Absorption	China
Heilongjiang electric power research institute	Post combustion	Chemical process	China
Heilongjiang forest engineering & environmental research institute	Material based/Not disclosed	Membranes, Diffusion	China
Henan normal university	Post combustion	Absorption	China
Henan polytechnic university	Pre combustion	Absorption	China
Henan university of science & technology	Pre combustion	Absorption	China
Hit yixing academy of environmental protection	Post combustion	Membranes, Diffusion	China
Hohai university	Post combustion	Adsorption	China
Hoseo university academic cooperation foundation	Post combustion	Absorption	S. Korea
Huadian electric power research institute	Post combustion	Chemical process	China
Huaibei normal university	Post combustion	Absorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
Huaneng clean energy research institute Huaqiao university	Pre combustion	Absorption	China
	Pre combustion	Absorption	China
	Post combustion	Absorption	China
	Pre combustion	Absorption	China
	Post combustion	Absorption	China
	Pre combustion	Absorption	China
	Pre combustion	Absorption	China
	Pre combustion	Chemical process	China
	Pre combustion	Absorption	China
	Post combustion	Absorption	China
	Pre combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Chemical process	China
	Pre combustion	Absorption	China
	Pre combustion	Absorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Chemical process	China
	Post combustion	Absorption	China
	Pre combustion	Absorption	China
	Pre combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
Huazhong agricultural university	Pre combustion	Chemical process	China
	Pre combustion	Absorption	China
	Post combustion	Chemical process	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Material based/Not disclosed	Adsorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Post combustion	Absorption	China
Huazhong university of science & technology	Post combustion	Membranes, Diffusion	China
	Oxyfuel combustion	Chemical process	China
	Pre combustion	Adsorption	China
	Post combustion	Absorption	China
	Pre combustion	Adsorption	China
	Post combustion	Adsorption	China
	Pre combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Chemical process	China
	Post combustion	Adsorption	China
	Post combustion	Chemical process	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Pre combustion	Adsorption	China
	Post combustion	Adsorption	China
	Material based/Not disclosed	Adsorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Post combustion	Adsorption	China
	Material based/Not disclosed	Adsorption	China
Hubei university	Post combustion	Absorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
Hunan city university	Material based/Not disclosed	Adsorption	China
Hunan normal university	Post combustion	Chemical process	China
Hunan university	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Pre combustion	Absorption	China
	Pre combustion	Absorption	China
	Post combustion	Absorption	China
	Pre combustion	Absorption	China
	Post combustion	Adsorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Pre combustion	Chemical process	China
	Post combustion	Absorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Material based/Not disclosed	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Material based/Not disclosed	Absorption	China
	Material based/Not disclosed	Absorption	China
	Material based/Not disclosed	Absorption	China
Ifp energies nouvelles	Post combustion	Absorption	France
	Post combustion	Absorption	France
	Post combustion	Absorption	France
	Post combustion	Absorption	France
	Post combustion	Absorption	France
	Post combustion	Absorption	France
	Post combustion	Absorption	France
	Post combustion	Absorption	France
	Post combustion	Absorption	France
	Post combustion	Adsorption	France
	Post combustion	Absorption	France

Current assignees	Combustion Technology	Route - Separation Process	Country
	Post combustion	Absorption	France
	Post combustion	Adsorption	France
	Post combustion	Absorption	France
	Post combustion	Absorption	France
	Post combustion	Absorption	France
	Post combustion	Absorption	France
	Post combustion	Absorption	France
	Pre combustion	Chemical process	France
	Post combustion	Absorption	France
	Post combustion	Absorption	France
	Post combustion	Absorption	France
	Pre combustion	Absorption	France
	Post combustion	Absorption	France
	Post combustion	Absorption	France
	Pre combustion	Absorption	France
	Pre combustion	Absorption	France
	Pre combustion	Absorption	France
	Post combustion	Rectification, Condensation	France
	Post combustion	Absorption	France

Current assignees	Combustion Technology	Route - Separation Process	Country
	Post combustion	Absorption	France
	Post combustion	Adsorption	France
	Post combustion	Absorption	France
	Post combustion	Rectification, Condensation	France
	Pre combustion	Absorption	France
	Pre combustion	Absorption	USA
	Pre combustion	Chemical process	France
	Post combustion	Adsorption	France
	Post combustion	Absorption	France
	Pre combustion	Adsorption	France
	Pre combustion	Absorption	France
	Pre combustion	Absorption	France
IHI university of tokyo	Post combustion	Absorption	Japan
	Post combustion	Absorption	Japan
	Post combustion	Absorption	Japan
	Post combustion	Absorption	Japan
Incheon university industry academic cooperation foundation	Post combustion	Adsorption	S. Korea
	Post combustion	Membranes, Diffusion	S. Korea
	Post combustion	Membranes, Diffusion	S. Korea

Current assignees	Combustion Technology	Route - Separation Process	Country
Industrial technology research institute national central university	Direct air capture	Chemical process	Chinese Taipei
Industry academia cooperation of sejong university	Post combustion	Absorption	S. Korea
Industry academic cooperation foundation hanyang university	Post combustion	Membranes, Diffusion	S. Korea
	Post combustion	Membranes, Diffusion	S. Korea
	Post combustion	Chemical process	S. Korea
	Post combustion	Membranes, Diffusion	WIPO Patent application
	Post combustion	Membranes, Diffusion	S. Korea
	Post combustion	Membranes, Diffusion	S. Korea
	Pre combustion	Membranes, Diffusion	S. Korea
Industry academy cooperation corps of sunchon national university	Post combustion	Chemical process	S. Korea
Inner mongolia university	Post combustion	Absorption	China
Inner mongolia university of technology	Post combustion	Chemical process	China
	Pre combustion	Chemical process	China
Instalaciones inabensa	Post combustion	Adsorption	Spain
Instalaciones inabensa	Post combustion	Adsorption	Spain
Institute for advanced engineering - korea	Oxyfuel combustion	Chemical process	S. Korea
	Pre combustion	Chemical process	S. Korea
	Post combustion	Absorption	S. Korea

Current assignees	Combustion Technology	Route - Separation Process	Country
Institute of coal chemistry, chinese academy of science	Pre combustion	Adsorption	China
	Post combustion	Adsorption	China
	Pre combustion	Adsorption	China
	Pre combustion	Adsorption	China
	Pre combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Material based/Not disclosed	Absorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
Institute of engineering thermophysics chinese academy of sciences	Pre combustion	Chemical process	China
	Post combustion	Absorption	China
	Pre combustion	Absorption	China
	Pre combustion	Absorption	China
	Material based/Not disclosed	Absorption	China
	Pre combustion	Adsorption	USA

Current assignees	Combustion Technology	Route - Separation Process	Country
Institute of nuclear energy research atomic energy council executive yuan r o c	Pre combustion	Adsorption	USA
	Pre combustion	Chemical process	USA
	Material based/Not disclosed	Adsorption	Chinese Taipei
	Post combustion	Absorption	Chinese Taipei
Institute of process engineering chinese academy of sciences	Pre combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Pre combustion	Absorption	China
	Post combustion	Adsorption	China
	Pre combustion	Absorption	China
	Pre combustion	Chemical process	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Material based/Not disclosed	Adsorption	China
Institutul national de cercetare dezvoltare pentru tehnologii criogenice si izotopice icsi	Material based/Not disclosed	Absorption	Romania

Current assignees	Combustion Technology	Route - Separation Process	Country
Japan aerospace exploration agency	Post combustion	Absorption	Japan
Jianghan university	Pre combustion	Absorption	China
	Post combustion	Membranes, Diffusion	China
	Post combustion	Membranes, Diffusion	China
	Post combustion	Adsorption	China
	Post combustion	Membranes, Diffusion	China
	Post combustion	Membranes, Diffusion	China
	Material based/Not disclosed	Membranes, Diffusion	China
	Material based/Not disclosed	Membranes, Diffusion	China
	Material based/Not disclosed	Membranes, Diffusion	China
	Material based/Not disclosed	Membranes, Diffusion	China
	Material based/Not disclosed	Membranes, Diffusion	China
	Material based/Not disclosed	Adsorption	China
Jiangsu university	Material based/Not disclosed	Adsorption	China
Jiangsu university of science &technology	Post combustion	Adsorption	China
	Post combustion	Absorption	China
Jiangxi normal university	Post combustion	Membranes, Diffusion	China
Jilin normal university	Post combustion	Adsorption	China
Jilin university	Post combustion	Adsorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Post combustion	Adsorption	China
	Post combustion	Chemical process	China
	Post combustion	Chemical process	China
Jining university	Post combustion	Adsorption	China
Kanazawa university	Direct air capture	Absorption	Japan
Kanazawa university	Post combustion	Absorption	Japan
King abdullah university of science & technology	Post combustion	Adsorption	USA
	Direct air capture	Adsorption	USA
	Post combustion	Absorption	USA
	Pre combustion	Membranes, Diffusion	USA
	Post combustion	Adsorption	USA
	Post combustion	Adsorption	USA
	Post combustion	Membranes, Diffusion	USA
	Pre combustion	Adsorption	USA
	Pre combustion	Adsorption	USA
	Direct air capture	Absorption	USA
King fahd university of petroleum & minerals	Post combustion	Adsorption	USA
	Post combustion	Adsorption	USA
	Post combustion	Adsorption	USA

Current assignees	Combustion Technology	Route - Separation Process	Country
Kobe national university	Post combustion	Membranes, Diffusion	Japan
Kobe university	Pre combustion	Membranes, Diffusion	Japan
Kongju national university industry academia cooperation	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Adsorption	S. Korea
Konkuk university industrial cooperation	Post combustion	Absorption	S. Korea
	Material based/Not disclosed	Adsorption	S. Korea
	Material based/Not disclosed	Adsorption	S. Korea
	Post combustion	Adsorption	S. Korea
Korea advanced institute of science & technology	Post combustion	Adsorption	S. Korea
	Pre combustion	Absorption	S. Korea
	Pre combustion	Adsorption	S. Korea
	Pre combustion	Adsorption	S. Korea
	Post combustion	Adsorption	S. Korea
	Post combustion	Adsorption	S. Korea
	Post combustion	Chemical process	S. Korea
	Post combustion	Chemical process	S. Korea
	Post combustion	Adsorption	S. Korea
	Post combustion	Chemical process	S. Korea

Current assignees	Combustion Technology	Route - Separation Process	Country
	Post combustion	Chemical process	S. Korea
	Post combustion	Adsorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Adsorption	S. Korea
	Post combustion	Absorption	S. Korea
Korea carbon capture & sequestration r & d center	Post combustion	Absorption	S. Korea
Korea institute of energy research	Post combustion	Absorption	S. Korea
	Post combustion	Membranes, Diffusion	S. Korea
	Post combustion	Absorption	S. Korea
	Pre combustion	Membranes, Diffusion	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Pre combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Membranes, Diffusion	S. Korea
	Post combustion	Absorption	S. Korea
	Pre combustion	Absorption	S. Korea

Current assignees	Combustion Technology	Route - Separation Process	Country
	Pre combustion	Membranes, Diffusion	S. Korea
	Post combustion	Adsorption	S. Korea
	Post combustion	Adsorption	S. Korea
	Post combustion	Adsorption	S. Korea
	Post combustion	Adsorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Pre combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Pre combustion	Membranes, Diffusion	S. Korea
	Pre combustion	Membranes, Diffusion	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Pre combustion	Absorption	S. Korea

Current assignees	Combustion Technology	Route - Separation Process	Country
	Pre combustion	Absorption	S. Korea
	Post combustion	Adsorption	S. Korea
	Pre combustion	Adsorption	S. Korea
	Pre combustion	Chemical process	S. Korea
	Pre combustion	Adsorption	S. Korea
	Pre combustion	Absorption	S. Korea
	Post combustion	Adsorption	S. Korea
	Pre combustion	Absorption	S. Korea
	Pre combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Pre combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Pre combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Chemical process	S. Korea

Current assignees	Combustion Technology	Route - Separation Process	Country
	Post combustion	Absorption	S. Korea
	Pre combustion	Chemical process	S. Korea
	Pre combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Pre combustion	Membranes, Diffusion	USA
	Pre combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Pre combustion	Absorption	S. Korea
	Pre combustion	Chemical process	China
	Pre combustion	Membranes, Diffusion	S. Korea
	Pre combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Pre combustion	Absorption	S. Korea
	Pre combustion	Absorption	S. Korea
	Pre combustion	Absorption	S. Korea
	Pre combustion	Absorption	S. Korea
	Pre combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Pre combustion	Membranes, Diffusion	S. Korea

Current assignees	Combustion Technology	Route - Separation Process	Country
	Pre combustion	Membranes, Diffusion	S. Korea
	Post combustion	Absorption	S. Korea
	Pre combustion	Absorption	S. Korea
	Pre combustion	Adsorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Chemical process	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Oxyfuel combustion	Membranes, Diffusion	S. Korea
	Oxyfuel combustion	Membranes, Diffusion	S. Korea
	Material based/Not disclosed	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea

Current assignees	Combustion Technology	Route - Separation Process	Country
	Post combustion	Absorption	S. Korea
	Material based/Not disclosed	Absorption	S. Korea
	Post combustion	Adsorption	S. Korea
	Material based/Not disclosed	Absorption	S. Korea
	Material based/Not disclosed	Absorption	S. Korea
	Material based/Not disclosed	Absorption	S. Korea
	Material based/Not disclosed	Membranes, Diffusion	S. Korea
	Post combustion	Adsorption	S. Korea
	Material based/Not disclosed	Adsorption	S. Korea
	Post combustion	Adsorption	S. Korea
	Pre combustion	Chemical process	S. Korea
	Pre combustion	Chemical process	S. Korea
Korea institute of geoscience & minaral resources	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Adsorption	S. Korea
	Post combustion	Chemical process	S. Korea
	Post combustion	Chemical process	S. Korea
	Material based/Not disclosed	Chemical process	S. Korea

Current assignees	Combustion Technology	Route - Separation Process	Country
Korea institute of industrial technology	Post combustion	Adsorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Material based/Not disclosed	Absorption	S. Korea
	Material based/Not disclosed	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Biological process	S. Korea
	Material based/Not disclosed	Membranes, Diffusion	S. Korea
	Material based/Not disclosed	Membranes, Diffusion	S. Korea
	Pre combustion	Absorption	S. Korea
	Post combustion	Adsorption	S. Korea
Korea maritime university industry academic cooperation foundation	Post combustion	Absorption	S. Korea
Korea research institute chemical technology	Pre combustion	Adsorption	S. Korea
	Pre combustion	Absorption	S. Korea
	Pre combustion	Absorption	S. Korea

Current assignees	Combustion Technology	Route - Separation Process	Country
	Pre combustion	Absorption	S. Korea
	Pre combustion	Adsorption	S. Korea
Korea university industrial & academic collaboration foundation	Post combustion	Absorption	S. Korea
	Post combustion	Membranes, Diffusion	S. Korea
	Post combustion	Absorption	S. Korea
	Pre combustion	Adsorption	S. Korea
	Post combustion	Adsorption	S. Korea
	Post combustion	Adsorption	S. Korea
	Post combustion	Adsorption	S. Korea
	Pre combustion	Absorption	S. Korea
	Pre combustion	Biological process	S. Korea
	Post combustion	Chemical process	S. Korea
	Post combustion	Adsorption	S. Korea
	Post combustion	Chemical process	S. Korea
	Material based/Not disclosed	Adsorption	S. Korea
	Post combustion	Absorption	S. Korea
	Material based/Not disclosed	Adsorption	S. Korea
	Material based/Not disclosed	Adsorption	S. Korea
	Post combustion	Adsorption	S. Korea

Current assignees	Combustion Technology	Route - Separation Process	Country
	Material based/Not disclosed	Absorption	S. Korea
	Post combustion	Adsorption	S. Korea
Korean advanced institute science & technology	Post combustion	Chemical process	S. Korea
Krict korea research institute of chemical technology	Post combustion	Membranes, Diffusion	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Adsorption	S. Korea
	Pre combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Material based/Not disclosed	Adsorption	S. Korea
	Material based/Not disclosed	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Adsorption	S. Korea
Kunming university of science & technology	Pre combustion	Absorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Pre combustion	Absorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Pre combustion	Chemical process	China
	Post combustion	Absorption	China
	Pre combustion	Chemical process	China
	Post combustion	Adsorption	China
	Post combustion	Absorption	China
	Post combustion	Chemical process	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Chemical process	China
	Post combustion	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Post combustion	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Chemical process	China
	Post combustion	Adsorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Material based/Not disclosed	Adsorption	China
	Post combustion	Adsorption	China
	Material based/Not disclosed	Adsorption	China
Kyonggi university industry & academia cooperation foundation	Pre combustion	Membranes, Diffusion	S. Korea
Kyung hee university	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Pre combustion	Adsorption	S. Korea
	Post combustion	Adsorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Adsorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
Kyungpook national university industry academic cooperation foundation	Post combustion	Absorption	S. Korea
	Post combustion	Adsorption	S. Korea

Current assignees	Combustion Technology	Route - Separation Process	Country
	Pre combustion	Chemical process	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Material based/Not disclosed	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
Lehigh university	Post combustion	Adsorption	USA
Leland stanford junior university	Pre combustion	Adsorption	USA
Liaoning technical university	Material based/Not disclosed	Adsorption	China
Liaoning university of petroleum and chemical technology	Post combustion	Chemical process	China
	Post combustion	Chemical process	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Post combustion	Absorption	China
Linyi university	Post combustion	Absorption	China
	Post combustion	Adsorption	China
Mcgill university	Post combustion	Chemical process	USA
Mit - massachusetts institute of technology	Post combustion	Absorption	USA

Current assignees	Combustion Technology	Route - Separation Process	Country
	Pre combustion	Adsorption	USA
	Pre combustion	Adsorption	USA
	Post combustion	Adsorption	USA
	Post combustion	Chemical process	USA
	Post combustion	Absorption	USA
Monash university	Post combustion	Adsorption	Australia
Monash university	Post combustion	Adsorption	WIPO Patent application
Myongji university industry & academia cooperation	Post combustion	Chemical process	S. Korea
	Material based/Not disclosed	Adsorption	S. Korea
	Material based/Not disclosed	Adsorption	S. Korea
	Material based/Not disclosed	Adsorption	S. Korea
	Material based/Not disclosed	Adsorption	S. Korea
	Pre combustion	Adsorption	S. Korea
	Post combustion	Adsorption	S. Korea
	Material based/Not disclosed	Adsorption	S. Korea
Nagoya university	Material based/Not disclosed	Adsorption	Japan
Nanchang hangkong university	Post combustion	Absorption	China
	Post combustion	Chemical process	China
	Post combustion	Absorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Material based/Not disclosed	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
Nanchang university	Post combustion	Adsorption	China
	Post combustion	Chemical process	China
	Post combustion	Absorption	China
	Pre combustion	Adsorption	China
Nanjing normal university	Pre combustion	Chemical process	China
	Pre combustion	Adsorption	China
	Pre combustion	Chemical process	China
	Pre combustion	Chemical process	China
	Pre combustion	Chemical process	China
	Pre combustion	Absorption	China
	Post combustion	Chemical process	China
Nanjing university	Direct air capture	Adsorption	China
	Post combustion	Absorption	China
	Post combustion	Chemical process	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Post combustion	Absorption	China
	Post combustion	Chemical process	China
	Pre combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
Nanjing university of aeronautics & astronautics (nuaa)	Pre combustion	Chemical process	China
Nanjing university of information science & technology	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Adsorption	China
	Post combustion	Absorption	China
	Pre combustion	Absorption	China
	Pre combustion	Absorption	China
	Pre combustion	Absorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Material based/Not disclosed	Absorption	China
	Material based/Not disclosed	Absorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Material based/Not disclosed	Adsorption	China
Nanjing university of science & technology	Post combustion	Adsorption	China
	Post combustion	Absorption	China
	Post combustion	Adsorption	China
	Material based/Not disclosed	Adsorption	China
Nanjing university of technology	Post combustion	Membranes, Diffusion	China
	Pre combustion	Membranes, Diffusion	China
	Post combustion	Membranes, Diffusion	China
	Post combustion	Adsorption	China
	Material based/Not disclosed	Membranes, Diffusion	China
	Post combustion	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Membranes, Diffusion	China
	Material based/Not disclosed	Adsorption	China
	Direct air capture	Membranes, Diffusion	China
	Post combustion	Membranes, Diffusion	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Membranes, Diffusion	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Material based/Not disclosed	Adsorption	China
	Pre combustion	Absorption	China
Nanjing university nanjing university of technology	Post combustion	Absorption	China
National central university	Material based/Not disclosed	Chemical process	Chinese Taipei
National central university	Pre combustion	Chemical process	Chinese Taipei
National cheng kung university	Post combustion	Absorption	Chinese Taipei
	Material based/Not disclosed	Absorption	Chinese Taipei
	Pre combustion	Absorption	Chinese Taipei
	Post combustion	Adsorption	Chinese Taipei
National chunghsing university	Post combustion	Adsorption	Chinese Taipei
National ilan university	Post combustion	Adsorption	Chinese Taipei
National institute of advanced industrial science & technology	Post combustion	Absorption	Japan
	Pre combustion	Adsorption	Japan
	Post combustion	Absorption	Japan
	Post combustion	Absorption	Japan
National institute of advanced industrial science & technology	Pre combustion	Absorption	Japan
National taiwan university of science & technology	Post combustion	Adsorption	Chinese Taipei
National technology & engineering solutions sandia stc university of new mexico	Post combustion	Membranes, Diffusion	USA

Current assignees	Combustion Technology	Route - Separation Process	Country
National united university	Pre combustion	Membranes, Diffusion	Chinese Taipei
National university of defense technology	Material based/Not disclosed	Absorption	China
National university of singapore	Post combustion	Absorption	USA
Newcastle innovation university of newcastle	Pre combustion	Chemical process	Australia
Nihon university	Post combustion	Absorption	Japan
Ningbo institute of industrial technology chinese academy of sciences	Pre combustion	Adsorption	China
	Post combustion	Adsorption	China
	Pre combustion	Adsorption	China
	Pre combustion	Adsorption	China
	Post combustion	Membranes, Diffusion	China
	Material based/Not disclosed	Membranes, Diffusion	China
Ningbo nottingham new materials institute university of nottingham	Post combustion	Adsorption	China
Ningbo university	Pre combustion	Membranes, Diffusion	China
	Post combustion	Absorption	China
	Post combustion	Chemical process	China
	Post combustion	Chemical process	China
	Post combustion	Adsorption	China
Ningbo university of technology	Post combustion	Adsorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
Ningxia university	Post combustion	Adsorption	China
Nippon steel nippon steel & sumitomo metal research institute of innovative technology for the earth	Pre combustion	Absorption	Japan
North china electric power university	Oxyfuel combustion	Rectification, Condensation	China
	Pre combustion	Rectification, Condensation	China
	Pre combustion	Chemical process	China
	Post combustion	Adsorption	China
	Post combustion	Absorption	China
	Post combustion	Chemical process	China
	Post combustion	Adsorption	China
	Pre combustion	Absorption	China
	Pre combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Chemical process	China
	Post combustion	Chemical process	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Pre combustion	Absorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Pre combustion	Absorption	China
	Pre combustion	Membranes, Diffusion	China
	Pre combustion	Chemical process	China
	Post combustion	Chemical process	China
North china electric power university	Post combustion	Chemical process	China
	Material based/Not disclosed	Adsorption	China
North china university of water conservancy and electric power	Pre combustion	Absorption	China
North dakota state university university of north dakota	Post combustion	Absorption	USA
North university of china	Post combustion	Absorption	China
Northeast dianli university	Post combustion	Adsorption	China
Northeast forestry university	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
Northeastern university of china	Post combustion	Absorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Pre combustion	Adsorption	China
	Pre combustion	Adsorption	China
	Post combustion	Adsorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Material based/Not disclosed	Absorption	China
Northwest university	Pre combustion	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Absorption	China
Northwest university for nationalities	Material based/Not disclosed	Adsorption	China
Northwest university for nationalities	Material based/Not disclosed	Adsorption	China
Norwegian university of science & technology	Pre combustion	Membranes, Diffusion	Great Britain
Ohio state innovation foundation	Post combustion	Membranes, Diffusion	USA
Ohio state university research foundation	Post combustion	Chemical process	USA
	Material based/Not disclosed	Membranes, Diffusion	USA
Okayama national university okayama university	Post combustion	Adsorption	Japan

Current assignees	Combustion Technology	Route - Separation Process	Country
panasonic panasonic electric industry			
Okayama university	Material based/Not disclosed	Adsorption	Japan
Omsk state technical university	Post combustion	Chemical process	Russia
Panjin industrial technology institute of dalian university of technology	Material based/Not disclosed	Adsorption	China
Pohang university of science & technology postech	Post combustion	Adsorption	S. Korea
	Pre combustion	Absorption	S. Korea
	Pre combustion	Absorption	S. Korea
	Pre combustion	Absorption	S. Korea
	Post combustion	Biological process	S. Korea
	Post combustion	Adsorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Chemical process	S. Korea
	Material based/Not disclosed	Adsorption	S. Korea
	Post combustion	Chemical process	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Adsorption	S. Korea
Princeton university	Pre combustion	Adsorption	USA
Puerto rico university of	Pre combustion	Absorption	USA
Pusan national university industry-academic cooperation foundation	Post combustion	Absorption	S. Korea

Current assignees	Combustion Technology	Route - Separation Process	Country
	Post combustion	Absorption	S. Korea
Qatar university	Post combustion	Absorption	USA
Qilu university of technology	Post combustion	Adsorption	China
Qilu university of technology	Material based/Not disclosed	Absorption	China
Qingdao university	Material based/Not disclosed	Membranes, Diffusion	China
Qingdao university	Material based/Not disclosed	Adsorption	China
Qingdao university of science & technology	Post combustion	Absorption	China
	Post combustion	Adsorption	China
	Post combustion	Absorption	China
	Post combustion	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
Qiqihar university	Post combustion	Membranes, Diffusion	China
Queens university belfast	Pre combustion	Absorption	Great Britain
Research institue of innovative technology for the earth	Post combustion	Adsorption	Japan
Research institute of industrial science & technology	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea

Current assignees	Combustion Technology	Route - Separation Process	Country
	Post combustion	Absorption	S. Korea
	Pre combustion	Absorption	S. Korea
	Pre combustion	Absorption	S. Korea
	Post combustion	Chemical process	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Pre combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Material based/Not disclosed	Chemical process	S. Korea
	Material based/Not disclosed	Adsorption	S. Korea
	Material based/Not disclosed	Absorption	S. Korea
	Post combustion	Adsorption	S. Korea
Research institute of innovative technology for the earth	Pre combustion	Membranes, Diffusion	Japan
	Post combustion	Membranes, Diffusion	Japan

Current assignees	Combustion Technology	Route - Separation Process	Country
	Pre combustion	Absorption	Japan
	Post combustion	Membranes, Diffusion	Japan
	Pre combustion	Adsorption	Japan
	Post combustion	Absorption	Japan
	Post combustion	Membranes, Diffusion	Japan
Rice university	Direct air capture	Absorption	USA
	Post combustion	Adsorption	USA
	Post combustion	Adsorption	USA
	Pre combustion	Absorption	USA
	Post combustion	Adsorption	USA
	Post combustion	Adsorption	USA
	Material based/Not disclosed	Adsorption	USA
	Material based/Not disclosed	Adsorption	USA
	Material based/Not disclosed	Adsorption	USA
	Post combustion	Adsorption	USA
	Post combustion	Adsorption	USA
Rutgers university	Post combustion	Adsorption	USA
Saga university	Material based/Not disclosed	Absorption	Japan
Saint mary s university	Pre combustion	Absorption	USA

Current assignees	Combustion Technology	Route - Separation Process	Country
Seikei gakuen university of tokyo	Post combustion	Absorption	Japan
Seoul national university industry foundation	Material based/Not disclosed	Absorption	S. Korea
Seoul national university r&db foundation (snu)	Post combustion	Rectification, Condensation	S. Korea
	Post combustion	Absorption	S. Korea
	Material based/Not disclosed	Absorption	S. Korea
Shaanxi university of science and technology	Post combustion	Membranes, Diffusion	China
	Post combustion	Absorption	China
Shandong normal university	Post combustion	Chemical process	China
	Post combustion	Chemical process	China
	Post combustion	Chemical process	China
	Post combustion	Chemical process	China
	Material based/Not disclosed	Adsorption	China
Shandong sairui petroleum science & technology development shengli oilfield shengli exploration & design research institute	Post combustion	Absorption	China
Shandong university	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Post combustion	Chemical process	China
	Pre combustion	Chemical process	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
Shanghai advanced research institute chinese academy of sciences	Pre combustion	Chemical process	China
	Pre combustion	Adsorption	China
	Post combustion	Adsorption	China
	Material based/Not disclosed	Membranes, Diffusion	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
Shanghai jiao tong university	Pre combustion	Absorption	China
	Pre combustion	Rectification, Condensation	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Chemical process	China
	Post combustion	Adsorption	China
	Post combustion	Biological process	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Post combustion	Adsorption	China
	Pre combustion	Adsorption	China
	Pre combustion	Chemical process	China
Shanghai second polytechnic university	Pre combustion	Absorption	China
	Post combustion	Chemical process	China
Shanghai university	Pre combustion	Absorption	China
Shangqiu normal university	Material based/Not disclosed	Adsorption	China
Shantou university	Material based/Not disclosed	Adsorption	China
Shanxi normal university	Material based/Not disclosed	Adsorption	China
Shaoxing university	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Pre combustion	Absorption	China
	Post combustion	Adsorption	China
	Post combustion	Absorption	China
	Material based/Not disclosed	Adsorption	China
Shenyang aerospace university	Post combustion	Chemical process	China
Shenyang normal university	Material based/Not disclosed	Absorption	China
Shenyang university of chemical technology	Post combustion	Membranes, Diffusion	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Pre combustion	Membranes, Diffusion	China
Shenyang university of technology	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Material based/Not disclosed	Absorption	China
Shihezi university	Material based/Not disclosed	Membranes, Diffusion	China
Sichuan normal university	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Chemical process	China
	Post combustion	Chemical process	China
	Post combustion	Chemical process	China
	Post combustion	Chemical process	China
	Post combustion	Chemical process	China
Sichuan university	Pre combustion	Absorption	China
	Post combustion	Adsorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Membranes, Diffusion	China
	Post combustion	Chemical process	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Post combustion	Adsorption	China
	Post combustion	Absorption	China
Siemens technische universitaet berlin	Post combustion	Absorption	Germany
Singapore university of technology & design	Material based/Not disclosed	Membranes, Diffusion	Singapore
Sogang university	Post combustion	Absorption	S. Korea
Sogang university industry university cooperation foundation	Post combustion	Absorption	S. Korea
	Post combustion	Adsorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Adsorption	S. Korea
	Post combustion	Absorption	S. Korea
Sogang university sogang university industry university cooperation foundation	Post combustion	Absorption	S. Korea
South china normal university	Material based/Not disclosed	Adsorption	China
South china university of technology	Pre combustion	Chemical process	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Post combustion	Absorption	China
	Post combustion	Adsorption	China
	Post combustion	Absorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Chemical process	China
	Material based/Not disclosed	Absorption	China
	Material based/Not disclosed	Adsorption	China
	Post combustion	Membranes, Diffusion	China
	Material based/Not disclosed	Absorption	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Chemical process	China
	Post combustion	Adsorption	China
Southeast university nanjing	Post combustion	Absorption	China
	Post combustion	Chemical process	China
	Post combustion	Absorption	China
	Pre combustion	Absorption	China
	Post combustion	Rectification, Condensation	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Post combustion	Rectification, Condensation	China
	Pre combustion	Chemical process	China
	Pre combustion	Chemical process	China
	Post combustion	Adsorption	China
	Pre combustion	Adsorption	China
	Post combustion	Adsorption	China
	Pre combustion	Rectification, Condensation	China
	Pre combustion	Rectification, Condensation	China
	Pre combustion	Chemical process	China
	Pre combustion	Absorption	China
	Post combustion	Membranes, Diffusion	China
	Post combustion	Chemical process	China
	Post combustion	Chemical process	China
	Post combustion	Chemical process	China
	Post combustion	Chemical process	China
	Pre combustion	Chemical process	China
	Post combustion	Absorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Pre combustion	Absorption	China
	Post combustion	Chemical process	China
	Pre combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Adsorption	China
	Pre combustion	Absorption	China
	Pre combustion	Chemical process	China
	Post combustion	Chemical process	China
	Post combustion	Absorption	China
	Post combustion	Adsorption	China
	Post combustion	Chemical process	China
	Pre combustion	Chemical process	China
	Post combustion	Adsorption	China
	Post combustion	Absorption	China
	Post combustion	Adsorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Pre combustion	Chemical process	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Pre combustion	Adsorption	China
	Post combustion	Chemical process	China
	Post combustion	Adsorption	China
	Post combustion	Absorption	China
	Post combustion	Adsorption	China
Southwest state university	Pre combustion	Chemical process	Russia
	Post combustion	Chemical process	Russia
Sun yat sen university	Pre combustion	Absorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Pre combustion	Absorption	China
	Post combustion	Adsorption	China
	Post combustion	Absorption	China
	Post combustion	Adsorption	China
	Post combustion	Absorption	China
	Material based/Not disclosed	Membranes, Diffusion	China
Sungkyunkwan university	Post combustion	Absorption	S. Korea
Suzhou university of science & technology	Post combustion	Absorption	China
Taiyuan university of technology	Pre combustion	Chemical process	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Post combustion	Adsorption	China
	Post combustion	Absorption	China
	Post combustion	Membranes, Diffusion	China
	Pre combustion	Adsorption	China
	Post combustion	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Material based/Not disclosed	Membranes, Diffusion	China
	Post combustion	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Post combustion	Adsorption	China
	Pre combustion	Adsorption	China
	Post combustion	Chemical process	China
	Material based/Not disclosed	Adsorption	China
Taizhou university	Material based/Not disclosed	Membranes, Diffusion	China
Technische universitaet darmstadt	Post combustion	Adsorption	Germany

Current assignees	Combustion Technology	Route - Separation Process	Country
Technische universitaet dresden	Post combustion	Absorption	Germany
Technische universitaet muenchen	Pre combustion	Absorption	Germany
Technische universitat wien technische universität wien	Pre combustion	Absorption	Austria
Texas a & m university	Pre combustion	Adsorption	USA
Tianjin normal university	Post combustion	Adsorption	China
	Material based/Not disclosed	Adsorption	China
Tianjin polytechnic university	Post combustion	Membranes, Diffusion	China
	Post combustion	Membranes, Diffusion	China
	Post combustion	Absorption	China
	Pre combustion	Membranes, Diffusion	China
	Post combustion	Membranes, Diffusion	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Material based/Not disclosed	Membranes, Diffusion	China
	Material based/Not disclosed	Membranes, Diffusion	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
Tianjin university	Post combustion	Chemical process	China
	Post combustion	Membranes, Diffusion	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Post combustion	Absorption	China
	Post combustion	Chemical process	China
	Post combustion	Membranes, Diffusion	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Membranes, Diffusion	China
	Post combustion	Absorption	China
	Post combustion	Membranes, Diffusion	China
	Post combustion	Absorption	China
	Pre combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Membranes, Diffusion	China
	Post combustion	Membranes, Diffusion	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Pre combustion	Absorption	China
	Pre combustion	Adsorption	China
	Post combustion	Absorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Post combustion	Chemical process	China
	Post combustion	Membranes, Diffusion	China
	Pre combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Absorption	China
	Post combustion	Membranes, Diffusion	China
	Post combustion	Membranes, Diffusion	China
	Post combustion	Membranes, Diffusion	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Absorption	China
	Post combustion	Membranes, Diffusion	China
	Post combustion	Membranes, Diffusion	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Membranes, Diffusion	China
	Post combustion	Adsorption	China
	Material based/Not disclosed	Membranes, Diffusion	China
	Material based/Not disclosed	Membranes, Diffusion	China
	Material based/Not disclosed	Membranes, Diffusion	China
	Post combustion	Membranes, Diffusion	China
	Material based/Not disclosed	Membranes, Diffusion	China
	Material based/Not disclosed	Membranes, Diffusion	China
	Material based/Not disclosed	Membranes, Diffusion	China
	Material based/Not disclosed	Membranes, Diffusion	China
	Material based/Not disclosed	Membranes, Diffusion	China
	Material based/Not disclosed	Membranes, Diffusion	China
	Material based/Not disclosed	Membranes, Diffusion	China
	Post combustion	Membranes, Diffusion	China
	Material based/Not disclosed	Membranes, Diffusion	China
	Material based/Not disclosed	Membranes, Diffusion	China
	Material based/Not disclosed	Adsorption	China
	Post combustion	Absorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Material based/Not disclosed	Membranes, Diffusion	China
	Material based/Not disclosed	Membranes, Diffusion	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Absorption	China
	Material based/Not disclosed	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Membranes, Diffusion	China
	Post combustion	Biological process	China
	Post combustion	Adsorption	China
	Post combustion	Chemical process	China
	Post combustion	Chemical process	China
	Post combustion	Absorption	China
Tohoku university	Post combustion	Absorption	Japan
Tongji university	Pre combustion	Biological process	China
	Post combustion	Absorption	China
	Post combustion	Chemical process	China
Tsinghua university	Pre combustion	Absorption	China
	Pre combustion	Absorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Pre combustion	Absorption	China
	Post combustion	Absorption	China
	Pre combustion	Adsorption	China
	Pre combustion	Adsorption	China
	Pre combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	Chinese Taipei
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Pre combustion	Absorption	Chinese Taipei
	Pre combustion	Absorption	China
	Post combustion	Adsorption	China
	Pre combustion	Absorption	China
	Post combustion	Chemical process	China
	Pre combustion	Absorption	China
	Pre combustion	Absorption	China
	Post combustion	Chemical process	China
	Pre combustion	Absorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Post combustion	Adsorption	China
	Pre combustion	Absorption	China
	Pre combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Chemical process	China
	Post combustion	Chemical process	China
	Material based/Not disclosed	Absorption	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Post combustion	Absorption	China
	Post combustion	Adsorption	China
	Post combustion	Absorption	Chinese Taipei
Tunghai university	Post combustion	Absorption	Chinese Taipei
Uni for miljo biovitenskap institute for mat realfag teknologi uni for miljoe biovitenskap	Post combustion	Absorption	Norway
Univerity of newcastle upon tyne university newcastle university of newcastle upon tyne	Post combustion	Absorption	Great Britain
Universidad de cantabria	Pre combustion	Absorption	Spain

Current assignees	Combustion Technology	Route - Separation Process	Country
Universidad de oviedo	Post combustion	Adsorption	Spain
Universidad de sevilla	Post combustion	Chemical process	Spain
	Post combustion	Chemical process	Spain
	Post combustion	Absorption	Spain
	Post combustion	Absorption	Spain
	Material based/Not disclosed	Absorption	Spain
Universidad nacional autonoma de mexico	Material based/Not disclosed	Adsorption	Mexico
Universidade da coruna	Post combustion	Chemical process	Spain
	Post combustion	Chemical process	Spain
Universidade federal de minas gerais - ufmg	Pre combustion	Chemical process	Brazil
Universita degli studi di milano bicocca	Pre combustion	Absorption	Italy
Universitaet rostock	Post combustion	Rectification, Condensation	Germany
Universitatea de nord din baia mare	Post combustion	Chemical process	Romania
	Post combustion	Absorption	Romania
Universiti sains malaysia u s m universiti sans malaysia u s m	Pre combustion	Adsorption	Malaysia
University beijing	Post combustion	Chemical process	China
	Pre combustion	Absorption	China
	Material based/Not disclosed	Adsorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
University court of the university of aberdeen the university	Post combustion	Absorption	Great Britain
University de la sabana	Post combustion	Absorption	Colombia
University industry foundation yonsei	Pre combustion	Adsorption	S. Korea
University of alabama	Pre combustion	Membranes, Diffusion	USA
University of alabama	Post combustion	Membranes, Diffusion	USA
University of california	Pre combustion	Absorption	USA
	Pre combustion	Absorption	USA
	Pre combustion	Adsorption	USA
	Post combustion	Adsorption	USA
	Pre combustion	Adsorption	USA
	Post combustion	Adsorption	USA
	Material based/Not disclosed	Membranes, Diffusion	USA
University of colorado	Pre combustion	Membranes, Diffusion	USA
	Pre combustion	Chemical process	USA
	Material based/Not disclosed	Membranes, Diffusion	USA
University of florida	Pre combustion	Absorption	USA
University of fukui	Post combustion	Membranes, Diffusion	Japan
University of illinois	Post combustion	Absorption	USA
University of kentucky research foundation	Post combustion	Absorption	USA

Current assignees	Combustion Technology	Route - Separation Process	Country
	Pre combustion	Absorption	USA
	Post combustion	Absorption	USA
	Post combustion	Absorption	USA
	Post combustion	Absorption	USA
	Pre combustion	Absorption	USA
	Post combustion	Absorption	USA
University of leeds	Pre combustion	Absorption	Great Britain
University of massachusetts	Post combustion	Adsorption	USA
University of missouri	Post combustion	Adsorption	USA
	Post combustion	Adsorption	USA
University of nankai	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Pre combustion	Absorption	China
	Post combustion	Absorption	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Adsorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
University of notre dame du lac	Post combustion	Absorption	USA
University of ontario institute of technology	Pre combustion	Absorption	USA
University of pittsburgh university of west virginia	Post combustion	Adsorption	USA
University of queensland	Pre combustion	Absorption	Australia
University of regina	Post combustion	Absorption	USA
University of science & technology beijing	Post combustion	Adsorption	China
	Post combustion	Chemical process	China
	Post combustion	Chemical process	China
	Post combustion	Adsorption	China
	Material based/Not disclosed	Adsorption	China
University of science & technology liaoning	Post combustion	Absorption	China
	Post combustion	Adsorption	China
University of science & technology of china	Post combustion	Chemical process	China
	Pre combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Adsorption	China
	Post combustion	Absorption	China
University of shanghai for science & technology	Post combustion	Chemical process	China
	Post combustion	Chemical process	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Post combustion	Absorption	China
University of south carolina	Pre combustion	Membranes, Diffusion	USA
	Pre combustion	Membranes, Diffusion	USA
	Post combustion	Membranes, Diffusion	USA
University of south florida	Pre combustion	Adsorption	USA
University of southern california	Pre combustion	Adsorption	USA
	Pre combustion	Absorption	USA
	Pre combustion	Adsorption	USA
University of sydney	Pre combustion	Absorption	Australia
University of sydney	Pre combustion	Absorption	Australia
University of texas	Post combustion	Absorption	USA
	Post combustion	Absorption	USA
	Post combustion	Absorption	USA
	Post combustion	Absorption	USA
	Post combustion	Absorption	USA
	Post combustion	Absorption	USA
	Post combustion	Absorption	USA
	Post combustion	Absorption	USA
University of toronto	Material based/Not disclosed	Chemical process	USA

Current assignees	Combustion Technology	Route - Separation Process	Country
University of ulsan industry academic cooperation foundation	Post combustion	Chemical process	S. Korea
	Material based/Not disclosed	Absorption	S. Korea
	Material based/Not disclosed	Absorption	S. Korea
	Material based/Not disclosed	Adsorption	S. Korea
University of washington washington university in st louis	Pre combustion	Adsorption	USA
University of west virginia	Post combustion	Adsorption	USA
University of wyoming	Post combustion	Adsorption	USA
	Post combustion	Adsorption	USA
	Post combustion	Absorption	USA
	Post combustion	Adsorption	USA
	Pre combustion	Biological process	USA
University of xiamen	Post combustion	Adsorption	China
	Post combustion	Chemical process	China
	Post combustion	Adsorption	China
	Post combustion	Absorption	China
	Material based/Not disclosed	Adsorption	China
University sangmyung seoul industry academy cooperation foundation	Material based/Not disclosed	Chemical process	S. Korea
University suzhou science & technology	Post combustion	Biological process	China
University teknologi petronas	Material based/Not disclosed	Membranes, Diffusion	Malaysia

Current assignees	Combustion Technology	Route - Separation Process	Country
Uniwersytet im adama mickiewicza w poznaniu	Material based/Not disclosed	Adsorption	Poland
V topchiev institute of petrochemical synthesis ras	Post combustion	Absorption	Russia
Vilniaus gedimino technikos university	Post combustion	Chemical process	Lithuania
Vilniaus gedimino technikos university	Post combustion	Chemical process	Lithuania
Washington state university	Pre combustion	Biological process	USA
Weifang university	Post combustion	Adsorption	China
Wuhan harvest yangtze ecological technology research institute wuhan kaidi electric power	Pre combustion	Adsorption	China
Wuhan university	Post combustion	Adsorption	China
	Post combustion	Absorption	China
	Material based/Not disclosed	Chemical process	China
Wuhan university of technology	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Pre combustion	Chemical process	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Post combustion	Adsorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Membranes, Diffusion	China
Xi an university of architecture & technology	Post combustion	Chemical process	China
Xi an university of science & technology	Post combustion	Biological process	China
	Post combustion	Chemical process	China
Xi'an jiaotong university	Post combustion	Biological process	China
	Post combustion	Absorption	China
	Post combustion	Adsorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Pre combustion	Absorption	China
	Material based/Not disclosed	Adsorption	China
	Post combustion	Absorption	China
	Material based/Not disclosed	Adsorption	China
	Post combustion	Absorption	China
Xian polytechnic university	Pre combustion	Membranes, Diffusion	China
	Material based/Not disclosed	Membranes, Diffusion	China
Xiangtan university	Post combustion	Absorption	China
	Post combustion	Adsorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Adsorption	China
Xuyi attapulgite research & development center of guangzhou institute of energy conversion chinese academy of sciences	Post combustion	Adsorption	China
Yale university	Post combustion	Absorption	USA
Yamaguchi university	Post combustion	Absorption	Japan
Yangtze normal university	Post combustion	Adsorption	China
Yangzhou university	Post combustion	Adsorption	China
Yantai university	Post combustion	Absorption	China
Yonsei university industry academic cooperation foundation	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Membranes, Diffusion	S. Korea
	Post combustion	Absorption	S. Korea
	Pre combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Pre combustion	Adsorption	S. Korea
	Pre combustion	Membranes, Diffusion	S. Korea
	Post combustion	Absorption	S. Korea

Current assignees	Combustion Technology	Route - Separation Process	Country
	Material based/Not disclosed	Membranes, Diffusion	S. Korea
	Post combustion	Absorption	S. Korea
	Post combustion	Absorption	S. Korea
	Material based/Not disclosed	Adsorption	S. Korea
	Material based/Not disclosed	Adsorption	S. Korea
Yunnan university	Post combustion	Membranes, Diffusion	China
Yunnan university of nationalities	Material based/Not disclosed	Adsorption	China
Zachodniopomorski university technologiczny w szczecinie	Material based/Not disclosed	Adsorption	Poland
	Material based/Not disclosed	Adsorption	Poland
	Material based/Not disclosed	Adsorption	Poland
	Material based/Not disclosed	Chemical process	Poland
	Material based/Not disclosed	Adsorption	Poland
	Material based/Not disclosed	Adsorption	Poland
Zachodniopomorski university technology w szczecinie	Material based/Not disclosed	Chemical process	Poland
Zaozhuang university	Material based/Not disclosed	Adsorption	China
Zhejiang gongshang university	Post combustion	Adsorption	China
Zhejiang normal university	Post combustion	Adsorption	China
	Pre combustion	Adsorption	China
	Material based/Not disclosed	Absorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Material based/Not disclosed	Absorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
Zhejiang university	Post combustion	Absorption	China
	Post combustion	Adsorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Adsorption	China
	Post combustion	Absorption	China
	Pre combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Pre combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Chemical process	China
	Post combustion	Chemical process	China
	Pre combustion	Absorption	China
	Post combustion	Absorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Pre combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Chemical process	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Absorption	China
	Pre combustion	Absorption	China
	Post combustion	Absorption	China
	Post combustion	Chemical process	China
	Pre combustion	Absorption	China
	Post combustion	Adsorption	China
	Post combustion	Absorption	China
	Pre combustion	Adsorption	China
	Post combustion	Absorption	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Chemical process	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Post combustion	Adsorption	China
	Post combustion	Absorption	China
	Material based/Not disclosed	Adsorption	China
	Material based/Not disclosed	Absorption	China
	Post combustion	Adsorption	China
	Material based/Not disclosed	Adsorption	China
	Pre combustion	Membranes, Diffusion	China
	Material based/Not disclosed	Adsorption	China
	Pre combustion	Membranes, Diffusion	China

Current assignees	Combustion Technology	Route - Separation Process	Country
	Material based/Not disclosed	Absorption	China
Zhejiang university of technology	Pre combustion	Absorption	China
	Post combustion	Chemical process	China
	Pre combustion	Absorption	China
	Post combustion	Chemical process	China
Zhengzhou university	Material based/Not disclosed	Membranes, Diffusion	China
	Pre combustion	Chemical process	China
	Material based/Not disclosed	Membranes, Diffusion	China
Zhengzhou university of light industry	Post combustion	Adsorption	China

1.3 LIST OF CCS FACILITIES WORLDWIDE[121,122]

S.No.	Project Name	Company	Overall Status	Country Location	Plant Size or Capture Amount (MW)	Combustion/ Separation	Capture Technology	Amount of CO_2 Captured/Stored	Captured/ Stored Unit
1	Aalborg - Northern Jutland Power Station Project	Vattenfall	Hold	Denmark	411.00	Post-Combustion	Amines	4,932.00	Metric Tons Per Day
2	AES Shady Point	AES Corporation	Terminated	United States	320.00	Post-Combustion	Ethanol-Amino Solvent	200.00	Metric Tons Per Day
3	Air Products and Chemicals Inc. CCS Project	Air Products and Chemicals	Completed	United States	-	Industrial	Vacuum Swing Absorption	2,740.00	Metric Tons Per Day
4	Alberta Carbon Trunk Line	Enhance Energy	Active	Canada	-	-	-	40,004.00	Metric Tons Per Day
5	Alberta Saline Aquifer Project & Genesee Demonstration Project	EPCOR	Hold	Canada	150.00	Pre-Combustion	Amines	2,740.00	Metric Tons Per Day
6	Allison Unit CO_2-ECBM Pilot	Burlington Resources	Completed	United States	-	-	-	400.00	Metric Tons Per Day
7	Altmark Sequestration	Vattenfall	Hold	Germany	1,000.00	-	-	100,000.00	Metric Tons Total
8	American Electric Power - Great Bend IGCC	American Electric Power	Hold	United States	629.00	Pre-Combustion	-	-	-
9	American Electric Power - Mountaineer	American Electric Power	Terminated	United States	30.00	Post-Combustion	Alstom Chilled Ammonia Process	15,000.00	Metric Tons Total
10	American Electric Power - Northeastern Station	American Electric Power	Hold	United States	450.00	Post-Combustion	Alstom Chilled Ammonia Process	4,110.00	Metric Tons Per Day
11	American Electric Power - Red Rock Facility	American Electric Power	Terminated	United States	950.00	Post-Combustion	-	950.00	Megawatt
12	American Electric Power - Tanners Creek Plant	American Electric Power	Terminated	United States	500.00	Post-Combustion	-	500.00	Megawatt

[121] https://www.netl.doe.gov/coal/carbon-storage/worldwide-ccs-database
[122] https://co2re.co/FacilityData

S.No.	Project Name	Company	Overall Status	Country Location	Plant Size or Capture Amount (MW)	Combustion/ Separation	Capture Technology	Amount of CO_2 Captured/Stored	Captured/ Stored Unit
13	An Evaluation of the Carbon Sequestration Potential of the Cambro Ordovician Strata of the Illinois and Michigan Basins	Illinois State Geological Survey	Completed	United States	-	-	-	-	-
14	Aquistore Project	Petroleum Technology Research Centre (PTRC)	Active	Canada	-	Post-Combustion	Amines	1,000.00	Metric Tons Per Day
15	ARI Eastern Shale CO2 Injection Test	Advanced Resources International (ARI)	Completed	United States	229.00	Post-Combustion	-	300.00	Metric Tons Total
16	Aviva Corp Coolimba Oxyfuel Project	Coolimba Power	Terminated	Australia	400.00	Oxy-Combustion	-	7,946.00	Metric Tons Per Day
17	Belchatow CCS Project	Alstom Power	Terminated	Poland	858.00	Post-Combustion	Amines	4,932.00	Metric Tons Per Day
18	Belle Plaine Polygen Capture (for EOR)	TransCanada	Hold	Canada	500.00	Pre-Combustion	-	2,740.00	Metric Tons Per Day
19	Bellingham Cogeneration Facility	Northeast Energy Associates LP	Active	United States	320.00	Post-Combustion	Fluor Econamine	350.00	Metric Tons Per Day
20	Bent County IGCC Plant	Xcel Energy Inc.	Hold	United States	600.00	Pre-Combustion	-	4,200,000.00	Metric Tons Total
21	Big Sky Development Phase - Kevin Dome Project	Montana State University	Active	United States	-	-	-	1,000,000.00	Metric Tons Total
22	Big Sky Validation Phase - Basalt Injection	Montana State University	Completed	United States	-	-	-	977.00	Metric Tons Total
23	Bintulu CCS Project	Mitsubishi Heavy Industries	Hold	Malaysia	-	Post-Combustion	-	8,220.00	Metric Tons Per Day
24	Blackhorse Energy LLC - Small-Scale Injection Project	Black Horse Energy LLC	Completed	United States	-	-	-	52,000.00	Metric Tons Total
25	Boundary Dam Integrated CCS Project	SaskPower	Active	Canada	115.00	Post-Combustion	Amines	2,740.00	Metric Tons Per Day
26	Bow City Power Project	Bow City Power, Ltd.	Hold	Canada	1,000.00	Post-Combustion	Amines	2,740.00	Metric Tons Per Day
27	BP-Peterhead Hydrogen Power Plant/Miller Field Project	Shell	Terminated	Scotland	385.00	Post-Combustion	Amines	2,740.00	Metric Tons Per Day

S.No.	Project Name	Company	Overall Status	Country Location	Plant Size or Capture Amount (MW)	Combustion/ Separation	Capture Technology	Amount of CO_2 Captured/Stored	Captured/ Stored Unit
28	Browse LNG	Woodside	Terminated	Australia	-	Separation	Amines	-	-
29	Bulgarian TETs Maritsa East 2	TETs Maritsa Iztok 2 EAD	Hold	Bulgaria	1,450.00	Post-Combustion	-	3,600,000.00	Metric Tons Total
30	CAB-CS: Central Appalachian Basin CarbonSAFE Integrated Pre-Feasibility Project	Battelle Memorial Institute	Potential	United States	-	-	-	-	-
31	California CO_2 Storage Assurance Facility Enterprise (C2SAFE)	EPRI - Electric Power Research Institute	Potential	United States	-	-	-	-	-
32	Captain Clean Energy Project	Summit Power Group	Hold	Scotland	570.00	Pre-Combustion	-	10,412.00	Metric Tons Per Day
33	CarbFix	Carb Fix	Active	Iceland	303.00	Separation	-	5.48	Metric Tons Per Day
34	Carbon Dioxide Technology Corp - Lubbock Plant	Carbon Dioxide Technology Corporation	Completed	United States	50.00	Post-Combustion	Amines	1,200.00	Metric Tons Per Day
35	CarbonNet CCS Project	Victorian Government (Australia)	Active	Australia	-	-	-	13,700.00	Metric Tons Per Day
36	CarbonSAFE Illinois East Sub-Basin	Illinois State Geological Survey	Potential	United States	-	-	-	-	-
37	CarbonSAFE Illinois Macon County	Illinois State Geological Survey	Potential	United States	-	-	-	-	-
38	CarbonSAFE Rocky Mountain Phase I: Ensuring Safe Subsurface Storage of Carbon Dioxide in the Intermountain West	University of Utah	Potential	United States	-	-	-	-	-
39	Cash Creek IGCC	ERORA Group	Hold	United States	720.00	Pre-Combustion	-	-	-
40	CASTOR CO_2 from Capture to Storage	ELSAM - Elsam Power	Completed	Denmark	400.00	Post-Combustion	Amines	22.00	Metric Tons Per Day
41	CATO1 - Rotterdam ROAD project	E.ON Benelux	Terminated	Netherlands	250.00	Post-Combustion	Cryogenic	3,014.00	Metric Tons Per Day
42	CATO2 CO_2 Catcher	E.ON Benelux	Active	Netherlands	1,040.00	Post-Combustion	Amines	6.00	Metric Tons Per Day
43	CEMEX Inc. Cement CO_2 Capture Project	CEMEX Inc.	Terminated	United States	-	Industrial	Dry Sorbent	2,740.00	Metric Tons Per Day

S.No.	Project Name	Company	Overall Status	Country Location	Plant Size or Capture Amount (MW)	Combustion/ Separation	Capture Technology	Amount of CO_2 Captured/Stored	Captured/ Stored Unit
44	Century Plant Gas Processing	Occidental Petroleum	Active	United States	-	Pre-Combustion	-	23,016.00	Metric Tons Per Day
45	Characterization of the Miocene and Pliocene Formations in the Wilmington Graben, Offshore Los Angeles, for Large-Scale Geologic Storage of CO_2	GeoMechanics Technologies	Completed	United States	-	-	-	-	-
46	Characterization of the Most Promising Sequestration Formations in the Rocky Mountain Region	University of Utah	Completed	United States	-	-	-	-	-
47	China Resources Power (Haifeng) Integrated Carbon Capture and Sequestration Demonstration Project	China Resources Power (CRP)	Potential	China	2,740.00	Post-Combustion	Amines	2,740.00	Metric Tons Per Day
48	CO_2 Capture from Coffeyville Fertilizer Plant	Coffeyville Resources	Active	United States	-	Industrial	Not Currently Specified	2,400.00	Metric Tons Per Day
49	CO_2EuroPipe	Toegepast Natuurwetenschappelijk Onderzoek - TNO	Active		-	-	-	-	-
50	CO_2SINK Project (Ketzin)	European Commission	Completed	Germany	-	-	-	67,271.00	Metric Tons Total
51	Coastal Energy IGCC Project (Teesside)	Progressive Energy	Hold	United Kingdom	850.00	Pre-Combustion	-	6,302.00	Metric Tons Per Day
52	Collie South West Hub Project	Western Australian Department of Mines and Petroleum	Active	Australia	-	Pre-Combustion	-	6,850.00	Metric Tons Per Day
53	ConocoPhillips - Immingham Pre-Combustion Project	ConocoPhillips	Potential	United Kingdom	1,180.00	Post-Combustion	-	20,550.00	Metric Tons Per Day
54	CONSOL Energy - Sequestration of CO_2 in Unmineable Coal Seams	Consol Energy Inc	Completed	United States	-	Separation	Amines	4,516.00	Metric Tons Total

S.No.	Project Name	Company	Overall Status	Country Location	Plant Size or Capture Amount (MW)	Combustion/ Separation	Capture Technology	Amount of CO_2 Captured/Stored	Captured/ Stored Unit
55	CS Energy Callide Oxyfuels Project	CS Energy	Completed	Australia	30.00	Post-Combustion	Oxy-Fuel Combustion	82.20	Metric Tons Per Day
56	CSIRO Transportable Capture Unit Loy Yang (Victoria)	CSIRO - Australian Commonwealth Scientific and Industrial Research Organization	Active	Australia	10.00	Post-Combustion	Solvents	2.74	Metric Tons Per Day
57	CSIRO Transportable Capture Unit Munmorah (New South Wales)	CSIRO - Australian Commonwealth Scientific and Industrial Research Organization	Completed	Australia	-	Post-Combustion	Ammonia Absorption Technology	10.00	Metric Tons Per Day
58	CSIRO Transportable Capture Unit Tarong (Queensland)	CSIRO - Australian Commonwealth Scientific and Industrial Research Organization	Completed	Australia	450.00	Post-Combustion	Amines	4.11	Metric Tons Per Day
59	Dagang Huashi Power CCS + EOR	Tianjin DaGang Huashi	Potential	China	330.00	Post-Combustion	-	6,165.00	Metric Tons Per Day
60	Datang Daqing CCS Project	Datang Corporation	Hold	China	350.00	Oxy-Combustion	-	2,740.00	Metric Tons Per Day
61	DKRW Energy LLC	DKRW Energy LLC	Hold	United States	20,000.00	Pre-Combustion	Chilled Ammonia	20,000.00	Barrels Per Day
62	Don Valley CCS Power Project	Sargas	Potential	United Kingdom	650.00	Pre-Combustion	Cold Methanol (Rectisol)	13,700.00	Metric Tons Per Day
63	DONG Energy - High-Efficiency PC Plant in Griefswalde	DONG Energy	Terminated	Germany	1,600.00	Post-Combustion	Chilled Ammonia	90.00	% Reduction
64	Dongguan Taiyangzhou IGCC	Dongguan Taiyangzhou Power Corporation	Potential	China	750.00	Pre-Combustion	Cryogenic	2,740.00	Metric Tons Per Day
65	Duke Energy - Cliffside Plant	Duke Energy	Hold	United States	825.00	-	-	90.00	% Reduction
66	Duke Energy - Edwardsport Plant	Duke Energy	Hold	United States	618.00	Pre-Combustion	-	70.00	% Reduction
67	E.ON Coal Plant in Wilhelmshaven, Germany	E.ON	Completed	Germany	756.00	Post-Combustion	Fluor Econamine	70.00	Metric Tons Per Day
68	E.ON Kingsnorth Ruhrgas UK Post-Combustion Project	E.ON	Terminated	United Kingdom	1,600.00	Post-Combustion	Amines	20.00	% Reduction

S.No.	Project Name	Company	Overall Status	Country Location	Plant Size or Capture Amount (MW)	Combustion/ Separation	Capture Technology	Amount of CO_2 Captured/Stored	Captured/ Stored Unit
69	E.ON Pilot Plant in Heyden, Germany	E.ON	Completed	Germany	7.00	Post-Combustion	Amines	90.00	% Reduction
70	E.ON Ruhrgas Killingholme IGCC	E.ON	Terminated	United Kingdom	470.00	Pre-Combustion	Solvents	6,850.00	Metric Tons Per Day
71	E.ON Staudinger - Grosskrotzenburg Germany	E.ON	Active	Germany	510.00	Post-Combustion	Solvents	90.00	% Reduction
72	Ecofisk EOR (Pilot)	ConocoPhillips	Active	Norway	-	-	-	-	-
73	Enecogen Cryogenic CO_2 Capture	Eneco	Active	Netherlands	850.00	Post-Combustion	Cryogenic	24.66	Metric Tons Per Day
74	Enel Brindisi CCS Project	Enel	Active	Italy	660.00	Post-Combustion	Amines	21.92	Metric Tons Per Day
75	Engineering-Scale Demonstration of Mixed-Salt Process for CO_2 Capture	SRI International	Active	Norway	10.00	Post-Combustion	SRI International's Mixed-Salt Process	-	-
76	Engineering-Scale Testing of Transformational Non-Aqueous Solvent-Based CO_2 Capture Process at Technology Centre Mongstad	Research Triangle Institute	Active	Norway	10.00	Post-Combustion	RTI International's transformational Non-Aqueous Solvent (NAS)-Based CO_2 Capture Technology	-	-
77	Eni and Enel CCS Project	Enel and Eni	Active	Italy	660.00	Post-Combustion	Amines	21.92	Metric Tons Per Day
78	Establishing An Early Carbon Dioxide Storage (ECO2S) Complex in Kemper County, Mississippi: Project ECO2S	Southern States Energy Board	Potential	United States	-	-	-	-	-
79	Evaluation of Solid Sorbents as a Retrofit Technology for CO_2 Capture	ADA-ES, Inc.	Completed	United States	1.00	Post-Combustion	Solid sorbent	25.00	Metric Tons Per Day
80	EW Brown Generating Station	University of Kentucky	Active	United States	0.70	Post-Combustion	Solvents	-	-
81	Fairview ZeroCarbon Project	Australian Government	Terminated	Australia	100.00	Post-Combustion	Amines	274.00	Metric Tons Per Day

S.No.	Project Name	Company	Overall Status	Country Location	Plant Size or Capture Amount (MW)	Combustion/ Separation	Capture Technology	Amount of CO_2 Captured/Stored	Captured/ Stored Unit
82	Fenn Big Valley Project	Alberta Science and Research Authority	Completed	Canada	-	-	-	200.00	Metric Tons Total
83	Fertil-2 Capture Project	Ruwais Fertilizer Industries	Active	United Arab Emirates	400.00	Post-Combustion	Amines	-	-
84	FINNCAP - Meri Pori CCS Project	Fortum	Terminated	Finland	565.00	Post-Combustion	Siemens Energy Technology	3,288.00	Metric Tons Per Day
85	First Energy Bay Shore Plant	First Energy	Terminated	United States	153.00	-	Amines	438.40	Metric Tons Per Day
86	Frio Brine Pilot	Bureau of Economic Geology	Completed	United States	-	-	-	1,455.00	Metric Tons Total
87	FutureGen - Jewett	FutureGen Industrial Alliance Inc.	Terminated	United States	275.00	Pre-Combustion	-	-	-
88	FutureGen - Mattoon	FutureGen Industrial Alliance Inc.	Terminated	United States	275.00	Pre-Combustion	-	-	-
89	FutureGen - Odessa	FutureGen Industrial Alliance Inc.	Terminated	United States	275.00	Pre-Combustion	-	-	-
90	FutureGen - Tuscola	FutureGen Industrial Alliance Inc.	Terminated	United States	275.00	Pre-Combustion	-	-	-
91	FutureGen 2.0	FutureGen Industrial Alliance Inc.	Terminated	United States	200.00	Oxy-Combustion	Oxy-Fuel Combustion	2,740.00	Metric Tons Per Day
92	FuturGas Project	Strike Oil Limited	Hold	Australia	300.00	Pre-Combustion	-	2,055.00	Metric Tons Per Day
93	Galilee Power Project	Waratah Coal	Potential	Australia	900.00	Pre-Combustion	-	-	-
94	Geologic Characterization of the South Georgia Rift Basin for Source Proximal CO2 Storage	South Carolina Research Foundation	Completed	United States	-	-	-	-	-
95	Gorgon Project	Chevron	Active	Australia	41,100.00	Separation	-	9,042.00	Metric Tons Per Day
96	Great Lakes Energy Research Park	M&M Energy, LLC	Active	United States	250.00	Pre-Combustion	ConocoPhillips E-Gas Gasification	90.00	% Reduction
97	Greengen Project in China	GreenGen Co. Ltd.	Active	China	400.00	Pre-Combustion	-	-	-
98	Gulf of Mexico Miocene Mega Transect Site Characterization	University of Texas at Austin	Completed	United States	-	-	-	-	-

S.No.	Project Name	Company	Overall Status	Country Location	Plant Size or Capture Amount (MW)	Combustion/ Separation	Capture Technology	Amount of CO_2 Captured/Stored	Captured/ Stored Unit
99	Gulf Petrochemical Industries Company (GPIC) Capture Project	Gulf Petrochemicals Industries Company (GPIC)	Active	Bahrain	-	Separation	Mitsubishi HI Gasification (KS-1)	450.00	Metric Tons Per Day
100	H3 Capture Project - CO2CRC	CO2CRC - Cooperative Research Centre for Greenhouse Gas Technologies	Completed	Australia	1,675.00	Post-Combustion	Solvents	0.00	Metric Tons Per Day
101	Halten CO_2 Project (Draugen-Heidrun)	Statoil	Terminated	Norway	860.00	Post-Combustion	Amines	6,850.00	Metric Tons Per Day
102	HARP-Heartland Area Redwater Project	ARC Resources	Hold	Canada	-	Industrial	-	100,000.00	Metric Tons Total
103	Hassi-Touareg Sequestration	Schlumberger	Potential	Algeria	-	-	-	-	-
104	Hazelwood Post-Combustion 2030 Project	International Power Australia	Terminated	Australia	1,635.00	Post-Combustion	Amines	50.00	Metric Tons Per Day
105	Hiroshima Pilot Plant	Mitsubishi Heavy Industries	Active	Japan	1.00	Post-Combustion	Solvents	-	-
106	Hodonin CO_2 Separation Project	CEZ Group	Potential	Czech Republic	105.00	-	-	-	-
107	HRL IDGCC Project	HRL Developments	Active	Australia	600.00	Pre-Combustion	-	40.00	% Reduction
108	Hunterston Station CCS	Ayrshire Power	Terminated	Scotland	1,852.00	Post-Combustion	Ammonia Absorption Technology	-	-
109	Hunton Energy Freeport Plant	Hunton Energy	Terminated	United States	400.00	Pre-Combustion	-	21,920.00	Metric Tons Per Day
110	Hydrogen Energy California Project	Hydrogen Energy International LLC	Terminated	United States	400.00	Oxy-Combustion	Rectisol	7,124.00	Metric Tons Per Day
111	Hydrogen Power Abu Dhabi Project	Hydrogen Energy International LLC	Hold	United Arab Emirates	420.00	Pre-Combustion	Not Currently Specified	4,658.00	Metric Tons Per Day
112	ICO2N Network	ICO2N	Potential	Canada	-	-	-	-	-
113	Illinois Industrial Carbon Capture and Storage Project	Archer Daniels Midland	Active	United States	-	Industrial	Amines	2,740.00	Metric Tons Per Day
114	In Salah Gas Storage Project	In Salah Gas	Hold	Algeria	-	Separation	Ethanol-Amino Solvent	3,288.00	Metric Tons Per Day

S.No.	Project Name	Company	Overall Status	Country Location	Plant Size or Capture Amount (MW)	Combustion/ Separation	Capture Technology	Amount of CO_2 Captured/Stored	Captured/ Stored Unit
115	Initial Engineering Design of a Post-Combustion CO_2 Capture System for Duke Energy's East Bend Station Using Membrane-Based Technology	EPRI - Electric Power Research Institute	Active	United States	600.00	Post-Combustion	MTR Polaris™ Membrane System	-	-
116	Initial Engineering, Testing, and Design of a Commercial-Scale, Post-Combustion CO_2 Capture System on an Existing Coal-Fired Generating Unit	University of North Dakota	Active	United States	455.00	Post-Combustion	Mitsubishi Heavy Industries' (MHI's) KM CDR Process™ Using the KS-1™ Solvent	-	-
117	Integrated Carbon Capture and Storage in Kansas	University of Kansas Center for Research	Potential	United States	-	-	-	-	-
118	Integrated Carbon Capture and Storage in the Louisiana Chemical Corridor	Louisiana State University	Potential	United States	-	-	-	-	-
119	Integrated CCS Pre-Feasibility in the Northwest Gulf of Mexico	University of Texas at Austin	Potential	United States	-	-	-	-	-
120	Integrated Commercial Carbon Capture and Storage Pre-Feasibility Study at Dry Fork Station, Wyoming	University of Wyoming	Potential	United States	-	-	-	-	-
121	Integrated Mid-Continent Stacked Carbon Storage Hub	Battelle Memorial Institute	Potential	United States	-	-	-	-	-
122	Integrated Pre-Feasibility Study for CO2 Geological Storage in the Cascadia Basin, Offshore Washington State and British Columbia	Columbia University	Potential	United States	-	-	-	-	-

S.No.	Project Name	Company	Overall Status	Country Location	Plant Size or Capture Amount (MW)	Combustion/ Separation	Capture Technology	Amount of CO_2 Captured/Stored	Captured/ Stored Unit
123	Integrated Pre-Feasibility Study of a Commercial-Scale Commercial Carbon Capture Project in Formations of the Rock Springs Uplift, Wyoming	University of Wyoming	Potential	United States	-	-	-	-	-
124	Intermountain Power Agency	EPRI - Electric Power Research Institute	Active	United States	950.00	Post-Combustion	-	-	-
125	ION Engineering Commercial Carbon Capture Design & Costing (C3DC)	ION Engineering LLC	Active	United States	700.00	Post-Combustion	ION's Solvent CO2 Capture Technology	-	-
126	Jamestown BPU	Jamestown BPU	Potential	United States	40.00	Post-Combustion	-	98.00	% Reduction
127	Japan-China EOR Project	Chinese Government	Hold	China	2,740.00	Post-Combustion	-	2,740.00	Metric Tons Per Day
128	JAPEX CCS Project	JAPEX - Japan Petroleum Exploration Co., Ltd.	Active	Japan	-	-	-	548.00	Metric Tons Per Day
129	JCOP Yubari/Ishikari ECBM Project	General Environment Technos Co. Ltd.	Completed	Japan	-	-	-	415.00	Metric Tons Total
130	Jilin Oil Field EOR	China National Petroleum Company	Active	China	-	Industrial	Amines	2,192.00	Metric Tons Per Day
131	Joffre Viking EOR Project	Penn West Energy Corporation	Completed	Canada	-	Industrial	Not Currently Specified	39,566.00	Metric Tons Total
132	Judy Creek EOR	Pengrowth	Active	Canada	-	-	-	164.40	Metric Tons Per Day
133	K12-B CO_2 Injection Project	GDF SUEZ E&P Nederland B.V.	Active	Netherlands	-	Separation	MDEA Gas Separation Process	54.80	Metric Tons Per Day
134	Karsto NGCC Capture Project	Norwegian Government	Hold	Norway	420.00	Post-Combustion	Aker Kvaerner's Just Catch technology	274.00	Metric Tons Per Day
135	Kedzierzyn	Zaklady Azotowe Kedzierzyn S.A.	Terminated	Poland	300.00	Pre-Combustion	Gas Separation	6,850.00	Metric Tons Per Day
136	Kemper County IGCC Project	Southern Company	Terminated	United States	582.00	Pre-Combustion	Transport Integrated Gasification (TRIG)	8,220.00	Metric Tons Per Day

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137	Kentucky NewGas project	Kentucky NewGas	Terminated	United States	-	Pre-Combustion	ConocoPhillips E-Gas Gasification	13,700.00	Metric Tons Per Day
138	Klemetsrud Waste to Energy Plant	Oslo Municipality Waste-to-Energy Agency	Active	Norway	-	Post-Combustion	Amines	-	-
139	Korea CCS1	Korean Electric Power Corporation	Active	South Korea	300.00	Post-Combustion	Amines	2,740.00	Metric Tons Per Day
140	Kurosaki Chemical Plant Capture Project	Mitsubishi Heavy Industries	Active	Japan	18.00	-	Amines	330.00	Metric Tons Per Day
141	Kwinana Project	Hydrogen Energy International LLC	Terminated	Australia	500.00	Pre-Combustion	-	10,960.00	Metric Tons Per Day
142	Large Pilot Testing of Linde/BASF Advanced Post-Combustion CO_2 Capture Technology at a Coal-Fired Power Plant	University of Illinois at Urbana-Champaign	Active	United States	10.00	Post-Combustion	Linde-BASF Solvent System	-	-
143	Large Pilot Testing of the MTR Membrane Post-Combustion CO_2 Capture Process	Membrane Technology and Research, Inc (MTR)	Active	United States	200.00	Post-Combustion	MTR Polaris™ Membrane System	-	-
144	Ledvice CEZ Capture and Storage Project	CEZ Group	Potential	Czech Republic	660.00	Post-Combustion	-	-	-
145	Leucadia Energy Capture Project - Louisiana	Leucadia Energy LLC	Terminated	United States	-	Pre-Combustion	Cold Methanol (Rectisol)	12,330.00	Metric Tons Per Day
146	Lianyungang IGCC with CO2 Capture	Chinese Government	Terminated	China	1,200.00	Pre-Combustion	Gas Separation	2,740.00	Metric Tons Per Day
147	Liaohe EOR Project	Chinese Government	Completed	China	-	Post-Combustion	-	2,300.00	Metric Tons Total
148	Lima Polygen	Global Energy	Hold	United States	540.00	Pre-Combustion	-	7,672.00	Metric Tons Per Day
149	LINC Energy - Wyoming EOR	LINC Energy	Active	United States	-	-	-	500.00	Metric Tons Total
150	Luzhou Natural Gas Chemicals	Fluor	Active	China	158.92	Post-Combustion	Fluor Corporation's advanced Econamine FG Plussm Technology	160.00	Metric Tons Per Day

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151	Masdar CCS Project	Abu Dhabi Future Energy Company	Potential	United Arab Emirates	11,782.00	Pre-Combustion	Amines	11,782.00	Metric Tons Per Day
152	Matsushima Coal Plant Capture Project	Japanese Government	Completed	Japan	1,000.00	Post-Combustion	Amines	10.00	Metric Tons Per Day
153	Membrane-Sorbent Hybrid System for Post-Combustion Carbon Capture	TDA Research, Inc.	Active	Norway	10.00	Post-Combustion	MTR-TDA Membrane-Sorbent Hybrid System	-	-
154	Mesaba Energy Project	Excelsior Energy Inc.	Hold	United States	602.00	Pre-Combustion	ConocoPhillips E-Gas Gasification	12,330.00	Metric Tons Per Day
155	MGSC Development Phase - Illinois Basin Decatur Project	Illinois State Geological Survey	Completed	United States	-	Industrial	Not Currently Specified	999,215.00	Metric Tons Total
156	MGSC Validation Phase - Loudon Field	Illinois State Geological Survey	Completed	United States	-	-	-	39.00	Metric Tons Total
157	MGSC Validation Phase - Mumford Hills Field	Illinois State Geological Survey	Completed	United States	-	-	-	6,300.00	Metric Tons Total
158	MGSC Validation Phase - Sugar Creek Field	Illinois State Geological Survey	Completed	United States	-	-	-	6,560.00	Metric Tons Total
159	MGSC Validation Phase - Tanquary Site	Illinois State Geological Survey	Completed	United States	-	-	-	91.00	Metric Tons Total
160	Mitchell Energy Bridgeport Plant	Mitchell Energy	Completed	United States	-	Post-Combustion	Aqueous Amino Acid Salt-Based Solvent	500.00	Metric Tons Per Day
161	Modeling CO_2 Sequestration in a Saline Reservoir and Depleted Oil Reservoir to Evaluate The Regional CO2 Sequestration Potential of The Ozark Plateau Aquifer System, South-Central Kansas	University of Kansas	Completed	United States	-	-	-	-	-
162	Monash Energy C to L CO2 Capture and Storage Project	Monash Energy	Terminated	Australia	60,000.00	Pre-Combustion	-	35,620.00	Metric Tons Per Day

S.No.	Project Name	Company	Overall Status	Country Location	Plant Size or Capture Amount (MW)	Combustion/ Separation	Capture Technology	Amount of CO_2 Captured/Stored	Captured/ Stored Unit
163	Mongstad Cogeneration Plant with CO2 Storage	Statoil	Active	Norway	630.00	Post-Combustion	Alstom Chilled Ammonia Process	274.00	Metric Tons Per Day
164	Moomba Cooper Basin Carbon Storage Project	Santos	Hold	Australia	-	-	-	54,800.00	Metric Tons Per Day
165	MOVECBM Project	European Union	Completed	Poland	15.00	-	-	15.00	Metric Tons Per Day
166	MRCSP Development Phase - Michigan Basin Project	Battelle Memorial Institute	Active	United States	-	Separation	Gas Separation	1,000,000.00	Metric Tons Total
167	MRCSP Validation Phase - Appalachian Basin Test	Battelle Memorial Institute	Completed	United States	-	-	-	50.00	Metric Tons Total
168	MRCSP Validation Phase - Cincinnati Arch Geologic Test	Battelle Memorial Institute	Completed	United States	-	-	-	910.00	Metric Tons Total
169	MRCSP Validation Phase - Michigan Basin Geologic Test	Battelle Memorial Institute	Completed	United States	-	Separation	Gas Separation	60,000.00	Metric Tons Total
170	Mulgrave Capture Project - CO2CRC	CO2CRC - Cooperative Research Centre for Greenhouse Gas Technologies	Completed	Australia	1.10	Pre-Combustion	Amine Ammonia Membrane	741.00	Metric Tons Total
171	Nagaoka Storage Project	Japanese Government	Completed	Japan	-	-	-	40.00	Metric Tons Per Day
172	Nanko Natural Gas Pilot Plant	Kansai Electric Company	Active	Japan	2.00	Post-Combustion	Solvents	2.00	Metric Tons Per Day
173	Nebraska Integrated Carbon Capture and Storage Pre-Feasibility Study	Energy & Environmental Research Center - University of North Dakota	Potential	United States	-	-	-	-	-
174	Newark Basin Characterization of New York and New Jersey	Sandia Technologies, LLC	Completed	United States	-	-	-	0.00	Metric Tons Total
175	Nippon Steel CO_2 Capture Project	Nippon Steel	Completed	Japan	-	-	Amines	170.00	Metric Tons Per Day
176	North Bohemia Clean Coal Project	CEZ Group	Potential	Czech Republic	660.00	Separation	-	15.00	% Reduction

S.No.	Project Name	Company	Overall Status	Country Location	Plant Size or Capture Amount (MW)	Combustion/ Separation	Capture Technology	Amount of CO_2 Captured/Stored	Captured/ Stored Unit
177	North Dakota Integrated Carbon Storage Complex Feasibility Study	Energy & Environmental Research Center - University of North Dakota	Potential	United States	-	-	-	-	-
178	Northern Michigan Basin CarbonSAFE Integrated Pre-Feasibility Project	Battelle Memorial Institute	Potential	United States	-	-	-	-	-
179	Northwest Upgrader Refinery	North West Redwater	Active	Canada	150,000.00	Pre-Combustion	-	3,288.00	Metric Tons Per Day
180	NRG Energy Inc. (Huntley IGCC Project)	NRG Energy Inc.	Terminated	United States	680.00	Pre-Combustion	Mitsubishi HI Gasification (KS-1)	65.00	% Reduction
181	NRG Energy Inc. (Somerset Plant)	NRG Energy Inc.	Terminated	United States	380.00	Pre-Combustion	-	-	-
182	NRG Powerton Station	NRG Energy Inc.	Active	United States	1,538.00	Post-Combustion	Amines	-	-
183	Nuon Magnum IGCC Plant with Capture Option	Nuon	Hold	Netherlands	1,200.00	Pre-Combustion	Solvents	-	-
184	Nuon Power Buggenum	Nuon	Terminated	Netherlands	253.00	Pre-Combustion	-	822.00	Metric Tons Per Day
185	Oakdale NG Processing	Blue Source	Active	United States	-	Separation	-	1,096.00	Metric Tons Per Day
186	Ordos Basin Project	Shenhua Coal Trading	Active	China	24,000.00	Pre-Combustion	-	9,590.00	Metric Tons Per Day
187	Otway Basin Project - CO2CRC	CO2CRC - Cooperative Research Centre for Greenhouse Gas Technologies	Active	Australia	-	Separation	-	80,000.00	Metric Tons Total
188	OXYCFB300 Compostilla Project	Endesa	Active	Spain	323.00	Oxy-Combustion	Oxy-Fuel Combustion	100,000.00	Metric Tons Total
189	PCOR Development Phase - Bell Creek Project	Energy & Environmental Research Center - University of North Dakota	Completed	United States	50,000,000.00	Separation	Gas Separation	2,740.00	Metric Tons Per Day
190	PCOR Development Phase - Ft. Nelson Project	Energy & Environmental Research Center -	Hold	Canada	-	Separation	Amines	5,480.00	Metric Tons Per Day

S.No.	Project Name	Company	Overall Status	Country Location	Plant Size or Capture Amount (MW)	Combustion/ Separation	Capture Technology	Amount of CO_2 Captured/Stored	Captured/ Stored Unit
		University of North Dakota							
191	PCOR Validation Phase - Lignite Test	Energy & Environmental Research Center - University of North Dakota	Completed	United States	-	-	-	80.00	Metric Tons Total
192	PCOR Validation Phase - Northwest McGregor EOR Huff n' Puff Project	Energy & Environmental Research Center - University of North Dakota	Completed	United States	-	-	-	400.00	Metric Tons Total
193	PCOR Validation Phase - Zama Field Test	Energy & Environmental Research Center - University of North Dakota	Completed	Canada	-	Industrial	Gas Separation	84,986.00	Metric Tons Total
194	Pembina Cardium CO2 EOR Pilot	PennWest Exploration (formerly Penn West Energy Trust)	Completed	Canada	-	-	-	79.00	Metric Tons Per Day
195	PEMEX CCS Project	Petróleos Mexicanos (PEMEX)	Active	Mexico	-	Separation	Not Currently Specified	8,459,550.00	Metric Tons Total
196	Pernis Refinery Project	Shell	Terminated	Netherlands	117.00	Pre-Combustion	-	1,096.00	Metric Tons Per Day
197	Petrobras Lula Oil Field Offshore CCS Project	Petrobras	Active	Brazil	-	-	-	1,918.00	Metric Tons Per Day
198	Petrobras Miranga CO2 Injection	Petrobras	Active	Brazil	-	Pre-Combustion	MTR Membrane System	400.00	Metric Tons Per Day
199	Petrom Zero Emissions Plant (ZEP)	Petrom E&P	Potential	Romania	15.00	Oxy-Combustion	Oxy-Fuel Combustion	-	-
200	Petronas Gas Processing Capture Project	Petronas Fertilizer	Active	Malaysia	-	Separation	Amines	160.00	Metric Tons Per Day
201	Phulpur Urea Plant CO2 Recovery project	Indian Farmers Fertiliser Cooperative Limited	Active	India	-	Post-Combustion	Amines	1,940.56	Metric Tons Per Day
202	PICOREF Project	Gaz de France Production	Completed	France	-	-	-	-	-
203	Pioneer Project	TransAlta	Terminated	Canada	450.00	Post-Combustion	Chilled Ammonia	2,740.00	Metric Tons Per Day

S.No.	Project Name	Company	Overall Status	Country Location	Plant Size or Capture Amount (MW)	Combustion/ Separation	Capture Technology	Amount of CO_2 Captured/Stored	Captured/ Stored Unit
204	Porto Tolle	Enel	Hold	Italy	250.00	Post-Combustion	Solvents	2,740.00	Metric Tons Per Day
205	Post-Combustion Capture Project in Beijing	CSIRO - Australian Commonwealth Scientific and Industrial Research Organization	Active	China	845.00	Post-Combustion	Solvents	8.22	Metric Tons Per Day
206	Poza Rica EOR Project	Comisión Federal de Electricidad (CFE)	Potential	Mexico	250.00	Post-Combustion	Amines	8.00	Metric Tons Per Day
207	Prairie State Energy Campus	Prairie State Energy Campus	Active	United States	1,600.00	Post-Combustion	-	15.00	% Reduction
208	Praxair Inc. CO2 Capture and Sequestration Project	Praxair, Inc	Terminated	United States	-	Industrial	-	2,740.00	Metric Tons Per Day
209	Puertollano Plant	ELCOGAS S.A.	Active	Spain	335.00	Pre-Combustion	Pressurized Entrained Flow (Prenflo)	100.00	Metric Tons Per Day
210	Purdy, Sho-Vel-Tum EOR Project	Anadarko Petroleum Corporation	Active	United States	-	Pre-Combustion	Amino Acid-Based Solvents & Membranes	675,000.00	Metric Tons Total
211	PureGen Project	SCS Energy	Terminated	United States	500.00	Post-Combustion	-	90.00	% Reduction
212	Qinshui ECBM Project	Canadian International Development Agency	Completed	China	-	-	-	192.00	Metric Tons Total
213	QPC Quimica Methanol Production Plant	QPC Quimica	Active	Brazil	-	Post-Combustion	Amines	163.98	Metric Tons Per Day
214	Quest Carbon Capture and Storage Project	Shell	Active	Canada	225,000.00	Industrial	Amines	3,014.00	Metric Tons Per Day
215	Rangely-Webber EOR	Chevron	Active	United States	14,000.00	-	-	3,562.00	Metric Tons Per Day
216	RECOPOL Project	European Commission	Completed	Poland	-	-	-	2.08	Metric Tons Per Day
217	Riley Ridge Gas Plant	Denbury Onshore, LLC	Potential	United States	6,850.00	Pre-Combustion	Amines	-	-
218	RWE CCS Eemshaven	RWE	Hold	Netherlands	1,600.00	Post-Combustion	Amines	3,288.00	Metric Tons Per Day
219	RWE IGCC Plant with CO2 Storage	RWE Power	Hold	Germany	450.00	Pre-Combustion	-	7,124.00	Metric Tons Per Day

S.No.	Project Name	Company	Overall Status	Country Location	Plant Size or Capture Amount (MW)	Combustion/ Separation	Capture Technology	Amount of CO_2 Captured/Stored	Captured/ Stored Unit
220	RWE nPower - Aberthaw Capture Project in UK	RWE nPower	Active	United Kingdom	3.00	Post-Combustion	Cansolv Technologies' Capture Technology	50.00	Metric Tons Per Day
221	RWE nPower - Blyth Post-Combustion Project	RWE nPower	Terminated	United Kingdom	2,400.00	Post-Combustion	-	8,220.00	Metric Tons Per Day
222	RWE nPower - Tilbury Project in UK	RWE Power	Terminated	United Kingdom	1,131.00	Post-Combustion	-	90.00	% Reduction
223	RWE/BASF/Linde CO2 Capture Project Niederaussem	RWE Power	Completed	Germany	1,000.00	Post-Combustion	Amines	2,000.00	Metric Tons Total
224	Saline Joniche SEI	SEI	Terminated	Italy	1,320.00	Post-Combustion	-	0.00	Metric Tons Per Day
225	Salt Creek, Monell, Sussex Unit EOR	Anadarko Petroleum Corporation	Active	United States	-	-	-	5,480.00	Metric Tons Per Day
226	Sargas Husnes Norwegian Clean Coal Plant Project	Sargas	Hold	Norway	400.00	Post-Combustion	-	7,124.00	Metric Tons Per Day
227	Sargas Natural Gas CCS	Sargas	Hold	Norway	250.00	-	Sargas Natural Gas CCS	-	-
228	Sargas Vartan	Sargas	Completed	Sweden	3,288.00	Post-Combustion	Solvents	-	-
229	SaskPower Oxyfuel	SaskPower	Terminated	Canada	300.00	Oxy-Combustion	-	8,000.00	Metric Tons Per Day
230	Scale-Up and Testing of Advanced Polaris Membrane CO2 Capture Technology	Membrane Technology and Research, Inc (MTR)	Active	Norway	10.00	Post-Combustion	MTR Polaris™ Membrane System	-	-
231	Schwarze Pumpe (Vattenfall CO2-Free Oxyfuel Plant)	Vattenfall	Terminated	Germany	30.00	Post-Combustion	-	216.00	Metric Tons Per Day
232	Scottish and Southern Energy - West Yorkshire	Scottish and Southern Energy	Active	England	5.00	Post-Combustion	Amines	100.00	Metric Tons Per Day
233	Scottish Power - Cockenzie Project	Scottish Power	Terminated	United Kingdom	1,200.00	Post-Combustion	-	5.00	% Reduction
234	Scottish Power - Longannet Biomass Power	Scottish Power	Terminated	Scotland	2,400.00	-	-	-	-

S.No.	Project Name	Company	Overall Status	Country Location	Plant Size or Capture Amount (MW)	Combustion/ Separation	Capture Technology	Amount of CO_2 Captured/Stored	Captured/ Stored Unit
235	Scottish Power - Longannet CCS	Scottish Power	Terminated	Scotland	2,400.00	Post-Combustion	Amines	-	-
236	Searles Valley Minerals	Searles Valley Minerals	Active	United States	108.00	Post-Combustion	Amines	739.80	Metric Tons Per Day
237	SECARB Development Phase - Citronelle Project	Southern States Energy Board	Completed	United States	25.00	Post-Combustion	Amines	114,104.00	Metric Tons Total
238	SECARB Development Phase - Cranfield Project	Southern States Energy Board	Completed	United States	-	-	-	4,743,898.00	Metric Tons Total
239	SECARB Validation Phase - Black Warrior Basin Project	Southern States Energy Board	Completed	United States	-	-	-	252.00	Metric Tons Total
240	SECARB Validation Phase - Central Appalachian Basin Coal Test	Southern States Energy Board	Completed	United States	-	-	-	907.00	Metric Tons Total
241	SECARB Validation Phase - Plant Daniel Project	Southern States Energy Board	Completed	United States	-	-	-	2,740.00	Metric Tons Total
242	SECARB Validation Phase - Stacked Storage Test	Southern States Energy Board	Completed	United States	-	-	-	627,744.00	Metric Tons Total
243	Seminole Electric Cooperative	Seminole Electric Cooperative	Terminated	United States	750.00	Post-Combustion	-	13,800.77	Metric Tons Per Day
244	SEQ Zero Emission Power Plant (ZEPP)	SEQ Nederland B.V.	Completed	Netherlands	50.00	Post-Combustion	-	685.00	Metric Tons Per Day
245	Shanxi International Energy Oxyfuel Project	Shanxi International Energy Group Company, Ltd (SIEG)	Potential	China	350.00	Oxy-Combustion	Oxy-Fuel Combustion	6,850.00	Metric Tons Per Day
246	Shell Chemical CCS Project	Shell	Terminated	United States	-	Industrial	-	2,740.00	Metric Tons Per Day
247	Shenhua Ningxia CTL Project	Shenhua Group Corporation	Potential	China	10,000.00	Pre-Combustion	Solvents	-	-
248	Shute Creek Plant	ExxonMobil	Active	United States	0.00	-	ExxonMobil Controlled Freeze Zone (CFZ)	1,096.00	Metric Tons Per Day
249	Sigma Power Ariake Mikawa	Toshiba Corporation	Active	Japan	47.50	Post-Combustion	Amines	10.00	Metric Tons Per Day

S.No.	Project Name	Company	Overall Status	Country Location	Plant Size or Capture Amount (MW)	Combustion/ Separation	Capture Technology	Amount of CO_2 Captured/Stored	Captured/ Stored Unit
250	Sinopec Qilu Petrochemical CCS Project	Qilu Petrochemical Company (subsidiary of Sinopec)	Hold	China	1,370.00	Pre-Combustion	Cold Methanol (Rectisol)	1,370.00	Metric Tons Per Day
251	Sinopec Shengli Power Plant CCS Project	China National Petroleum Company.	Active	China	600.00	Post-Combustion	Amines	2,740.00	Metric Tons Per Day
252	Site Characterization for CO2 Storage from Coal-Fired Power Facilities in the Black Warrior Basin of Alabama	University of Alabama	Completed	United States	-	-	-	-	-
253	Site Characterization of the Highest-Priority Geologic Formations for CO_2 Storage in Wyoming	University of Wyoming	Completed	United States	-	-	-	-	-
254	Sleipner Project	Statoil	Active	Norway	-	Separation	Amines	2,740.00	Metric Tons Per Day
255	Slipstream Development and Testing of Siemens POSTCAP Capture and Separation Technology	Siemens Energy, Inc.	Completed	United States	2.50	Post-Combustion	Aqueous Amino Acid Salt-Based Solvent	50.00	Metric Tons Per Day
256	Slipstream Testing of a Membrane CO_2 Capture Process for Existing Coal-Fired Power Plants	Membrane Technology and Research, Inc (MTR)	Completed	United States	1.00	Post-Combustion	MTR Membrane System	20.00	Metric Tons Per Day
257	Snøhvit Field LNG and CO_2 Storage Project	Statoil	Active	Norway	-	Separation	Amines	1,918.00	Metric Tons Per Day
258	South Korea CCS2	Korean Electric Power Corporation	Active	South Korea	300.00	Oxy-Combustion	Oxy-Fuel Combustion	3,288.00	Metric Tons Per Day
259	Sumitomo Chemicals Capture Project	Sumitomo Chemicals	Active	Japan	-	Post-Combustion	Fluor Econamine	150.00	Metric Tons Per Day
260	Summit Energy - Texas Clean Energy Project (TCEP)	Summit Clean Energy Texas, LLC	Terminated	United States	400.00	Pre-Combustion	Rectisol	6,302.00	Metric Tons Per Day
261	Sunrise LNG Sequestration	Woodside	Active	Australia	-	Separation	-	-	-
262	Surat Basin CCS Project	General Electric	Terminated	Australia	400.00	Pre-Combustion	Amines	6,850.00	Metric Tons Per Day

S.No.	Project Name	Company	Overall Status	Country Location	Plant Size or Capture Amount (MW)	Combustion/ Separation	Capture Technology	Amount of CO_2 Captured/Stored	Captured/ Stored Unit
263	Swan Hills In-Situ Coal Gasification/Sagitawa h Power Project	Swan Hills Synfuels	Terminated	Canada	300.00	Pre-Combustion	-	3,562.00	Metric Tons Per Day
264	Sweeny Polygeneration with CO_2 Capture	ConocoPhillips	Terminated	United States	683.00	Post-Combustion	ConocoPhillips E-Gas Gasification	13,700.00	Metric Tons Per Day
265	SWP Development Phase - Farnsworth Unit Ochiltree Project	New Mexico Institute of Mining and Technology	Active	United States	-	Separation	Not Currently Specified	1,000,000.00	Metric Tons Total
266	SWP Validation Phase - Aneth EOR Sequestration Project	New Mexico Institute of Mining and Technology	Completed	United States	-	-	-	292,000.00	Metric Tons Total
267	SWP Validation Phase - Pump Canyon CO_2-ECBM Sequestration Demonstration	New Mexico Institute of Mining and Technology	Completed	United States	-	-	-	16,700.00	Metric Tons Total
268	SWP Validation Phase - SACROC CO_2 Injection Project	New Mexico Institute of Mining and Technology	Completed	United States	-	-	-	157,000.00	Metric Tons Total
269	Taichung CCS	Taiwan Power Company	Active	Taiwan	-	Post-Combustion	-	10,000.00	Metric Tons Total
270	Tampa Electric - Scale-Up of High-Temperature Syngas Cleanup Technology	Tampa Electric Power Company	Completed	United States	50.00	Pre-Combustion	MDEA Gas Separation Process	748.02	Metric Tons Per Day
271	Tarong Plant Algae Oil Project	MBD Energy	Active	Australia	450.00	Post-Combustion	Bio CCS Algal Synthesizer	1.92	Metric Tons Per Day
272	Taylorville Energy Center	Tenaska Inc.	Terminated	United States	630.00	Pre-Combustion	-	55.00	% Reduction
273	TEPCO Yokosuka	Tokyo Electric Power Company	Completed	Japan	1.00	Post-Combustion	Solvents	90.00	% Reduction
274	Total Lacq Project	Total	Completed	France	0.90	Post-Combustion	-	51,000.00	Metric Tons Total
275	Touchstone Bioconversion Pilot Plant	Touchstone Research Laboratory	Completed	United States	-	-	Not Currently Specified	0.01	Liter of Algae Per Minute
276	Trailblazer Energy Center	Tenaska Inc.	Terminated	United States	600.00	Post-Combustion	Fluor Corporation's Advanced Econamine FG	15,755.00	Metric Tons Per Day

S.No.	Project Name	Company	Overall Status	Country Location	Plant Size or Capture Amount (MW)	Combustion/ Separation	Capture Technology	Amount of CO_2 Captured/Stored	Captured/ Stored Unit
							Plussm Technology		
277	Turnu EOR	OMV - Austrian Mineral Oil Authority	Active	Romania	-	Separation	-	150,000.00	Cubic Meters Per Day
278	UKy-CAER Heat-Integrated Transformative CO_2 Capture Process for Pulverized Coal Power Plants	University of Kentucky Research Foundation	Active	United States	10.00	Post-Combustion	UKy-CAER Heat-Integrated Transformative CO2 Capture Process	-	-
279	ULCOS Florange	ArcelorMittal	Hold	France	0.00	Post-Combustion	Solid sorbent	1,370.00	Metric Tons Per Day
280	ULYSSES Sequestration	Providence Resources	Active	Ireland	-	-	-	-	-
281	University of Kansas - Small-Scale Injection Project	Kansas Geological Survey	Completed	United States	-	-	-	40,000.00	Metric Tons Total
282	Uthmaniyah CO2 EOR Demo Project	Saudi Aramco	Active	Saudi Arabia	-	Pre-Combustion	Amines	2,192.00	Metric Tons Per Day
283	Val Verde NG Plants	MCN Energy Group	Active	United States	0.00	Pre-Combustion	Gas Separation	3,562.00	Metric Tons Per Day
284	Vales Point Power Station CCS Demonstration	Delta Electricity	Terminated	Australia	1,320.00	Post-Combustion	Ammonia Absorption Technology	-	-
285	Vattenfall Janschwalde	Vattenfall	Terminated	Germany	3,000.00	Post-Combustion	Oxy-Fuel Combustion	4,658.00	Metric Tons Per Day
286	Veolia Environment CCS Project	Veolia Environment	Active	France	23.00	Post-Combustion	Multiple	548.00	Metric Tons Per Day
287	Virginia Tech - Small-Scale Injection Project	Virginia Polytechnical Institute (Virginia Tech)	Completed	United States	-	-	-	20,300.00	Metric Tons Total
288	W.A. Parish Post-Combustion CO_2 Capture and Sequestration Project	NRG Energy Inc.	Active	United States	240.00	Post-Combustion	Solvents	3,836.00	Metric Tons Per Day
289	Wallula IGCC Plant	Wallula Resource Recovery, LLC	Terminated	United States	700.00	Pre-Combustion	-	65.00	% Reduction
290	We Energies Pleasant Prairie Field Pilot	We Energies	Completed	United States	1.70	Post-Combustion	Alstom Chilled Ammonia Process	81.10	Metric Tons Per Day
291	West Texas and Llano Pipelines Power CCS	Trinity CO2 LLC	Active	United States	-	-	-	1,000.00	Metric Tons Per Day

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292	WESTCARB Validation Phase - Arizona Utilities CO_2 Storage Pilot	Arizona Public Service	Completed	United States	-	-	-	0.00	Metric Tons Total
293	WESTCARB Validation Phase - Northern California CO2 Reduction Project Reduction Project (G1)	C6 Resources	Completed	United States	-	-	-	0.00	Metric Tons Per Day
294	Western Kentucky CO_2 Test	Kentucky Geological Survey	Completed	United States	-	-	-	690.00	Metric Tons Total
295	Weyburn-Midale Project	Cenovus Energy	Completed	Canada	-	Pre-Combustion	Cold Methanol (Rectisol)	40,000,000.00	Metric Tons Total
296	White Rose CCS Project	Capture Power Limited	Potential	United Kingdom	450.00	Oxy-Combustion	Oxy-Fuel Combustion	-	-
297	Wolverine Power Supply Cooperative Inc. - Industrial Capture Project	Wolverine Power Supply Cooperative, Inc.	Terminated	United States	600.00	Industrial	Amines	822.00	Metric Tons Per Day
298	Yanchang Integrated Carbon Capture and Storage Demonstration Project	Shaanxi Yanchang Petroleum Group	Active	China	1,205.60	Pre-Combustion	Cold Methanol (Rectisol)	137.00	Metric Tons Per Day
299	Yates Oil Field EOR Operations	Kinder Morgan	Active	United States	-	-	-	20,800.00	Barrels Per Day
300	Yulin Coal to Chemicals CCS	Shenhua Group	Potential	China	-	Industrial	Solvents	5,480.00	Metric Tons Per Day
301	ZENG Worsham-Steed	CO2 Global	Potential	United States	70.00	Oxy-Combustion	-	870.00	Metric Tons Per Day
302	ZeroGen Project	State of Queensland	Terminated	Australia	80.00	Pre-Combustion	-	1,150.80	Metric Tons Per Day
303	Abu Dhabi CCS Phase 2: Natural gas processing plant	-	Advanced Development	United Arab Emirates	-	Pre-combustion	-	-	-
304	Acorn (Minimum Viable CCS Development)	-	Advanced Development	United Kingdom	-	Under evaluation	-	-	-
305	Acorn Scalable CCS Development	-	Early Development	United Kingdom	-	Under evaluation	-	-	-

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306	Alberta Carbon Trunk Line (ACTL) with Agrium CO2 Stream	-	In Construction	Canada	-	Pre-combustion	-	-	-
307	Alberta Carbon Trunk Line (ACTL) with North West Redwater Partnership's Sturgeon Refinery CO_2 Stream	-	In Construction	Canada	-	Pre-combustion	-	-	-
308	Australia-China Post Combustion Capture (PCC) Feasibility Study Project	-	Advanced Developmen t	China	-	Post-combustion	-	-	-
309	Caledonia Clean Energy	-	Early Developmen t	United Kingdom	-	Post-combustion	-	-	-
310	CarbonNet	-	Advanced Developmen t	Australia	-	Under evaluation	-	-	-
311	CarbonSAFE Illinois - Macon County	-	Advanced Developmen t	USA	-	Under evaluation	-	-	-
312	China Resources Power (Haifeng) Integrated Carbon Capture and Sequestration Demonstration	-	Early Developmen t	China	-	Post-combustion	-	-	-
313	Chinese-European Emission-Reducing Solutions (CHEERS)	-	Advanced Developmen t	China	-	Pre-combustion	-	-	-
314	DMX™ Demonstration in Dunkirk	-	Advanced Developmen t	France	-	Post-combustion	-	-	-
315	Dry Fork Integrated Commercial Carbon Capture and Storage (CCS)	-	Advanced Developmen t	USA	-	Post-combustion	-	-	-
316	Ervia Cork CCS	-	Early Developmen t	Ireland	-	Under evaluation	-	-	-

S.No.	Project Name	Company	Overall Status	Country Location	Plant Size or Capture Amount (MW)	Combustion/ Separation	Capture Technology	Amount of CO_2 Captured/Stored	Captured/ Stored Unit
317	Fuel Cell Carbon Capture Pilot Plant	-	Advanced Development	USA	-	Under evaluation	-	-	-
318	Gundih CCS Pilot	-	Advanced Development	Indonesia	-	Pre-combustion	-	-	-
319	Guohua Jinjie CCS Full Chain Demonstration	-	Advanced Development	China	-	Post-combustion	-	-	-
320	Huaneng GreenGen IGCC Demonstration-scale System (Phase 2)	-	In Construction	China	-	Pre-combustion	-	-	-
321	Huaneng GreenGen IGCC Large-scale System (Phase 3)	-	Early Development	China	-	Pre-combustion	-	-	-
322	Huazhong University of Science and Technology Oxy-fuel Project	-	In Construction	China	-	Oxy-fuel	-	-	-
323	Hydrogen 2 Magnum (H2M)	-	Early Development	Netherlands	-	Under evaluation	-	-	-
324	Hydrogen Energy Supply Chain (HESC) project	-	Advanced Development	Australia	-	Pre-combustion	-	-	-
325	HyNet North West	-	Early Development	United Kingdom	-	Pre-combustion	-	-	-
326	Integrated Midcontinent Stacked Carbon Storage Hub	-	Advanced Development	USA	-	Under evaluation	-	-	-
327	Integrated Surat Basin CCS Project	-	Advanced Development	Australia	-	Post-combustion	-	-	-
328	Inventys and Husky Energy VeloxoTherm Capture Process Test	-	Advanced Development	Canada	-	Pre-combustion	-	-	-
329	Korea-CCS 1 & 2	-	Early Development	South Korea	-	Post-combustion	-	-	-

S.No.	Project Name	Company	Overall Status	Country Location	Plant Size or Capture Amount (MW)	Combustion/ Separation	Capture Technology	Amount of CO_2 Captured/Stored	Captured/ Stored Unit
330	Lake Charles Methanol	-	Advanced Development	USA	-	Pre-combustion	-	-	-
331	LEILAC	-	In Construction	Belgium	-	Direct separation	-	-	-
332	Mikawa Post Combustion Capture Demonstration Plant	-	In Construction	Japan	-	Post-combustion	-	-	-
333	Net Zero Teesside	-	Early Development	United Kingdom	-	Under evaluation	-	-	-
334	Northern Gas Network H21 North of England	-	Early Development	United Kingdom	-	Pre-combustion	-	-	-
335	Norway Full Chain CCS	-	Advanced Development	Norway	-	Under evaluation	-	-	-
336	Osaki CoolGen Project	-	In Construction	Japan	-	Pre-combustion	-	-	-
337	OXY and Carbon Engineering Direct Air Capture and EOR Facility	-	Early Development	USA	-	DAC	-	-	-
338	OXY and White Energy Ethanol EOR Facility	-	Early Development	USA	-	Pre-combustion	-	-	-
339	Pilot Carbon Storage Project (PCSP) - Zululand Basin, South Africa	-	Advanced Development	South Africa	-	Under evaluation	-	-	-
340	Port of Rotterdam CCUS Backbone Initiative (Porthos)	-	Advanced Development	Netherlands	-	Under evaluation	-	-	-
341	Project ECO2S: Early CO2 Storage Complex in Kemper County	-	Early Development	USA	-	Under evaluation	-	-	-
342	Project Tundra	-	Advanced Development	USA	-	Post-combustion	-	-	-

S.No.	Project Name	Company	Overall Status	Country Location	Plant Size or Capture Amount (MW)	Combustion/ Separation	Capture Technology	Amount of CO_2 Captured/Stored	Captured/ Stored Unit
343	Shenhua Ningxia CTL	-	Early Development	China	-	Pre-combustion	-	-	-
344	Sinopec Eastern China CCS	-	Early Development	China	-	Pre-combustion	-	-	-
345	Sinopec Qilu Petrochemical CCS	-	In Construction	China	-	Pre-combustion	-	-	-
346	Sinopec Shengli Power Plant CCS	-	Early Development	China	-	Post-combustion	-	-	-
347	South West Hub	-	Early Development	Australia	-	Pre-combustion	-	-	-
348	The Clean Gas Project	-	Early Development	United Kingdom	-	Post-combustion	-	-	-
349	Wabash CO2 Sequestration	-	Advanced Development	USA	-	Pre-combustion	-	-	-
350	Yanchang Integrated Carbon Capture and Storage Demonstration	-	In Construction	China	-	Pre-combustion	-	-	-

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