Chapter 2

Overview of Carbon Capture, Utilisation, and Storage Technology

March 2021

This chapter should be cited as

ERIA (2021), 'Overview of Carbon Capture, Utilisation, and Storage Technology', in Kimura, S., K. Shinchi, S. Kawagishi, and U. Coulmas (eds.), *Study on the Potential for the Promotion of Carbon Dioxide Capture, Utilisation, and Storage in ASEAN Countries.* ERIA Research Project Report FY2020 no.21, Jakarta: ERIA, pp.14-27.

Chapter 2

Overview of Carbon Capture, Utilisation, and Storage Technology

1. Capture

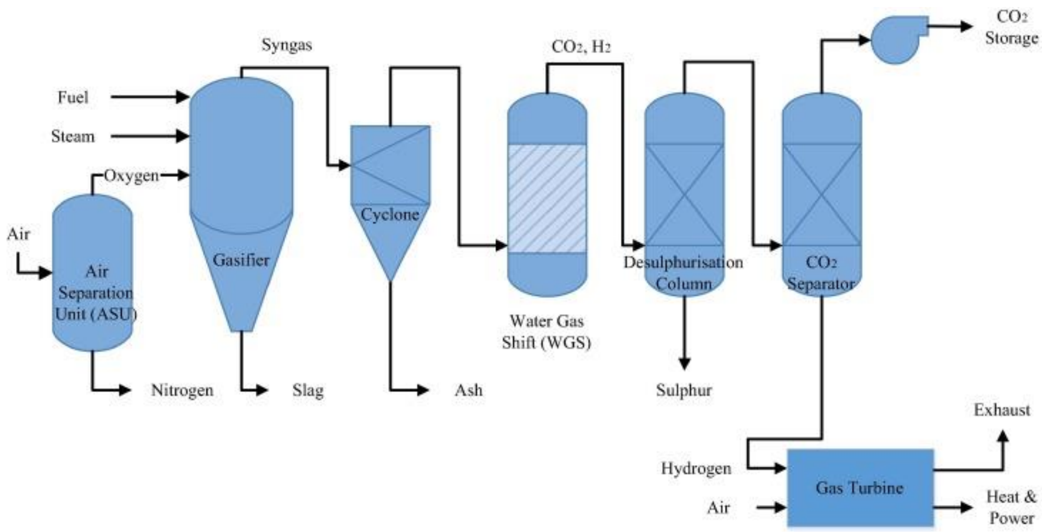
1.1 Technology overview

There are four main types of capture process. Depending on the industrial process, the type of power plant, or the geographical conditions, pre-combustion capture, post-combustion capture, oxy-fuel combustion, or direct air capture is applied. For each type, there are multiple technological approaches, which will be explained in the following sections.

1.1.1. Pre-combustion capture:

Pre-combustion capture is a process in which carbon is extracted from a fossil fuel (i.e., gas, oil, or coal) before it is burnt. This is done by a pre-treatment process called 'gasification', in which the fuel is heated under low pressure with a limited amount of oxygen. The product is called 'synthesis gas', or just 'syngas', and is used in gas turbine generators at power plants. It primarily consists of carbon monoxide (CO) and hydrogen. In the next stage, steam is added to the syngas. This converts the carbon monoxide to carbon dioxide (CO_2) and separates the hydrogen, which can also be used as a fuel. Pre-combustion recovery is mainly used in industrial facilities, such as natural gas processing, whilst the application to power plants is still limited to a few integrated gasification combined cycle (IGCC) coal plants. The process scheme of pre-combustion capture is described in Figure 2.1.

Figure 2.1. Process Scheme of Pre-combustion CO_2 Capture



CO_2 = carbon dioxide.
Source: Theo et al. (2016).

Research efforts are being made in several fields to improve the efficiency and commerciality of the pre-combustion process, including for membrane systems and solvent- or sorbent-based capture methods.

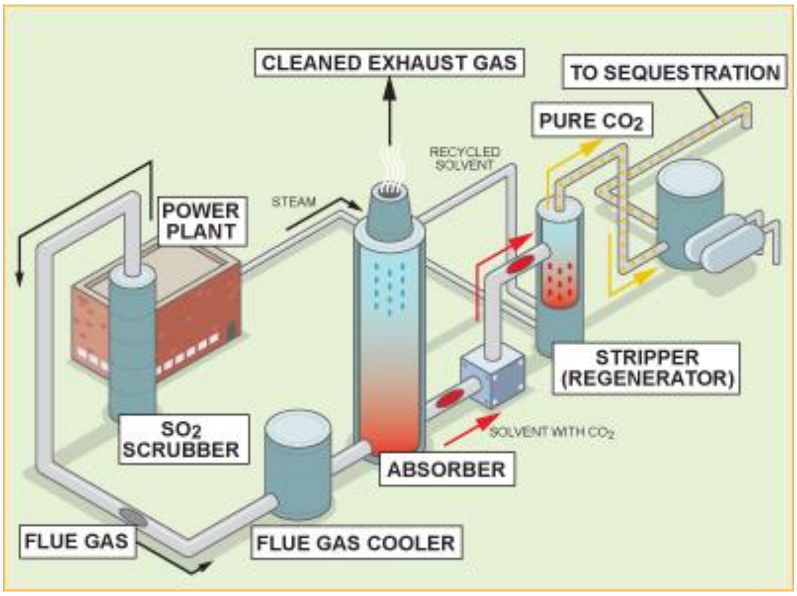
1.1.2. Post-combustion capture

Post-combustion carbon capture removes CO_2 after the fossil fuel has been burned. The CO_2 is separated from the exhaust flue gas before it is released to the atmosphere. The CO_2 can be recovered using several different methods. One option is to use liquid solvents, which can absorb CO_2 from flue gas. The absorption liquid is heated to produce high-purity CO_2. This technology is suited to retrofit application and is, therefore, widely used at a variety of industrial facilities, such as iron and steel plants using blast furnaces, refining plants using process heaters, and cement plants using rotary kilns. However, it is a highly energy-intensive method. Further options are sorbent-based and membrane-based capture methods.

Sorbent-based technology follows a similar concept to the solvent-based method. The sorbent-based method is expected to be less energy-intensive, but at this stage, the technology is considered less developed than solvents.

The membrane-based process offers numerous potential advantages, such as 'no hazardous chemical storage, handling, disposal or emissions issues, simple passive operation, tolerance to high SO_x and NO_x content, a reduced plant footprint, efficient partial CO_2 capture, and diminished need for modifications to the existing power plant steam cycle' (US NETL, 2020). The cost-efficiency and durability of the membranes (important for application at large-scale facilities), as well as the relatively low purity of the captured CO_2, are challenges for further development. The process scheme of post-combustion capture is described in Figure 2.2.

Figure 2.2. Process Scheme of Post-combustion CO_2 Capture

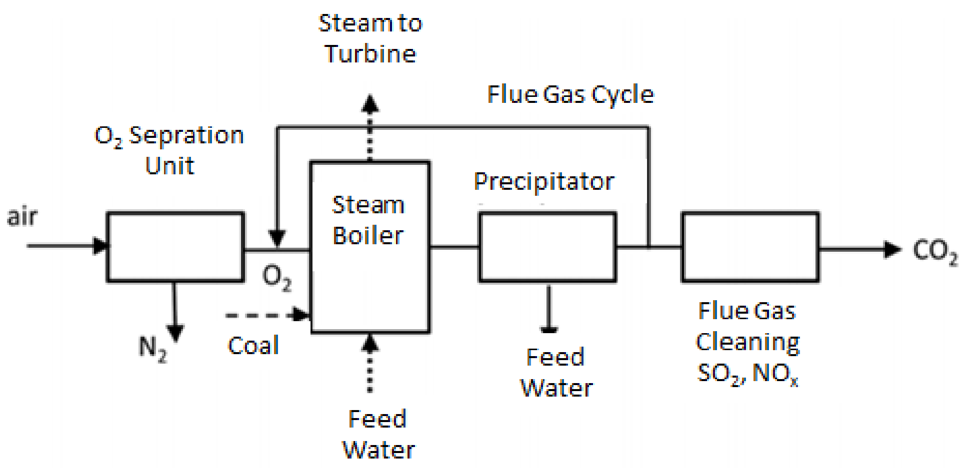


CO_2 = carbon dioxide.
Source: Clean Air Task Force (2020).

1.1.3. Oxy-fuel combustion

Oxy-fuel combustion, as described in Figure 2.3, uses almost pure oxygen instead of air to burn a fossil fuel. This produces an exhaust gas consisting of water vapour and CO_2, which can be easily separated, after being dried and compressed, to produce high-purity CO_2. It is a relatively cost-intensive technology that requires large-scale equipment to be installed. However, it can be used in combination with other separation/recovery technologies.

Figure 2.3. Process Scheme of Oxy-fuel CO_2 Capture



CO_2 = carbon dioxide, N_2 = nitrogen, NO_x = nitrogen oxides, O_2 = oxygen, SO_2 = sulphur dioxide.
Source: Markewitz et al. (2012).

Since the construction is such that an oxygen separation unit and a flue gas recycle device are added to the conventional power plant configuration, it can not only be applied to new power plants but can also be applied to retrofit existing power plants.

1.1.4. Direct air capture

Direct air capture (DAC) technologies extract CO_2 directly from the atmosphere, making it a unique example under the four carbon capture processes explained in this section. Compared to the other three technologies, DAC is still in the early stages of development. There are currently two major technology approaches. One is a liquid system, in which a hydroxide solution reacts with CO_2 to remove it from the air. Another approach is based on solid sorbents, similar to the post-combustion capture process. Solid sorbent filters chemically bind with CO_2. When the filters are heated, they release the concentrated CO_2 (IEA, 2020c).

Both are technically feasible but are highly energy- and cost-intensive. Compared to the flue gas at fixed point capturing, the CO_2 intensity in the atmosphere is 200–300 times more dilute. This results in low capturing efficiency and is, therefore, more expensive.

It is, however, the only technology that can capture CO_2 already released into the atmosphere. This makes DAC not only a potential carbon-neutral technology but even a potential carbon-negative technology; but only potentially, because the technology

consumes a lot of energy. To make DAC truly carbon-negative, it needs access to enough 'green' electricity.
Another advantage of DAC is the possibility to cover CO_2-intensive areas that cannot be covered by fixed point capturing. DAC offers the possibility to capture emissions from traffic at ports, airports, or even large intersections.

2. Transport

There are two major methods of transporting captured CO_2 to storage locations or utilisation sites, shipping and pipelines. CO_2 is typically compressed to a pressure of about 8 megapascals, reducing the transportation cost. CO_2 pipelines are already in use for the transport of CO_2 to enhanced oil recovery sites, but there are also efforts to utilise existing natural gas pipelines. Other feasible options for rather limited volumes of CO_2 are trains and roads.

3. Utilisation

An essential part of making CCUS an economically sustainable concept is the utilisation of CO_2. Changing CO_2 from an environmental burden that has to be disposed of somewhere to an economical asset that can be traded as any other resource, would create a new value cycle. This value cycle would offer a positive incentive for emitters to invest in CO_2 capturing and makes CCUS less dependent on public funding.
There are multiple approaches to utilising CO_2 as a resource. The food and beverage industry, fuel industry, construction industry, and agriculture are four sectors spearheading the research and development to find feasible applications. Products from these sectors are all essential on a global scale. This means that if CO_2-utilising products can be made for these sectors, the market will automatically be huge and the products will not require long-distance transportation.

3.1. Food and beverages

A popular example of CO_2 utilisation in the food and beverage industry is beverage carbonation. In this process, CO_2 is added to a beverage to impart sparkle. Conventional bottling plants obtain the required CO_2 from industrial gas companies or they have their own on-site CO_2-generating plant that combusts fossil fuel for the purpose of producing CO_2.
Several beverage and bottling companies are already using CO_2 captured from power plants to create sparkling drinks. Some are even more ambitious and have installed DAC-facilities on their plants. In both cases, the CO_2 must be purified to meet the strictest requirements for food and beverage purposes.
Another approach in the food and beverage industry is the production of protein, which can be used to make alternative meat products. Start-ups in Finland and the United States are developing a method to convert CO_2 into a protein powder. This approach still needs further development for commercial-scale production. It is, however, an environmental innovation in more ways than one. In addition to the utilisation of CO_2, it has the potential to reduce the environmental footprint of the livestock industry.

3.2. Fuel

Petrochemical fuels, such as gasoline or diesel, have always been at the centre of the discussion on greenhouse emissions and air pollution. Even though electric mobility is becoming more popular and more common, the fact is that the demand for fossil fuels is still huge.

CO_2 can be used as a raw material to produce fuels, for example through Fischer–Tropsch synthesis. In this chemical process, captured CO_2 is usually combined with hydrogen. It is a very energy-consuming process, but, nevertheless, there are multiple projects in this field around the world.

There are also approaches to combine CO_2 with hydrogen that is generated from non-fossil fuels to produce low-carbon synthetic fuels. The main target for this synthetic biogas is in many cases jet fuel, but it can also be used to produce gasoline.

Both approaches are highly energy-intensive. To make the fuel low carbon, the processes require a stable and large-scale supply of renewable energy. At this point, the financial feasibility for commercial scale production of the fuels is still very difficult to guarantee.

3.3. Agriculture

The carbon footprint of the agriculture sector is one of the biggest. This of course is understandable as it supplies food to the global population, feeds livestock, and produces cotton for the apparel industry. There are, nevertheless, some attempts to reduce the carbon footprint.

Utilising CO_2 for the production of fertilisers is one of them. India, amongst other countries, is actively promoting technology to separate CO_2 from the exhaust gases that arise during ammonia production and use the separated CO_2 as a raw material to produce urea. Urea in turn is used to produce nitrogen-release fertiliser.

The second attempt has a symbiotic effect on agriculture and the environment. To increase the yield of plants, the air in greenhouses gets enriched with CO_2. Additional CO_2 in the atmosphere accelerates photosynthesis and provides a greater rate of growth. It also protects the plants from drought and certain diseases. Conventionally, this happens using CO_2 generators that combust natural gas for the purpose of producing CO_2, in a similar manner to the previously described bottling plants. There are now attempts to reuse the captured CO_2 from power plants or industrial sites. Additionally, these sites can also supply the waste heat to the greenhouses.

It is important to mention that even though these processes have indeed the potential to utilise CO_2 on a larger scale, they do not offer a final solution regarding CO_2 reduction. Most of the CO_2 injected into greenhouses or used for fertilisers is ultimately released back into the atmosphere. The measures are, nevertheless, important for marketising CO_2 as a tradable resource.

3.4. Construction

Large utilisation potential is also expected from the construction industry. Cement, a major construction material and a huge source of CO_2 emissions, could become a gamechanger in this aspect.

One approach is the mineralisation of CO_2. Here, CO_2 is converted to calcium carbonate, which is the main component of cement's raw material, limestone. Another one is to infuse CO_2 during concrete production to make high-strength concrete. A number of large projects for both approaches are underway, whilst multiple start-ups are coming up with new CO_2-utilising materials that offer an alternative or might even replace conventional cement.

In contrast to CO_2-utilising products such as food and beverages, synthetic fuels, or fertilisers, these processes could theoretically be able to store CO_2 for longer periods of time.

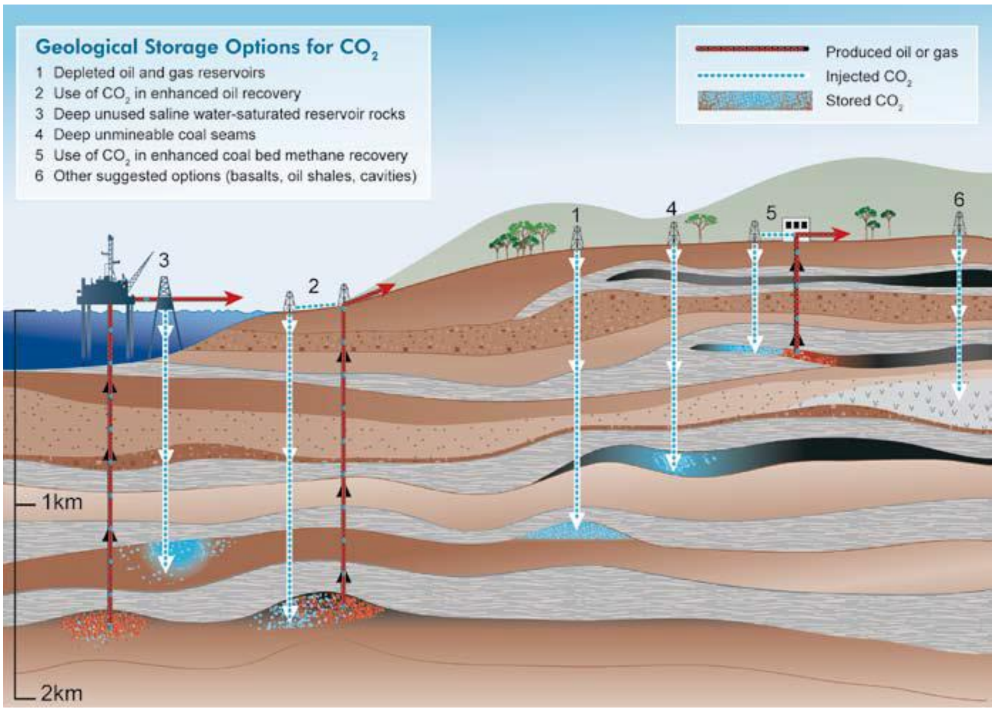
4. Storage

4.1. Technology overview

Storing CO_2 involves the injection of captured CO_2 into a deep underground geological reservoir of porous rock overlaid by an impermeable layer of rocks, which seals the reservoir and prevents the upward migration of CO_2 and its escape into the atmosphere.

There are several types of reservoir suitable for CO_2 storage. Figure 2.4 is a famous diagram contained in the IPCC Special Report on Carbon Dioxide Capture and Storage (Metz et al., 2005) showing options for a CO_2 reservoir, namely (1) depleted oil and gas fields, (2) enhanced oil recovery, (3) deep unused saline water-saturated reservoir rocks, (4) deep un-mineable coal seams, and (5) enhanced coal bed methane recovery.

Figure 2.4. Options for Storing CO_2 in Deep Underground Geological Formations



CO_2 = carbon dioxide, km = kilometre.
Source: Metz et al. (2005).

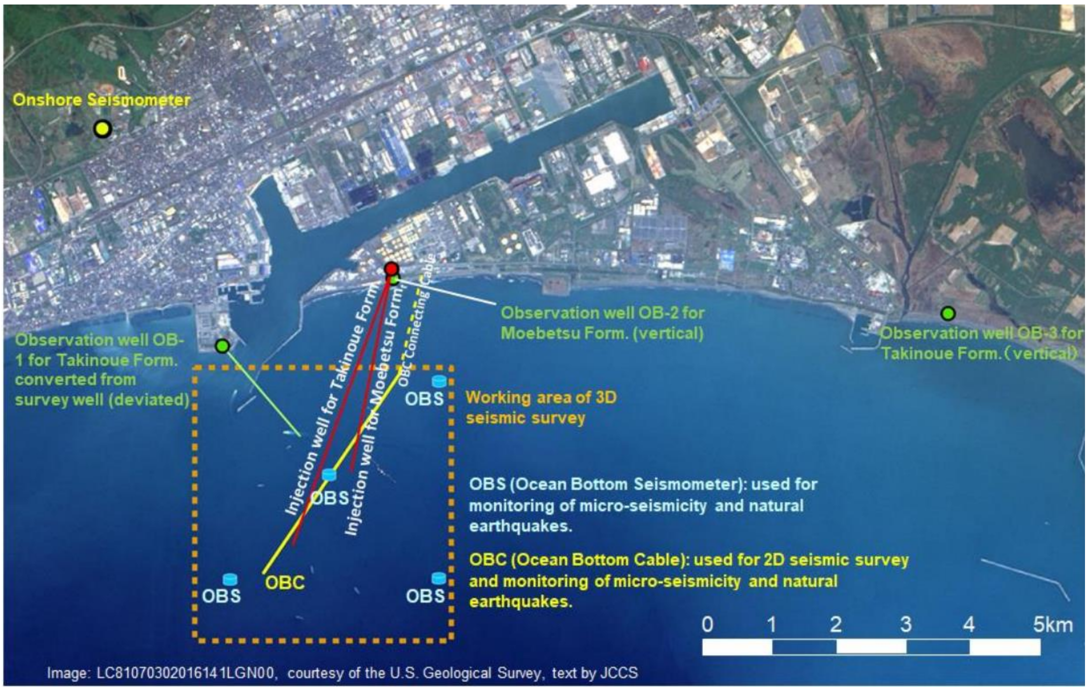
To geologically store CO_2, CO_2 must first be compressed, usually to a dense supercritical fluid. The reservoir must be at a depth of 800 metres or greater to retain the CO_2, where the injected CO_2 will be in a dense supercritical state. According to Metz et al. (2005), with this aspect, potential CO_2 reservoirs can be categorised into three types as follows:

- Deep saline formations: Layers of porous and permeable rocks saturated with salty water (brine), which are widespread in both onshore and offshore sedimentary basins.
- Depleted oil and gas reservoirs: Porous rock formations that have trapped crude oil or gas for millions of years before being extracted and which can similarly trap injected CO_2.
- Deep coal seams: Solid coal has a very large number of micropores into which gas molecules can diffuse and be tightly adsorbed. Adsorption is the main storage mechanism in coal seams at high pressure.

After injection, the CO_2 is permanently trapped in the reservoir through several mechanisms: structural trapping by the seal, solubility trapping in pore space water, residual trapping in individual or groups of pores, and mineral trapping by reacting with the reservoir rocks to form carbonate minerals. The nature and the type of the trapping mechanisms for reliable and effective CO_2 storage, which vary within and across the life of a site depending on the geological conditions, are well understood thanks to decades of experience in injecting CO_2 for enhanced oil recovery (EOR) and dedicated storage (IEA, 2020a).

There are a number of experiences in Asia as well, including EOR projects and dedicated storage projects in China and research and development activities in the Republic of Korea. Japan has also experienced geological storage since 2003 and commissioned the northern Tomakomai CCS facility in 2016, which was the world’s first offshore CCS project in a populated area (GCCSI, 2020d; Massachusetts Institute of Technology, 2016). The outline of the Tomakomai CCS Project is described in Figure 2.5.

Figure 2.5. CO_2 Storage Site of the Tomakomai CCS Project



Source: METI, NEDO, and JCCS (2020).

4.2. Key technologies for carbon storage

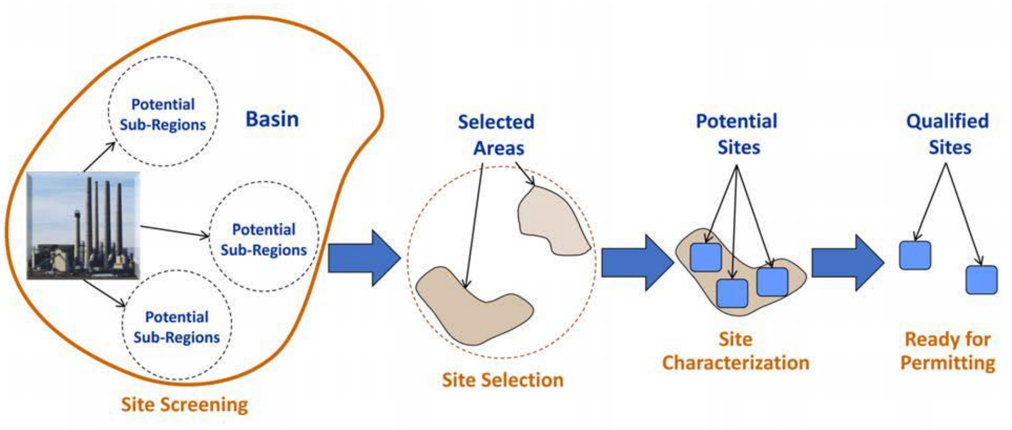
4.2.1. Geologic storage analysis

Before setting up a geological CO_2 storing project, it is necessary to appropriately select a site and characterise the geologic storage formation before site qualification. According to the Best Practices Manual of Site Screening, Site Selection, and Site Characterization for Geologic Storage Projects by US NETL (2017a), the following should be considered in the site development and evaluation process:

- Establish that the site has the resources to accept and safely store the anticipated quantity of CO_2 at the desired injection rate for the storage project.
- Provide input data to models required to predict site performance in terms of pressure change and CO_2 plume evolution.
- Minimise the probability of adverse effects on the environment.
- Identify and address any potential regulatory, subsurface ownership, site access, and pipeline issues.
- Ensure the site has the capability to meet the performance standards established for the project, such as operational efficiency, reliability, and safety.
- Ensure alignment of national, regional, and local social, economic, and environmental interests.

US NETL (2017a) breaks down the process into phases as in Figure 2.6, and there are a number of data obtained from the technologies used in these processes.

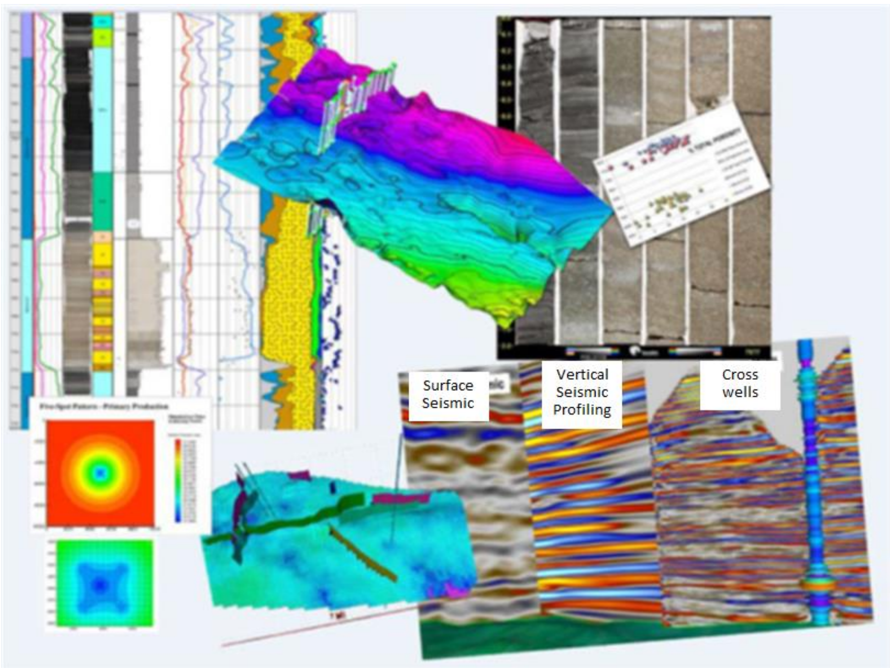
Figure 2.6. Analysis Procedure to Select an Appropriate Storage Site



Source: US NETL (2017a).

US NETL (2017a) describes examples of collected data for site characterisation as shown in Figure 2.7, namely physical core, core analysis data, log data, 2D and 3D seismic data, vertical seismic profiling (VSP) data, and reservoir simulations.

Figure 2.7. Examples of Collected Data in Site Characterisation



Source: US NETL (2017a).
Note: Author added site characterisation labels for clarification.

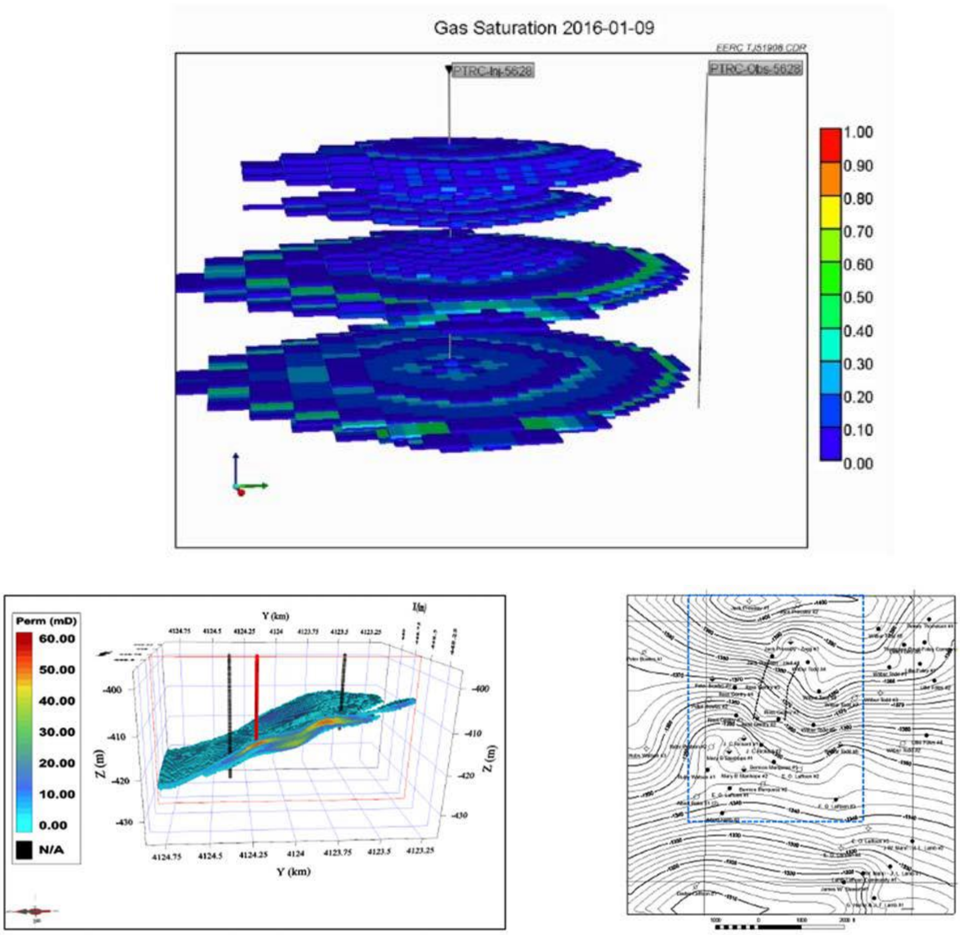
After site characterisation, it is necessary to conduct injected CO_2 behaviour simulation and risk assessment processes before the facility design and actual CO_2 injection. In simulating injected CO_2 behaviour, numeric simulation models (NSMs) are a key technology. Examples of NSMs and the outcome of the CO_2 behaviour analysis are depicted in Table 2.1 and Figure 2.8, respectively.

Table 2.1. Examples of Numeric Simulation Models for CO_2 Storage Simulation

Name of Code	Developer/ Supplier	Coupling	Processes Modeled
NFFlow-FRACGEN	NETL	H	Two-phase, multi-component flow in fractured media
Eclipse 100 Eclipse 300	Schlumberger	T,H	Non-isothermal black oil multiphase flow in porous media Non-isothermal compositional multiphase flow in porous media
MASTER	NETL	T,H	Black oil simulator, compositional multiphase flow
TOUGH2 (TOUGH+)	LBNL	T,H	Non-isothermal multiphase flow in unfractured and fractured media
Nexus (VIP) ® Reservoir Simulation Suite	Halliburton	T,H	Compositional simulator with dual porosity, sorption
PHREEQC	USGS	T,H	Speciation, batch-reaction, 1-D transport, and inverse geochemical calculations
Hydrotherm	USGS	T,H	2-phase groundwater flow and heat transport
General Purpose Research Simulator (GPRS)	Stanford University	T,H	Multiphase/compositional flow code
GMI – SFIB	Geomechanics International	M	3-D stress modeling for compressional (wellbore breakout) and tensional (tensile wall fractures) stress failure, fracture modeling

LBNL = Lawrence Berkley National Laboratory, GMI-SFIB = GeoMechanics International-Stress and Failure of Inclined Boreholes, NETL = National Energy Technology Laboratory, PHREEQC = PH REdox Equilibrium, USGS = United States Geological Survey.
Source: US NETL (2017b).

Figure 2.8. Example of CO_2 Storage Simulation Outcome Image



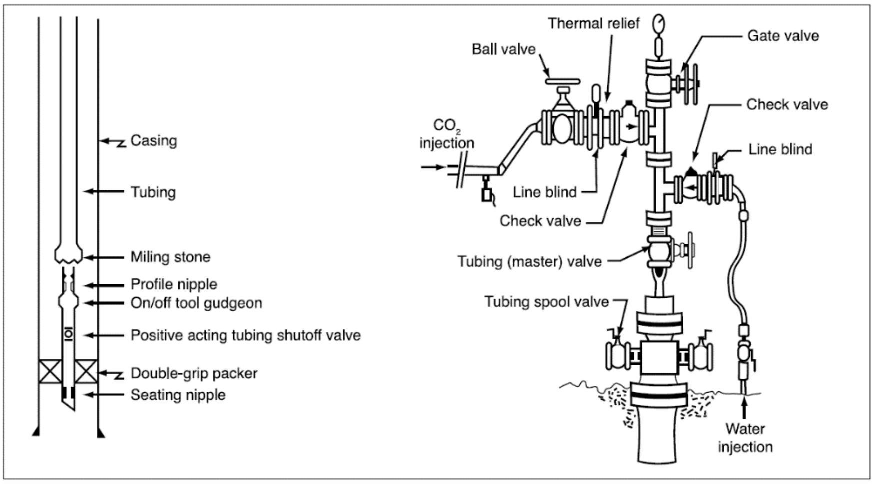
Source: US NETL (2017b).

4.2.2. Injection and field operation technology

After a suitable site is identified with the technology described in the previous section, one has to consider the way to inject large quantities of CO_2 into the subsurface and to operate the site effectively and safely.

The design of a CO_2 injection well is very similar to that of a gas injection well in an oil field or natural gas storage project. As shown in Figure 2.9, injection wells commonly are equipped with two valves for well control, one for regular use and one reserved for the safety shutoff. In acid gas injection wells, a downhole safety valve is incorporated in the tubing so that if equipment fails at the surface, the well is automatically shut down to prevent backflow.

Figure 2.9. Typical CO_2 Injection Well and Wellhead Configuration



CO_2 = carbon dioxide.
Source: Metz et al. (2005).

In addition, well abandonment technology is also important because the CO_2 could migrate up the well and into shallow drinking water aquifers from storage formation if a well remains open.

Overall, the tasks for injection and field operation as categorised as follows:

- Production systems: fluid separation, gas gathering, production satellite, liquid gathering, central battery, field compression, and emergency shutdown systems.
- Injection systems: gas re-pressurisation, water injection, and CO_2 distribution systems.
- Gas processing systems: gas processing plant, hydrogen sulphide removal systems, and sulphur recovery and disposal systems.

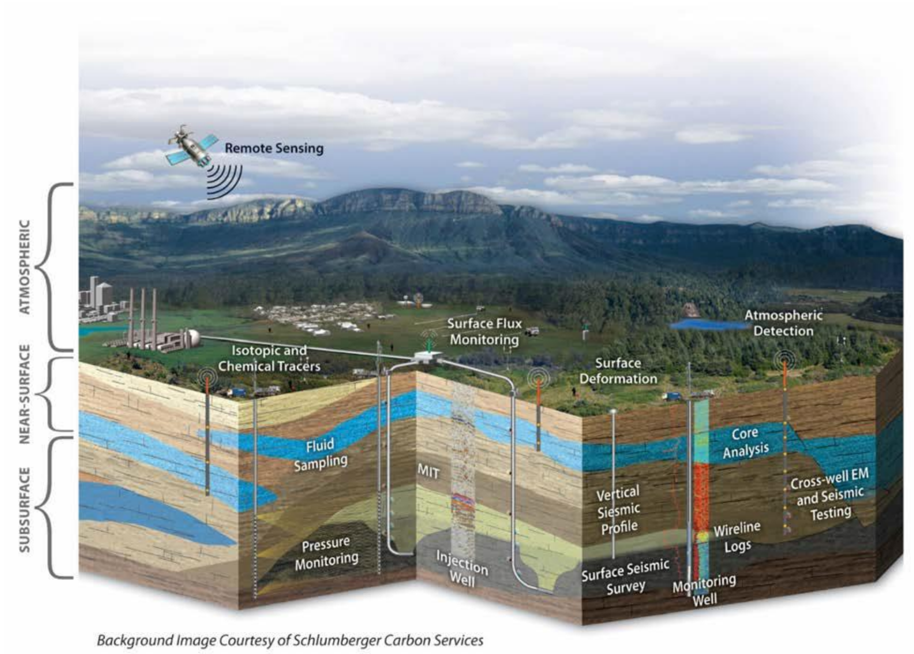
4.2.3. Monitoring and verification technology

Monitoring and verification technologies are necessary to prevent CO_2 leakages from the storage formation and to ensure CO_2 containment. There are three areas for monitoring and verification: atmospheric, near-surface, and subsurface monitoring as shown in Figure 2.10.

The purpose of atmospheric and near-surface monitoring is to detect manifestations of CO_2 potentially released from storage. The most common atmospheric monitoring techniques are optical CO_2 sensors, atmospheric tracers, and eddy covariance flux measurements. Near-surface monitoring techniques include geochemical monitoring in the soil and vadose zone, geochemical monitoring of the near-surface groundwater, surface displacement monitoring, and ecosystem stress monitoring.

Subsurface monitoring provides the information for storage operational control and the assessment of the performance of the storage formation. It includes monitoring the evolution of the dense-phase CO_2 plume, assessing the area of elevated pressure caused by the injection, and measuring to determine that both the pressure and CO_2 are within the expected and acceptable areas and migrating in a way that does not damage resources or the integrity of the storage.

Figure 2.10. Diagram of Atmospheric, Near-surface, and Subsurface Monitoring



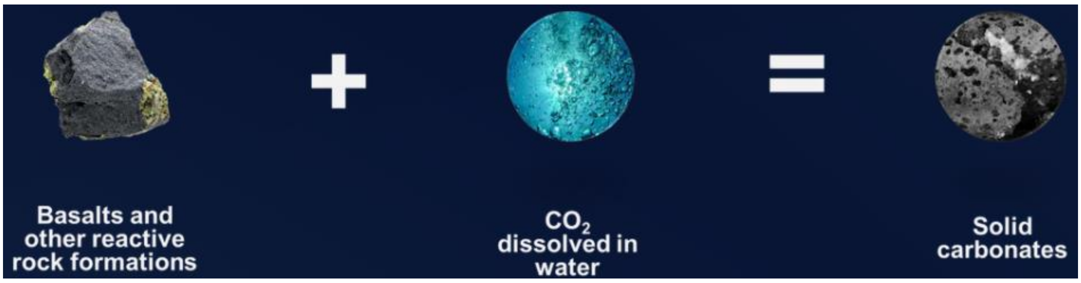
EM = electromagnetic, MIT = mechanical integrity testing.
Source: US NETL (2017b).

4.3. New technology to fixate CO_2

As written in previous sections, injected CO_2 is fixed by structural trapping by the seal, solubility trapping in pore space water, residual trapping in individual or groups of pores, and mineral trapping by reacting with the reservoir rocks to form carbonate minerals, in general. In principle, it is necessary to separate CO_2 from other acid compounds like sulphur oxides (SO_x), nitrogen oxides (NO_x), hydrogen sulphide (H_2S) and fluorine (F) in captured gasses.

However, there is new technology to fix CO_2 without separation. The concept of the technology is shown in Figure 2.11.

Figure 0-1. Diagram of Atmospheric, Near-surface, and Subsurface Monitoring



CO_2 = carbon dioxide.
Source: Carbfix (2020).

The technology is called 'Carbfix' and demonstrated at a geothermal power plant operated by ON Power in Iceland. Carbfix, the company, is named the same as the technology. According to Carbfix's website, the technology has the following features (Carbfix, 2020):

- No chemicals used, other than water (or seawater).
- Co-capture of other soluble gases, such as SO_x, NO_x, H_2S, and fluorine. These polluting gases participate in reactions underground, forming minerals to various extents.
- Less-stringent requirements for pipes and casing materials than for purified CO_2.

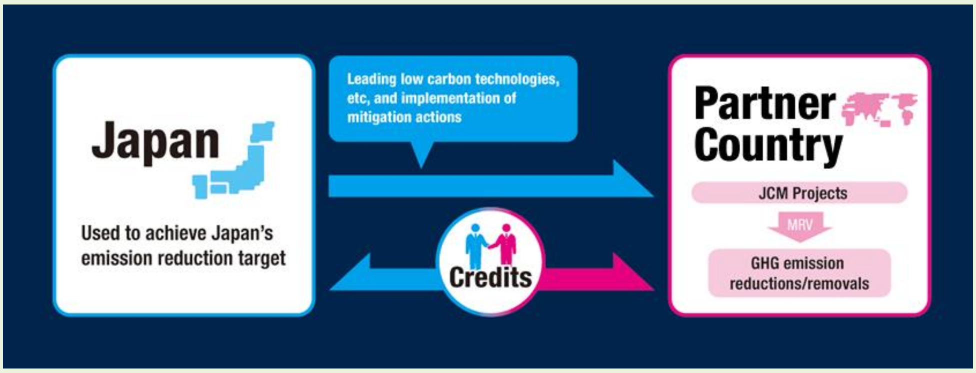
There is also an advantage of Carbfix for storage formation restriction. It can be applied to mineral storage, which is different from the typical storage formations for conventional CCS technology. The Carbfix website says that about 5% of the continents are covered by favourable rocks for carbon mineralisation, and the global storage potential is greater than the emissions of the burning of all fossil fuels on Earth.

5. Summary

This chapter introduced the gist of technologies involved in CCUS and the key components. As described above, some of the technologies have a good track record, and there is significant progress in their demonstration in Asia as well.
Utilisation shows great potential as it entails the possibilities of creating value-added industrial products, such as cement, fertiliser, hydrogen, and so on. However, it is important to note that the carbon fixation aspect needs to be carefully considered if CO_2 utilisation is implemented for the purpose of carbon sequestration. The storage technology is described more in detail compared to other technologies also for the reason of its significance when CO_2 sequestration is taken into account. It is paramount for project developers to select appropriate sites, apply well treatment, conduct site operations, and ensure proper monitoring so there is no leakage of CO_2, especially when issuing carbon credits with a market mechanism, such as the Joint Crediting Mechanism. Accordingly, it will be vital to establish 'viable and affordable' monitoring methods applied to post-injection sites in pursuing CCUS dissemination in Asian countries.

Box 2. Joint Crediting Mechanism

The Joint Crediting Mechanism (JCM) is a mechanism initiated by the Government of Japan where mitigation actions implemented through cooperation with partner countries are measured, verified, and reported to produce emissions offsets that are shared amongst participating governments and the private sector and can be counted towards the emissions reduction targets of the participating countries.
It was first started with Mongolia in 2013 and now counts 17 participating countries. Included in the signatories are ASEAN countries, such as Cambodia, Indonesia, Lao PDR, the Philippines, Thailand, and Viet Nam.



Source: Carbon Markets Express (2020).