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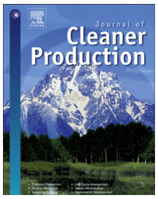

Carbon dioxide storage schemes: Technology, assessment and deployment☆

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ABSTRACT

Carbon Capture and Storage is the only technology available to mitigate large-scale greenhouse gas emissions from fossil fuel based power and industrial sectors in the near future. When technology to capture carbon dioxide (CO_2) is relatively mature and commercially available for power and industrial sectors, safe, reliable and long-term storage of captured CO_2 remains a key uncertainty affecting widespread deployment of Carbon Capture and Storage technology yet. In this paper, the authors assessed techno-economic aspects of geological CO_2 storage options, from CO_2 transportations, various geological storage approaches, to CO_2 leakage monitoring. Compared with depleted oil/gas reservoirs and coal seams, deep saline aquifers possess much larger storage capacities and may be possibly near many CO_2 emission sites due to widespread distributions. If CO_2 storage is combined with enhanced industrial production (e.g. oil, natural gas), it has a greater potential to reducing the overall cost of CO_2 storage. Potential CO_2 leakage may be the main barriers to the development of CO_2 geological storage. It is recommended to make full use of big data mining approach in selection and approval of CO_2 geological sites, estimation of storage capacities, assessment of potential leakage risks, awarding of carbon credits, as well as analysis of public acceptations. At the same time, as a leakage-free CO_2 storage option, CO_2 mineralization & industrial utilization is to trap CO_2 permanently in stable minerals by reactions with metal oxides and forming stable carbonates. These CO_2 mineralization & industrial utilization schemes need to guarantee sustainable or environmentally friendly processes and satisfy basic principles of industrial ecology if implemented on a large industrial scale. Currently, most of CO_2 storage schemes are still in the early stage of technological development and are still far from large-scale commercialization. The high cost, high energy penalty, safety and reliability, and policy uncertainties are main barriers for the implement of carbon storage schemes.

1. Introduction

Carbon dioxide (CO_2) emissions from the burning of fossil fuels and industrial processes are the major contributors to global warming, account for 78% of the increase in global greenhouse emissions while residential and commercial buildings, forestry/deforestation and agriculture sectors also contributed substantial quantities of greenhouse emissions during 1970–2011. The current CO_2 concentration in the atmosphere has increased by more than 100 ppm since pre-industrial levels (IPCC, 2014). In 2014, the concentration reached 400 ppm and it continues to increase. Unfortunately, even with growing public awareness of climate change, fossil energy still dominates power and industrial sectors; especially coal is prevalent in developing countries due to its relatively low cost and global distribution. Carbon capture and storage (CCS) technology has the potential to be one of the most cost effective technologies for decarburization of power and industrial sectors with the additional advantage that it allows for ongoing use of conventional fossil fuels like coal, so CCS may be strategically important for mitigating global greenhouse gas emissions. CCS

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technology involves capturing CO_2 emissions at the industrial combustion sources (mainly from coal power plants, cement factories, or steel production blast furnaces, etc.), compressing it, transporting and injecting it into appropriate geological storage sites (e.g. depleted oil or gas reservoirs, saline aquifers, coal seams). In this way, long-term isolation of CO_2 from the atmosphere may be achieved. Although the technology to capture CO_2 is relatively mature, safe, reliable and long-term storage of captured CO_2 continues to contribute to the uncertainty, which is currently preventing wide-spread deployment of CCS technologies.

Based on the IPCC (2014), one of the main storage options is onshore and off shore geological storage of anthropogenic CO_2, which was first, proposed in the 1970s as a greenhouse gas mitigation strategy. However, no significant research was done until the early 1990s (Galán and Aparicio, 2014). Geological storage of CO_2 is to inject CO_2 into deep saline aquifers, oil and gas reservoirs, coal seams etc. In the immediate future, storage in geological reservoirs seems especially promising, however, its investments involve huge construction and operating costs with the expectation of long lifetimes and high utilization hours, which become a main obstacle (Zhang, 2015; Li et al., 2015a,b). When CO_2 geological storage is combined with enhanced industrial production, the cost for CO_2 can be significantly cut. Moreover, existing big data (e.g. seismic surveys, geophysical well log suites, core data) and previous experience in the oil/gas production industries can help to solve some of the technological obstacles, especially CO_2 storage with enhance oil recovery has been practiced in Weyburn Oilfield (Canada) since 1954 and SACROC oilfield (Texas, USA) since 1974. At present, about 4% of U.S. oil is produced through this approach (Carpenter and Koperna, 2014; Xie et al., 2014).

Potential CO_2 leakage may be the main barrier to the development of CO_2 geological storage. As a leakage-free CO_2 storage option, CO_2 mineralization and industrial utilization may function to trap CO_2 permanently in stable minerals by reactions with metal oxides and forming stable carbonates. The main disadvantage is relatively high cost and low efficiency. Some industrial utilization schemes can only store CO_2 temporarily and emit CO_2 usually to the atmosphere at the end of the product's life, which can range from days or weeks (e.g. CO_2-based fuels) to years (e.g. CO_2-based polymers), while other industrial utilization schemes (e.g. CO_2-based cement) can store CO_2 permanently. These CO_2 mineralization and industrial utilization schemes need to guarantee sustainable or environmentally friendly processes and satisfy basic principles of industrial ecology if implemented on a large industrial scale.

In this paper, we will comprehensively assess techno-economic aspects of various CO_2 storage schemes. In Section 2, we review main CO_2 transportation approaches to storage sites and related industrial standards. In Section 3, we assess various geological reservoirs for CO_2 storage, including injection of CO_2 underground purely for the purpose of storage or the use of CO_2 as a solvent to enhance industrial production. In Section 4, since potential CO_2 leakage may be the main barrier to the development of CO_2 geological storage, we will assess main monitoring methods for CO_2 leakage. In Sections 5–6, we discuss CO_2 mineralization and industrial utilization as non-monitoring and leakage-free CO_2 storage options. In Section 7, we focus on potentials and development of CO_2 storage projects in China, the largest CO_2 emitter in the world. In Section 8, we give some discussions and conclusion.

2. Transporting CO_2 to geological storage sites

Before storage, the captured high CO_2 from power and industrial sectors must be transported to geological storage sites. Trucks, pipelines and ships are three options for CO_2 transport (see Table 1). Truck transport has relatively large leakage risk, high transport costs, and only a relatively small amount can be transported per load, so it is not suitable for large-scale CCS projects (Ming et al., 2014). Pipelines are considered to be the most reliable transportation method. Industry has more than 40 years of experience with pipeline transportation of CO_2. Most of that CO_2 was transported for usage in enhanced oil recovery fields. A pipeline of 5000 km is being used in the United States for CO_2 transport (Ming et al., 2014; Pires et al., 2011). The main technical problems involve pipeline integrity, flow assurance, safety and operational considerations. The most cost-efficient CO_2 transport is to compress CO_2 under supercritical conditions, at pressures ranging 80–150 bar, at which it exists as a liquid with a density of about 900 kg m^3 (Pires et al., 2011).

Depending on various industrial sectors (e.g. energy production, cement factory, refining) and on the type of capture process, the captured CO_2 mixture contains many impurities such as N_2, H_2, O_2, Ar, Hg, H_2O, SO_x, H_2S, etc, which will change the thermodynamic properties of the CO_2 mixtures: N_2 can affect the CO_2 transport process by its low boiling point. A small amount of N_2 can change flow conditions from single phase flow to two-phase flow (Huh et al., 2011); a 2% concentration of H_2 in CO_2 can reduce the molar density up to 25% compared to pure CO_2 (Sanchez-Vicente et al., 2013); the presence of water in the CO_2 stream can form carbonic acid or hydrate when CO_2 dissolves in water with dispersed water droplet in CO_2 fluid being saturated; the water also reacts with other acidic compounds to form acids (e.g. H_2SO_3, H_2SO_4), which may produce a durability risk due to internal corrosion damage of steel pipelines (Sim et al., 2014). These impurities can be controlled by air pollution control devices during the stage of CO_2 capture. In general, approximately 80–95% of the SO_2 and 50% of the SO_3 can be removed by wet flue gas desulfurization (FGD) scrubbers, although deep desulfurization can be achievable, such an operation is not economically favorable; Mercury concentrations can be also controlled by a similar wet FGD system; NO_X can be controlled by the use of low NOx burners (LNBs) with a catalytic reduction (SCR) unit; N_2 can be controlled by the use of physical membrane; Fly ash can be collected and removed by electrostatic precipitators (ESPs); and the water content can be lowered by gas conditioning (Lee et al., 2009; Rubin et al., 2012). Understanding and managing these thermodynamic properties of CO_2 mixtures are essential for the design and the operation of CO_2 transport systems. Sim et al. (2014) discussed protection strategies against internal corrosion and suggested that the use of stainless steels is the most feasible protection if satisfactory dehydration cannot be achieved. Visser et al. (2008) recommended maximum allowable concentrations of impurities in the CO_2 for safe transportation in pipelines: The water level was found to be 500 ppm to minimize risks of free water and hydrate formation. The safe carbon monoxide level should not be more than 2000 ppm from a health and safety perspective, and the total volume for all non-condensable gases (N_2, H_2, CH_4, O_2, Ar, etc) should not be greater than 4%.

Ships may be economically attractive for long distance CO_2 transport for sea storage sites. The ship-based transport of CO_2 would require that CO_2 be compressed or liquefied. Furthermore, a liquefied-CO_2 transport ship would have to be capable of processing boil-off gas while at sea. For a low storage temperature, more liquid can be transported and the cost of re-liquefaction is reduced. However, extra cost is incurred for liquefaction. For a high storage temperature, while the energy costs can be reduced, the cost of tank manufacture will be higher and less CO_2 can be transported. Compared with same compression ratio method and intermediate pressure optimization method, Jeon and Kim (2015) recommended using intermediate pressure optimization with the same discharge

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Table 1
Main CO_2 transportation systems (Ming et al., 2014; Pires et al., 2011; Svensson et al., 2004).

	Cost	Leakage risk	Transport capacity	Location of storage sites	Intermediate storage facilities
Pipelines	Low (~2 US dollars/ton for 250 km)	Low	Large	Land or Sea	No
Ships	Low (~1 US dollars/ton for 250 km)	Low	Large	Sea	Yes
Trucks	High (~25 US dollars/ton for 250 km)	High	Small	Land	Yes

temperature method for a multi-stage compression system for the re-liquefaction cycle of a liquefied-CO_2 transport ship due to its reliability. For ocean storage sites, one option is the CO_2 injection at great depths where it dissolves or forms hydrates or heavier than water plumes that sinks at the bottom of the ocean. It may cause ocean acidification and threat ocean ecosystem, so this option is not considered again (Amouroux et al., 2014). Another option is the CO_2 injection at geologic structures beneath the continental shelf. Similar to geological storage sites in land, it is considered to be of low risk.

3. Geological storage of CO_2

As the most important stage of CCS, CO_2 storage entails injecting CO_2 emitted from fossil-fuel burning power stations and factories into underground geological structures. This means the captured CO_2 does not go into the atmosphere, thereby reducing the increase in atmospheric CO_2 and slowing down the rate of climate change. Broadly speaking, geological storage refers to any method which results in the permanent storage of CO_2 beneath the surface of the Earth. This could include injection of CO_2 underground purely for the purpose of storage or the use of CO_2 as a working fluid or solvent to enhance industrial production. The oil and gas reservoirs have already been used for this purpose, of enhancing recovery of fossil fuels. Other useful products include enhanced recovery of coal-bed methane, underground water, shale gas, geothermal, noble minerals, etc (see Table 2).

Geological reservoirs worldwide have a potential storage capacity of 236 Gt of CO_2 (Stangelend, 2007). In general, the requirements for safe geological storage sites are: (i) adequate porosity and thickness (storage capacity) and permeability (injectivity). The potential storage unit must have sufficient pore volume to store all the injected CO_2 and the formation characteristics must allow near wellbore injectivity; (ii) a satisfactory sealing caprock must be used which ensures the containment of appropriate fluids; (iii) a stable geological environment to avoid compromising the integrity of the storage site; (iv) the minimum depth limit of the storage reservoir is 914 m since it ensures that the CO_2 would be in a supercritical state with high density, low viscosity, good fluidity and then minimize the storage volume and easily flow within pores or fractures in rock masses (Cooper, 2009; Warwick et al., 2013; Li et al., 2014b).

Geological structures into which CO_2 can be injected can be either onshore or offshore. Due to concerns over access to land, adverse effects on property pricing, and risks to human health, the public may be against to deploy CCS onshore. Offshore CO_2 storage may reduce the potential for such public perception issues and may be easier to be accepted by the Public (Mabon et al., 2014). The selection of a geological reservoir with appropriate subsurface characteristics is vital to ensure the success of any geologic storage undertaking and to also maximize the volume of CO_2, which can be stored at that site. Moreover, CO_2 in the subsurface can undergo a sequence of geochemical interactions with the rock and with water that will further increase storage capacity and effectiveness (Galán and Aparicio, 2014). Accurate and useful geologic models on assessment of CO_2 storage capacity rely on the quality of the data, including large amounts of geologic data both prior to and through the monitoring of injection operations. Big data from global seismic surveys, modern geophysical well log suites, core data, and down hole pressure and temperature measurements will provide a strong support for selection of geological reservoirs and estimation of their storage capacities. Jonsson et al. (2014) suggested utilizing an artificial neural network and big data from geophysical survey to generate a synthetic approximation of subsurface characteristics without the full-scale drilling.

3.1. *Storage of CO_2 in deep saline aquifers*

Compared with depleted oil and gas reservoirs and coal seams, deep saline aquifers possess much larger storage capacities with widespread distributions. Moreover, deep saline aquifers have greater regional coverage and then they may be possibly near many CO_2 emission sites (Cooper, 2009). Saline aquifers can store about 10,000 billion tons of CO_2, which is 20–500% of predicted emissions to 2050 (De Silva et al., 2015). Some countries have begun to inject CO_2 into deep saline aquifers for long-term geological storage. The Gorgon project starting in 2009 is the first operating project in the worldwide (Flett et al., 2008). The Australian Government has committed $60 million to the Gorgon project as part of the low carbon emissions technology demonstration fund. About 200 million standard cubic feet per day of CO_2 are injected and 60–80,000 barrels of water per day are produced, but the water has not been used for further industrial utilization. More than 100 million tonnes of CO_2 will be expected to be injected and safely stored (Trupp et al., 2013). Starting from 2011, SHENHUA Group of China injected 100,000 tCO_2 per year to deep saline aquifers in

Table 2
Main CO_2 geological storage schemes.

Types	Capacity	Distance to CO_2 emission sites	Industrial implementation or demonstration	Mature	Industrial production	Economic value of Industrial production
Deep saline aquifers	Huge	Near (possibly)	Since 2009	Immature	Water/Brine	Low
CO_2-EOR	Large	Far	Since 1954	Mature	Oil	High
CO_2-EGR	Large	Far	Since 2004	Immature	Natural Gas	High
CO_2-ECBM	Large	Near (possibly)	No	Immature	Coal-bed methane	High
CO_2-ESGR	Large	Far	No	Immature	Shale Gas	High
CO_2-EGS	Small	Far	No	Immature	Geothermal Energy	High
CO_2-IUL	Small	Far	No	Immature	Uranium ore	High

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Erdos, Inner Mongolia, China (Ming et al., 2014).

Deep aquifers are geologic layers of porous rock that are saturated with brine and are located at 700–3000 m below ground level. Generally, such location's top is a layer of much less permeable caprock. The capability of an aquifer to store CO_2 is controlled by the depositional environment, structure, stratigraphy and pressure/temperature conditions. Injecting CO_2 into a saline formation may pressurize the saline formation and potentially alter formation properties and/or induce leakages if not properly managed. In order to achieve the security and stability of the large-scale geological storage of CO_2, the pumping of saline waters becomes a potential solution. This type of storage is the so-called CO_2 storage with deep saline water recovery (CO_2-EWR) (Kobos et al., 2011; Li et al., 2015b). For pumped water with low salinity, strong reservoir pressure derived from CO_2 injection can be utilized as a driving force for desalination to achieving drinking-water standards as well as industrial or agricultural water quality requirement (Li et al., 2015b). The cost for deep saline water desalination with reservoir pressure is approximately 32–40 US cents/m^3. For pumped water with high salinity, the rich $MgCl_2$ contained can be employed to mineralize CO_2. On average, 1 ton of $MgCl_2 \cdot 6H_2O$ may mineralize 0.15 ton of CO_2, and simultaneously produce 0.18 ton of hydrogen chloride, as well as 0.29 ton of magnesium carbonate (Xie et al., 2014). In addition, potassium, bromine and lithium contained can also produce potential economic and social benefits. Currently, all of these are under the status of laboratory studies, but it provides a feasible program for the future industrial development and utilization of brine resources (Li et al., 2015b). Therefore, the CO_2-EWR technology may be effective to help to alleviate the water shortage situation, and may help to reduce a series of ecological and environmental problems (Li et al., 2015b).

Injection of large volumes of CO_2 into deep saline aquifers can perturb the subsurface environment, leading to physical, geochemical and biogeochemical changes of geological reservoirs. The main CO_2 trapping mechanisms include hydrodynamic trapping (structural, stratigraphic), solubility trapping, and geochemical tapping (or mineral trapping). In hydrodynamic trapping, due to capillary forces, the CO_2 is held within porous formations below a cap-rock of low permeability. The CO_2 isolated blobs are of the size of the pores of the rocks, tens to hundreds of micrometers (Zhao et al., 2014). Trapped saturations are at least 10% and more typically 30% of the pore volume of the rock. Solubility trapping pertains to CO_2 being dissolved into the groundwater, which plays important roles in the migration of CO_2. The solubility of CO_2 ranges from 2% to 6%. The CO_2 solubility in water decreases as temperature and salinity increase. However, the large volume of regional-scale aquifers provides attractive options for CO_2 storage (Streimikiene, 2012). Geochemical trapping (or mineral trapping), refers to the processes in which CO_2 reacts with natural fluids and minerals in the subsurface, which can lead to the safest and most effective approach to permanently trap CO_2 for a long time. Geochemical trapping process is significantly affected by temperature, pressure, salinity, aquifer thickness, tilt angle, anisotropy, aquifer layers, as well as the mineral composition of the formation rock (De Silva et al., 2015). Reactions with Ca/Mg/Fe-bearing silicate minerals are the most promising for CO_2 storage because these silicates neutralize the added acidic CO_2 and provide alkali metals that trap CO_2 through the precipitation of carbonate (Streimikiene, 2012). Wang et al. (2013) evaluated the reactivity of the common reservoir mineral dolomite with water-saturated supercritical CO_2. Dolomite dissolves and new carbonate mineral precipitates are formed by reactions with the water-saturated supercritical CO_2. Temperature and reaction time control the composition, morphology, and extent of formation of new carbonate minerals. Although this process is comparatively slow, potentially taking a thousand years or longer, its storage permanence and potentially large storage capacity make it a desirable feature of long-term storage (Galán and Aparicio, 2014).

The injection of CO_2 into deep saline aquifers would cause the brine pH to decrease, concurrently increasing the ability of the brine to leach metals (e.g. Fe, Cu, Zn and Na) from the aquifer rocks. These metals maybe further fractionate from the brine into the CO_2, allowing the CO_2 to act as a solvent (Fischer et al., 2010). In the event of a CO_2 leak, this kind of brine–CO_2 metal fractionation may create a risk of contamination, as these elements carried by the CO_2 could be remobilized to adjacent aquifer systems. However, for a tightly-sealed storage reservoir, metals are transported to more distal, lower-pressure regions and will be precipitated as metal carbonates, resulting in the mineral trapping of CO_2 (Rempel et al., 2011). In addition, N_2 has a potential impact on the dissolution trapping mechanism of CO_2 in geological storage. Co-injecting CO_2 with N_2 for long-term geological storage may make the CO_2 leakage through fractures or faults more likely. Moreover, the CO_2 dissolution rate per unit area of the reservoir decreases with the increasing N_2 mole fraction in the feed gas and thus the total CO_2 storage capacity is reduced (Li et al, 2015a). Therefore, while co-injecting N_2 with CO_2 reduces the capture cost, it simultaneously increases the cost of risk management during long-term storage. It is important to find an optimal balance among capture, transportation and storage.

3.2. Storage of CO_2 with enhanced industrial production

Converting a pure CO_2 storage process to value-added CO_2 injection process and possibly accelerating the implementation of CCS has attracted interest worldwide (Wei et al., 2015). Storage of CO_2 with enhanced industrial production has a great potential to enable large-scale CO_2 storage at reasonable cost since it can help to reduce CO_2 emissions and enhance industrial production at the same time. This approach includes enhance oil recovery (CO_2-EOR), natural gas recovery (CO_2-EGR), coal-bed methane (CO_2-ECBM), shale gas (CO_2-ESGR), geothermal energy (CO_2-EGS), and in situ uranium leaching (CO_2-IUL).

3.2.1. Enhanced oil recovery (EOR)

Depleted oil reservoirs are a leading target for CO_2 storage and offer one of the most readily-available and suitable storage solutions. When CO_2 is turned into a supercritical fluid at about 73.8 bar pressure and 31.1 °C, it is soluble in oil. The resulting solution has lower viscosity and density than the parent oil, thus enabling production of some of the oil in place from depleted reservoirs. After that, the produced fluids are separated on a platform with CO_2 recycled in situ. In general, 1 t of CO_2 injection facilitates the extraction of 1.5 t of oil (Amouroux et al., 2014). Compared with water injection, the technology of CO_2 flooding to achieve enhanced oil recovery (EOR) can increase oil production significantly and reduce the life cycle carbon emissions of conventional oil production by 25–60%. A relatively high percentage of the injected CO_2 is safely stored after production is stopped, for example, for Darquien oil field in Iran, about 75% of the injected CO_2 was stored (Hasanvand et al., 2013). Retention of CO_2 is due to: (a) dissolution into oil not flowing to the producing wells; (b) dissolution into the formation waters; (c) chemical reaction with minerals in the formation matrix; (d) accumulation in the pore space vacated by the produced oil; (e) leakage and dissolution into the subjacent aquifer; (f) loss into nearby geological structure (Olea, 2015). Currently, CO_2-EOR is mature and has been practiced for many years, e.g. Weyburn Oilfield, Canada since 1954, SACROC oilfield in Texas, USA since 1974. At present, about 4% of U.S. oil is produced through CO_2-EOR (Carpenter and Koperna, 2014; Xie et al., 2014). Globally, CO_2-EOR

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has the potential to produce 470 billion barrels of additional oil and to store 140 billion metric tons of CO_2 which is equivalent to the greenhouse gas emissions from 750 large one GW size coal-fired power plants over 30 years (Carpenter and Koperna, 2014). The major limiting factor that is impeding the widespread development of CO_2-EOR is that ample quantities of CO_2 do not exist to meet the demand from potential EOR operators. Thus, not only does CCS need CO_2-EOR to help promote economic viability for CCS, but also CO_2-EOR needs CCS to ensure adequate CO_2 supplies to facilitate growth in production from CO_2-EOR projects (Carpenter and Koperna, 2014).

3.2.2. Enhanced natural gas recovery (EGR)

Similarly to EOR, by injecting CO_2 into depleted gas wells (i.e., re-pressurization), the pressure of the well would be increased to a level that would make the gas being easily forced out of the well by the CO_2 (Jeon and Kim, 2015). The EGR process is technically feasible since the high density and viscosity of CO_2 relative to methane creates a high displacing efficiency (Hussen et al., 2012). The incremental natural gas recovery enhanced by CO_2 can give additional revenue, so the overall cost of CO_2-EGR may be reduced compared to pure CO_2 geological storage in depleted gas fields. The process of CO_2 injection into natural gas reservoirs is still at the very early stage of development (Khan et al., 2013). The first field-scale EGR project is the Rotliegend K12-B gas reservoir, located offshore of the Netherlands, starting from 2004 (Honari et al., 2015). The risk of leakage is low since the natural gas has been sealed for millions of years in gas reservoir, but excessive CO_2 injection makes the reservoir gas sour and increases CO_2 concentration in the production stream (Zangeneh et al., 2013), at the same time, it may have the potential to leak methane as well as CO_2 (Holloway et al., 2007).

3.2.3. Enhanced coal bed methane technology (ECBM)

Injection of CO_2 in coalbeds with adequate permeability and high gas saturation is considered to be an attractive option for storage. Methane is predominantly physically adsorbed to the large internal surface area of the micro-pores in the coal. Because CO_2 is adsorbed more strongly than methane, the injection of CO_2 will result in expelling methane. CO_2-ECBM envisages the injection and storage of CO_2 with the concomitant production of methane. Another advantage is that these coalbeds are often located in the vicinity of many current or future coal-fired power plants, so CO_2 transportation costs can be reduced. Potential coal beds suitable to CO_2 storage are at the depth of 300–900 m (Bachu, 2007). However present knowledge on reactivity of injected CO_2 and coal, under in situ conditions is still insufficient to assess its significance (Mazumder et al., 2006), therefore, ECBM is still an immature technology.

3.2.4. Enhanced shale gas recovery (ESGR)

The potential storage of CO_2 in organic-rich gas shales is also attracting increasing interest. The process of CO_2-ESGR is to inject CO_2 into a shale stratum to increase the recovery efficiency of shale gas. In shale gas reservoirs, natural gas exists as free gas in the pores and open or partially open natural fractures and also as adsorbed phase on clay and kerogen surfaces. Similar to CO_2-ECBM, gas shale reservoirs appear to adsorb methane while preferentially adsorbing CO_2.

3.2.5. Enhanced geothermal system (EGS)

Instead of water or brine, Brown (2000) showed that the use of supercritical CO_2 as the heat exchange fluid in enhanced geothermal system (EGS) has significant potential to increase their productivity, contribute further to reducing carbon emissions and increase the economic viability of geothermal power generation (an important green energy). The higher pressure within the reservoir compared with its surroundings will force the supercritical CO_2 fluid to diffuse into the surrounding rock masses through faults, fractures and pores. In general, this fluid loss is not recoverable unless the reservoir is negatively pressured for a long period of time (Xu et al., 2016). In addition, the free gas and chemical interactions between CO_2 and reservoir rocks would be via primary CO_2 trapping mechanisms (Karsten, 2006). Although EGS were first proposed about 15 years ago, it has not yet been practically implemented.

3.2.6. Enhanced in situ uranium leaching (IUL)

CO_2-IUL is a novel technology for sandstone-type uranium mining. The key process is to inject CO_2 and leach uranium ore out of geological formation through reaction with ore and minerals in ore deposits (Wei et al., 2015). The main risk linked to CO_2-IUL is radiation exposure.

4. Monitoring CO_2 leakage

If geological CO_2 storage options are to be relied upon to be a safe and reliable option for mitigating global warming, it is important to assure that each storage reservoir retains the major part of the CO_2 isolated from the atmosphere for long periods of time (centuries or millennia). Moreover, the CO_2 leakage will cause asphyxiation, death of small animals in low-level enclosed areas and change of the water or soil pH. Exposure to concentrations of CO_2 higher than 10% may lead to adverse health effects for humans. In addition, CO_2 injected into deep geological strata could result in micro-seismic events or geochemical changes (Maul et al., 2007). Therefore, CO_2 storage safety is crucial, both for avoiding harmful effects to people & the environment and successful long-term mitigation. However, performance assessments for the geological storage of CO_2 are challenging due to data shortage, particularly for potential impacts on ecosystems. Big data from seismic surveys, modern geophysical well log suites, core data, and down hole pressure and temperature measurements, provide a strong support for assessing potential leakage risks (Carpenter and Koperna, 2014).

Currently, leak from monitored CO_2 injection sites has been minimal to non-existent for decades. Properly designed wells, soundly executed drilling programs, prudent storage operations and existing data and experiences for oil/gas industries should mitigate the risk of well blowouts (Holloway et al., 2007). Since the majority of leaks from underground CO_2 storage reservoirs may be similar to natural carbonated springs and mofettes in sedimentary basins, larger, potentially more dangerous, leaks could occur from the storage reservoir through unidentified natural pathways (Holloway et al., 2007), where the sealing efficiency of cap rocks above potential CO_2 storage reservoirs plays a key role for safe storage. Except for caprock fractures, mineral dissolution and re-precipitation due to reaction with water-saturated CO_2 may affect the integrity of the caprock. The quantitative assessment of leakage risks and leakage rates is very important for storage reservoir approval, public acceptance and the awarding of credits for stored CO_2 quantities. Moreover, the leakage risk also has a significant adverse impact for CO_2 storage projects with enhanced industrial production (e.g. CO_2-EOR, CO_2-EGR) and could limit the quantity of CO_2 injected (Walker et al., 2013).

Leakage through caprocks may occur in three ways: rapid leakage by seal-breaching or damage of well casing; long-term leakage controlled by capillary sealing efficiency and permeability; diffusive loss of dissolved gas through water-saturated pore space (Busch et al., 2008). Direct monitoring tools and techniques can be used to measure concentrations of CO_2, near well bores in the subsurface or by taking surface measurements. Most

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monitoring schemes should be undertaken by the combination of physical, chemical, acoustic and biological methods. Once CO_2 injection begins, a program for monitoring of conditions in the injection zone and CO_2 distribution is necessary to manage the injection process, delineate and identify leakage risks, verify and provide input into computational models and provide early warnings of failure (Streimikiene, 2012). When CO_2 injection has ended, the stability of CO_2 storage may increase rather than decrease through time. The reasons are that reservoir pore fluid pressure is likely to be greatest during the injection period, then trapping mechanisms will become more effective with time, finally fluid pressures will gradually decrease. The IPCC (2014) suggested that the proportion of CO_2 retained by an appropriately selected and managed site is likely to exceed 99% over 1000 years.

For onshore geological CO_2 storage projects, the relatively high background levels of soil CO_2 (0–15%) coupled with its seasonal and diurnal modulation, make immediate surface detection of a small CO_2 leak difficult. Nazzari et al. (2013) suggested co-injecting of perfluorocarbon tracers (PFTs) during the CO_2 geological storage and monitor at the surface for CO_2 leaks through collecting and analyzing for PFTs in soil-gas samples. Since PFTs are very stable, have no biological effects and its atmospheric background concentration is very low, PFTs may be a useful tool, especially for monitoring low level leakage. Leaked CO_2 through the soil may lead to additional local greenhouse gas emissions. Zhang et al. (2015) examined the relationship between CO_2 leakage and CH_4& N_2O emissions. The results demonstrated that in general, the amount of additional CH_4& N_2O emissions was negligible when compared with the amount of leaked CO_2; their cumulative global warming potentials only accounted for 0.03% and 0.06%, respectively.

For offshore geological CO_2 storage projects, deep, time-lapse seismic monitoring of the storage reservoirs along with monitoring of reservoir pressure can detect anomalies. Since ocean acoustic tomography can measure changes of seawater density, it is also suggested to be another approach in detecting CO_2 leakage from the seafloor. When multiple acoustic transponders are mounted on the seafloor, one can detect CO_2 leakages over a wide area (Shitashima et al., 2013). Once an anomaly is detected, a full assay of carbonate chemistry for the dissolved phase and/or via the direct sampling of gas bubbles can confirm whether CO_2 is present (Blackford et al., 2015). Hvidevold et al. (2015) suggested optimizing the layout of a fixed array of chemical sensors by using the probability of detecting a leak as a metric. Compared to an equally spaced array, the probability of detecting a leak can be nearly doubled by an optimal placement of the available sensors. Finally, leakage can be determined through the application of tracer technology or by imaging leakage pathways from the storage complex (Blackford et al., 2015). Except for fixed chemical sensors on seafloor, autonomous underwater vehicles (AUVs) are also suggested to narrow the location of CO_2 leakages over a wide area. Main chemical sensors on AUVs are composed of an ion-sensitive field effect transistor (ISFET) as a pH electrode and a chloride ion-selective electrode (Cl-ISE) as a reference electrode, and of the pCO_2 sensor based on this pH sensor (Shitashima et al., 2013).

5. CO_2 mineralization

Mineralization of CO_2 is an important technology due to its scalability for small/medium scale emitters and offers a non-monitoring and leakage-free CO_2 storage option due to the thermodynamically stable nature of the solid carbonates formed (Wang and Maroto-Valer, 2013). Currently, the EU CCS Directive contains only geological storage as the storage option for CO_2 and excludes CO_2 mineralization as a storage option. Since all CCS technologies are currently in a relatively early stage of development, this exclusion seems unreasonable (Kainiemi et al., 2015).

Mineralization is designed to reduce CO_2 emissions by reacting it with rocks rich in magnesium/calcium oxide or with appropriate industrial solid wastes to produce solid mineral carbonates, which can provide safe storage capacity (Sanna et al., 2013). Mineralization of CO_2 can be divided into below ground mineralization and above ground mineralization. The former involves the injection of CO_2 into the geological formation where it forms carbonates with alkaline minerals, which is often considered to be a part of geological storage. The above ground mineralization can be used in processes that require processing of the mineral prior to conversion into carbonates. In CO_2 mineralization, it is fixed with calcium or magnesium oxide as a silicate mineral to form stable carbonates. There are two chemical processes involved, which include CO_2 absorption and CO_3^- ion precipitation. The reactions related to these two processes were presented by Zhou and Wang (2014) as:

$$CO_2+2NaOH = Na_2CO_3+H_2O$$

$$Na_2CO_3+Ca(OH)_2= CaCO_3 + 2NaOH$$

Based on these reactions, CO_2 from the exhaust gases can be captured and stored in a solid form. Sanna et al. (2013) further investigated mixtures of $MgSO_4$ and ammonium carbonate to serve a CO_2 carrier and to form the precipitate, hydromagnesite. The highest carbonation efficiency documented was 93.5% at 80 °C and 1:4:3 as Mg:NH_4 salts:NH_3 molar ratio. Because mineralized CO_2 does not have storage safety issues (e.g. possible leakages), monitoring is not necessary.

In order to overcome low efficiency and high cost in the process of CO_2 mineralization, there is a need to find recyclable solvents (Wang and Maroto-Valer, 2013). Solid waste residue (SWR) generated from the large-scale industrial processes such as coal-fired power plant (CFPP), cement plant, steel, paper, oil shale industry and solid waste incineration are increasing annually; also some SWRs are harmful to the humans and to the environment. Since these industrial SWRs contain substantial alkali and alkali earth metals, the mineral carbonation with SWR may be used to mineralize CO_2. Moreover, CO_2 can be partially recovered from the instable carbonated (or bi-carbonated) SWR products for future CO_2 resource utilization. Wee (2013) investigated the potential of the carbon storage technology using coal fly ash (CFA) in the laboratory scale. The technology can be classified into wet and dry processes. In the wet process, the components Ca, Na, Mg and K in CFA were dissolved into solution by leaching and subsequently used for storage of CO_2. In the dry process, CFA can be used as the sorbent for CO_2 capture and storage. Noticing that the CO_2 emissions from coal-fired power plant are the largest, the use of CFA in the storage of CO_2 can save the cost for CO_2 transport. Moreover, this method can make the stabilization of the harmful components present in CFA such as Cd, Pb,Cr, As, Se, Al, and S at the same time. Sun et al. (2013) suggested the utilization of lime mud from paper mill as CO_2 sorbent in calcium looping process, but its efficiency of lime mud is relatively low since the high chlorine content in lime mud lead to more pronounced sintering and decrease the carbonation conversion.

6. Storage of CO_2 through industrial utilization

Industrial utilization of CO_2 represents a promising approach for reducing carbon emissions. Some industrial utilization schemes can only store CO_2 temporarily and emit CO_2 usually to the atmosphere at the end of the product's life, which can range from days or weeks (e.g. CO_2-based fuels) to years (e.g. CO_2-based polymers), while other industrial utilization schemes (e.g. CO_2-based cement) can

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store CO_2 permanently (Bruhn et al., 2016).

Various innovative construction products can be manufactured while storing CO_2 at the same time. Instead of traditional high-temperature clinkering method, Jo et al. (2015) provides a novel approach for the production of a CO_2-stored cementitious material, where the hydrothermal synthesis of a cementitious material is performed utilizing carbonated lime infused with silica fume and hydrated alumina. In iron and steel industry, due to high calcium-silicate content, all types of steel slag (EAF, BOF and ladel slag) show potential to react with CO_2 for production of cementitious material. The key carbonation reactions of dicalcium silicate and tricalcium silicate are

$$2(2CaO \cdot SiO_2) + CO_2 + 3H_2O = 3CaO \cdot 2SiO_2 \cdot 3H_2O + CaCO_3$$

$$2(3CaO \cdot SiO_2) + 3CO_2 + 3H_2O = 3CaO \cdot 2SiO_2 \cdot 3H_2O + 3CaCO_3$$

Amounts of stored CO_2 increase with increasing time of carbonation curing. At the same time, these processes can contribute strength development greater than that in ordinary Portland cement (Higuchi et al., 2014). In general, these carbonation processes can be carried out at steel mill by using the locally produced ladle slag and flue gas CO_2 to make building products with a much reduced embodied energy in comparison to Portland cement products (Mahoutian et al., 2014). In addition, Higuchi et al. (2014) suggested using the additive (dicalcium silicate γ phase: γ-$2CaO \cdot SiO_2$) and coal fly ash to produce concrete with CO_2 storage, where γ-$2CaO \cdot SiO_2$ can be manufactured using a by-product containing $Ca(OH)_2$ and SiO_2 powder.

CO_2 can be used as a feed stock for chemical engineering. Current CO_2 chemical feedstock accounts for only about 0.5–2% of emissions, but in the future, it could be expected to mitigate 700 megatons of CO_2 per year (Leung et al., 2014; Morrison et al., 2016). Using highly purified CO_2, many high added value chemicals can be synthesized for the benefit of a wide variety of sectors of the chemical industry. At high pressure and high temperature, methane can be synthesized by reaction with CO_2 and H_2 using metallic catalyst (Ni), while methanol can be synthesized by reaction of CO_2 and H_2 using a metallic catalyst (copper and zinc oxides on an alumina based ceramic, $Cu/ZnO/Al_2O_3$). Here H_2 is often generated by electrolysis of seawater using a renewable energy such as wind or solar (Amouroux et al., 2014). CO_2 can also be utilized to make organic carbonates like dimethyl carbonate, propylene carbonate, etc., or inorganic carbonates like sodium carbonate or calcium carbonate. In addition, CO_2 is also used to prepare salicylic acid, an important intermediate for pharmaceuticals (Yang and Wang, 2015).

CO_2 can be used as thermochemical energy storage. Methane reforming with carbon dioxide is a good approach for solar thermochemical storage and other high temperature energy storage. The product syngas, including hydrogen and carbon monoxide, can efficiently store the absorbed solar energy. As the operating temperate is 800 °C, the total energy efficiency is about 70% (Lv et al., 2015).

7. Storage potentials of CO_2 and commercial deployments in China

China's energy consumption structure is dominated by coal. Coal-fired power plants are the main source of CO_2 emissions and account for about 50% of total emissions. As one of the countries of economy growing fastest in the world, China has become the largest CO_2 emitter. At present, carbon emissions in China are approximately 10 billion tons per year. In order to mitigate global warming, China committed to abate its emissions per unit of economic output by 60–65% of 2005 levels by 2030 in November 2015. Carbon storage can be part of that sustainable development of China, particularly in the medium to long term. According to statistics by the National Energy Administration of China, estimated emission reduction through carbon storage technology in China will be up to 2.5–3.5 billion tons per year, equivalent to 26–37% of Chinese annual emissions. In 2013, China's key policy making entities, *National Development & Reform Commission* and *Ministry of Science & Technology*, emphasized the importance of demonstration projects for the widespread development of carbon storage. However, compared with Europe and USA, China lags behind in the research and development of carbon storage technology. Currently, the primary difficulties facing in China include: (1) lack of clear storage site selection criteria and site investigation techniques; (2) lack of methods for evaluation of site mechanical stability; (3) need for further development of emergency and remedial measures for CO_2 leakage (Lui et al., 2014).

In China, there is a huge resource for carbon storage, especially, the storage capacity in deep saline formations accounting for 99% of total geological storage capacity. The capacity of geological reservoirs for CO_2 storage in China and the corresponding enhanced industrial production are shown in Table 3.

In the western region of China, rich in coal resources and poor in water resources makes coal power and coal chemical industries face dual high pressure with severe water shortage stress and carbon emission reduction at the same time while China's eastern region faces groundwater over exploitation and related man-made geological hazards (Li et al., 2015b). The CO_2 storage with deep saline water recovery has a great potential to solve these problems. For pumped water with low salinity, strong reservoir pressure derived from CO_2 injection can be utilized as a driving force for desalination to meet life drinking as well as industrial or agricultural demands. The first project on storing CO_2 in saline aquifer layer is SHENHUA CCS industrialization demonstration project. It has successfully injected supercritical CO_2 into the target layer since January 2, 2011, which is the first large-scale CO_2 saline aquifer storage project of the whole process in the world (Bai et al., 2012). The injection site is located in Erdos, Inner Mongolia, China and 100,000 tCO_2 are injected every year (Ming et al., 2014). Moreover, CO_2 injection in the SHENHUA CCS project will not impact coal mining above the CO_2 storage reservoir if a proper and precise design and monitoring scheme can be followed (Li et al., 2014b). The SHENHUA CCS project will provide a unique opportunity for initiating other similar initiatives in the world.

Due to the low permeability, low storage intensity, and unclear definition of un-minable coal reservoirs in China, CO_2 storage with EOR/EGR is more likely to be implemented than CO_2-ECBM (Li et al., 2011). China imported 280 million tons of crude oil in 2012 and the external dependency reached 58%, which is a serious threat to China's energy security. Compared to other countries, the oil reservoir conditions in China are relatively poor, deeply buried, and high-viscosity of crude oil (Lv et al., 2015). CO_2-EOR provides one of the important means to ensure an oil supply of China, and the gap between the world and China in this field is not very large. The first China's CO_2-EOR project was initiated in 2009 at the Jilin Oilfield in north-east China. The CO_2 is obtained from the nearby Changchun Gas Field where the CO_2 content is around 22.5%. Until April 2013, this project injected nearly 217,000 tonnes of CO_2 with a storage efficiency of over 96% and the remainder was returned to the surface via production wells (Lui et al., 2014). Lv et al. (2015) investigated Shengli Oilfield (the second largest oil field in China) and indicated that the enhance oil recovery can increase by 6.7%. The total injection volume is expected to reach to 5.63×10^6 t, and CO_2 sequestration rate is 60.5%, and the possibility of CO_2 leakage is weak in the vertical direction along faults.

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Table 3
Potential CO_2 storage capacity and Enhanced Industrial Production in China (Wei et al., 2015; Li et al., 2011).

Types	CO_2 storage capacity	Enhanced Industrial Production
CO_2-EOR	>4 billion tons	>1 billion tons oil
CO_2-EGR	>4 billion tons	>64.7 billion cubic meters natural gas
Deep saline aquifers	1210–4130 billion tons	1330 to 6190 billion tons water.
CO_2-ECBM	6.5–14.8 billion tons	288–659 trillion cubic meters coalbed methane

As a non-monitoring and leakage-free CO_2 storage option, China has also huge potentials in the development of CO_2 mineralization and industrial utilization. China has become the biggest producer in the global cement industry since 1985. The cement industry accounts for 14.8% of total CO_2 emissions from China (Huisingh et al., 2015). In 2013, China produced 2.42 billion tonnes of cement (~60% of global cement production) (Liu et al., 2016). The introduction of CO_2 industrial utilization in cement industry will play a key role in helping China to meet its national carbon emissions reduction target. At the same time, China is the biggest iron and steel producer in the world. In 2012, it produced 658 Mt of pig iron and 716 Mt of crude steel, representing 59% and 46% of the world's production, respectively. The iron and steel industry in China accounted for 10% of total CO_2 (Huisingh et al., 2015). China has also consumed 48.2% of the world's coal, and 48.0% of China's coal consumption is used by the power generation industry (Liang et al., 2013). The produced steel slag, coal fly ash and other industrial solid wastes can be used well for CO_2 mineralization and industrial utilization. In addition, as the largest chemical industry in the world, China has huge potentials in the development of CO_2 chemical utilization, especially in high added value chemicals by using highly purified CO_2. However, currently CO_2 mineralization and industrial utilization in China is just at the very early stage of technological development.

A high public acceptance is one of critical factors for widespread deployment of various CCS projects in China. According to a survey by Li et al. (2014a), although more than 67% of Chinese believed that climate change is an important issue for China and has a negative influence on national development of both society and economy, 57.2% of Chinese do not know about CCS technologies. Therefore, the public awareness of CCS was unclear. It is necessary to have more effective public education and communication policies, such as organizing public education, promoting information exchange and communication, establishing information disclosure of CCS projects, etc.

8. Discussion and conclusions

Carbon capture and storage (CCS) is among the essential technologies in the mitigation of greenhouse gases, especially CO_2. Currently, rising energy production is associated closely with increasing fossil-carbon emissions. Before our societal metabolism is radically transformed towards low/no fossil-carbon economies, CCS represents one of the most economic options allowing time for continued use of abundant fossil fuels while new green technologies are developed for transportation and electric power generation. IEA's analysis suggests that in the near future, CCS is expected to be responsible for over 20% of the carbon abatement target, especially in developing countries. Although CCS has been accepted as a clean development mechanism approach under the Kyoto Protocol, the current carbon trading mechanism is inadequate to strongly promote investments on CCS. CCS technology involves capturing, transporting, and storing the CO_2 securely. When technology to capture CO_2 is relatively mature and commercially available for power plants, safe, reliable and long-term storage of captured CO_2 continues to be a key uncertainty affecting widespread deployment of CCS technology.

One of the main CO_2 storage options is geological storage, which is based upon injection of CO_2 into deep saline aquifers, oil and gas reservoirs, coal seams etc. The storage capacity of each option varies from hundreds of millions of tons to billions of tons. Compared with depleted oil and gas reservoirs and coal seams, deep saline aquifers possess much larger storage capacities and may be possibly near many CO_2 emission sites due to widespread distributions. On the other hand, if CO_2 storage is combined with enhanced industrial production (e.g. oil, natural gas), it has a greater potential for reducing the overall cost of CO_2 storage. Although currently leak from monitored CO_2 injection sites has been minimal to non-existent for decades, potential CO_2 leakage may be one of the main barriers to the development of CO_2 geological storage projects. A suitable monitoring system should be well developed by the combination of physical, chemical, acoustic and biological methods. Big data from seismic surveys, modern geophysical well log suites, core data, and down hole pressure and temperature measurements and previous experiences in oil/gas industries will provide a strong support for selection of CO_2 geological reservoirs, estimation of their storage capacities and assessment of the potential risks.

CO_2 mineralization and industrial utilization is another option which offers a leakage-free CO_2 storage option. It does not need to be monitored due to the thermodynamically stable nature of the solid carbonates formed. Solid waste residue (SWR) generated from the large-scale industrial processes contains substantial alkali and alkali earth metals, which may be used to mineralize CO_2. Industrial utilization of CO_2 is currently more attractive than pure geological storage since it can produce high-value products from problematic SWRs and reduce CO_2 emission with relatively low cost and energy consumption. Some industrial utilization schemes can only store CO_2 temporarily and emit CO_2 usually to the atmosphere at the end of the product's life, which can range from days or weeks (e.g. CO_2-based fuels) to years (e.g. CO_2-based polymers), while other industrial utilization schemes (e.g. CO_2-based cement) can store CO_2 permanently. These novel CO_2 mineralization and industrial utilization schemes need to guarantee sustainable or environmentally friendly processes and satisfy basic principles of industrial ecology if implemented on a large industrial scale.

Currently, carbon storage schemes are still in the early stage of technological development and are still far from large-scale commercialization. The high cost, high energy penalty, safety & reliability, and policy uncertainties are main barriers for the implement of carbon storage schemes. Moreover, a high public acceptance is also a critical element in order to obtain wide-spread deployment of diverse CO_2 storage schemes. Public opposition often leads to costly delays and cancellations of these projects. Geological storage of CO_2 will be perceived to have less risk than nuclear technologies, but could be perceived as being somewhat riskier than fossil fuels, coal burning pollution, and other widely accepted technological hazards (Singleton et al., 2009). Compared with geological storage, the public acceptance might be higher for CO_2 mineralization and industrial utilization since it is a leakage-free CO_2 storage option (Xie et al., 2015). In general, currently public awareness of CCS is very low. Under limited surveys, only approximately 28% in Europe and 44% in Canada have heard of the technology (Seigo et al., 2014a,b). In developing countries, public awareness is much lower than that. It is recommend using a big data mining to extract detailed popular opinions on CCS from millions of people, thousands of organizations, hundreds of countries with the help of various survey, media and websites. At the same time, it is essential to have more effective public education and communication policies and practices, such as organizing public education, promoting information exchange and communication, establishing information disclosure of CCS projects, etc.

As the largest CO_2 emitter, China faces dual pressures of the obligation of emissions reduction globally and sustainable development domestically. CCS may be necessary in China to enable the country to meet the long-term climate protection target of the international community to which China is increasingly committing itself in the near future (Viebahn et al., 2015). Compared with Europe and USA, China lags behind in the research and development of CCS technology, especially CO_2 storage technologies. Since CCS has been accepted as a clean development mechanism (CDM) approach, China should make full use of the opportunity of CDM to obtain more advanced CO_2 storage technologies. International cooperation between China and developed countries will help to build capacity in the area of CO_2 storage among Chinese researchers, policy makers and professionals from academia, government, and industry. Many important cooperation projects, such as Cooperation Action Carbon Capture and Storage China-EU project (COACH), China-Australia Geological Storage of CO_2 Project (CAGS), have been successfully carried out. Especially, CAGS will create the first Chinese Geological Storage Atlas in the near future through an assessment of Chinese sedimentary basins. Currently, China generates 80% of its power by burning coal and it will not change greatly in next decades, so widespread implement of CO_2 storage project will play a key role to assist China to achieve the transition to a low fossil-carbon economics in the near future. Although China's key policy making entities, *National Development & Reform Commission* and *Ministry of Science & Technology*, have emphasized this, Chinese governments should carry out a more comprehensive geophysical survey with the help of big data mining and set up a series of industrial standards and laws for CO_2 transportation, storage and leakage monitoring as soon as possible. At the same time, as the largest industry country in the world, China should pay attention to the technology development of CO_2 mineralization and industrial utilization, which make substantial contribution to CO_2 mitigation in the middle and long term.

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