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Carbon Capture and Storage: History and the Road Ahead

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ABSTRACT

The large-scale deployment of carbon capture and storage (CCS) is becoming increasingly urgent in the global path toward net zero emissions; however, global CCS deployment is significantly lagging behind its expected contribution to greenhouse gas emission reduction. Reviewing and learning from the examples and history of successful CCS practices in advanced countries will help other countries, including China, to promote and deploy CCS projects using scientific methods. This paper shows that the establishment of major science and technology CCS infrastructures in advanced countries has become the main source of CCS technological innovation, cost reduction, risk reduction, commercial promotion, and talent training in the development and demonstration of key CCS technologies. Sound development of CCS requires a transition from pilot-scale science and technology infrastructures to large-scale commercial infrastructures, in addition to incentive policies; otherwise, it will be difficult to overcome the technical barriers between small-scale demonstrations and the implementation of million-tonne-scale CCS and ten-million-tonne-scale CCS hubs. Geological CO_2 storage is the ultimate goal of CCS projects and the driving force of CO_2 capture. Further improving the accuracy of technologies for the measurement, monitoring, and verification (MMV) of CO_2 storage capacity, emission reduction, and safety remains a problem for geological storage. CO_2 storage in saline aquifers can better couple multiple carbon emission sources and is currently a priority direction for development. Reducing the energy consumption of low-concentration CO_2 capture and the depletion of chemical absorbents and improving the operational efficiency and stability of post-combustion CO_2 capture systems have become the key constraints to large-scale CCS deployment. Enhanced oil recovery (EOR) is also important in order for countries to maximize fossil fuel extraction instead of importing oil from less environmentally friendly oil-producing countries.

1. Introduction

Carbon capture and storage (CCS) or carbon capture, utilization, and storage (CCUS) is recognized internationally as an indispensable key technology for mitigating climate change and protecting the human living environment (Fig. 1) [1–3]. Both the International Energy Agency (IEA) [4] and the Carbon Sequestration Leadership Forum (CSLF) [5] have stated that, in order for the energy sector to achieve net zero emissions by 2050, the global scale of CCS in 2030 and 2050 must respectively be 10–15 times and 100 times greater than the current 40 $Mt \cdot a^{-1}$ as of 2020. The Intergovernmental Panel on Climate Change (IPCC) [6] has projected that the cost of mitigation will rise by 138% in 2100 if CCS technologies are not adopted. CCS is listed as one of three mandatory emission reduction technologies in the four key emission reduction technology pathways [7] in the 1.5 °C special report released by the IPCC in 2018.

The IEA [8] has summarized four strategic areas in which CCUS should be used to address emissions: existing infrastructure, low-carbon hydrogen production, the most challenging emission in sectors such as heavy industry and aviation, and removing carbon from the air. Both CCS technology and renewable energy technology are key technologies for mitigating climate change; however, from the perspective of land use, CCS is an underground-space utilization technology, and coal-fired power plants plus CCS require a much smaller land area than solar and wind power plants. Coal power/natural gas power generation plus CCS is still the

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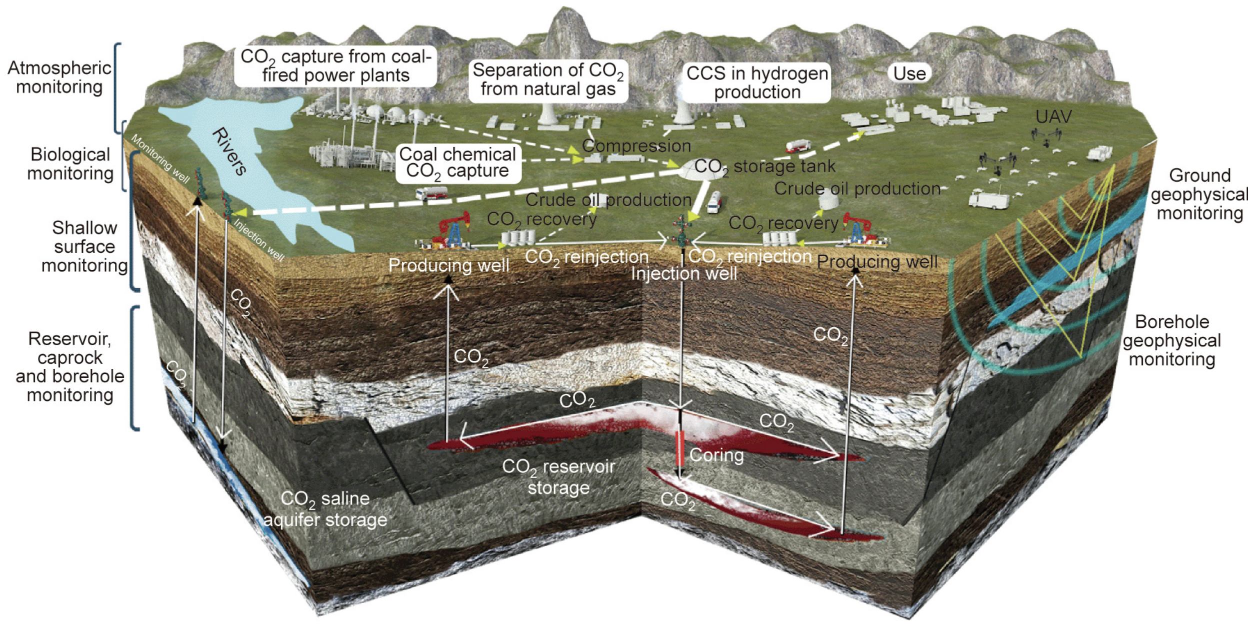

Fig. 1. The CCS industry chain and its driving factors. UAV: unmanned aerial vehicle.

cornerstone of power production safety and stability on the premise that renewable energy cannot provide large-scale industrial power and presents intermittency and energy-storage problems that are difficult to solve. In addition, CCS technology is the only effective option for direct and rapid emission reductions from fossil-energy-based large-scale sources such as the steelmaking, cement, and chemical industries [8]. CCS will become a large industry on the same scale as the oil and gas industry (Fig. 2).

Scholars' predictions for the role CCS will play in China's carbon neutrality pathway differ [9–11], with different prediction models corresponding to differences in the magnitude of CCS's contribution to China's emission reduction and in the amount of government investment in the future. Some Chinese scholars regard CCS technology as a "minimum" technology rather than a necessary technology, and thus do not rank it high enough in importance to predict its contribution to China's emission reduction. However, China is heavily dependent on coal, so we consider a higher emission reduction contribution value from CCS to be preferable. For example, according to the latest Asian Development Bank (ADB) forecast, the contribution of CCS to emission reduction in China must reach $(0.3–1.2) \times 10^8\ t{\cdot}a^{-1}$ in 2030, $(8.5–25) \times 10^8\ t{\cdot}a^{-1}$ in 2050, and $(13–26) \times 10^8\ t{\cdot}a^{-1}$ in 2060 in order for China's carbon neutrality goal to be achieved [12]. Given the anticipated emission reduction needs of the Belt and Road countries in the future, widespread use of CCS will give Chinese enterprises more room to expand. Negative emission technologies, such as direct air capture (DAC) and bioenergy with carbon capture and storage (BECCS), are futuristic and require scaling up to determine their economic viability.

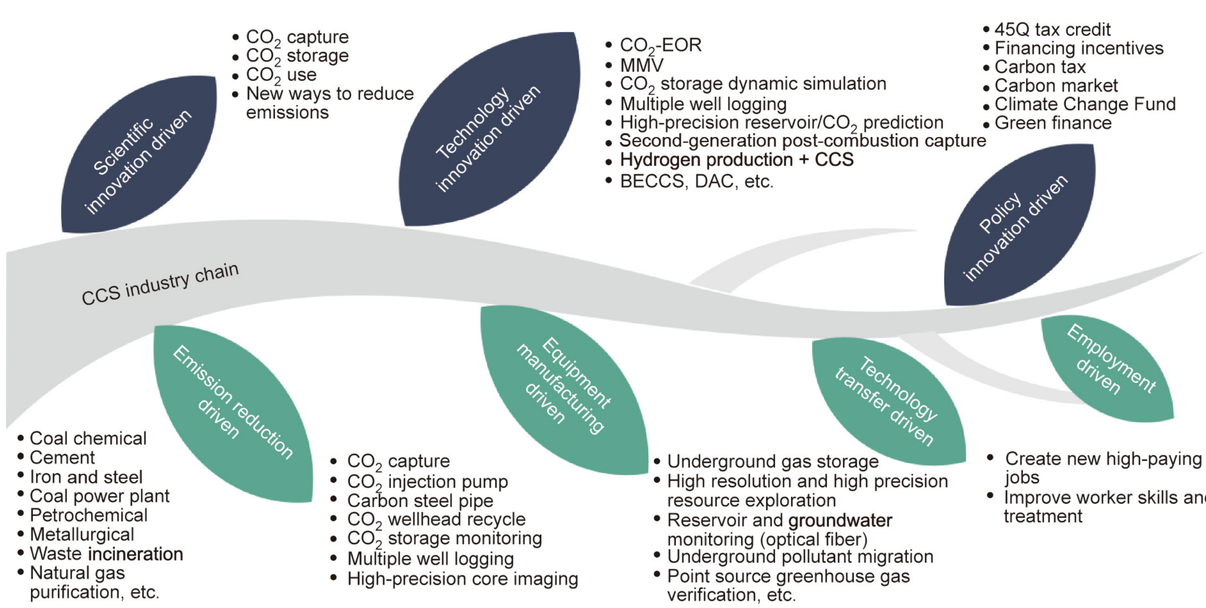

Fig. 2. The CCS industry chain and its driving factors. MMV: measurement, monitoring, and verification; BECCS: bioenergy with carbon capture and storage; DAC: direct air capture; EOR: enhanced oil recovery.

2. Review of the origin of CCS project development

CO_2-enhanced oil recovery (EOR) has been carried out in the United States and Canada since the 1960s. The world's first large-scale CO_2-EOR project, Scurry Area Canyon Reef Operating Committee (SACROC), has been implemented by Chevron in the oilfield in Scurry County, Texas since January 26, 1972 [13]. The CO_2 for this project comes from the natural CO_2 fields in Colorado and is pipelined to the oilfield for flooding. More than 175 million tonnes of natural CO_2 in total were injected in the SACROC project during 1972–2009 [14].

However, the concept of CO_2 capture, transport, and storage in the modern sense, as a means of reducing anthropogenic CO_2 emissions, was first proposed by Marchetti [15]. The Sleipner CCS project, which began in 1996, and the IEA Greenhouse Gas (IEAGHG) Research and Development Programme Weyburn–Midale CO_2 Monitoring and Storage Project (Weyburn Project for short), which began in 2000, were the first international demonstrations of the large-scale capture, utilization, and storage of anthropogenic CO_2 emissions.

The Sleipner CCS project, which is a scientific research and large-scale commercial demonstration project implemented by Equinor under the influence of the Norwegian carbon tax policy, captures the CO_2 separated in the natural gas purification process and injects it into deep saline aquifers for storage and emission reduction. The project has stored more than 20 million tonnes of CO_2 in total since 1996. The project has carried out advanced monitoring for 20 consecutive years and has achieved remarkable scientific research results [16].

The Weyburn Project is the world's most complete multidisciplinary scientific research project on the geological storage of CO_2. It has been ongoing for 12 years with a scale of 1.8 $Mt{\cdot}a^{-1}$ of CO_2 injection and has safely stored over 35 million tonnes of CO_2 since October 2000. The Weyburn Project is conducted at the largest geoscience test site in the world, which was established in the Weyburn field in Southern Saskatchewan, Canada, with the joint support of Natural Resources Canada, the US Department of Energy, the Saskatchewan government, and other government agencies and enterprises [17–19]. After completion of the planned scientific research, the project has been converted into a commercial project.

The success of the Weyburn Project has established the irreplaceable role of CCS technology in reducing greenhouse gas emissions (Fig. 3). Firstly, it is the world's first project to carry out the large-scale capture and long-distance transportation of low-cost and high-concentration CO_2 from the use of coal (i.e., the Dakota Gasification Company) for EOR and storage. It has demonstrated that it is possible to use CCS technology to reduce the CO_2 generated by coal—which contributes the highest proportion of carbon emissions in fossil energy use—on a large-scale, rapid, and low-cost basis, so as to make clean use of coal. Secondly, the project benefits from relying on CO_2-EOR; in the absence of government subsidies, the project has been in good operation for more than 20 years and has established the most successful CCS commercialization model. Thirdly, after solving the problem of how to effectively and efficiently capture and store CO_2 emission sources from the high-concentration coal chemical industry, the organizers of the Weyburn Project targeted the capture and storage of low-concentration CO_2 emitted from coal-fired power plants, and built the world's first 1 $Mt{\cdot}a^{-1}$ post-combustion CO_2 capture facility at Unit 3 of the SaskPower Boundary Dam Power Station (abbreviated to BD3), so as to transport the CO_2 to the Weyburn oilfield for EOR and storage. Moreover, since the excess CO_2 captured at the power plant can be stored in nearby saline aquifers when the demand of the oil company for CO_2 is low, the SaskPower cooperated with the Petroleum Technology Research Centre (PTRC) to build the Aquistore scientific research facility for the geological storage of CO_2 in deep saline aquifers.

The Weyburn Project has also made the utilization of CO_2 flooding into the best business model for CCS development without government incentives; therefore, "U" has been added to the concept of CCS for "utilization" and is widely praised internationally. However, among the commitments and efforts countries are currently making to achieve carbon neutrality goals, some forms of CO_2

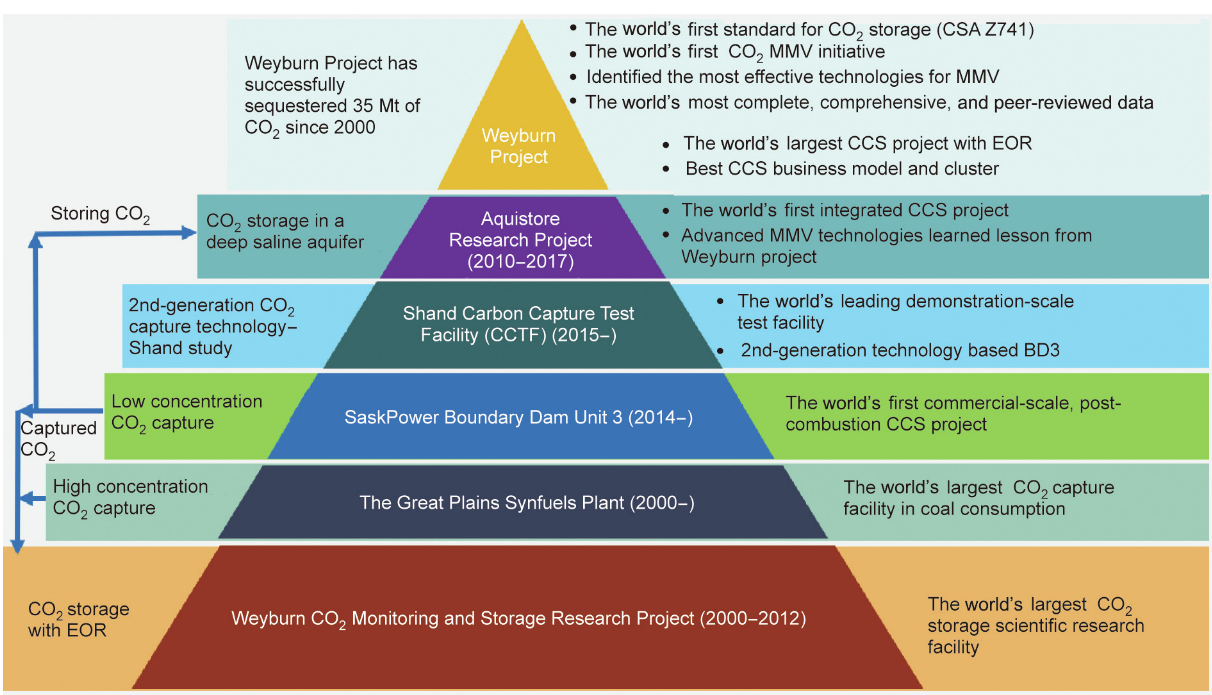

Fig. 3. Scientific research facilities and solid scientific research laid the foundation for the success of the Weyburn Project. CSA: Canadian Standards Association; BD3: Unit 3 of the SaskPower Boundary Dam Power Station.

utilization, such as CO_2-EOR, have not been fully effective in reducing emissions on a large scale [20]. Thus, this paper does not discuss CO_2 utilization such as CO_2 flooding and so forth.

3. Classification of CCS projects

There are many classification methods for CCS projects, with that of the Global CCS Institute (GCCSI) [21] being the most well-known. The GCCSI takes projects that capture, transport, and store 400 $kt \cdot a^{-1}$ CO_2 from industrial emission sources, or projects that capture and store 800 $kt \cdot a^{-1}$ CO_2 from coal-fired power plants, as the threshold for large-scale pilot testing, demonstration, or commercialization projects. According to the GCCSI 2020 report, there are currently 65 commercial projects in the world, 26 of which are in operation, while others are at different stages of development.

CCS projects can also be classified according to the source of CO_2—that is, CO_2 from natural gas separation (e.g., Sleipner), carbon capture in the coal chemical plant (e.g., Great Plains Coal Gasification Plant), hydrogen production in oil refining (e.g., Shell Quest [22] and Tomakomai), coal power plants (e.g., SaskPower Boundary Dam and Petra Nova), carbon capture in steelworks (e.g., Al Reyadah), biomass energy capture (e.g., Decatur), and DAC (e.g., Carbfix and Climeworks, Heidelberg Cement's ongoing Norwegian Norcem's Brevik cement plant, and the Canada Lehigh Cement Company). Projects that directly use CO_2 from the natural CO_2 fields for flooding and storage are not considered to be carbon emission reduction projects, and thus are not considered as CCS projects.

The storage used in CCS projects can be divided into types such as storage in saline aquifers, storage with CO_2-EOR, storage in abandoned oil and gas fields, and storage in basalt [23]. CO_2 storage projects in basalt include Carbfix [24] in Iceland and Tomakomai [25] in Japan. However, although the Tomakomai project successfully injected CO_2 in sandstone, attempts at CO_2 storage in basalt were not ideal. As a result, the Tomakomai reservoir has low injectivity and does not exhibit high-temperature conditions like those of the basalt of the Carbfix project; thus, no mineralized storage has been achieved. Given these results, the potential for future CO_2 storage in basalt does not appear to be high at present.

The development history of CCS projects, the scientific problems encountered, and the technological progress achieved can be better understood by classifying CCS projects according to scientific research and commercial demonstration or operation. As mentioned above, although the United States has carried out large-scale CO_2 flooding since 1972, CO_2-EOR technology focuses on EOR that part of injected CO_2 remains in the reservoir and part of CO_2 comes out with oil from producing wells, rather than on the geological storage of CO_2 and CO_2 emission reduction. When CO_2 flooding technology turns to CO_2 geological storage in either saline aquifers or oil reservoirs, the first questions to be answered are: Is the CO_2 safely stored? How can the location of the stored CO_2 be verified? How can the CO_2 storage capacity of different scales be verified? What technology and equipment are used to monitor the safety of CO_2 storage over the long term? These questions must be solved by CCS research projects and infrastructures; they are also the basis for the commercial promotion of CCS. The Weyburn Project was a scientific research project with the goal of achieving CO_2 monitoring and storage, while carrying out monitoring and testing as completely as possible [18,26,27]. The standard Canadian Standards Association (CSA) Z741 geological storage of carbon dioxide was based on research from this project, and was in turn the basis for the international standard International Standards Organization (ISO)/Technical Committees (TC) 265 carbon dioxide capture, transportation, and geological storage.

The Sleipner project involves offshore monitoring research on the large-scale geological storage of CO_2. Four-dimensional (4D) seismic monitoring and time-lapse gravity monitoring from this project revealed the principle behind CO_2 migration and accumulation underground during the process of CO_2 injection. Other internationally influential CCS science and technology infrastructures (Table 1 [28,29]) include the Aquistore, Cooperative Research Center for Greenhouse Gas Technologies (CO2CRC) Otway, Tomakomai, Ketzin, and the world's first biomass CCS research project, Decatur Project, among others. These science and technology infrastructures have a high level of construction technology and advanced monitoring technologies and equipment, and cover pre-injection site research on the geological storage of CO_2, monitoring and research in the injection stage, and continuous monitoring and research after injection (post-injection and post-closure). Early research infrastructures for the geological storage of CO_2 include a geological CO_2 storage test site in Nagaoka, Japan, and the K12-B Offshore CO_2 Injection Project in the Netherlands, among others.

However, on the whole, these CCS science and technology infrastructures focus on geological storage and are designed for conducting research on the measurement, monitoring, and verification (MMV) of geological storage and testing the feasibility of monitoring technology for storage capacities from 10 $kt \cdot a^{-1}$ to 1 $Mt \cdot a^{-1}$. Except for the Weyburn Project, whose research focus is storage with EOR, the research focus of all the other projects is CO_2 storage in saline aquifers. This is because saline aquifers have much larger storage space than oil reservoirs in terms of storage potential. Projects involving CO_2 storage in saline aquifers capture and store CO_2 in the vicinity of the emission sources, thereby avoiding the cost of building long-distance CO_2 transportation pipelines. Moreover, storage of CO_2 in saline aquifers does not need to be taken into consideration the reduction or termination of oil companies' demand for CO_2 due to changes in international oil prices. Such projects generally have a lower net-carbon emission reduction cost than the storage of EOR projects. When storing CO_2 in saline aquifers, it is not necessary to capture a very high concentration of CO_2. Therefore, CO_2 storage in saline aquifers is the current direction of CCS development.

However, CO_2-EOR should not be discounted, as this process creates a revenue stream to pay for a portion of the currently expensive capture process. Technically speaking, CO_2 geological storage in saline aquifers is currently carried out by means of direct injection; that is, no fluid is pumped out of the saline aquifers to reduce the *in situ* pore pressure. This method differs from the CO_2 flooding method, which involves flooding oil and gas reservoirs with CO_2 to replenish the storage pressure. Injecting CO_2 into saline aquifers is more likely to result in a pore pressure that is higher than the *in situ* pore pressure, which in turn leads to the rupture of caprocks, opening of reservoir cracks, opening of faults, and other leakage risks. However, the ongoing international CO_2 storage project in saline aquifers (e.g., Sleipner, Shell Quest, Tomakomai, Aquistore, CO2CRC Otway) proves that such risks are controllable.

4. Key issues of CO_2 capture

The difficulty of CO_2 capture lies in its large scale and the need to achieve low energy consumption or low cost when it is used for low-concentration emission sources (e.g., coal-fired and gas-fired power plants, steelworks, the cement and chemical industries, and waste incineration). According to a breakdown of the capital expenditure investment of 790.3 million CAD in the Shell Quest CCS project [30], the costs of the capture, transportation, and storage of CO_2 with a concentration of 17% in the 1 $Mt \cdot a^{-1}$ heavy oil

Table 1
Typical global CCS science and technology infrastructures and their characteristics.

Name	Capture type and scale	Transportation	Storage	Characteristics
Weyburn, Canada	The 3 Mt·a^{-1} coal gasification unit of the US Dakota Gasification Company; the 1 Mt·a^{-1} post-combustion capture unit of the Canada SaskPower Boundary Dam Power Station	320 km pipeline from the United States to Canada; 80 km pipeline from the SaskPower Boundary Dam Power Station to the oilfield	CO_2 storage with EOR at a depth of 1450 m; about 1.8 Mt·a^{-1}; injection started in October 2000; the Weyburn field alone has stored a total of more than 35 million tonnes of CO_2 thus far	The world's largest scientific research facility for geological storage of CO_2; the most advanced, comprehensive, and complete MMV in the world, including 3D three-component seismic monitoring (performed three times), 3D nine-component seismic monitoring (performed three times), 80-level 3D three-component VSP monitoring in wells (performed three times), passive seismic monitoring (performed five times), fast and slow S-wave logging, surface environment monitoring, and so forth; the largest scale geological CO_2 storage datasets obtained; basis for the formation of the CSA Z741 geological storage of carbon dioxide standard in Canada and the United States
Aquistore, Canada	The 1 Mt·a^{-1} post-combustion capture unit of the Canada SaskPower Boundary Dam Power Station	10 km pipeline transportation to the saline aquifer storage point (straight-line distance of 3.4 km)	Storage in a 3400 m underground deep saline aquifer; injection started in 2015; has stored a total of 350 000 t of CO_2	Learned from the experience of the monitoring technology used in the Weyburn Project and promoted the development of permanent monitoring equipment and technology for the geological storage of CO_2; currently the world's deepest geological CO_2 storage project (3400 m), with the most difficult monitoring technology; layout of facilities for permanent 3D seismic monitoring, borehole fiber optic DAS VSP, deep-well fiber optic temperature, pressure DTS, passive seismic monitoring, tiltmeter/GPS (surface horizontal and vertical deformation), environmental monitoring, and so forth [28]; 3D seismic monitoring and environmental monitoring was carried out multiple times before injection in order to detect the repeatability of the monitoring technology and analyze non-CO_2 injection factors
Sleipner, Norway	Separation of CO_2 from the natural gas of Sleipner Vest Field, with a scale of 850 kt·a^{-1} CO_2; capture technology and chemical solvents (amine absorption)	Separation of CO_2 on an offshore platform and injection of CO_2 into deep saline aquifers below the seabed	Storage of CO_2 in 800–1100 m deep saline aquifers below the seabed; injection started on September 15, 1996; the world's first offshore CCS project; has stored about 17 million tonnes of CO_2 in total so far	Injection into two sets of saline sandstone aquifers; the world's first time-lapse gravity monitoring project, through which it was found that the reservoir density decreased after CO_2 injection; 3D seismic monitoring with marine streamers (performed eight times); deep subsurface monitoring, which was technically difficult and technically advanced. The main research goal was to determine the movement process of pinnate fluids in reservoirs after CO_2 storage underground; data were acquired and recorded using a comprehensive monitoring technology; data analysis facilitated safe CO_2 storage operations in complex reservoirs and environmental assessment
CO2CRC Otway, Australia	Separation of CO_2 from natural gas, CO_2 concentration of 80%, methane concentration of 20%	2.25 km pipeline	Storage in saline aquifers 1565 m deep; injection started in September 2009; a total of 80 000 t of CO_2 have been stored	Determination of the injection rate in different stages according to scientific tasks; research on geophysical monitoring and imaging technology at different CO_2 injection rates, and especially at small CO_2 injection rates; the world's first facility for studying the impact of CO_2 injection on the sealing property of faults; possesses the most complete site experimental facilities and indoor experimental facilities at present; layout of facilities for permanent 3D seismic monitoring, borehole fiber optic DAS VSP, passive seismic monitoring, surface deformation, environmental monitoring, and so forth
Ketzin, Germany	Small-scale industrial hydrogen-production project Schwarze Pumpe	Transportation with tankers	Storage in deep saline aquifers 630–650 m underground; injection started on June 30, 2008 and ended on August 29, 2013; a total of 67 271 t of CO_2 were stored	Most successful 4D seismic monitoring in the world; most successful monitoring with the resistivity method; unique combination of borehole monitoring with geophysical surface monitoring; long-term monitoring after well closing; main research goal was the movement process of pinnate fluids in reservoirs after CO_2 storage underground; the analysis performed used a comprehensive monitoring technology that facilitated safe CO_2 storage operations in complex reservoirs and environmental assessment; achieved the most successful prediction of the CO_2 reserves and storage capacity
Tomakomai, Japan	Capture of high-concentration CO_2 (industrial separation/chemical adsorption) in the hydrogen-production process of refineries, at a rate of 100 kt·a^{-1} CO_2	Injection of CO_2 from the capture end into the injection well located on the land	Storage in two sets of seabed saline aquifers 1000 and 3000 m deep, respectively; horizontal well injection mode; a cumulative storage of 300 110 t of CO_2 from April 6, 2016 to November 22, 2019	Used HiPACT equipment, developed jointly by JGC and BASF, to capture CO_2; utilized a chemical absorption process of newly developed absorbing solvents with characteristics such as stable thermal degradation resistance and excellent CO_2 absorption performance; achieved CO_2 liquid–vapor separation process and energy conservation at high pressure (3–5 atm (1 atm = 101325 Pa)), thus greatly reducing the energy and cost burden of CCS projects, as well as the cost of CO_2 recovery and compression from 25% to 35%; developed an advanced and unique ocean-bottom cable; achieved four-component time-lapse seismic monitoring, marine streamer 4D seismic monitoring, ocean-bottom seismometer monitoring, land borehole monitoring, and earthquake network-combined monitoring systems; involved the injection of CO_2 from land into two sets of seabed sandstone and basalt formations
In Salah, Algeria	Separation of CO_2 (5.5% CO_2 content) from natural gas in the Salah Oil Field of BP (Algeria), with a scale of 1.0–1.2 Mt·a^{-1} CO_2	Direct separation of CO_2 from wellhead natural gas; transportation of CO_2 to the CO_2 injection well	Storage in a deep saline aquifer 20 m thick and 1880 m underground; injection started in August 2004, and ended in June 2011 due to caprock leakage risks caused by injection after monitoring analysis; a total of 3.8 million tonnes of CO_2 were stored	Injection into one set of saline aquifers; performed the world's first research on surface-deformation monitoring with InSAR, through which it was found that, after CO_2 injection into the saline aquifer deep underground, the surface deformed significantly [29], possibly causing a risk of leakage through the caprock; 3D seismic monitoring (performed multiple times), micro-seismic monitoring, and tiltmeter/GPS; borehole wall leakage was found during wellbore integrity monitoring, possibly due to the geochemical reaction of well cement with CO_2

VSP: vertical seismic profiling; DAS: distributed acoustic sensing; DTS: distributed temperature sensing; GPS: Global Positioning System; HiPACT: high pressure acid-gas capture technology; JGC: Japan Gasoline Company; BASF: Badische Anilin-und-Soda-Fabrik; InSAR: interferometric synthetic aperture radar.

hydrogen-production process are about 55%, 16%, and 5%, respectively. The cost of CO_2 capture for low-concentration emission sources always accounts for the great majority of CCS investment, while the cost of geological storage is the lowest. In addition to the high cost of investment in carbon capture facilities, there is still room for the optimization and improvement of the compression process and steam energy consumption; moreover, the very high solvent degradation rate requires the replenishment of solvents in large quantities during the operation of capture facilities, increasing the operating cost and the cost of capture.

The CO_2 capture process also presents various additional challenges, including limited land space, a limited water resource utilization rate, tolerance to other flue gas components (i.e., the need to adapt to the emission sources of different flue gas components including iron and steel, cement, smelting, etc.) and other local power plant standards (e.g., the main operation and maintenance intervals and the reduction of output loads). The scale of capture is also an important indicator of technological advancement, as large-scale post-combustion capture has many benefits. Many of the abovementioned performance issues are being solved. For example, companies such as China Huaneng Group are exploring how to adjust the solvent makeup for each flue gas in order to reduce degradation issues.

The scientific community has carried out a great deal of research in the field of low-concentration CO_2 capture technologies [31–34], but there are few technologies that can be commercialized on a large scale. As the world's first post-combustion CO_2 capture facility for a megaton-scale coal-fired power plant, the completion and operation of the SaskPower BD3 capture facility in Canada is a milestone. The capture facility has been in stable operation since it was first put into operation on October 2, 2014. As of the end of May 2021, it has captured a total of 4.143519 million tonnes of CO_2. Its annual actual capture capacity is greater than 75% of the designed scale. The capture process uses Shell's Cansolv technology, which is an integrated SO_2–CO_2 thermal capture process that uses a proprietary amine solvent. These solvents are regenerated using low-pressure steam from the power plant. At the SaskPower BD3 capture facility, the high energy requirements for the regeneration of amine-based solvents, solvent degradation, and so forth require optimization and improvement [35]. Among the second-generation capture technologies supported by the US Department of Energy, Linde/Badische Anilinund-Soda-Fabrik (BASF)'s advanced aqueous amine solvent process [36] achieves a capture energy consumption of less than 2.7 $GJ\cdot t^{-1}$ of CO_2 (at an unknown operation scale), and the smallest amine-based solvent degrades during 5500 h of operation. Baker Hughes' compact carbon capture technology is more suitable for most emission sources for which the space for capture land is not reserved, and has a good application prospect.

The coal-powered Petra Nova plant contains the largest coal-fired power-plant CO_2 capture facility in the world, with an annual CO_2 capture capacity of 1.4 $Mt\cdot a^{-1}$. CO_2 capture is carried out using Kansai Mitsubishi's CO_2 recovery process. The process uses a proprietary KS-1 solvent (a sterically hindered amine), which is regenerated using the steam from an independent gas-fired power plant. The CO_2 generated from the Petra Nova post-combustion plant is used for EOR, so low oil prices will affect the operation of the capture facility until regulations are in place to reduce industrial carbon footprints.

Projects with landmark CO_2 capture facilities include the capture project of the United Arab Emirates (UAE) Al Reyadah steel plant, which has a capture capacity of 800 $kt\cdot a^{-1}$ CO_2 and uses the gas-based direct reduced iron (DRI) process; the UK Drax biomass power-generation capture facility, which is under construction, with a projected capture capacity of 4 $Mt\cdot a^{-1}$; the 400 $kt\cdot a^{-1}$ Norcem Brevik CO_2 capture project by Norway Heidelberg Cement; the 400 $kt\cdot a^{-1}$ capture facility for the Fortum Oslo Varme waste incineration process; the 6 $Mt\cdot a^{-1}$ CO_2 capture facility of the Mustang Station Natural Gas Power Plant; the full-scale 800 $kt\cdot a^{-1}$ capture facility that is about to be built for the Canadian Heidelberg Caspian Lehigh Cement Plant; and the 750 $kt\cdot a^{-1}$ capture facility for chemical processes such as hydrogen production by Shell (Canada) Polaris. The 3 $Mt\cdot a^{-1}$ CO_2 capture facility of the Kemper County integrated coal gasification combined cycle (IGCC) was unsuccessful; however, the ambition shown by this project and the accumulation of experience from it are still useful as an exploration of large-scale pre-combustion CO_2 capture technology.

The characteristics of industrialized technological progress: The experience and lessons learned in the early operation of technologies are applied to improve the design and operation of the next-generation equipment, thereby improving efficiency and reducing capital and operating costs. It was the success of the SaskPower BD3 capture facility that led to the subsequent establishment of the second-generation post-combustion capture technology for the Shand Power Station, which is based on the operation practice of the first-generation CO_2 capture facility but reduces the project cost by 67% [8,37].

5. The status quo of China's CCS projects

At present, China does not possess full-process CCS science and technology infrastructures, and current CCS research is carried out through small-scale full-process CCS pilot test projects and CO_2-EOR demonstrations [38–41]. The main goal of these projects is to study CO_2-EOR in order to improve oil recovery. Field-level research on the safety of CO_2 geological storage in China is insufficient. Although many scholars have carried out related monitoring studies [42,43], there is not enough evidence to confirm CO_2 storage capacity, CO_2 distribution, and storage safety; moreover, Chinese scholars are not significantly involved in researching the geological storage of CO_2. China is inherently deficient in its CCS-related scientific research level, technical level, and investment funds, and a very big gap exists between China's CCS research infrastructures and those of advanced countries.

China's early CO_2-EOR projects in China National Petroleum Corporation (CNPC) and Sinopec used CO_2 from the natural CO_2 fields for CO_2 flooding and storage. However, as mentioned earlier, such projects cannot be recognized as CCS and emission reduction projects. The subsequent Shenhua Ordos Saline Aquifer CCS Demonstration, Jingbian CCS, Sinopec Zhongyuan Oilfield CO_2-EOR, and CNPC Changqing Oilfield CO_2-EOR are demonstrations based on low-cost and high-concentration CO_2 captured from coal chemical plant [38–41].

Current CO_2 capture experiments and demonstrations based on low-concentration CO_2 sources include the CR-Power (Haifeng) carbon capture test facility built by China Resources Holdings in Guangdong in May 2019, the 100 $kt\cdot a^{-1}$ CO_2 capture unit of the Shanghai Shidongkou Second Power Plant built by the China Huaneng Group in 2009, the 60 $kt\cdot a^{-1}$ pre-combustion capture facility of the Tianjin IGCC Power Plant completed by the China Huaneng Group in 2017, the 50 $kt\cdot a^{-1}$ post-combustion capture facility of the Anhui Baimashan Cement Factory, and the newly built 150 $kt\cdot a^{-1}$ CO_2 capture facility of the Guohua Jinjie Power Plant of the National Energy Group in Shaanxi. However, there is no downstream large-scale storage or utilization project for these CO_2 capture facilities, so they cannot complete long-term capture and full-load operation tests. There is a large gap between China and the United States and Canada in terms of the testing of capture technologies, including the testing of different types of adsorbents, operational efficiency, operational stability, energy consumption, and—especially—the scale of capture.

6. Key scientific and technical issues in the geological storage of CO_2

CCS projects are based on actual geological storage capacity, the safety of geological storage, and the monitoring, reporting and verification (MRV) of CO_2 emission reductions [44]. This is the basis for enterprises to enter the carbon trading market and obtain government incentives, such as the 45Q tax credit in the United States and carbon tax in Norway and Canada. Early in 2008, the National Academy of Engineering regarded carbon storage as one of the 14 major unsolved engineering challenges in the 21st century. In 2019, the *MIT Technology Review* listed carbon storage as the first of the top 10 technical challenges in the world. The most critical scientific and technical issue is how to study and develop a series of technical methods for the MMV of field-level geological storage of CO_2, and then to assess the underground storage risk and storage capacity, and ensure the safety of long-term underground storage. The US Department of Energy began funding CCS research in 1997, and its initial investment focused on geological storage [45,46]. It is only once the geological storage problem is solved that the destination of captured CO_2 can be ascertained, which in turn drives the development of CCS projects.

6.1. Safety and risk monitoring

Concerns about the safety and risks of the geological storage of CO_2 have always been one of the primary CCS-related topics in the scientific community and among the public [47,48]. The risks of the geological storage of CO_2 mainly come from three aspects: ① Direct leakage channels may be present, such as injection or production wells connecting geological storage bodies, underground water layers, and the atmosphere [49–51]; ② the CO_2 injected underground might induce earthquakes, open faults, or breaks through caprocks, resulting in leakage; and ③ external forces such as natural earthquakes might damage geological CO_2 storage bodies (including borehole walls) so as to cause leakage. During the operation of injection or production wells, the wellbore may narrow, expand, rupture, or collapse, and corrosion of old well casings and cement sheaths may occur, creating leakage paths with the highest risk in CO_2 geological storage. Wellbore integrity ensures the safety of geological storage. Therefore, the US National Environmental Protection Agency (EPA) has established the Class VI Rule for CO_2 geological storage wells, which aims to ensure the safety of wellbores and the long-term safety of geological storage during CO_2 injection.

Two CCS scientific research facilities in Nagouka and Tomakomai, Japan, focus on investigating whether natural earthquakes will cause damage and leakage risks to geological CO_2 storage facilities. Geological CO_2 storage bodies in these two areas of Japan have experienced multiple earthquakes, including earthquakes with magnitudes of 6.8 and 6.7 and epicenters just 20 and 30 km away, which did not cause any leakage in the projects [52–54]. Scholars from the Research Institute of Innovative Technology for the Earth (RITE) checked the borehole wall integrity of the Nagouka Project before and after the earthquakes, assessed the seismic bottom hole pressure and injection facilities, conducted air tightness/pressure tests [55], and demonstrated the safety of the wellbore by means of acoustic cement bond log (CBL) and hole imaging.

However, CO_2 that has been injected underground might induce earthquakes, resulting in danger due to the opening of faults or the breakthrough of caprocks. This issue presents difficulties in safety monitoring and early warning, as the relevant pressure-change law and CO_2 flow direction are unknown. A paper published by Zoback and Gorelick [56] in 2012 triggered a debate among scientists by pointing out that CO_2 injection and geological storage may induce earthquakes, and that even a small earthquake will cause CO_2 to escape to the surface. The main problem with this perspective lies in the fact that Zoback's experimental research was based on granite; however, it is extremely unlikely for granite to be used as the sealing layer or caprock in actual storage. Secondly, it is unreasonable to deem that the permeability of both joints and fractures in caprocks will increase in all cases so as to form a path allowing the migration of CO_2 to the surface. The degree of increase in the permeability of joints and fractures depends on multiple factors such as rock type, stress state, and fillers. In fact, in many cases, large faults exhibiting a large degree of slippage play a sealing role and have no impact on permeability. This is the case with reservoirs in California (USA), Iran, and even China's Bohai Bay Basin; despite frequent large earthquakes, oil and gas reservoirs can still be preserved very well without leakage. In these regions, the faults themselves play a sealing role rather than being fluid-migration channels; in fact, the reservoirs of oil and gas were originally formed in previous geological periods because the faults blocked the migration of oil and gas. The fault discussed by Zoback is a huge fault extending from a deep injection layer to the surface. The possibility of such faults in a basin is very low, and they can be avoided in the selection of geological storage sites. MIT scholars [57] and Carnegie Mellon University scholars [58] have all deemed the possibility of generating huge faults by earthquakes induced by CO_2 injection and storage to be extremely low.

Geoscience Australia [59] is taking the lead in studying the safety of fault sealing in a field-scale CO_2 injection project being carried out at the CO2CRC Otway scientific test site. So far, no leakage of CO_2 along the fault has been found. Of course, similar to the induction of earthquakes by oilfield water flood development and geothermal exploitation [60], large-scale fluid injection may induce earthquakes [61]. In order to prevent the induction of earthquakes during CO_2 injection, pressure control is the most important regulatory measure [62], as the activation of faults and caprock breakthroughs are mainly caused by pressure changes.

6.2. Fault activation and caprock breakthrough

An assessment of the safety and risks of geological storage of CO_2 requires an investigation on whether the injected CO_2 will break through a complete structure or lithologic trap, such as wellbores, multiple sets of faults, or caprock combinations. The following considerations need to be ascertained and understood: the CO_2 storage capacity of geological traps; the migration and accumulation principles of CO_2 injected into reservoirs in strata; the possibility of leakage or seepage caused by the opening of faults or caprocks by the injection pressure or external forces; possible paths of CO_2 leakage; whether CO_2 will escape to the shallow surface to pollute underground drinking water and cause damage to the surface ecological environment; if CO_2 leaks through breaking caprock or opening the fault firstly but does not escape to the surface, whether multiple sets of caprocks in the overlying strata of reservoirs will continue to seal and isolate the CO_2 for a second time; and how to ensure wellbore integrity and ascertain whether reservoir engineering, technology, and so forth will cause wellbore damage and CO_2 leakage.

Research on the safety and risks of the geological storage of CO_2 has already been carried out internationally in a series of large-scale geological storage and scientific research projects that focus on researching field-level safety and risk monitoring and verification. Some scholars consider that a small part of the injected CO_2 might have broken through the caprocks and faults and entered the overlying strata in the Weyburn Project (personal communication). Because it was impossible to conduct field-level monitoring in the overlying saline aquifer, the possible breakthrough position was not known. It could not be detected using geochemical methods, and no abnormal noise was found through passive seismic monitoring. During the injection process—and especially after the storage was completed—the use of geophysical (4D seismic) methods were the only feasible means to monitor and verify the caprocks and overlying strata [26,63].

China has also carried out a number of small-scale CO_2-EOR and storage projects and CO_2 storage demonstration projects in saline aquifers in Ordos [38,39,64]; however, the focus of these projects is CO_2-EOR [65]. While there are many numerical simulations for the research and verification of geological storage safety, there are few studies on the field-level and large-scale risk monitoring and verification of caprocks and faults; thus, the distribution scope, safety, and storage capacity of CO_2 underground cannot be definitively known. Surface 4D seismic monitoring of CO_2 injections has only been carried out in the Gao-89 block of the Sinopec Shengli Oilfield [66]. Although the findings of domestic CO_2-EOR projects have not been publicly reported, the leakage of CO_2 along borehole walls into the overlying strata is currently the predominant risk. No CO_2 leakage caused by fault opening has been observed in any of the CO_2-EOR projects at home and abroad.

The petroleum industry has very mature and successful experience in studying and predicting the integrity of caprocks. Of course, concerns about the storage process still remain: For example, when CO_2 is in contact with the caprock, will the geochemical reaction of CO_2 with the rocks affect the pores and permeability [67]? What is the mineralization situation of CO_2 in reservoirs? Will CO_2 diffuse to caprocks and then corrode leakage channels? What are the requirements for caprock thickness in order to seal off CO_2? Nevertheless, the preservation and sealing of existing natural CO_2 in gas fields have demonstrated that these concerns are unnecessary [68–70].

At present, more than 90% of geological CO_2 storage projects are being carried out in oil reservoirs; however, deep saline aquifers are still the largest geological CO_2 storage spaces and those with the greatest potential. White et al. [71,72] used InSAR data to observe the surface deformation near a CO_2 injection well with saline aquifers that was carried out by BP and others in In Salah, Algeria; the researchers then supported the hypothesis that the reservoir was fractured and the bottom caprock was broken through after nearly four million tonnes of CO_2 had been injected into the 950 m deep saline aquifer, although no CO_2 leakage was observed on the surface. No surface deformation has been observed in other large-scale CO_2 storage projects around the world, such as the Weyburn Project in Canada.

Verdon et al. [29] compared the stress deformation caused by the three megaton-scale geological storage projects Sleipner, In Salah, and Weyburn. The comparison showed that the impact of injection pressure on the safety of geological storage is the greatest for low-permeability saline aquifers. Pressure control is a key scientific problem to be solved for the safety and future leakage risks of geological storage of CO_2 in either reservoirs or saline aquifers [62].

Of course, assuming that CO_2 breaks through a set of caprock or opens a fault and then enters the previous set of strata, as long as the CO_2 is blocked by multiple sets of overlying caprocks layer by layer, it is not considered to be leakage. Research conducted by Rinaldi et al. [73] showed that induced seismic activities related to fault resurrection will not necessarily open a new flow path for leakage. A single induced event in a layer is usually insufficient to substantially change the permeability over the entire length of the fault. In that case, even if changes occur in the permeability of a certain section of the fault, it does not mean that CO_2 will migrate upward along the entire fault, break through multiple sets of caprocks, and then enter the overlying drinking water layer [74].

6.3. MMV of CO_2 geological storage capacity

Many scholars have carried out core experiments and numerical simulation studies on caprock sealing properties and fault opening under the conditions of the chemical and physical actions of CO_2–saltwater–strata [75,76], deepening our understanding of the possibility of the evolution of caprocks and faults during the long-term geological storage of CO_2. However, the physical and chemical changes in these reservoirs, as well as changes in the chemical reactions of CO_2–water–rocks in caprocks and faults [67], are relatively small compared with changes in formation pressure and CO_2 saturation [77], and thus are not easily observed and monitored. The safety of geological CO_2 storage has a mutually corroborating relationship with geological CO_2 storage capacity. The monitoring and verification of geological CO_2 storage capacity can identify both emission reductions and leakage risks that may be predicted when the injection volume is not equal to the storage capacity. The most critical parameters are formation pressure and CO_2 saturation, because an increase in formation pressure after CO_2 injection may induce breakthrough through caprocks and faults, as well as borehole wall breakage. In addition, CO_2 saturation is a key parameter in determining the underground distribution scope of CO_2 and calculating the storage capacity. Of course, monitoring of CO_2 distribution has to demonstrate that CO_2 may or may not break through multiple sets of caprocks or open multiple sections of faults and then enter the shallow surface or the atmosphere before the occurrence of real leakage is ascertained. Monitoring of the surface environment and monitoring of underground phreatic aquifers are also important links in determining whether CO_2 will leak to the surface or to the shallow surface.

Borehole observation is the most direct method to monitor the safety of the geological storage of CO_2. However, in most cases, the risk of breakthrough through caprocks and faults is not around the injection wells, and the scope of well monitoring is very limited. Relying on surface geophysical monitoring, and especially 4D seismic techniques, to monitor changes in underground geological storage bodies has become the preferred technical means for geological CO_2 storage projects around the world [16,27,78]. In all CCS science and technology infrastructures (Table 1), 4D seismic imaging has become the most effective evidence to prove the safety, distribution scope, and distribution status of the geological storage of CO_2. The Ketzin project accurately predicted CO_2 saturation and CO_2 storage capacity [79], which may be related to the relatively shallow CO_2 storage. The Aquistore project drew many lessons from the Weyburn Project, deployed permanent geophones, and used Vibroseis to avoid the problem of non-repetitive shot point locations in two vintages of 3D seismic monitoring with dynamite sources. Borehole distributed acoustic sensing (DAS) technology was used to obtain pressure, temperature, and VSP monitoring data at different depths at the same time without affecting CO_2 injection in the well [80]. Meanwhile, 4D surface seismic monitoring before CO_2 injection was carried out to study the impact of changes in shallow-surface elastic parameters caused by seasonal changes on 4D seismic differential information [81]. It was demonstrated that CO_2 distribution could still be imaged by means of seismic monitoring under the conditions of a 10 kt injection scale and CO_2 injection in the deepest (3400 m) saline aquifer in the world [82]. The distribution and saturation of CO_2 at a depth of 1500 m and with an injection volume of 5000 t were successfully imaged using CO2CRC Otway advanced 4D seismic monitoring with a buried DAS array, 4D VSP with optical fibers on the tubing, and continuous seismic sources [83]. To image CO_2 distribution, the Sleipner [16] and Tomakomai [25] projects used marine 4D seismic monitoring technology, which is the most effective monitoring means for the storage of CO_2 in deep saline aquifers. Sleipner

[84] carried out time-lapse gravity monitoring and was the first to demonstrate the effectiveness of low-cost gravity monitoring technology for the monitoring of large-scale geological storage of CO_2. The combination of time-lapse gravity monitoring with seismic monitoring improves the accuracy of seismic prediction of CO_2 storage capacity.

However, when using conventional P-wave information, it is difficult to identify whether the difference between two vintages of seismic monitoring comes from changes in pressure or from CO_2 saturation [78,85]. Therefore, the Weyburn Project used advanced 4D and three component (4D3C) seismic monitoring technology and combined P-waves with converted waves to distinguish pressure changes from CO_2 saturation changes. Although many difficulties still remain in the processing and interpretation of 4D converted-wave data at present, and the expected results have not been achieved, this represents the forefront of seismic monitoring technology.

An issue with CO_2 saturation—a key parameter in predicting CO_2 storage capacity—is that it is difficult to accurately determine the CO_2 saturation in a well; in particular, after CO_2 injection, it is more difficult to accurately measure CO_2 saturation in a cased well than that in the uncased well. The Nagaoka project was the first to carry out geophysical logging more than 40 times in a well after CO_2 injection and has thus become a model for identifying CO_2 changes before and after injection in reservoirs and in different stages by logging multiple times [55,86]. At present, the monitoring results of underground CO_2 distribution mainly provide the CO_2 distribution in a set of strata. When monitoring the CO_2 injected into two sets of saline aquifers—such as the volcanic and volcaniclastic Miocene Takinoue formation at 2400 to 3000 m which is the second CO_2 injection layer in the Tomakomai project—no monitoring images for CO_2 distribution have been obtained. Further research on monitoring and imaging methods to obtain the CO_2 distribution status in multiple sets of reservoirs is necessary in order to determine whether CO_2 enters other reservoirs from the injection layer, and then whether geological storage is safe. The MMV of geological CO_2 storage requires the combination and mutual corroboration of multiple disciplines such as geology, geophysics, geochemistry, petroleum engineering, and more in order to demonstrate the safety of long-term geological CO_2 storage.

7. Concluding remarks

Based on the experience of advanced countries in CCS development, CCS in other countries will undergo a gradual transition from low-cost and high-CO_2-concentration capture from coal chemical plant, low-cost natural gas purification and capture combined with flooding and storage, or direct storage in saline aquifers, to low-concentration tail gas capture in coal-fired power plants, refining and hydrogen production, steelworks, cement, and so forth. The difficulty in capture technology still lies in the large-scale capture of low-concentration CO_2 tail gas with low energy consumption, while the difficulty of geological storage lies in how to carry out field-level MMV to determine geological CO_2 storage capacity, emission reductions, and storage safety.

The science and technology CCS infrastructures that have been built in advanced countries play a crucial role in the understanding of basic scientific problems related to CCS, reduction of the cost of whole-process CCS technology, monitoring of the safety of long-term geological storage, R&D of advanced technologies, and further commercialization, promotion and demonstration, and talent training. Sharing the CCS research results and knowledge of advanced countries makes it possible to accelerate the reduction of the cost and risks of CCS and the commercial layout of CCS in other countries; however, the complexity of geological conditions makes it difficult to directly replicate many technologies and achieve the desired results using them. For example, CO_2-EOR in China has not achieved the same high recovery and stable flooding results as in North America. Insufficient studies and understanding of scientific issues such as the storage status, migration and accumulation principles, and safety of CO_2 injected underground have restricted the large-scale development of CO_2-EOR and storage. Without the research and technical support of scientific CCS research facilities, even if the construction of large-scale CCS projects was carried out, it would be difficult to run the projects consecutively, and thus the goal of large-scale rapid emission reduction would not be achieved.

CCS hubs, in which various carbon emitters are matched with appropriate local carbon storage areas and carbon transport is established excellent, can achieve the cost reduction and large-scale reduction of emissions from different types of emission sources within a region; thus, such hubs are the development direction of future commercial CCS projects. However, a CCS hub has higher requirements for the geological storage capacity of storage sites, and the detailed and accurate selection of geological storage sites is particularly important. The CO_2 storage potential and injection capacity of a storage site determine the scale of the capture and transmission pipelines and the construction scale of the CCS hub.

The key direction for the future development of geological CO_2 storage is the storage of CO_2 in saline aquifers, followed by the storage of CO_2 in oil reservoirs and abandoned gas fields. The storage of CO_2 in saline aquifers allows more types of high-carbon emission sources to be located nearby, which reduces the construction cost of long-distance CO_2 transportation pipelines and the carbon footprint in the production and laying of steel pipes. Storage in saline aquifers does not require the emission of CO_2 to be captured into high-purity CO_2 in order to reduce the cost of capture. During the deployment of CCS, it is necessary to improve the energy utilization efficiency and reduce the carbon footprint in each link of the entire process, calculate from the perspective of the entire process, and achieve net emission reduction at the lowest cost.

According to the construction period of successful large-scale CCS projects in advanced countries, it takes 5–10 years from site selection to the completion and operation of a CCS project. To achieve the 2030 CCS emission reductions estimated by the IEA and CSLF, action must start now; otherwise, the long-term temperature goal of the Paris Agreement cannot be achieved. Of course, the most important factors in the successful development of CCS in advanced countries such as the United States, Norway, and Canada are the country's incentive policies (e.g., 45Q), carbon taxes, and restraint policies on enterprises' carbon emissions. The European Union and China's carbon markets have a positive role to play in promoting CCS technology. The increase in carbon prices will help CCS to gradually move toward profitability and commercialization.

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Compliance with ethics guidelines

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