Role of Carbon Capture and Storage in Meeting the Climate Mitigation Target

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Abstract Scientific studies over the years have clearly indicated warming of global climate due to rising concentration of anthropogenic greenhouse gas emissions. Continued emissions are certain to lead to catastrophic consequence. Deliberating on this very important issue of sustainability of the entire earth for a long period, the global community finally reached consensus during the Paris Climate Agreement in 2015 to limit the temperature rise to 2 °C by 2050 and even try to achieve a lower temperature rise. Amongst other options like adoption of renewables on a much larger scale, fuel switching, and increasing power system efficiency; carbon capture and storage is perceived to be another feasible option for meeting this global climate mitigation target. Carbon capture and storage (CCS) essentially means chemically capturing CO_2 from power plants running on fossil fuels, especially coal, transport and then store it permanently in some geological formation beneath the earth. As per the estimate of International Energy Agency, 12% of the total greenhouse gas emissions totaling about 94 Gt of cumulative CO_2 emissions have to be stored into the subsurface geological formations up to 2050. Considerable research and development work backed by experience gained through demonstration and commercial projects, the technology is mature now. Although the first CCS project commenced operation more than twenty years back, the progress has been slow over the years due to many techno-economical factors and other policy issues. However, in the recent years, there has been significant progress in actual deployment of the technology with more than 21 large-scale running projects and projects under advanced construction. Furthermore, a number of projects are in the pipeline. The total installed capacity of all these projects is approximately 70 Mt of CO_2 per year. Although CCS is a proven technology now, notwithstanding the recent growth in deployment, the rate of adoption is still not in track to meet the global target set for 2050.

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1 Introduction

1.1 Global Warming and Rising CO_2 Concentration

A series of scientific studies over the last few decades have consistently pointed towards warming of the environment due to anthropogenic greenhouse gas (GHG) emissions. The major source of greenhouse gas is CO_2 emission from usage of fossil fuels. In the nineteenth century French physicist Joseph Fourier and Irish physicist John Tyndall first described the earth's natural "greenhouse effect" due to the existence of water vapor and a few other gases. A few years later, Swedish chemist Svante Arrhenius predicted that industrial-age coal burning would enhance this natural greenhouse effect. However, they said that this effect might be beneficial for future generations. The first evidence of rising global temperature came in 1938 when British engineer Guy Callendar collated records from 147 weather stations to show that the global temperature had risen over the previous century. He also showed a corresponding rise in CO_2 concentration over the same period and suggested that this rise in CO_2 concentration might be the cause of warming. However, Charles David Keeling gave the first unequivocal proof of rise in CO_2 concentration in 1958 when he systematically measured atmospheric CO_2 for four years at Mauna Loa in Hawaii and in Antarctica. Continued recordings at Mauna Loa indicated that half a century after the first recording, the CO_2 concentration had risen from 315 to 380 ppm in 2008 and then to over 400 ppm in 2012 [1]. Satellite images captured over the last few decades clearly show reduction in ice cover over the Arctic. A very disturbing trend emerged from the data collated by National Snow & Ice Data Center (NSIDC) on sea ice cover and depicted in Fig. 1, which shows that for the first time in the history of data recording since 1978, the sea ice cover did not grow during September–November in 2016.

1.2 Global Warming and International Actions

A US President's Advisory Committee panel in 1965 indicated that greenhouse effect is a matter of "real concern". But, the series of international environment conferences, starting from Stockholm in 1972 to Montreal in 1987, did not explicitly address the global climate change issue until the formation of Intergovernmental Panel on Climate Change (IPCC) in 1988. Following the first assessment report of IPCC released in 1990, which indicated a rise in global temperature by 0.3°–0.6 °C over the last century due to anthropogenic emission, the governments agreed on the United Nations Framework Convention on Climate Change (UNFCCC) during the Earth Summit at Rio in 1992 "stabilizations of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". Since then, IPCC have come up with a series of assessment reports. The latest one, the fifth

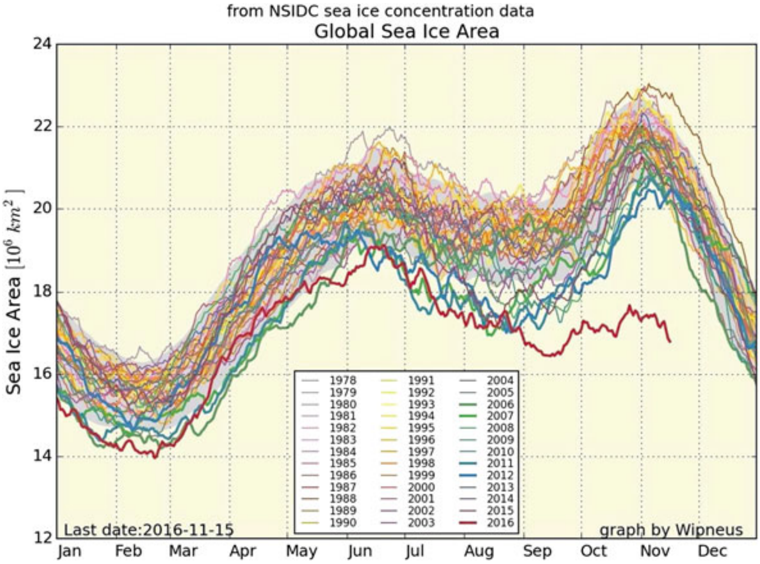

Fig. 1 Global sea ice variation statistics from 1978 to 2016 [2]

assessment report, was released in 2013. In between, a number of international negotiations took place starting from the Kyoto Protocol in 1997 to the UN Mexico summit in 2010 for reaching to a consensus on taking definitive actions for limiting global warming. Some positive actions were definitely observed but international politics and compulsions back home prevented some of the largest GHG emitting countries in the world in agreeing and coming to common platform, which might lead to result-oriented actions.

IPCC fifth assessment report (AR5), the latest in the series of IPCC reports, highlights the changes in earth's environment, trends in global greenhouse gas emissions, and the likely consequences of further warming. Following are some of the excerpts from the report [3]:

- Earth's surface was found to be successively warmer during the last three decades and the warmest 30-year period of the last 1400 years in the Northern Hemisphere was the period between 1883 and 2012. Based on globally averaged combined land and ocean surface temperature data, warming of 0.85 °C was recorded over the period 1880–2012.
- The rate of mass loss at the Greenland and Antarctic ice sheets is much larger over 2002–2011 compared to the corresponding 20-year period of 1992–2001. Glaciers have continued to shrink almost worldwide. In response to increased surface temperature and changing snow cover, it is very likely that permafrost temperatures have increased in most regions since the early 1980s.
- Between 1901 and 2010, the global mean sea level rose by 0.19 m.

- Large increases in the atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) have resulted due to anthropogenic GHG emissions between 1750 and 2011. Cumulative anthropogenic CO_2 emissions during the period to the atmosphere were 2040 ± 310 $GtCO_2$. Out of this, about 40% of the emissions have remained in the atmosphere (880 ± 35 $GtCO_2$). The rest was removed naturally from the atmosphere and stored in land and in the ocean. About 50% of the anthropogenic CO_2 emissions have occurred in the last 40 years.
- Despite a growing number of climate change mitigation policies total anthropogenic GHG emissions have continued to increase over the last three decades, which has reached 49 ± 4.5 $GtCO_2$-eq/year in 2010. Out of this, fossil fuel combustion and industrial processes contributed about 78% of the total GHG emissions increase from 1970 to 2010.
- Unless substantial efforts are undertaken to reduce GHG emissions beyond those in place, growth in global population and economic activities will lead to persistent growth in emissions, which may result in 3.7–4.8 °C global mean surface temperature increase in 2100 from compared to pre-industrial levels.
- To limit the rise in temperature to 2 °C relative to pre-industrial levels, the maximum allowable atmospheric concentrations is about 450 ppm CO_2 equivalent. For this to happen, cumulative CO_2 emissions from all anthropogenic sources since 1870 should remain below about 2900 $GtCO_{2.}$ Out of this, the cumulative emission by 2011 is about 1900 $GtCO_2$.

Under UNFCCC a landmark agreement was reached at the 21st conference of parties (COP21) in Paris in December 2015 between all the participating countries [4]. It could well be a turning point is fighting global climate change, which states “holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change.” To achieve that goal, countries should “reach global peaking of greenhouse gas emissions as soon as possible, recognizing that peaking will take longer for developing country parties, and to undertake rapid reductions thereafter.”

2 Carbon Capture and Storage Technology

2.1 Need for Carbon Capture and Storage

It is quite evident from the discussion in the last section that stabilizing the global climate would require large-scale effort to reduce anthropogenic GHG emissions. The most effective process to achieve this would be to completely stop burning of fossil fuels as soon as possible. Significant progress has been made towards adoption of alternate and renewable energy and the world will continue to strive for zero carbon emission. However, it is quite likely that fossil fuels will continue to burn for power generation and other industrial processes in the next decades to come. In this context, ‘carbon capture and storage’ (CCS) or carbon sequestration, a technology that prevents release of large amounts of CO_2 into the atmosphere generated through burning of fossil fuels, becomes important. CCS involves chemically capturing CO_2 from the flue gas of large industrial plants, compressing it for transportation, and then injecting into subsurface rock formations for permanent storage.

2.2 *Carbon Capture*

Capturing CO_2 is the first step in carbon capture and storage, which can be applied to large-scale emission sources like fossil fuel-fired power generation, natural gas processing, fertiliser production, manufacturing of industrial materials such as cement, iron and steel etc. Large-scale capture technologies have been operational at in the natural gas and fertiliser industries for quite some time and have recently been tried in the power sector. Three basic types of CO_2 capture; pre-combustion, post-combustion and oxyfuel with post-combustion have been practised. Pre-combustion capture process involves conversion of fuel into a gaseous mixture of hydrogen and CO_2. The hydrogen is then separated and burnt with no production of CO_2. The remaining CO_2 is compressed for transport and storage. The process is relatively more complex than post-combustion, which make the technology almost impossible to apply to existing power plants but is used in natural gas processing. Post-combustion capture process separates CO_2 from flue gas. CO_2 is captured using a liquid solvent or by employing other separation methods. In the absorption-based approach, the absorbed CO_2 in the solvent once absorbed by the solvent is released by heating to form a high purity CO_2 stream. This technology is widely used to capture CO_2 for subsequent use mainly in the food and beverage industry. In oxyfuel combustion process, oxygen is used in place of air for combustion of fuel. The combustion produces exhaust gas comprising primarily of water vapour and CO_2, can be easily separated to produce a high purity CO_2 stream.

2.3 *Geological CO_2 Storage*

Geological storage involves injection of captured CO_2 into deep subsurface rock formations, thereby preventing it from being released into the atmosphere. Many subsurface geological systems exist in the world, which can retain centuries’ worth of CO_2 captured from industrial processes. Based on the current status of technology, the following primary geological formations, as depicted in Fig. 2, can be the potential targets for storage.

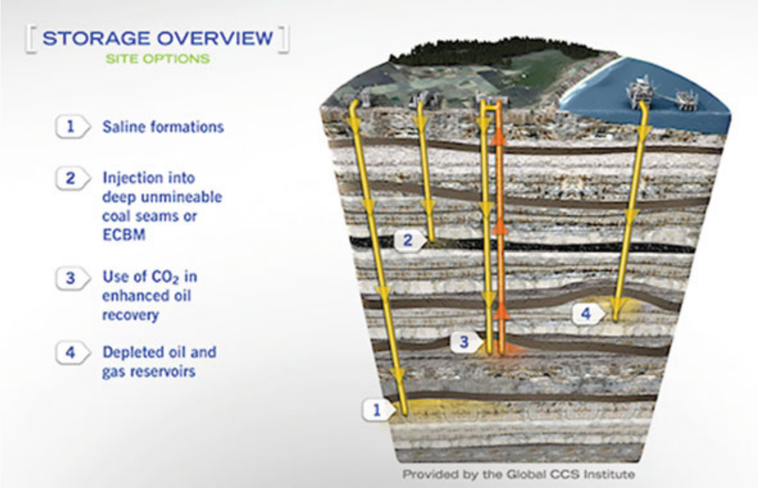

Fig. 2 Sites for geological CO_2 storage. *Source* www.globalccsinstitue.com

2.3.1 Saline Formations

Deep saline formations are the rock layers that bear non-potable saline water. The salinity of water may range from slightly brackish to a few times than the salinity of seawater. Only the formations, which are overlain by an impervious cap rock are suitable sites for permanent storage. Geological storage of CO_2 takes place through a combination of mechanisms, which include physical and chemical trapping. The process takes place over a large range of time and scale [5]. Physical trapping involves immobilization of CO_2 as free gas or supercritical fluid. There are two types of physical trapping mechanisms. The first one, known as static trapping, occurs in stratigraphic and structural traps. The other mechanism, known as residual trapping, takes place in the pores at residual gas saturation. When CO_2 dissolves in subsurface fluids, chemical trapping occurs, and finally the trapped CO_2 may induce chemical reactions with the rock matrix leading to mineral trapping. Under favorable circumstances, trapped CO_2 may continue migrating up within the subsurface at extremely low velocity. As a consequence, it would take tens of thousands to millions of years for the CO_2 to potentially reach the surface [6]. Theoretically, saline aquifers have the largest storage capacity of all geological sites and currently a number of CCS projects in saline aquifers are in operation.

2.3.2 Deep Unmineable Coal Beds

Methane gas is found abundantly in coal beds, where methane molecules are stored in the coal micropores in adsorbed form. This methane gas is extracted from the coal beds, known as coalbed methane (CBM), is an important source of natural gas worldwide. However, coal has much higher adsorption affinity to CO_2 than methane. When CO_2 is injected into coal beds that are too deep or uneconomic for mining presents distinct advantages. First, CO_2 is adsorbed into the coal leading to permanent storage. Second, adsorbed CO_2 molecules replace methane molecules from the adsorption site leading to additional methane release, the process known as enhanced coalbed methane (ECBM) recovery. Although methane is also a greenhouse has, it is much cleaner than coal and can be burnt in place of coal leading to much lower CO_2 emission. A number of pilot projects have been taken up for CCS in coal beds and ECBM recovery. This includes Alison unit in USA, Fenn Big Valley in Canada, Qinshui basin in China, Yubari in Japan, and Recopol in Poland. However, the general observation from these pilots is that CO_2 injection leads to lowering of permeability of coal, which seriously affects the gas flow process. The science of CO_2-coal interaction is yet to be adequately developed and the immediate scientific challenge for success of this process is to develop ways for overcoming this loss of permeability in coal beds. As a consequence, although regarded as a value-added option for CCS with the promise of additional methane recovery from the coal beds, no large-scale CCS projects in coal beds have been taken up till date.

2.3.3 Oil and Gas Reservoirs

Oil and gas reservoirs can store CO_2 under two different circumstances. There are many oil and gas fields, where major parts of the available hydrocarbon reserves have been extracted and the operations are no more viable. These depleted oil and gas reservoirs offer potential sites for CO_2 storage. The injected CO_2 gas can stay in the reservoir rock formation the same way the hydrocarbon has been staying there for millions of years. In the operating oil and gas fields, when the reservoir pressure becomes low to prevent free flow of oil into the well, injection of a miscible fluid like CO_2 can alter density and viscosity of the fluid resulting in easier flow of fluid from the reservoir to the well. This process is known as enhanced oil recovery (EOR). EOR has been practiced for several decades in the petroleum industry. But with increasing focus on combating climate change and CCS coming to the forefront as an emission mitigation option, greater attention is being paid to the potential for CO_2-EOR as a tool to support geological CO_2 storage. CO_2-EOR practices can be modified to deliver significant capacity for long-term CO_2 storage.

2.3.4 Bio-CCS

A more recent addition to CCS technology is bio-CCS, where a CCS project is combined with an industrial facility burning biomass for energy generation or consuming biomass as part of the process (e.g., Ethanol plants). In bio-sequestration, which is a part of natural carbon cycle, plants absorb CO_2 from the atmosphere and use this CO_2 for growth. In the industrial facilities burning or processing biomass the CO_2 is released back into the atmosphere. Therefore, energy production from biomass can be treated as 'carbon neutral', as it absorbs the CO_2 but then releases it back into the atmosphere upon combustion or processing. However, when CO_2 from the combustion or processing of the biomass is captured and then stored in geological formations instead of being released into the atmosphere, there may be net removal of CO_2 from the atmosphere, resulting in negative emission.

2.4 Global CO_2 Storage Capacity

Both onshore and offshore sedimentary basins with potential for CO_2 storage exist throughout the world. The estimates of the technical potential for different geological storage options are given in Table 1 [5]. These estimates and the associated uncertainties are based on assessment of literature and include both of regional bottom-up and global top-down estimates. Needless to say that in the absence of detailed assessment, these overall estimates vary widely with high degree of uncertainty. This is mainly due to the fact that detailed knowledge of saline formations is quite limited in most parts of the world. For oil and gas reservoirs, however, uncertainty is the estimate is relatively less, as this is based on the calculation involving replacement of original hydrocarbon volumes with CO_2 volumes. It should be noted that, with the exception of EOR, all these reservoirs would not be available for CO_2 storage until the depletion of hydrocarbons. Furthermore, pressure changes and geomechanical effects due to hydrocarbon production in the reservoir may reduce available capacity.

3 Status of CCS Deployment

The concepts of capture of anthropogenic CO_2 and geological storage as a greenhouse gas mitigation option first came in the seventies, but the idea gained credibility in the nineties through a series of research projects. The subsurface disposal of acid gas (a by-product of oil production with up to 98% CO_2) in some oilfields of North America provided additional useful experience. By the late 1990s, a number of privately and publicly funded research programs were underway in North

Table 1 Storage capacity of various geological storage options [5]

Sink type	Lower estimate (Gt CO_2)	Upper estimate (Gt CO_2)
Oil and gas reservoirs	675	900
Deep unmineable coal seams	3–15	200
Saline formations	1000	Possibly 10^4

America, Japan, Europe, and Australia. Consequently, a few oil companies exploring geological storage as a mitigation option in gas fields with high natural CO_2 content. The projects included Natuna in Indonesia, In Salah in Algeria, and Gorgon in Australia. The world's first large-scale CO_2 storage project (1 $MtCO_2$ per year) was initiated in 1996 by Statoil at the Sleipner Gas Field in the North Sea. Since then, as the level of confidence in the technology increased through successful operation of demonstration and full-scale projects, geological storage of CO_2 has grown from a novel concept to one that is increasingly regarded as a potentially important and practically implementable mitigation option.

Currently, there are 21 large-scale CCS projects in operation or under construction throughout the globe [7]. The list of these projects is given in Table 2 and location of some key CCS projects is shown in Fig. 3 [8]. These 21 projects have capacity to capture around 37 million tonnes of CO_2 per annum (Mtpa). Furthermore, as given in Table 2, there are seven more projects in the advanced deployment stage with a total CO_2 capture capacity of around 8 Mtpa. The growth from 10 large-scale operational projects to the current 21 has taken place over the last decade. A further 11 large-scale CCS projects, shown in Table 3, are in early stages of development planning (the Evaluate and Identify stages) with a total CO_2 capture capacity of around 21 Mtpa [8]. Highlights of some key CCS projects are as follows.

- The Sleipner CO_2 Storage facility was the first in the world to inject CO_2 into a dedicated geological storage setting. The Sleipner facility, located offshore Norway, has captured CO_2 as part of the Sleipner area gas development since 1996. The captured CO_2 is directly injected into an offshore sandstone reservoir. Approximately 0.85 million tonnes of CO_2 is injected per annum and over 16.5 million tonnes have been injected since inception to January 2017.
- The Great Plains Synfuels plant, located in North Dakota, produces high purity CO_2 as part of its coal gasification process. Carbon dioxide capture capacity of the plant is approximately 3 Mtpa. The captured CO_2 is transported via pipeline to the Weyburn and Midale Oil Units in Saskatchewan, Canada, for use in enhanced oil recovery. Around 35 million tonnes of CO_2 has been captured and transported to date.
- Petra Nova Carbon Capture, operational since January 2017, is the world's largest post-combustion CO_2 capture system presently in operation. Production unit 8 of the W. A. Parish power plant near Houston, Texas, was retrofitted with a 1.4 Mtpa post-combustion CO_2 capture facility. The captured CO_2 is transported via pipeline to an oil field near Houston for enhanced oil recovery.
- Abu Dhabi CCS Project, the world's first application of CCS to iron and steel production, was launched on 5 November 2016. The project captures approximately 0.8 Mtpa of CO_2 from ESI plant in Abu Dhabi and used for enhanced oil recovery.
- Illinois Industrial Carbon Capture and Storage Project is the world's first large-scale bio-CCS project with capacity of 1 Mpta. This is also the first CCS project in the US with storage of CO_2 into deep saline formation.

Table 2 Large scale CCS projects under operation, construction, and advanced deployment

Project name	Country	Operation date	Capacity (Mtpa)	Storage type
In operation				
Terrel Natural Gas Processing Plant	US	1972	0.4-0.5	EOR
Enid Fertlizer	US	1982	0.7	EOR
Shute Creek Gas Processing Plant	US	1988	7.0	EOR
Sleipner CO_2 Storage	Norway	1996	1.0	Dedicated geological storage
Great Plains Synfuels Plant and WeyburnMidale	Canada	2000	3.0	EOR
Snohvit CO_2 Storage	Norway	2008	0.7	Dedicated geological storage
Century Plant	US	2010	8.4	EOR
Air Products Steam Methane Reformer	US	2013	1.0	EOR
Coffyville Gasification Plant	US	2013	1.0	EOR
Lost Cabin Gas Plant	US	2013	0.9	EOR
Petrobas Santos Basin Pre-Salt Oil Field CCS	Brazil	2013	1.0	EOR
Boundary Dam CCS	Canada	2014	1.0	EOR
Quest	Canada	2015	1.0	Dedicated geological storage
Uthmaniyah CO_2-EOR Demonstration	Saudi Arabia	2015	0.8	EOR
Abu Dhabi CCS	UAE	2016	0.8	EOR
Illinois Industrial CCS	US	2017	1.0	Dedicated geological storage
Petro Nova Carbon Capture	US	2017	1.4	EOR
In construction				
Gorgon CO_2 Injection	Australia	2017	3.4–4.0	Dedicated geological storage
Alberta Carbon Trunk Line with Agrium CO_2 Stream	Canada	2018	0.3–0.6	EOR
Alberta Carbon Trunk Line with North West Strugeon Refinery CO_2 Stream	Canada	2018	1.2–1.4	EOR
Yanchang Integrated CCS Demonstration	China	2018	0.4	EOR

(continued)

Table 2 (continued)

Project name	Country	Operation date	Capacity (Mtpa)	Storage type
Advanced deployment				
Sinopec Qilu Petrochemical CCS	China	2019	0.5	EOR
Rotterdam Opslag en Afsvang Demonstration Project	Netherlands	2019–20	1.1	Dedicated geological storage
CarbonNet	Australia	2020s	1.0–5.0	Dedicated geological storage
Sinopec Shengli Power Plant CCS	China	2020s	1.0	EOR
Lake Charles Methanol	US	2021	4.2	EOR
Texas Clean Energy Project	US	2021	1.5–2.0	EOR
Norway Full Chain CCS	Norway	2022	1.3	Dedicated geological storage

- Quest, located in Alberta, Canada, retrofitted CO_2 capture facilities to three steam methane reformers at the existing Scotford Upgrader. Launched in 2015, Quest has the capacity to capture approximately 1 Mtpa of CO_2. The captured CO_2 is transported via pipeline to the storage site for dedicated geological storage.
- Yanchang Integrated CCS is an industrial CCS development located in Yulin City, Shaanxi Province, China. Yanchang Petroleum, through affiliates, is developing CO_2 capture facilities at two coal-to-chemicals plants. The smaller scale capture source of 0.05 Mtpa CO_2 capture capacity has been in operation since 2012, while the larger CO_2 source of 0.36 Mtpa CO_2 is currently in construction and may be operational by the end of 2018. Captured CO_2 would be used for enhanced oil recovery in oil fields in the Ordos Basin in central China.
- CarbonNet is working on the potential to establish a commercial scale CCS network. It would involve bringing together multiple CO_2 capture projects in Victoria's Latrobe Valley, transporting the CO_2 via pipeline and injecting deep into offshore underground storage sites in the Gippsland region. It plans an initial capacity to capture, transport and store in the range of 1–5 Mtpa of CO_2 during the 2020s.

Fig. 3 Location of some key CCS projects [7]

Table 3 CCS projects under early deployment

Project name	Country	Operation date	Capacity (Mtpa)	Storage type
Riley Ridge Gas Plant	US	2020	2.5	EOR
Sinopec Eastern China CCS	China	2020	0.5	EOR
China Resources Power Integrated CCS Demonstration Project	China	2020s	1.0	Dedicated geological storage
HuanengGreenGen IGCC Large-Scale System	China	2020s	2.0	EOR
Korea CCS-1	South Korea	2020s	1.0	Dedicated geological storage
Korea CCS-2	South Korea	2020s	1.0	Dedicated geological storage
Shanxi International Energy Group CCS	China	2020s	2.0	Not specified
Shenhua Ningxia CTL	China	2020s	2.0	Not specified
Teesside Collective	UK	2020s	0.8	Dedicated geological storage
Caledona Clean Energy	UK	2022	3.8	Dedicated geological storage
South West Hub	Australia	2025	2.5	Dedicated geological storage

4 Future of CCS

4.1 Estimated Future Contribution of CCS

As detailed in Sect. 1.2, as per the Paris agreement, an ambitious target was set to keep the temperature rise to “well below 2 °C” and also to continue efforts towards 1.5 °C. Substantial efforts will be required to deploy all low-emissions technologies as rapidly and extensively as possible, which would include adoption of large-scale CCS projects. So far the use of fossil fuels in power generation and industrial processes is concerned, CCS remains the only technology solution capable of delivering significant emissions reduction from these sources. In the 2005 IPCC Special Report on CCS the climate experts recognized the role of CCS in constraining future temperature increase [5]. This recognition continued to gather support and subsequently, the IPCC Fifth Assessment Report (AR5), published in 2014, highlighted that the availability of CCS and bioenergy with CCS (BECCS) will be “critical in the context of the timing of emissions reductions” [3]. The AR5 also indicated that it would be difficult to limit atmospheric concentrations to about 450 parts per million (ppm) CO_2-equivalent, which corresponds to the temperature increases of around 2 °C, with limited deployment of CCS.

The role of different options for limiting the temperature rise to 2 °C (2DS) from the "no action" scenario of 6 °C (6 DS) temperature rise, as assessed by the International Energy Agency (IEA), are shown in Figs. 4 and 5 [9]. A portfolio of technologies need to deployed for meeting the target. This will include renewables, increased efficiency, nuclear, fuel switching, and CCS. In the 2 °C scenario (2DS), CCS including negative emissions from BECCS needs to deliver 94 Gt of cumulative CO_2 emission reduction during the period 2013 to 2050. CO_2 reduction through CCS amounts to 12% of the required cumulative CO_2 emission reductions compared to 32% by renewables, 10% by fuel switching, and 38% by increasing end-use efficiency. The 94 Gt of CO_2 captured and stored by CCS through 2050 under the 2DS comprises, shown in Fig. 5, include emissions from all sources. Out of this total capture, power sector needs to account for the majority, which stands at 52 $GtCO_2$ or 55% of the total CO_2 capture. Roughly 29 $GtCO_2$ or 31% of the total needs to be captured from the industries like production of chemicals (38%), iron and steel (33%) and cement (29%). The remainder (about 13 $GtCO_2$) would need to be captured from biofuel production and gas processing [9].

As the net balance of emissions during the later half of the century is warranted, negative emissions from bio-CCS (BECCS) would assume increased importance. The role of negative emissions in achieving more ambitious climate targets was analysed in the IPCC AR5 and is now receiving more attention following Paris. BECCS is the most mature of the negative emission technology options and could generate as much as 10 $GtCO_2$ of negative emissions per year [9]. The world's first large-scale BECCS project, the Illinois Basin Decatur Project in the United States,

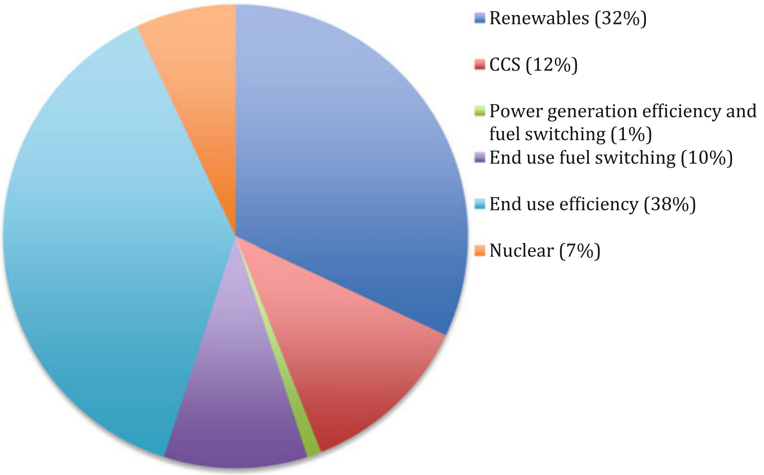

Fig. 4 Contribution of different low emission technologies to global emission reduction

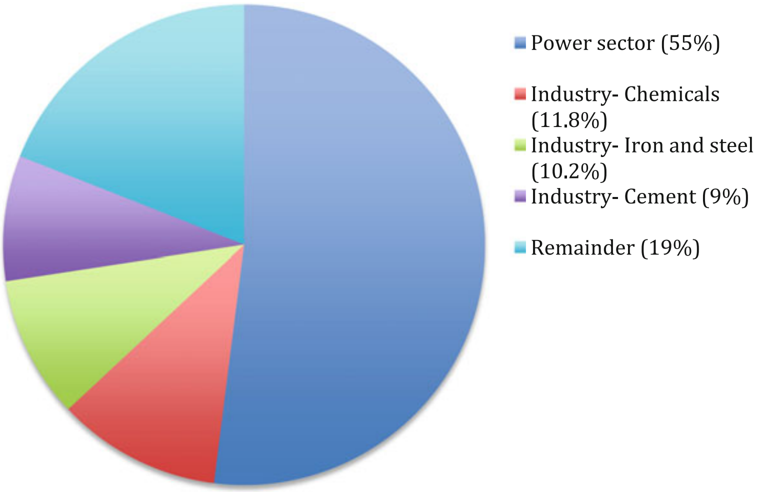

Fig. 5 Sources of CO_2 capture under 2 DS scenario

is in the process of commissioning, which is designed to capture 1 $MtCO_2$ per year from a bio-ethanol plant. However, there are many technical, economic and social challenges associated with the technology that needs to be addressed for wider scale deployment of BECCS. Of particular importance are the availability of sustainable biomass and access to CO_2 storage sites in the vicinity.

Although the global portfolio of CCS projects continue to rise with a current capacity including the existing and planned projects is around 70 Mt of CO_2 capture per year, the task ahead is huge. Being on course to a 2 °C reduction path would require significant acceleration and a few fold order increase in current CCS deployment from the current level to around 6.1 $GtCO_2$ in 2050, requiring average growth of more than 15% per year [9].

Significant advancements have been made through dedicated research and development over the last 20 years on capture, transport and storage technologies. The costs have come down and the technologies are now being applied on a commercial scale. While research and development efforts will continue to be crucial in further refinement and improvement in the technologies, major breakthroughs and reduction in cost can only be achieved through actual deployment at large scales.

4.2 Role of Policy—Past and Future

Although recognition of CCS by climate experts has increased over time, CCS deployment has been hampered by fluctuations in policy and levels of financial support. Prior to the release of the IPCC Special Report on CCS in 2005, considerable interests and activities built up starting from the first ministerial-level meeting of the Carbon Sequestration Leadership Forum (CSLF) in 2003. Subsequently, the plans and activities momentum continued to build. In 2008, European Union (EU) released its CCS directive. The first IEA technology roadmap for CCS was released in 2009 and G8 leaders committed to launch twenty large-scale CCS projects by 2010. However, the global financial crisis put brakes on many of these ambitious projects. Between 2010 and 2016 a number of large-scale CCS projects were cancelled and the announced commitments for funding were either scaled down or withdrawn across Europe, the United States and Australia. United Kingdom's GBP 1 billion CCS commercialization program was cancelled in 2015. In a major blow to CCS, two highly prospective and important projects—White Rose and Peterhead were cancelled in 2015. The Peterhead CCS project proposed to apply CCS to gas-fired power station while the White Rose was planned for demonstration of oxy-fuel capture technology at higher scale. Shale gas revolution leading to cheap availability of natural gas in the US led to the cancellation of many CCS projects. Recently, Kemper County project, which was a major clean-coal technology project with power generation from lignite gasification and concomitant CCS was cancelled in favor of power generation through natural gas. Prevailing global low price of crude provided threat to CO_2-EOR and CCS investments.

Amongst all these gloomy developments, however, there have been a few encouraging developments as well in the recent years. In 2015, China and United States announced a bilateral CCS initiative. China also released its CCS Roadmap developed by the Asian Development Bank and the National Development and Reform Commission. As stated in Sect. 3, six large-scale projects are expected to commence operation within the next two years, including two further projects in power generation. The Paris negotiations have also provided required fillip to global climate policy and accelerate the transition to near zero net emissions. It is expected that the post-Paris period would offer sufficient impetus towards regaining momentum in CCS deployment and adopting new approaches.

The future for CCS will ultimately depend on efforts required for strengthening and expansion of the climate response globally. The Paris Agreement provided an extremely significant milestone with the potential to influence future CCS deployment. It is clear that the world is not on track for achieving the Paris ambitions and significant gap exists between the actions needed and the actions currently planned for emission reduction. Bridging this gap will require high levels of political commitment. The pace, purpose, and intensity with which various countries and their governments now undertake this task will ultimately determine the future of CCS deployment.

5 Conclusion

Twenty years of research, development and demonstration has increased the confidence in CCS technology. Although detailed site characterization is required before employing this technology to a particular site, it can be concluded with reasonable certainty that sufficient geological sites are available across the globe for storage of the captured CO_2. One major concern of CCS is substantial cost addition to the industrial process. However, in the existing scenario, complete switching to other low-carbon technologies is not only feasible but costly as well. CCS is vital for meeting the 2 °C global temperature rise targeted and mandated in Paris agreement. It is calculated that about 12% of the total GHG reduction will come from CCS by 2050. The pace of development in adoption of CCS has gained momentum in the recent years. However, given the quantum of CO_2 reduction, achieved so far, appears to be a big challenge.

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