Draft 2030 Roadmap for
Carbon Capture Utilization and Storage (CCUS)
for Upstream E&P Companies

सत्यमेव जयते
पेट्रोलियम एवं प्राकृतिक गैस मंत्रालय
MINISTRY OF PETROLEUM AND NATURAL GAS
Government of India

DISCLAIMER

The document sets out a roadmap for adoption of CCUS/ CCS technologies in India. The proposals set out in the roadmap and the attached annexures are only indicative in nature and do not in any way constitute any offer or confer any rights by the Government. The proposals made are not final/ conclusive and are subject to any further amendments as desired by the Government to be consistent with the Government policies. The information contained in sections of the document reflects data that was derived from both public and internal data of some E&P companies. The committee shall have no liability for errors, omissions or inadequacies in the information contained herein or for interpretation thereof.

Preface

At COP26 summit in Glasgow, Hon'ble Prime Minister Shri Narendra Modi announced the Panchamrit to mitigate climate change including achieving net zero by 2070. For a developing economy like India, whose emissions are yet to peak, this calls for unprecedented transformation of all the sectors. Oil and Gas industry has a crucial role to play in this energy transition. Accelerated adoption of renewable energy and improvement in energy efficiency measures have been thrust areas but climate scientists and agencies consider injection of anthropogenic CO2 into the sub-surface to be indispensable if global warming targets are to be met. Both IEA and IPCC consider CCS/CCUS to be a key element in the portfolio of technologies essential for keeping global warming within 2 degree Celsius. O&G companies with their skill set are well poised to spearhead CCS/CCUS initiatives in India.

CCUS can potentially cater to both energy security and emission abatement aspiration of the nation. Accordingly, the Ministry of Petroleum and Natural Gas, Government of India in coordination with various stakeholders has initiated efforts for development and implementation of Carbon Capture, Utilization and Storage (CCUS)/ Carbon Capture and Storage (CCS) techniques in the oil and gas sector in India. A task force titled 'Upstream for CCS/CCUS' (UFCC) to this effect has been constituted. Further, to develop and implement a practicable framework to accelerate research and development on carbon capture, utilization and storage in India, a MoU has been signed between MoPNG and IIT Bombay.

The committee has submitted draft of the report titled "2030 Roadmap for CCUS for Upstream E&P Companies". The document is now being circulated amongst stakeholders for their suggestions and comments. I urge all the stakeholders in the E&P industry to provide their valuable insights and comments on the document. Your suggestions will definitely help in making the roadmap more conclusive and relevant.

Committee Members

Chairman

1. Shri Amar Nath, Additional Secretary, MoPNG

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1. Shri Asheesh Joshi, Director (Exploration), MoPNG
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14. Shri Naresh Lalwani, JSW Steel

TOR No.	Term of Reference (TOR)#
1	Assessment and evaluation of CO_2 storage potential of India & Sink Mapping
2	Assessment of the opportunities available for re-opening abandoned oilfields by O & G companies and providing CCS services to the other industries
3	Review of CCS/CCUS technologies used across the world and assess their feasibility for implementation in India & Source Mapping
4	Identify suitable projects in the Upstream E&P sector where CCS/CCUS can be implemented
5	Develop Policy & Regulatory framework for CCS/CCUS
6	Develop financial framework for CCS/CCUS
7	Assess methods for improvement and cost reduction of Capture technologies
8	Assess methods and way forward for development of CO_2 transport infrastructure
9	Create dedicated workforce for Research & implementation of CCS/CCUS in O & G Companies

Order attached as Annexure

CONTENT

Chapter-1

Introduction

1. Introduction

The role of Carbon Capture, Utilisation, and Storage (CCUS) in climate change mitigation has been a topic of discussion for over two decades. The Intergovernmental Panel on Climate Change's (IPCC) Special Report on Global Warming of 1.5°C and the recent series of announcements made by nations on net-zero have enthused the proponents of this technology, given the potential the technology can play in reducing emissions.

India too has made a commitment to become net zero by 2070. Addressing the 26th COP at Glasgow, the Hon'ble PM announced the Panchamrit to mitigate climate change including achieving net zero by 2070. Consequently, various steps including promoting renewable and alternate energy sources such as solar, wind, hydrogen, reducing emission from vehicles through adoption of B-VI norms, increasing green cover, promoting R&D, adoption of carbon neutral technologies like CCS/ CCUS have started gaining prominence.

CCUS/ CCS has emerged as one of the technologies to mitigate climate change. Also, there have few limited efforts made historically to understand the potential of the CCUS technology and associated geological assessment. However, the high cost of capital has been a significant barrier to adopting CCUS technology despite the technology enjoying nearly five decades of global development, since USA's Carbon dioxide Enhanced Oil Recovery (CO2-EOR) project. Apart from the technical aspects, politico-economic aspects also play crucial role in carving the path for CCUS adoption in low carbon transition. India being a price sensitive market, the additional cost to be borne due to CCUS could be detrimental in a more extensive policy context. In view of future net zero objective and strong commitment towards environment, there is an essential requirement for India to examine options to reduce its carbon intensity further, for which CCS/CCUS could be the key option.

In order to provide opportunity for collaboration and knowledge sharing to the industry and prepare a unified and practical strategy for development and implementation of (CCS/CCUS) techniques in upstream E&P in India, MoPNG has constituted a committee titled as "Upstream for carbon Capture, Utilization and Storage (UFCC)" under Chairmanship of Additional Secretary (Exploration)-MoPNG. The committee has broadly worked as per TOR and prepared "2030 Roadmap for Carbon Capture, Utilization and Storage" which shall provide necessary direction and guidelines for all Oil & Gas companies in India to develop and scale up CCS/CCUS techniques.

1.1 Global warming and IPCC resolution

The Intergovernmental Panel on Climate Change (IPCC) is the leading international body for the assessment of climate change. In its Fifth assessment report (2013-2014) it assesses all relevant options for mitigating climate change through limiting or preventing greenhouse gas emissions, as well as activities that remove them from the atmosphere.

It also describes a number of potential mitigation scenarios:

- To avoid 2 degrees C (3.6 degrees F) of warming relative to pre-industrial time, the report indicates that atmospheric concentrations of greenhouse gases need to be stabilized at around **450 ppm CO2-eq or lower**. Given that we are currently around 430 CO2-eq, this is a tall order, requiring large-scale changes in energy systems and land use.
- The aggregate economic cost of mitigation varies widely, but generally increases based on the stringency of the level of mitigation. In general, the costs of mitigation only offsets a relatively small fraction of global projected economic growth for the 21st century.
- **If we do not strengthen mitigation efforts between now and 2030, it will be more difficult and more expensive to achieve warming targets, such as avoiding 2 degrees of warming relative to pre-industrial levels.**

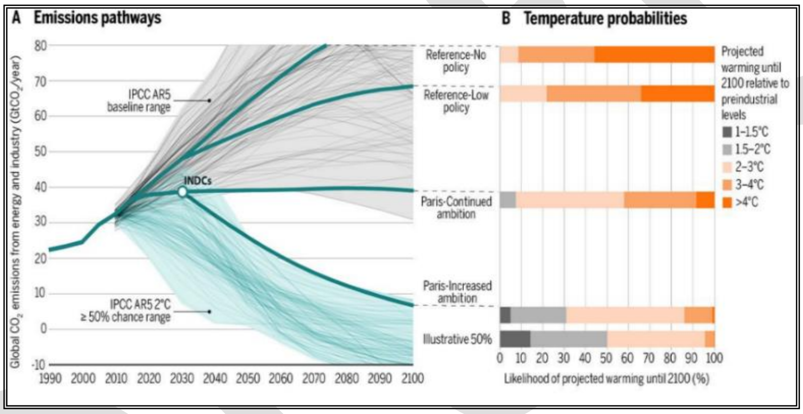


Figure 1 Global CO_2 Emission pathways

Source: IPCC Fifth Assessment Report, Summary for policymakers,2014

1.2 Global and India emission data

Carbon dioxide emissions, primarily from the combustion of fossil fuels, have risen dramatically since the start of the industrial revolution. Most of the world's greenhouse gas emissions come from a relatively small number of countries. China, the United States, and the nations that make up the European Union are the three largest emitters on an absolute basis. Per capita greenhouse gas emissions are highest in the United States and Russia.

Emissions of carbon dioxide and other greenhouse gases are primary drivers of climate change and global warming and present one of the world's most burning challenges.

Figure 2 indicates, how the planet has warmed during the period between 1961 and 1990. The red line represents the average annual temperature trend through time, with upper and lower confidence intervals shown in light grey. It is observed that; over the last few decades, global temperatures have risen sharply — to approximately 0.7℃ higher than our 1961-1990 baseline. When extended back to 1850, we see that temperatures then were a further 0.4℃ colder than they were in our baseline. Overall, this would amount to an average temperature rise of 1.1℃.

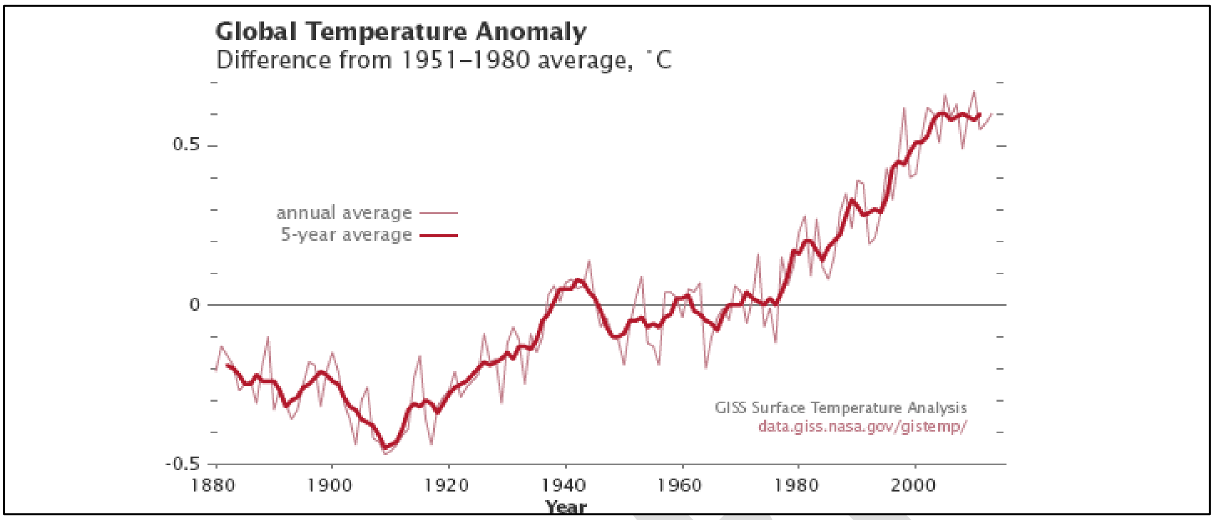


Figure 2 Global Average Temperature

Source: data.giss.nasa.gov

1.3 CO2 Emission-India perspective

India is the third largest emitter of CO2 emissions after China and USA. Presently it emits close to 2.65 GT of CO2 annually which is approximately 7% of the world's total CO2 emissions in 2019 (this is very minimal compared to ~ 28% of the world's share of CO2 emitted by China and ~ 15% of the world's share by USA). In India, the energy sector contributes to 68.7% of GHG emissions, followed by agriculture (19.6%), industrial processes (6%), land-use change (3.8%) and forestry (1.9%), and waste. However, while taking total emissions into account it has also to be factored in that India is among the lowest per capita emitters and requires energy to develop and prosper. Despite this, India has voluntarily taken all out measures to progressively decouple its economic growth with GHG emissions. In fact, India's emission intensity of GDP has reduced by 24% between 2005 to 2016 thereby allowing it to achieve its target of reduction of emission intensity of GDP by 20-25% from 2005 levels much before 2020 and is well on its way to reduce the GDP's emission intensity by 33-35% below 2005 levels by 2030.

To further accelerate India's endeavour towards combating climate change, the Hon'ble Prime Minister of India has put forth a five- fold strategy or Panchamrit at COP 26 in Glasgow. The Panchamrit or "gift of five elixirs" include:

i. India will get its non-fossil energy capacity to 500 gigawatts by 2030

ii. India will meet 50 per cent of its energy requirements till 2030 with renewable energy

iii. India will reduce its projected carbon emission by one billion tonnes by 2030

iv. India will reduce the carbon intensity of its economy by 45 per cent by 2030

v. India will achieve net zero by 2070

However, to achieve the desired target of climate mitigation in general and attaining the targets set out by PM in COP26, it will require large scale decarbonization of various industrial sectors in India. Carbon Capture, Utilization & Storage (CCUS/ CCS) is deemed to be one of the predominant techniques which may be taken up by the upstream E&P industry to contribute towards achieving these targets.

1.4 Need for Carbon Capture, Utilization and Storage

In the fight against climate change, processes and technologies related to Carbon Capture, Utilization and Storage (CCUS) / Carbon Capture and Storage (CCS) are essential. Recent International Panel on Climate Change (IPCC) studies have also indicated the central role carbon capture is going to play in decarbonizing the environment. In fact, pathways that aim for limiting warming to 1.5 °C by 2100 will have to rely on large-scale deployment of carbon dioxide removal (CDR) measures. One such method which can play a prominent role is CCUS/ CCS which has been charted by IEA as one of the four pillars of global energy transformation (the others being RE-based electrification, bioenergy and H2). CCUS processes are depicted in Fig 3 given below.

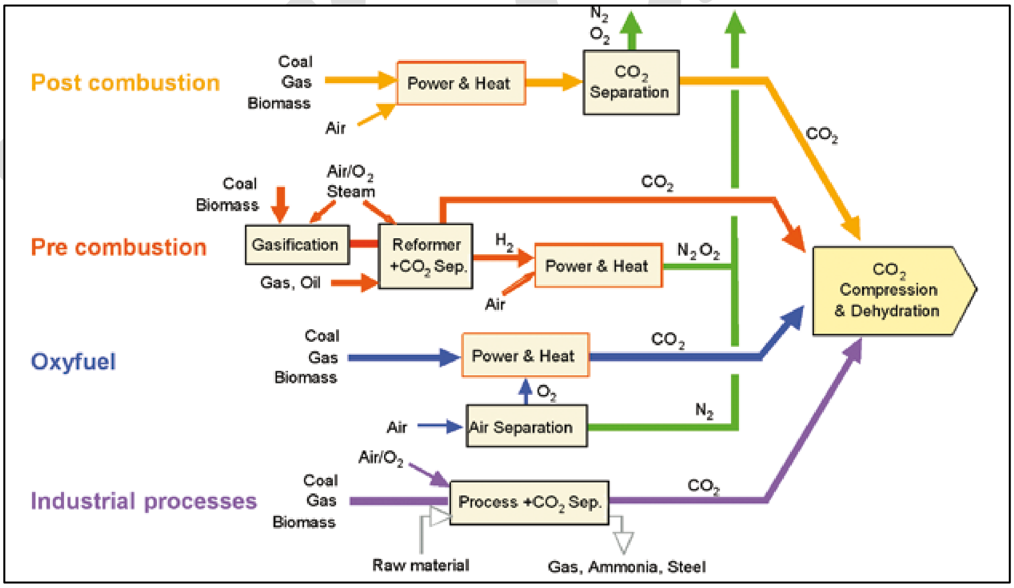


Figure 3 Carbon Capture (Source: Carbon Capture and Storage, IPCC)

CCS / CCUS processes capture carbon dioxide. The captured CO2 is then transported to a suitable site for its final long-term storage (i.e., geological or ocean storage) or is used for Enhanced Oil/ Gas Recovery or it is converted into other components and products, such as chemical feedstocks, fuels or building materials, which are otherwise typically derived from fossil-based resources.

Fundamental steps of CCUS process are:

- CO_2 Capture from anthropogenic sources
- Compression
- Transportation
- Utilization and storage

Carbon capture systems are divided into three categories based on the stage at which the carbon capture phase occurs:

- Post-combustion- separating CO2 from exhaust gases after burning of fossil fuel
- Pre-combustion- removing CO2 from fossil fuels before combustion is completed
- Oxy-combustion- the process of burning the fuel with nearly pure oxygen

Post-combustion carbon capture is the most amenable to retrofit, of the three and thus the most common technique of carbon capture from existing plants.

According to international organizations such as the IPCC and the IEA, subsurface injection of CO_2 is essential for meeting sustainable development goals (SDG) and keeping global temperature rise below 2°C (Figure 4).

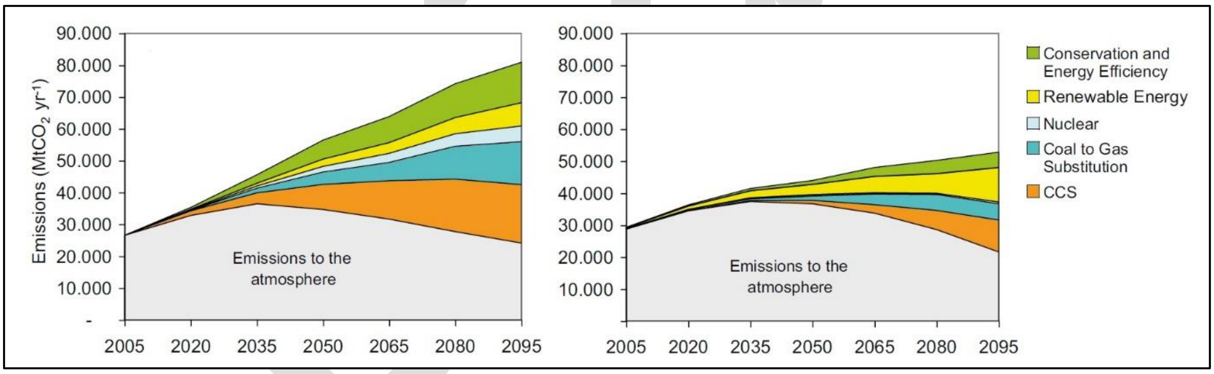


Figure 4: CCS contributes 15% of total emission curtailment in SDG scenario

Source: Carbon Capture and storage, IPCC

Significance of Carbon Capture and Storage (CCS) in the portfolio of emission curtailment measures can be gauged from the fact that, scenario having no CCS in the port-folio (rest everything same) is indicative of overall cost increase of 138% from the situation where CCS in included in the port-folio (Figure 5).

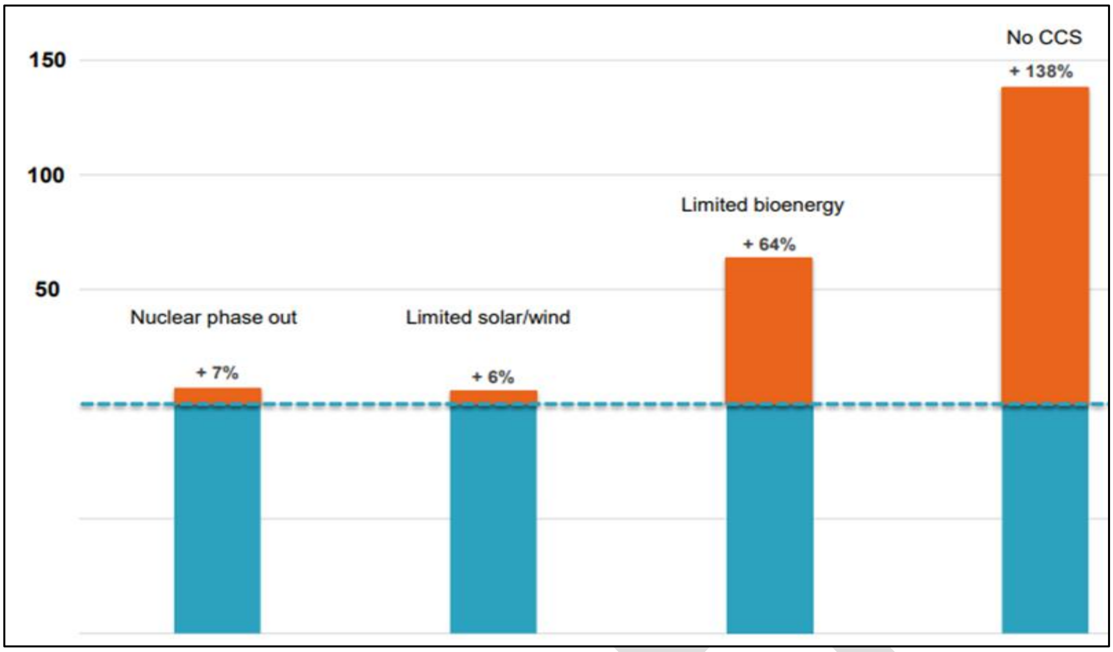


Figure 5: Percentage increase in Mitigation Cost Without CCS, IPCC 5th AR

Source: IPCC Fifth Assessment Report, Summary for policymakers,2014

The prospect of climate change, as well as the importance of fossil fuels in global energy supply, particularly for developing nations, has sparked renewed interest in carbon capture and storage. The portfolio of emission reduction technologies covers a wide range of options and can potentially have multiple winners. It should not be viewed in terms of one alternative versus the other. Hence, as significant progress is being made in adoption of renewable energy in our energy mix, it is imperative to ensure that critical technologies like CCUS get their due attention, in view of their potential role in climate change mitigation.

1.5 Status of CCUS Globally

All major economies of World including USA, China, Japan, and UK are very optimistic about the role of CCUS in their pathway to sustainable development, with several projects already under operation and many more under advanced stage of being executed. Southeast Asian countries including Indonesia and Malaysia have also included CCUS in their pathway to sustainable development. Figure 6 indicates the progress of various CCS projects worldwide.

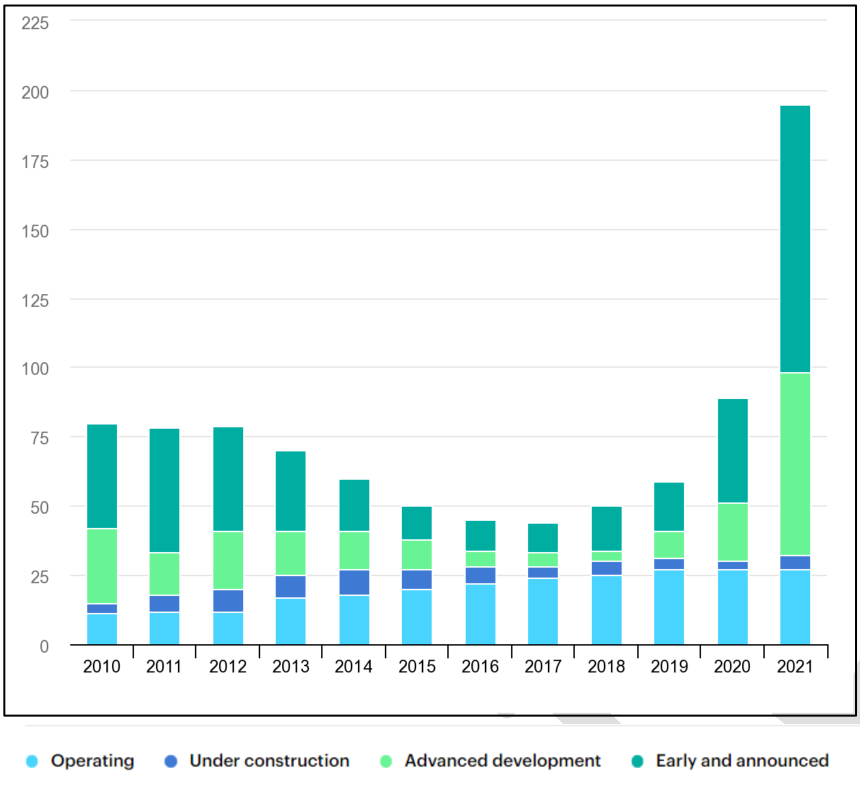


Figure 6: Capacity of Global CCS projects in various stages of development, Source IEA, Global pipeline of commercial CCUS facilities operating and in development, 2010-2021, IEA, Paris

Some of the noteworthy developments are:

- CCUS is one of key element of ten-point plan for a green industrial revolution announced by UK Government. UK government has announced grants for 2 CCUS clusters.
- To ensure accelerated deployment of CCUS, USA has already implemented a tax incentive law called **45Q,** which has provision of giving tax benefit to the tune of USD 50 to USD 35 per ton of anthropogenic CO2 injected in the sub-surface for pure sequestration and CO2-EOR respectively.
- Most of the countries have established Centre of Excellence for CCUS for Nationwide co-ordination and policy & regulation formulation.
- Among recent encouraging developments in the CCUS, one of the most significant is the positive final investment decision taken, after considerable deliberation, by the Norwegian government in favour of a major full-chain CCS project, now called Longship. The total cost, capital plus ten years of operation, is estimated at 25.1 billion NOK (USD 2.7 billion), with the Norwegian government contributing 16.8 billion NOK (USD 1.8 billion).

Moreover, as reported by Global CCS Institute many countries are gradually including CCS in their Nationally Determined Contribution (NDC) as per country's Paris

Agreement commitment. Currently, already 14 countries have declared CCS to be part of their NDC (Figure 7).

	INDC	1ST NDC	1ST NDC UPDATE	2ND NDC
Australia	–	✗	✓	
Bahrain	–	✓		
Canada	✓	✗	✓	
China	✓	✓		
Egypt	–	✓		
Iran	✓			
Iraq	✓			
Malawi	✓	✓		
Mongolia	✗	✗	✓	
Norway	–	✓	✓	
Saudi Arabia	✓	✓		
South Africa	✓	✓		
UAE	–	✓		✓
United States	✗	✓		

✓ NDC MENTIONS CCS
✗ NDC DOES NOT MENTION CCS
– NOT AVAILABLE

Figure 7: Counties having mention of CCS in their NDC, GCCSI-Report-2021

Details on global status of CCUS projects may be seen at **Appendix 2**

1.6 Need of CCUS in India & Net Zero

In recent years, India has taken extra-ordinary strides in renewable capacity development. Despite these efforts, many long-term forecasts indicate that fossil fuels would continue to play a key role in India's energy system in foreseeable future. With over 1.3 billion population, India is one of the fastest growing major economies in the world and it needs sustained sources of energy to fuel its growth and cater to the aspirations of its huge population. On the other hand, looking at the emission front, India, albeit with very less per capita emission, is the third largest CO_2 emitter in the world. As per the Nationally Determined Contributions (NDC) of Paris Agreement, India has ratified to decrease its emission intensity of GDP by 33- 35 percent by 2030 from 2005 level. In this regards CCUS offers win-win proposition by not only curtailing atmospheric emissions but also promoting various mechanisms via which the captured CO2 may potentially be utilized for enhanced oil recovery from mature oil fields or for production of chemicals & fuels.

Chapter-2

CCUS: Technology

2. CCUS: Technological options

2.1 CO2 capture options

CO2 capture is critical as well as most expensive step of the CCS process. A range of commercial technologies for capturing CO2 are widely used in industrial processes today. Common applications include the removal of CO2 impurities in natural gas treatment and the production of hydrogen, ammonia, and other industrial chemicals. The captured CO2 is simply emitted into the atmosphere in most of the cases. In some cases it is used for manufacturing other chemicals. CO2 is also captured from a portion of the flue gases produced at power plants burning coal or natural gas. In these cases, the captured CO2 is sold as a commodity to nearby industries such as food processing plants. However, as a global scenario, only a small amount of CO2 captured is utilised to manufacture industrial products, and the rest of it is emitted to the atmosphere. CCUS/ CCS therefore can play a crucial role in capturing CO2 and aiding towards achieving mitigation goals.

Since most anthropogenic CO2 is a by-product of the combustion of fossil fuels, CO2 capture technologies generally are classified as either **pre-combustion** or **post-combustion** systems. In the former carbon is removed before a fuel is burned while in the latter carbon is removed after burning of fuel. A third approach, called **oxyfuel or oxy-combustion**, does not require a CO2 capture device. This concept is still under development and not yet commercial. Another mechanism to capture CO2 is **direct air capture**. The aim in all of the above cases is to capture, store and sequester pure stream of CO2 which is then compressed to a dense “supercritical” state, where it behaves as a liquid, thereby making it easier and cheaper to transport and store. The CO2 compression step is commonly included as part of the capture system since it is usually located at the industrial plant.

2.2 Technological Solutions for Carbon Capture

CO2 capture technologies are the technologies that prevent emission of CO2 generated by industrial processes or fossil fuel-based power plant to the atmosphere. These technologies separate CO2 from the gaseous stream and produce a CO2 rich (>90% CO2) stream that can be readily compressed and transported to the storage or utilization site.

A variety of technologies currently exist for separation and capture of CO2 from gas streams. These technologies are designed on different physical and chemical processes such as absorption, adsorption, membranes, and cryogenics. Other new technologies for capturing and utilizing CO2 from flue gases like Microbial and Algal systems are also being developed.

Flow chart below indicates a list of available carbon capture technologies:

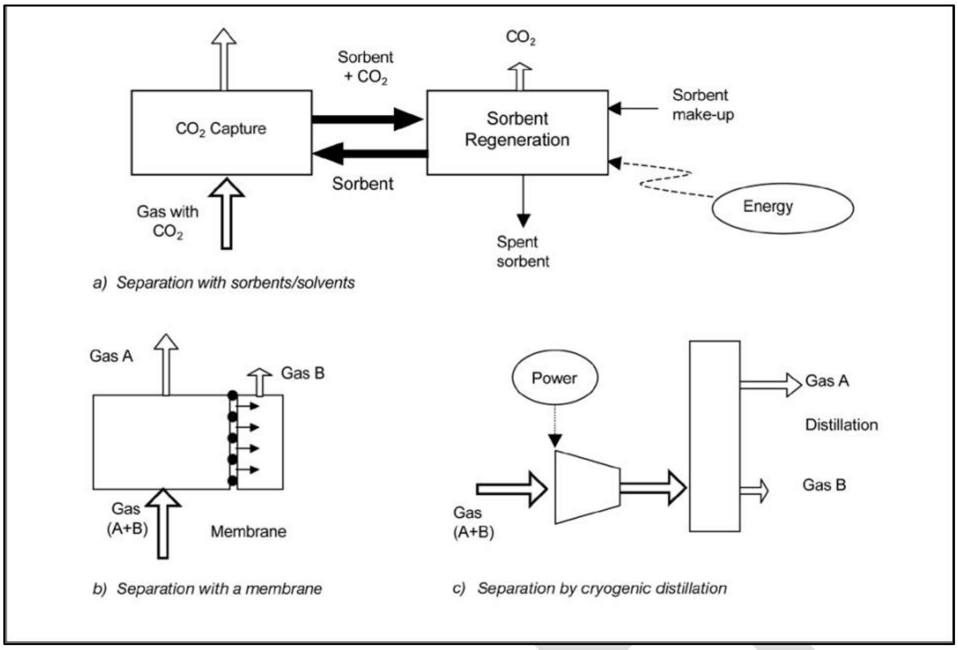


Figure 8 Technological options for Carbon capture and utilization

Source: Carbon Capture and Storage, IPCC

The technological solutions mentioned in Figure 8 depending upon the process condition and product requirement, can be mapped against the relevant carbon capture system namely, post combustion, pre- combustion, oxy- combustion and Direct Air Capture as depicted in table below.

Table 1 Mapping of Carbon Capture System and Technology

CO2 Capture System	**CO2 capture technology**
Post Combustion	Absorption Membranes Adsorption Cryogenic / Microbial / Algal
Pre-Combustion	Absorption Membranes Adsorption Cryogenic / Microbial / Algal
Oxy-combustion	Separation is not required. Instead, purification is required to remove SOx, NOx, H2O.
Direct Air Capture (DAC)	Absorption Membranes Adsorption Cryogenic / Microbial / Algal

Chapter-3

CO_2 Transportation

3. Transport of CO_2: Mode and Mechanism

In CCS/CCUS technology, transport is the stage which links sources and storage sites. Among all the process involved in CCUS, transport is considered the most matured process. In the field of hydrocarbon, pipelines routinely carry large volumes of natural gas, oil, condensate over distances of thousands of kilometres, both on land and in the sea. In India alone, ~ 25000 KM oil & gas pipelines are in operation with major capacity additions planned in near future.

3.1 Pipeline Transportation

Transport of CO2 in pipelines is a known and a mature technology and will continue to remain as one of the most common method of transporting very large quantities of CO2 involved in CCS. From the 34 operational large scale & small commercial CCUS projects worldwide, 76% primarily utilize pipeline to transport CO2. However, a major amount of additional work will be needed to explore the ways in which pipeline networks and common carriage systems will be holistically developed, considering all aspects of transportation from capture point to storage. A global overview of CO2 transportation by pipelines may be seen at **Appendix-3**. In addition, transport pipeline health and safety regulations will also be needed to be developed to generate public confidence in the technology.

3.2 Marine Transportation

Currently, ship transportation occurs on a small scale mainly in Europe, however, it is gaining acceptance for large-scale volumes in shore-based capture facilities due to low capital requirement as well as flexibility that it offers. The flexibility of shipping could facilitate the initial development of CO2 capture hubs. Capture location, transport distance, capacity, delivery location, shipping schedule, number of ships, service speed, technical restrictions etc. are some of the factors which will play crucial role in marine transport of CO2. In marine transportation system, delivery point may be onshore where CO2 is unloaded from the ships into temporary storage tanks or it may be offshore like ocean storage option where ships are required to unload to a platform, to a floating storage facility, to a single buoy mooring or directly to a storage system.

3.3 Road / Rail Transport

Transport of CO2 by truck or rail is only viable for small quantities since these options are expensive when compared with pipeline. Trucks could complement ship transportation for CO2 capture hubs where delivery locations of ships are coastal distribution terminals from where it will be transported to the customers by tanker trucks.

3.4 Cross border pipeline transportation

Transboundary movement of CO2 involves cross-border land and maritime transport. Regional approaches to CO2 transport and storage infrastructure could enable faster and more widespread uptake of CCUS. Intergovernmental collaboration on development of large, shared CO2 storage resources could allow multiple facilities and countries to access the resources & could support CCUS investment in locations where storage capacity is either limited or where its development faces delays. Such an approach could incorporate offshore CO2 storage together with CO2 shipping, providing additional flexibility and contingency in the CCUS value chain where several storage facilities are available. Efforts to develop shared infrastructure could be based on international experience like the Northern Lights CO2 transport and storage project in Norway.

3.5 Implementation – Indian perspective

Indian Oil Corporation Ltd IOCL has taken up an initiative for reducing CO_2 emissions at its refineries through Carbon Capture, Utilization, and Storage (CCUS).

Accordingly, it is planning India's first industrial-scale carbon capture project at its 13.7 MMTPA Koyali refinery, located in Vadodara, Gujarat. To ensure the utilization of the captured CO2, IOCL has entered into a Memorandum of Understanding (MoU) with Oil and Natural Gas Corporation (ONGC). The major share of the CO2 captured at the IOCL Koyali Refinery shall be treated, compressed, and transported through pipelines to the Gandhar oil field of ONGC, located a distance of about 110 km from the IOCL Koyali Refinery.

At Gandhar, the captured CO2 would be used for Enhanced Oil Recovery (EOR), thereby increasing oil production from the old and matured oilfields of ONGC, while also ensuring the utilization and permanent storage of the CO2. IOCL also envisages selling a part of the captured CO2 to food and beverage companies located in Gujarat, in the vicinity of the Koyali Refinery.

Similar CCUS project are under study for other Refineries of IOCL also.

Some of the other initiatives regarding adoption of CCUS/ CCS technologies have been discussed in detail at Chapter 5.

3.6 Pipeline Cost & Economics

Transportation costs are highly dependent on type, location, geology, scale, and distance. For long distance transportation of more than 1000 KM, typically marine transportation is cheaper than pipeline. Nature of expenditure also varies between different modes of transportation. While pipeline costs are heavily dominated by capital expenses, shipping costs are dominated by operational and fuel expenses. There is no doubt that onshore pipeline presents the lowest cost of transportation for large volumes of CO2. Economies of scale are extremely visible in CO2 pipeline transport as costs per metric ton decrease as the quantity of CO2 transported increase, making large-scale projects more economically attractive. Pipelines located in remote and sparsely populated regions cost about 50–80% less than in highly populated areas. For a densely populated country like India, identification of low populated area for long pipeline network poses a significant challenge.

3.6.1 Other infrastructure and expenses

CO2 is transported at pressure ~1080 psi or above to increase transportation efficiency. Owing to high pressure operation, CO2 pipeline transportation is associated with high pressure equipment like Compressor or booster pump station.

Moreover, unlike natural gas pipelines, high pressure CO2 pipelines are not self-arresting in terms of longitudinal failure and thus require the installation of crack arrestors.

Terrain has a strong influence on pipeline costs and accounts for largest uncertainty in cost estimation. Typically trenching is required to install a pipeline as it is generally underground. Interference with water bodies like river/lake, existing structure / roads can increase cost significantly.

In CO2 pipeline transportation, it is cheaper to collect CO2 from several sources into a single pipeline than to transport smaller amounts separately. In many locations around the world, efforts to develop CCUS hubs – that is, industrial centres with shared CO2 transport and storage infrastructure – have started. The principal benefit of a hub approach is the potential for economies of scale to reduce unit costs for CO2 transport and storage, including through greater efficiencies and reduced duplication in the planning and construction of CCUS infrastructure. Developing CCUS hubs with shared infrastructure can aid towards the viability of the projects.

O&M costs will also cover a significant amount of the expenditure. Typically, O&M costs will include expenditures related to electricity consumption for booster compressor, dehydration system, control systems, manpower cost for operation & inspection, overhead consumables, spares as well as regular maintenance (e.g. pigging) along the pipeline. O&M costs are not readily available. However, few guidelines are available for estimating O&M cost as percentage of installed capital cost. These guidelines can provide a first impression of O&M cost which needs India specific factors to arrive at reasonable accurate estimate.

3.7 Risk and Safety with CO2 Transportation and Storage

Although large scale CCS projects have the benefits of reducing CO2 emissions, yet they come with their fair share of risks and health, safety and environmental concerns. The concern of CO2 leakage from deep reservoirs where it will be sequestered, is the greatest, considering the damage it can cause in case of any unwarranted leakages. Leakage from pipelines by which the CO2 is transported is also a serious concern.

These concerns shall have to be taken into account and addressed as and when large scale implementation of CCS projects is done.

Therefore, rigorous, and transparent safety standards need to be developed, implemented, and monitored in order to minimize any risks and failures.

A few points of consideration for ensuring safety and minimization of risk while implementation of a CCUS project is:

i. CO_2 toxicity and hazards
ii. Risk analysis of CO_2 pipelines
iii. Risk associated with CO_2 storage
iv. Risk associated with CO_2 transport
v. Ensuring that existing guidelines for CO_2 pipelines and system are complied with

Chapter-4

Geological CO_2 Storage

4. Sub-surface injection of CO_2

The last step in a CCS project is the permanent storage of CO2. Currently, most of the operating projects worldwide inject CO2 into geological formations. Geological storage and its trapping mechanisms are well understood because of decades of experience from the oil industry. More than 75% of current operating CCUS projects inject CO2 into oil producing reservoirs to enhance oil recovery (EOR) whereas ~25% of the projects inject CO2 into dedicated geological formations. Commercial storage in dedicated geological formations began in 1996 with Equinor's Sleipner project in Norway, and it is slowly gaining traction. Current operating projects are geographically dispersed in Australia, Qatar, Canada, Norway, and the United States.

Any formation deep enough with suitable seal, porosity, and permeability could be a potential storage site; saline formations and oil and gas fields meet the requirements.

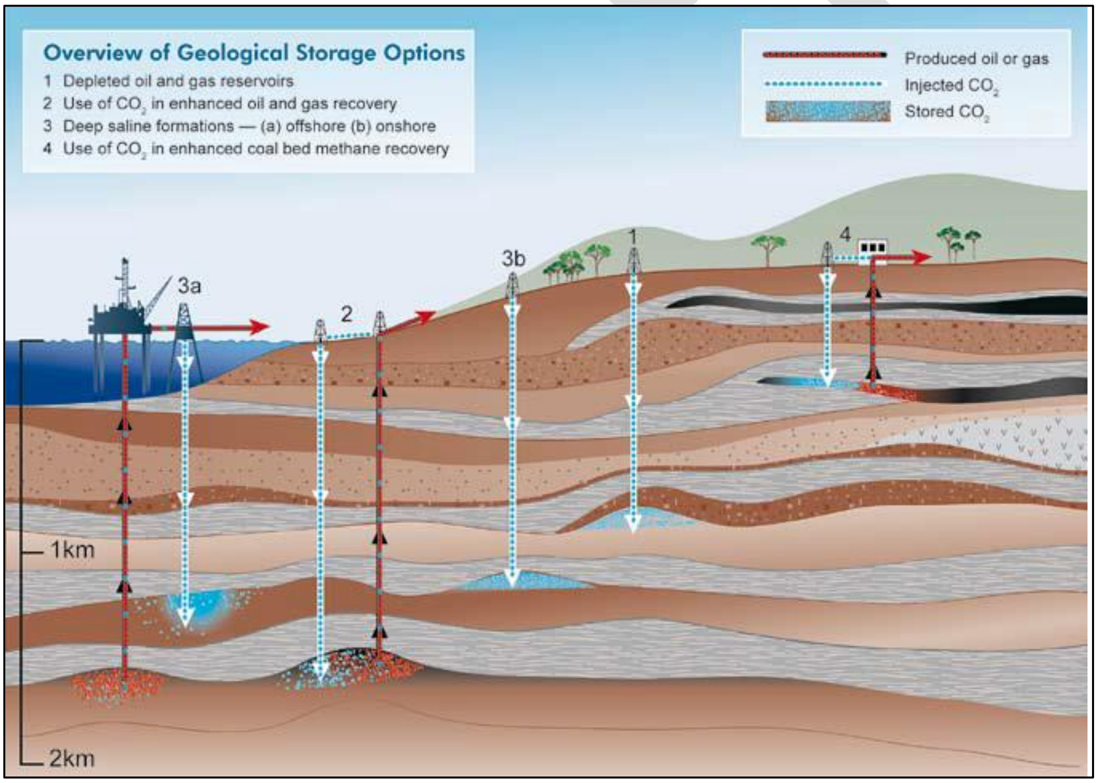


Figure 9 Typical CO2 storage illustration (Source: Carbon Capture and Storage, IPCC Report, 2005)

Global geological storage capacity is well understood for oil and gas fields but uncertain for other formations such as saline formations While oil and gas fields have the capacity to meet the CCUS project demand, their geographic location is limited, which could be a significant challenge for the upcoming projects. As a result, there is a possibility that the upcoming CCUS projects will shift storage types from mainly EOR in oil and gas fields to dedicated geological storage in saline formations.

4.1 Clustering and Source-Sink Matching

Carbon dioxide for enhanced oil recovery (CO2 EOR) not only ensures enhanced oil production but also results in the sequestration of a part of CO2 injected into the reservoir thereby resulting in reduced overall GHG emissions. However, the success of CO2 EOR sequestration depends on the proper sources-sinks integration which in turn requires qualitative theoretical source-sink matching is usually conducted.

Clustering and source-sink matching can be systematically worked out by identifying the best sources of CO2, identifying the most suitable sink and finally creating linkages between the source and sinks.

The estimation of India's storage and sinks potential is needed to be conducted practically with detailed geological and geophysical data. The uncertainty with respect to existing storage capacity assessments for India could have implications for source-sink matching. Hence following steps must be taken to achieve a detailed assessment, enabling the matched capacity:

- Generate an effective storage potential by applying site-specific efficiency factors
- Determine detailed locations of possible storage sites to enable precise, quantitative source-sink matching to be conducted
- Derive a practical storage potential considering economic conditions, potential problems regarding acceptance in the regions concerned and technical feasibility problems such as injection rates at the bore wells.

4.2 Storage Resource Classification

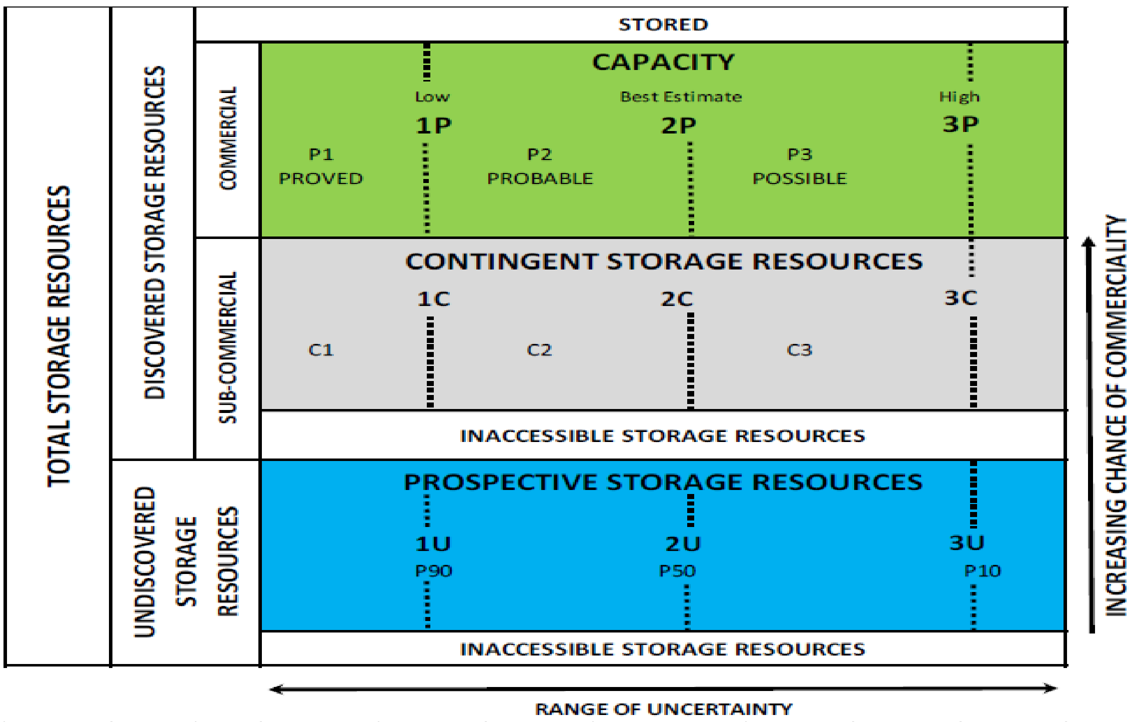


Figure 13 SPE Resources Classification Framework: 2017 (Source: Society of Petroleum Engineers)

Figure 13 is a graphical representation of the SPE storage resources classification system. The system defines the major storage resource classes: Stored, Capacity, Contingent Storage Resources, and Prospective Storage Resources, as well as Inaccessible Storage Resources. The “Range of Uncertainty” on the horizontal axis reflects a range of storable quantities (e.g., pore volume potentially accessible within a geologic formation by a project), while the vertical axis represents the “Chance of Commerciality,” which is the chance that the project will be developed and reach commercial storage status. The following definitions apply to the major subdivisions within the resources classification:

Total Storage Resources: The quantity of storage estimated to exist in geologic formations. It includes that quantity of storage estimated, as of a given date, to be possible in known and characterized geologic formations before injection, plus those estimated quantities in undiscovered or uncharacterized geologic formations. (Total Storage Resources is the sum of Discovered and Undiscovered Storage Resources.)

Discovered Storage Resources: The estimated quantity of Total Storage Resources, as of a given date, in which the potential for storage has been ascertained within an assessed geologic formation.

Stored: The quantity of Discovered Storage Resources that has been exploited by a given date: This equates to the cumulative quantity of CO2 injected and stored. While all storage resources are estimated, and Stored is measured in terms of CO2 metering specifications, the total injected quantities (CO2 plus associated injectants) are also measured, as required in support of engineering analyses.

4.3 Estimation of CO_2 storage capacity: Indian perspective

To estimate the total CO_2 storage resources, the cumulative pore space available in the rock formations needs to be quantified. Next, the fraction of that space that can be accessed by CO_2 and has potential to trap it has to be calculated

4.3.1 Geologic storage potential of Indian basins

Vishal et al. (2021b) reviewed various methodologies used worldwide for storage potential assessment and developed theoretical and effective capacity estimates for CO_2 storage in the major sedimentary basins in India based on the latest available data. Four storage methods with sufficient potential were identified: storage through CO_2 enhanced oil recovery (EOR), enhanced coal bed methane recovery (ECBMR), in deep saline aquifers, and basalt formations.

Storage through CO_2 EOR

CO_2 EOR has been identified as one of the primary pathways for advancing CCUS in India (TIFAC, 2018). The benefit of the extraction of hydrocarbons makes it an economical way of storing CO_2 in the subsurface. Extensive geological characterization of the region also reduces the costs of exploration. The depleted fields also provide confidence in storage due to the presence of proven reservoirs.

The CO_2 storage capacities in the seven oil-producing basins of India have been calculated (Vishal et al., 2021b) using the most current resources and reserves data for oil-producing basins in India provided by DGH (DGH, 2020). Based on the resource-reserve pyramid, the cumulative theoretical, effective, and viable capacities for India are 3.4 Gt, 2.07 Gt, and 1.2 Gt, respectively (Figure 15). The individual capacities for the seven basins are listed in Table 1.

Table 1 CO_2 storage capacities of major oil-producing basins in India through EOR (Vishal et al., 2021b)

	Krishna–Godavari	Mumbai	Assam shelf	Rajasthan	Cauvery	Assam–Arakan	Cambay	India (Total)
CO_2 storage capacity (Mt)	658.69	1597.24	667.48	312.52	99.5	67.01	657.25	3402.43

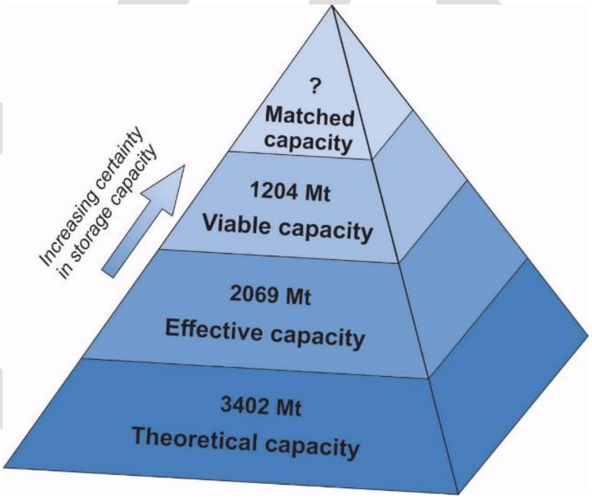


Figure 15 Total theoretical, effective, and viable CO_2 storage capacities of India through EOR represented on the resource-reserve pyramid (Vishal et al., 2021b)

Storage through CO_2 ECBMR

Currently, India has 319 Gt of coal reserves spread across Gondwana Basin and north-eastern India. The majority of the coal formations are rich in methane. This combined with proximity to large-point sources of CO_2 provides a large prospect for

ECBM recovery in India. Moreover, more than 90% of the coal resources are of the non-coking grade, which is considered to have ample potential for CO_2 storage (Holloway et al., 2009).

The total CO_2 storage capacity of the Indian coal reservoirs ranges between 3.5 Gt and 6.3 Gt depending on the methodology applied (Vishal et al., 2021b). The coalfields are categorised into reservoirs with very high, high, and moderate storage potential. Furthermore, eight sedimentary basins cover all the CBM-bearing coalfields, majority of which are concentrated in the Satpura-South Rewa-Damodar basin.

Storage in saline aquifers

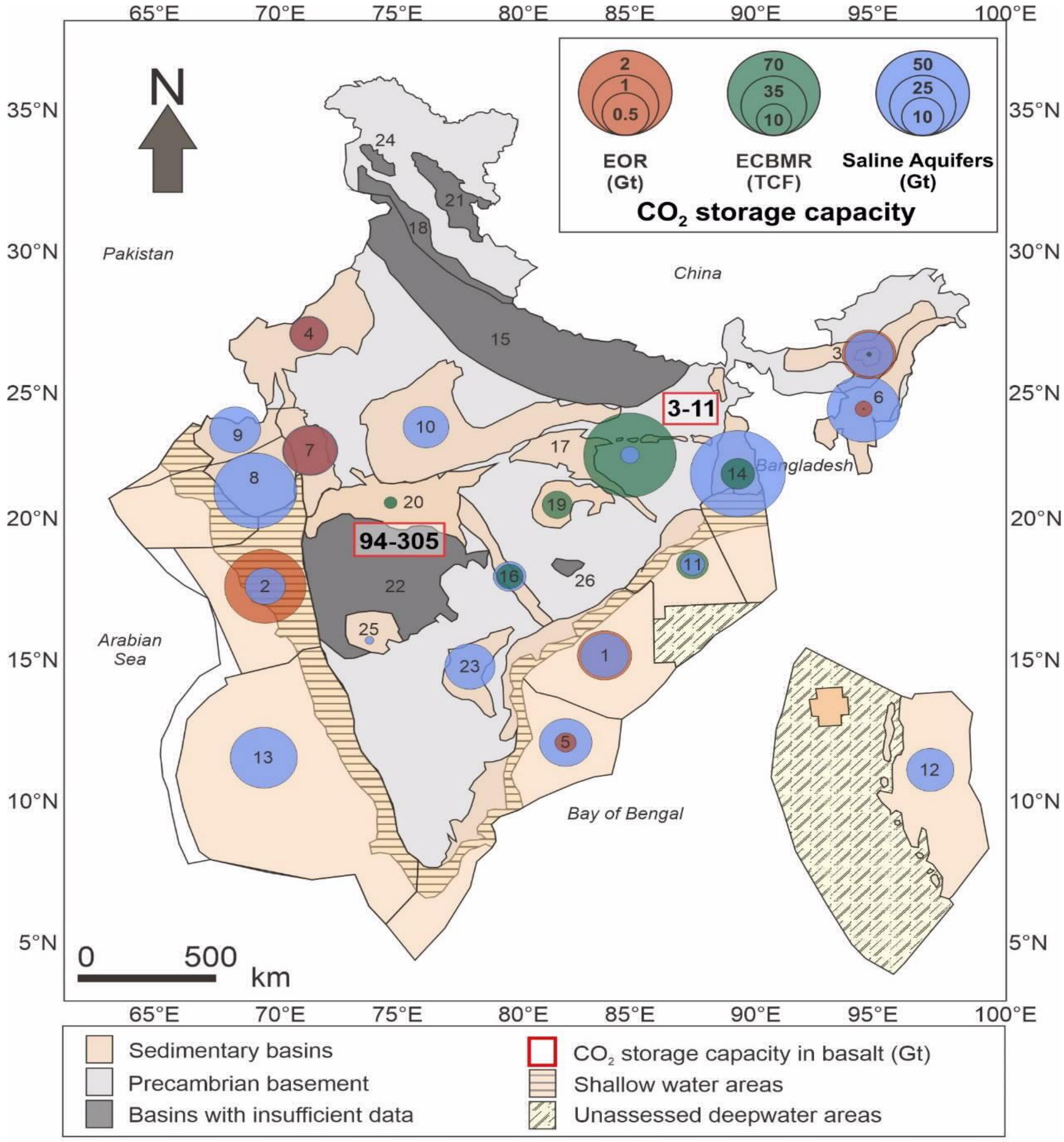
Deep saline aquifers represent a huge untapped potential for CO_2 storage around the world. The capacity for CO_2 storage in aquifers is quantified by applying storage efficiency factors to available pore volume in formations. The total storage potential for the sedimentary basins in India is estimated to be 291 Gt of CO_2 (Vishal et al., 2021b), based on a modified US DoE method (Goodman et al., 2011). The sedimentary basins are divided into Category-I, Category-II, and Category-III basins and have storage potential of 108.6 Gt, 82.75 Gt, and 100 Gt, respectively (Table 2). Figure 17 shows the storage potential of the major basins on the map of India.

Table 2: CO_2 storage capacities in deep saline aquifers of the major sedimentary basins in India (Vishal et al., 2021b)

S. No.	Sedimentary Basins	Area (km^2)	CO_2 storage capacity (Gt)
	Category-I Basins		***108.66***
1	Krishna–Godavari	230000	13.39
2	Mumbai Offshore	212000	9.26
3	Assam Shelf	56000	14.16
4	Rajasthan	126000	7.34
5	Cauvery	240000	16.08
6	Assam–Arakan Fold Belt	80825	32.3
7	Cambay	53500	16.13
	Category-II Basins		***82.75***
8	Saurashtra	194114	39.74
9	Kutch	58554	15.6
10	Vindhyan	202888	11.81
11	Mahanadi–NEC (North East Coast)	99500	3.25
12	Andaman–Nicobar	225918	12.35
	Category-III Basins		***99.68***
13	Kerala–Konkan–Lakshadweep	580000	25.33
14	Bengal-–Purnea	121994	51.58
15	Ganga–Punjab	304000	-
16	Pranhita–Godavari	30000	6.14
17	Satpura–South Rewa–Damodar	57180	1.87
18	Himalayan Foreland	30110	-
19	Chhattisgarh	32000	0.11
20	Narmada	95215	-
21	Spiti–Zanskar	32000	-
22	Deccan Syncline	237500	-
23	Cuddapah	40100	14.24
24	Karewa	6671	-
25	Bhima–Kaladgi	8300	0.41
26	Bastar	5360	-
	India (Total)		**291.09**

Storage potential in basalts

CO_2 storage in basalts offers a significant advantage of mineral trapping through which CO_2 is converted into carbonates ensuring permanent sequestration. India has a significant presence of basalts in the form of the Deccan Volcanic Province (DVP) and the Rajmahal traps. Together, they cover more than 500,000 sq. km. of area. They have the potential to sequester an estimated 97–316 Gt of CO_2, most of which lies in the DVP (Figure 16).



Category-I basins	Category-II basins	Category-III basins
1. Krishna-Godavari	8. Saurashtra	13. Kerala-Konkan
2. Mumbai Offshore	9. Kutch	14. Bengal-Purnea
3. Assam-Shelf	10. Vindhyan	15. Ganga-Punjab
4. Rajasthan	11. Mahanadi	16. Pranhita-Godavari
5. Cauvery	12. Andaman	17. Satpura-South Rewa-Damodar
6. Assam-Arakan Fold belt		18. Himalayan Foreland
7. Cambay		19. Chhattishgarh
		20. Narmada
		21. Spiti-Zanskar
		22. Deccan Syncline
		23. Cuddapah
		24. Karewa
		25. Bhima-Kaladgi
		26. Bastar

Figure 16: CO_2 storage capacity of major geological formations in India through CO_2 EOR, ECBMR, in saline aquifers, and basalt. The basins in grey were excluded from the calculations due to insufficient data (Vishal et al., 2021b)

4.3.2 Classification of Basins based on storage prospect

The sedimentary basins in India have been classified based on their 'storage prospectivity,' which is a combination of their total storage capacity and storage feasibility. The storage feasibility refers to the presence of adequate infrastructure and exploration maturity of the basins. Based on their extensive exploration, the category-I basins are ranked the highest in storage feasibility, while Category-II and Category-III basins show lower feasibility. The basins are thus divided into four categories: basins with very high potential, high potential, moderate potential, and low potential (Figure 17).

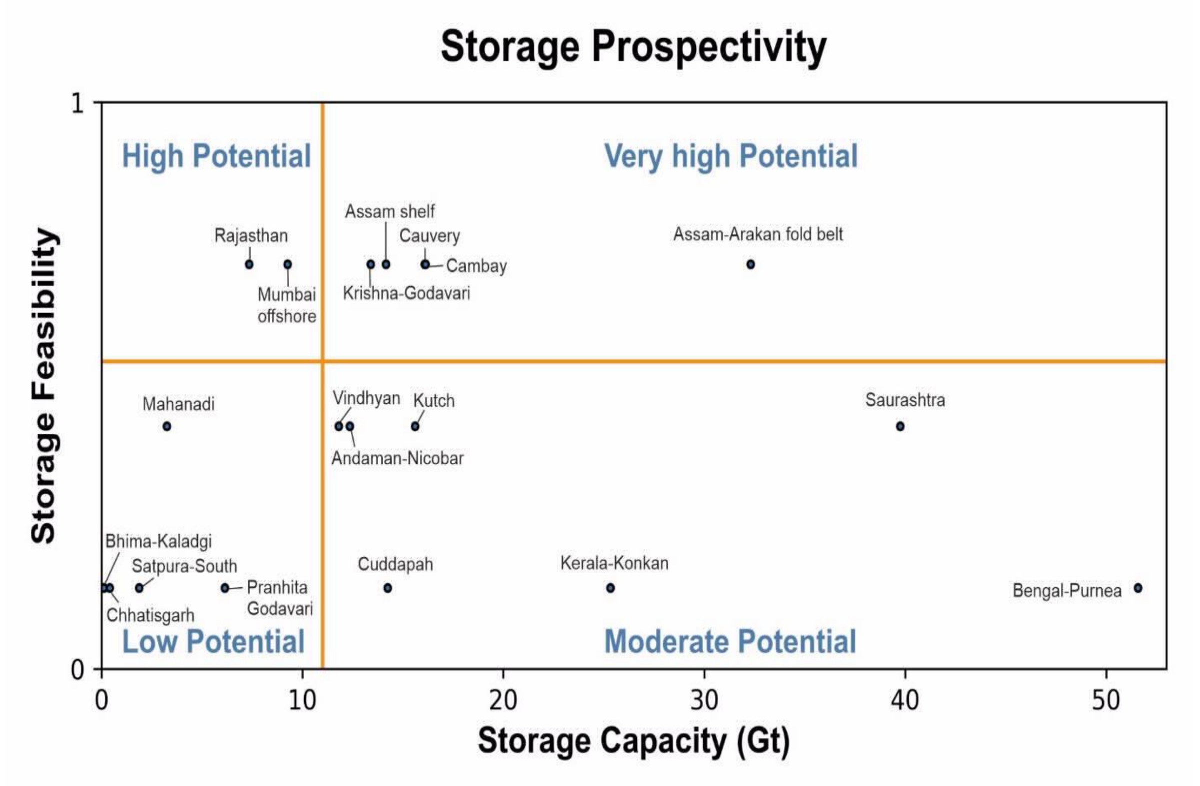


Figure 17: Classification of the major sedimentary basins in India based on Storage Prospectivity (Vishal et al., 2021b)

4.3.3 Technology readiness level and potential Sources & Sinks

Presently the overall technology readiness level of CCS in India hasn't crossed level Vishal et al. (2021 a, b) carried out a detailed assessment of the Technology Readiness Levels (TRL) and the CO_2 storage capacity estimates in a first step to developing CO_2 storage pathways in India. They highlighted the requirement to develop a hubs/clusters strategy for India for large-scale deployment of CCUS. CCS hubs and clusters operations are an effective way to connect a number of nearby CO_2 emitters and storage sites using shared transportation facilities and expedite the CCS development (Global CCS Institute, 2019). This greatly reduces the overall costs and risks than that of standalone projects. The UK and the Netherlands are developing CCS hub projects for dedicated geological storage in the North Sea (Sun et al., 2021). In this section, a source-to-sink assessment has been presented based on a systematic source-to-sink assessment through the identification of CO_2 emission points across different industrial sectors (Source: Vishal et al., submitted for publication). Fig. 18 represents the distribution of large-scale point emission sources (LPS) from sectors such as power, steel, cement, fertilizers, and refinery. The LPSs were identified and mapped on the basis of their CO_2 emission in Arc-GIS. The GIS platform was used to prepare the distribution maps of CO_2 from different sources, define the clusters of CO_2 emissions, and identify the sources of CO_2 within onshore and offshore categories. The most likely storage locations based on a source-sink map of identified LPSs and storage in Category I sedimentary basins and Category I CBM fields. The clustering is done on the basis of the annual GHG emissions and geographical distributions. In the final step, circular zones of radius 100km, 150km, and 200 km were created from the Euclidian centres of the basins, and LPSs falling outside 150km zones were filtered out. For offshore basins, namely Cauvery, Krishna-Godavari, and Western Offshore, an additional zone of 300 Km was identified. Source-sink clusters in this study were formed in such a way that the total cost of CO_2 avoidance in the supply chain is minimum, which includes the cost of transportation and pipelines. It was observed that the formation of integrated clusters helps in cost optimization through a sectoral collaboration of industrial partners.

Suitable sources and the sink spaces will have to be identified for uninterrupted supply of CO_2 for EOR operations as well as for sustained operation of CO_2 storage.

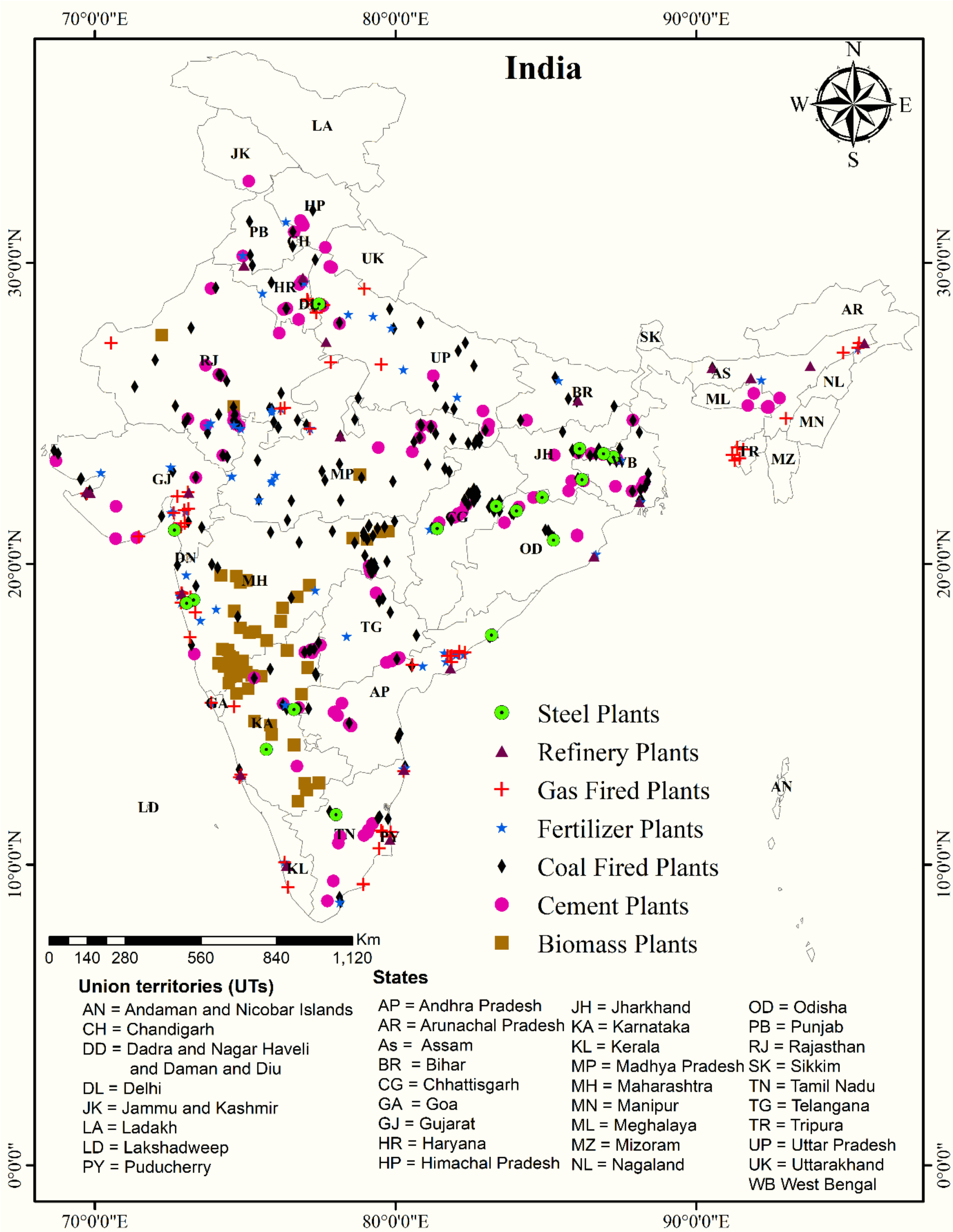


Figure 18 Location map for distribution of large point sources of CO2 emissions in India, across major industrial sectors. (Source: Vishal et al., submitted for publication)

Chapter-5

Identified Projects

5. Identified Projects

ONGC after detail study of potential source and sink identified the Gandhar field of Gujarat as a candidate reservoir for the first large scale demonstration project with Koyali refinery of IOCL as the source of CO2. ONGC and IOCL in collaboration worked for the feasibility study of the project.

5.1 ONGC fields identified for CCUS:

The project envisages capturing of CO2 from IOCL's Koyali refinery, its transportation through pipeline, and finally its utilization in Gandhar oilfield of ONGC for EOR & sequestration. This project marks attempt in India towards planning the maiden CO2 EOR project and has potential to reduce carbon footprint of both upstream and downstream O&G operation. Therefore, a comprehensive methodology has been adopted in carrying out feasibility study of all aspects of a CO2-EOR as CCUS project from capture at IOCL end to transportation & EOR & sequestration aspects at oilfield end in GS-9 and GS-11 sands of Gandhar field.

Feasibility studies of CO_2-EOR as CCUS project typically comprise of following broad steps:

- Source-sink matching
- Preliminary screening of reservoirs for CO_2 EOR
- Laboratory studies
- Compositional numerical simulation for production-injection forecasting and determining the sequestration potential
- Feasibility study of capture plant, CO2 transportation and produced fluid processing facilities at oilfield end
- Techno-economical evaluation

5.1.1 Source-Sink Matching

Matching of large point source of carbon dioxide to its potential sink in aging oilfield is fundamental pre-requisite of a CO2-EOR as a CCUS project. A suitable source-sink matching not only ensures long term decarbonisation of industrial source but also has a significant bearing on overall economic feasibility of the project. While on one hand, Cambay basin of Western India is one of the oldest oil producing basins of India, on other, the Western Indian region is also counted among the most industrialized regions of the nation. This makes the area a natural choice for scouting for Source-Sink matching. IOCL Koyali Refinery, at an approximate distance of 80 km away from ONGC's Western onshore field of Gandhar was found to be a suitable candidate for sourcing CO2 for EOR. Subsequent to this, Memorandum of Understanding between ONGC and IOCL was signed regarding furtherance for mutual goal of CCUS

5.1.2 Sub-surface feasibility studies: ONGC

ONGC identified Gandhar field, as a candidate for CO_2-EOR studies, owing to following reasons:

- Gandhar field a is multi-layered clastic reservoir and is in mature stage of water flood after being prolific producer for decades. GS-9 & GS-11 sands were identified having recovered 44% and 33% respectively.
- Since these two reservoirs are producing with very high water cut after successful secondary recovery, it is no longer possible to significantly improve recovery without application of any EOR process
- Petro-physical properties and current reservoir pressure makes it a suitable candidate for miscible gas injection
- Ankleshwar Asset has the experience of successfully operating India's only miscible gas injection project since 1998
- Most importantly, Gandhar field being in close proximity to industrial zone is likely to have nearby CO_2 sources

Subsequently, IRS, ONGC carried out detail technical feasibility studies through laboratory investigation followed by reservoir simulation of miscible CO_2 injection in multiple reservoirs of Gandhar and shortlisted GS 9 & GS 11 sands as primary candidates for the CO_2 EOR.

As CO_2 injection for EOR is planned for the first time in India, IRS engaged global expert agencies for the following:

1) Sub-surface considerations: Evaluation of work done by IRS regarding reservoir simulation of CO_2-EOR and profile generation

2) Surface considerations: Feasibility of CO_2 pipeline and surface facilities

Sub-surface Aspects

IRS-ONGC studied technical feasibility in terms of characterization of reservoir fluid and estimation of requisite pressure for attainment of miscibility of CO_2 in reservoir oil. Laboratory experiments were carried out for determination of minimum miscibility pressure (MMP) for CO_2 as a solvent. Encouraged by laboratory results, compositional simulation study was carried out for the two reservoirs of Gandhar field, GS-9 and GS-11.

Simulation results envisage CO_2 injection from 2025-26 and production from 2026-27. Injection shall start one year prior to production is to ensure that reservoir pressure reaches above Minimum Miscibility Pressure (MMP). The project envisages drilling of 75 new wells and CO_2 injection @ 1500 tpd for 20 years. Since this is a CCUS project, ~6.5 MMt of CO_2 is expected to be sequestered during the project life. Sand wise break up are as follows:

5.1.3 Surface Aspects Feasibility of carbon capture plant: IOCL

Broad specifications of CO_2 required at IOCL battery limit are:

a) >96% CO_2 purity by volume,
b) Pressure of 100 bar (g), and
c) Temperature of 40 – 45 °C

The take-off point for ONGC shall be the plant boundary of the IOCL Koyali Refinery. Subsequent transport of CO_2 through pipeline and injection of CO_2 into oil field for oil recovery will be under the scope of ONGC.

Feed Source

The Koyali Refinery is a complex refinery with multiple CO_2 sources such as the Hydrogen Generation Unit (HGU), Power Plant, Fluid Catalytic Cracking (FCC), Crude Distillation Unit (CDU) / Vacuum Distillation Unit (VDU) as well as heaters and boilers. Amongst these, the HGUs generate clean and the most concentrated gas streams in terms of CO_2 (20-70 vol%). Due to high CO_2 concentration and partial pressure off-gas from HGUs has been selected for economically viable CO_2 capture. Out of total four (4) HGUs at Koyali Refinery, two HGUs have been shortlisted for feed to the Carbon Capture facility.

HGUs have following gas streams where CO_2 can be captured:

(i) Shifted Syngas – CO_2 concentration: 19 – 20 vol%
(ii) PSA Tail Gas – CO_2 concentration: 63 – 65 vol%
(iii) Flue Gas – CO_2 concentration: 18 – 20 vol%

In view of the highest concentration of CO_2 in PSA tail gas and to reduce the cost of capture for this 1500 TPD requirement, PSA tail gas from HGUs having 63-65 vol% CO_2 concentration has been selected as the feed source for the Carbon Capture facility.

Technologies considered for Carbon Capture

Following technologies have been evaluated as possible technologies for carbon capture from Koyali Refinery:

Chemical solvent-based Absorption:

It is preferred when dealing with gas streams that are lean in CO_2 and have relatively lower pressures, such as flue gases. The cheap availability of steam is also a key factor as regenerating the solvent requires large quantities of steam. CO_2 capture from the HGU flue gases has not been considered further as this may lead to high cost of capture for such small capacity requirement.

Physical solvent-based Absorption

These separation technologies work well on gas streams with relatively higher CO_2 concentration and pressure. With respect to CO_2 capture from IOCL Koyali refinery, the only possible gas stream where this technology can be applied is the shifted syngas stream emanating from the HGUs.

Syngas has not been considered as one of the potential source points for carbon capture due to the significant modifications required in SMR operations. Therefore, physical solvent-based CO2 capture technology, which is best suited for syngas stream, has not been considered for this project.

Adsorption

This option is suitable for pre-combustion capture, where the gas stream has high pressure and a high CO2 concentration. Adsorption-based technology (e.g. CO2-PSA) has not been considered for further evaluation, as the purity of CO2 generated using such technologies is about 95% and cannot serve the purpose of EOR-grade CO2 as specified by ONGC, i.e. >96 vol%. Also, recovery through this technology is lower.

Cryogenic Separation

Preferred in cases where the cost of power is low and also feed CO2 concentration is very high. Cryogenic separation process applied to PSA tail gas can generate CO2 of the desired purity. This is leading to the lowest cost of capture for this project.

Based upon the total cost of CO2 capture (including Capex, Cash cost and operating cost), **Cryogenic separation technology** has been selected for CO2 capture from PSA tail gas at Koyali Refinery.

Quality and specifications of Final CO2 product

(i) Quantity of CO2 for EOR: **1500 TPD** (As per Agreed Capacity Operation).
(ii) CO2 pressure @ IOCL battery limit: **100 bar (a)** (at Supercritical State)
(iii) CO2 temperature @ IOCL battery limit: **45 °C.**
(iv) CO2 Quality:

CO2	> 96 vol%
N2	< 1 vol%
C1	< 1 vol%
C2	< 1 vol%
Moisture	< 500 ppmv
H2S	< 25 ppmv
NOx	< 25 ppmv
Sox	< 25 ppmv
CO	< 25 ppmv
Oxygen	< 100 ppmv
Other impurities	< 1 vol%

5.1.4 Feasibility of CO2 pipeline and surface facilities: ONGC

Based on the envisaged production and injection profile, total surface feasibility study with the following objectives was conducted by M/s Toyo Engineering, Japan

- Assessment of CO_2 transport from CO_2 Capture plant (IOCL Koyali) to ONGC facility via pipeline
- Assessment of compression and injection requirements for CO_2 injection in the field
- Conceptualization of surface facility for produced fluid handling, CO_2 separation, produced CO_2 recycle for compression and re-injection.
- Evaluation of CAPEX & OPEX for cost estimation for the identified options

The salient recommendations of the study are as below:

- 8” pipeline of API 5L Grade X70 of SCH 20 having 85 kms length is considered from IOCL Koyali refinery to Gandhar considering inlet pressure of 100 bar at Koyali end. CO_2 shall be transported in dense/supercritical phase, in line with the best international practises thereby optimizing pipeline size and cost.
- Feasibility study was divided into three sections i.e. initial phase, study phase & evaluation phase. These phases involve
    - In the Initial phase, analysis of production / injection profiles, screening for existing facility details, preparation of Design basis document,
    - During study phase, facility development options & operation mode are identified. Areas of feasibility were identified such as pipeline study, compression strategy, operation flexibility, CO_2 management, phasing philosophy etc. based on economic operation flexibility for different options and HSE / Risk mitigation (HAZID). Facility development options (network topology) were nominated as next step. These options were evaluated based on several criteria and candidate options (CCS/ CCUS hubs and clusters) shall be considered in further studies.
    - In the Final phase, feasibility was studied w.r.t material selection, compression strategy, layout philosophy etc. Overall concept for power supply, distribution & control are prepared. Internal HAZOP study is carried out to identify safety & HSE related aspects for CO_2 handling. Conceptual documents such as P&IDs, equipment list & utility summary are prepared for cost estimation. Based on this +/-30% CAPEX & OPEX cost estimation is carried out.

In the final recommendation

- ✓ GGS-1 Gandhar is considered as CO_2-hub
- ✓ Incoming CO_2 from IOCL shall be piped directly to CO_2-hub. At hubs, CO_2 pressure is increased from 100 kg/cm2 to 230 kg/cm2 using pumps and sent to wells for injection.
- ✓ GGS-1 Gandhar CO_2- hub shall have facilities for treatment of CO_2 mixed gases produced from the wells.
- ✓ All the produced gases shall be transported to CO_2-hub where CO_2 shall be extracted, dehydrated and re-pressurised for making CO_2 suitable for re-injection using suitable facilities.

5.2 Oil India fields identified for CCUS

Oil India Limited (OIL) in collaboration with a global expert have developed EOR strategies and identified Barail Sand of Naharkatiya Oilfield as a possible candidate for CO2 EOR. The CO2 EOR in Naharkatia Oilfield is an endeavour of OIL to align its objective in line with the vision of Government of India to reduce carbon foot print by 2030. In this regard, OIL has carried out following studies for the identification of the reservoir

- Preliminary Screening of Reservoirs for CO_2 EOR
- Laboratory Studies
- Numerical Simulation for production-injection forecasting
- Identification of Pilot Pattern for CO2 Flooding

Key Findings and Recommendations of the Study

- The south-west area of the NHK079D field was selected as a pilot area. The area has newer wells, with potential fewer mechanical complications, good water injection response and favorable petrophysical properties.
- One inverted 5 –spot patterns is selected which require drilling of one injector well.
- The pilot is designed to run for 5 years, utilizing existing wells and production facilities.
- CO2 requirement is around 67 tons per day
- An incremental Oil gain of around 0.26 MMm^3 (around 2%) is achieved over the base case through CO2 injection.

Current project envisages capturing of CO2 from IOCL's Digboi refinery, its transportation through pipeline/ road transport, and finally its utilization in Naharkatiya oilfield of OIL. Feasibility study of Capture Plant, CO2 transportation and produced fluid processing facilities at oilfield end and Techno-economical Evaluation is planned and is in initial stage of implementation. Further, OIL has identified Dikom Field for Carbonated Water Injection (CWI) after a successful study though Joint Industry Project (JIP) with a globally recognised University.

Reservoirs selected for CCUS

Reservoir	Avg Porosity, %	Net Pay Thickness, m	Avg oil saturation, %	Avg Permeability, md	Reservoir Temp, °C	Initial Static Bottom-hole Pressure (SBHP), Ksc
Dikom LK+TH Sand (Well NHK438 Block)	15	17	41	1262	101	393
NHK Main Barail 3rd Sand (Well NHK079D Block)	21	40	48	43.4	82	276

5.3 Prospective Fields for CO2-EOR as CCUS/CCS: Preliminary Screening

Selecting a method or combination of methods to use for EOR application, is performed based on a detailed study of each specific field. Since most EOR techniques involve complex physics, the evaluation proceeds in stages with the objective of reducing the uncertainty in application of an EOR technique that will achieve technical and economic success. (Fig-20)

The first step involves **ranking & screening** of Suitable EOR processes for the Reservoir based on Environment (offshore/Onshore), Lithology, Rock & Fluid characteristics. This information is compared with screening criteria for various recovery methods. These criteria, based on past field successes and failures, can provide a positive match for some EOR technologies. In this stage, more than one EOR processes can be ranked in order of preference for applicability in the reservoir.

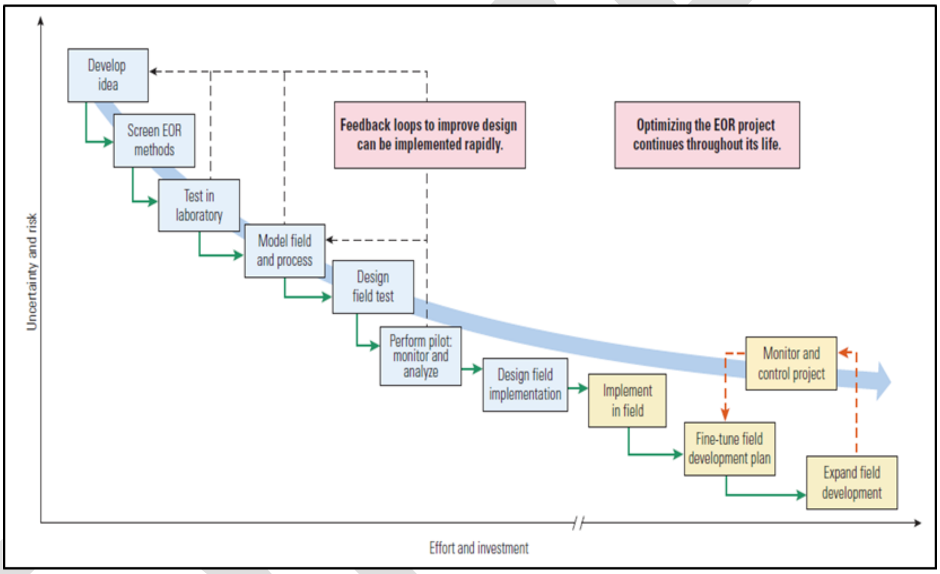


Figure 20 EOR Roadmap (Source: Oil Field Review 2010-11)

Once the number of feasible EOR technologies has been narrowed, the evaluation typically moves into the laboratory. In the first phase analysis of results is performed based on target oil & availability of injectants. Then, Laboratory Investigation of Selected EOR Process(es) is carried out. This stage further screen out the processes for selection of most suitable EOR process. Laboratory studies typically involves, two parts: 'Fluid-Fluid & Rock-Fluid interaction studies' and 'displacement studies', though it can vary from process to process. Through Fluid-Fluid & Rock-Fluid interaction studies, the parameters such as Minimum Miscibility Pressure (MMP), adsorption, Interfacial tension (IFT) etc. are determined. It is important to examine not only the positive aspects, such as miscibility and wettability alteration, but also any negative ones, such as scaling. Then, flow studies are conducted, using either sand packs or cores. At each of these laboratory stages, potential EOR methods can be eliminated or tailored for the specific field Application.

After the laboratory studies, design of field pilot is carried out through simulation. It typically involves Simulation of 1D core flood displacement studies & Field scale simulation for Pilot Design on history matched model. The simulation is carried out to study the effect of the EOR method in the dynamic model to predict recovery. Simulation includes finding an appropriate well configuration, spacing and pattern, as well as the proper injectants and injection strategy. Major unknowns, such as formation heterogeneity, are evaluated using multiple iterations of the simulator with different model parameters. If the simulation indicates the project meets company technical and financial requirements, then it can be used to design the next stage of field pilot test.

5.3.1 Properties of reservoirs identified for CCS/ CCUS

5.3.1.1 Reservoirs owned by ONGC and identified for CO2- EOR as CCUS

A. Gandhar: Ankleshwar Area

Properties	GS-8A+8B	GS-5C	GS-4	GS-3A	GS-1
Average Porosity, %	19	17.2	19.3	16.3	18
Net Pay Thickness, m	3.77	5.25	4.93	7.37	4.61
Average oil saturation, %	55	60	58.1	55	62
Average Permeability, md	115	223	350	0.3-1146	350
Reservoir Temperature, °C	129	128	130	148	132
Initial Static Bottom-hole Pressure (SBHP), Ksc	286	293	304	339.8	322.8
Saturation Pressure , Ksc	266	293	304	339.8	322.8
Solution Gas-oil Ratio , (V/V)	403	391	472	345	650
Viscosity, cp	0.14	0.13	0.2	0.19	0.2
Formation Volume factor at initial pressure, (v/v)	2.62	2.44	2.22	1.79	2.86
Oil Gravity, °API	41.1	41.6	40.7	35.7	41.6

B. Assam Area

Reservoir	Average Porosity , %	Net Pay Thickness, m	Average Permeability, md	Reservoir Temperature, °C	Initial Static Bottom-hole Pressure (SBHP), Ksc
Geleki BMS	12-18	15-30	20-50	105	400
Geleki BCS	12-16	4-20	10-30	76	350-370
Geleki TS-6	15-17	15-20	2-20	85	315-320
Geleki TS-5B	15-20	10-25	20-60	86	305

Lakhmani TS-4B	20	5-15	5-75	88	285-295
Lakhmani LBS-2	14	5-20	17	114	380
Lakhmani LBS-1	14	8-20	5-10	115	380
Lakwa TS-6	13-20	5-20	30-100	87-92	312-325
Laiplingaon LBS-II	13-14	10-20	10-100	99	350
Lakwa TS-2	15-25	20-70	100-1000	74	246
Lakwa TS-3	22	11-13	50-300	76-84	250-265
Geleki TS-5A1	17-22	5-20	30-100	76	300
Geleki TS-4B	16-20	10-20	10-100	76	294

5.3.1.1 Reservoirs owned by Oil India Limited and identified for CO2- EOR as CCUS

A. List of initially screened 23 reservoirs for CCUS

Reservoir	Avg Porosity, %	Net Pay Thickness, m	Avg Perm, md	Reservoir Temp, °C	SBHP, Ksc
Baghjan Langpar Sand (Well BGN001 Block)	15	8	348	98	418
Bazaloni Barail 4th+5th Sand (Well BZL001 Block)	20	73	151	73	241
Bhogpara Langpar Sand (Well BPR004 Block)	16	10	400	98	427
Bhogpara LK+TH Sand (Well BPR005 Block)	16	10	400	103	412
Bhogpara LK+TH Sand (Well BPR005D Block)	21	6	400	93	412
Bhogpara LK+TH Sand (Well BPR015 Block)	16	6	400	94	391
Chabua-Matimekhanamekhana Langpar Sand (Well CBA001 Block)	13	7	500	99	391
Chabua-Matimekhanamekhana LK+TH Sand (Well CBA001D Block)	15	8	550	95	465
Jaipur Barail 4th+5th Sand (Well NHK330 Block)	18	17	7	101	342
Jaipur Tipam Lower Sand (Well NHK454 Block)	16	18	41	88	282
Jaipur Tipam Upper Sand (Well NHK362D Block)	17	22	112	71	235
Jaipur Tipam Upper Sand (Well NHK412 Block)	16	23	112	72	235
Kamkhat LK+TH Sand (Well KMT001 Block)	15	15	425	110	378
Khagorijan LK+TH Sand (Well KGJ001D Block)	20	5	350	110	403
Moran Barail Lower Sand (Well MRN002 Block)	20	16	75	101	343
Moran Barail Lower Sand (Well MRN040 Block)	20	14	6	106	339
North Balijan Langpar Sand (Well NBJ001 Block)	18	5	350	96	405
North Balijan LK+TH Sand (Well NBJ002D Block)	16	5	85	101	354
North Balijan LK+TH Sand (Well NHK520 Block)	18	5	150	93	371
Santi Barail 3rd Sand (Well NHK236 Block)	15	12	39	99	337
Tarajan Barail 2nd Sand (Well TRN001D Block)	15	6	5	105	389

Tarajan Barail Extra Sand (Well TRN005E Block)	15	13	5	100	352
Tarajan Barail 3rd Sand (Well TRN001 Block)**	15	26	5	102	392

Oil India Limited have also identified some of its abandoned reservoirs for evaluation of possibility of Geological CO2 sequestration. The reservoirs have been screened based on the depth, seal thickness and reserves. However detailed feasibility study for identification of suitability of the reservoirs is planned to be carried out considering the dense population of the area and proximity to thrust zone. The Possible reservoirs for CCS is given below:

B. Probable Reservoirs for pure CCS

Reservoir	Average Porosity, %	Net Pay Thickness, m	Average oil saturation, %	Average Permeability, md	Reservoir Temp, °C	SBHP, Ksc
Kathalguri Barail 5th Sand (Well NHK275 Block)	15	12	64	7	90	329
Moran Barail Extra Sand (Well MRN042 Block)	20	14	66	75	105	360
Moran Barail Lower Sand (Well MRN011 Block)	20	12	57	46	98	342
Tarajan Barail 3rd Sand (Well TRN001 Block)#	15	26	64	5	102	392

Chapter-6

CCUS Policy Overview

6. Policy considerations

CCUS/ CCS, for quite some time now, has been considered and discussed as an effective tool to mitigate climate change. However, the conceptualization and implementation of the concerned projects has not been very encouraging. This is mainly due to the economic and technological constraint related to significant high cost associated with the capture and transportation of CO2 as well as lack of policy & regulatory framework. However, few nations like USA, Canada, UK, Norway, Australia and China have already made some headway in creation and implementation of a roadmap for implementation of CCS/CCUS projects. India too has made some progress and has initiated studies related to various potential EOR projects.

One thing common in all the countries where CCUS & CCS have gained momentum, is the constant initial support received from the Government. However, every country needs to develop its own path towards decarbonization. Hence, for India, where expenditure on public health, social welfare and education will remain of utmost importance, a model of public-private partnership aided by the funding from the Govt. and the international climate fund agencies could be a rational and pragmatic way for few initial projects till an economically viable business model is evolved for CCS & CCUS.

CCS/CCUS, as has been reiterated over the years, face some specific challenges in the initial scaling-up phase, which needs to be addressed through policies. As summarized in *"Energy Technology Perspectives 2020, Special Report on Carbon Capture, Utilisation and Storage" of IEA* these challenges include:

- High capital investment for CO2 capture, storage and related infrastructure
- Co-ordination across multiple sectors and stakeholders
- Uncertainty surrounding long-term ownership and liability for stored CO2
- Untested insurance and finance markets
- Public related concerns to storage (particularly onshore) in some regions

The ultimate objective of a successful policy will be to overcome these challenges and facilitate the creation of a sustainable and viable market for CCUS/CCS. This however will require participation of both public & private sectors to invest and engage in the technology. It will also require implementation of few pilot/demonstration projects to start with which will act not only as a proof of concept but also facilitate learning by doing. The policy shall also address the issue of investment challenge and facilitate development of a viable CCUS/CCS market in the long term. All these challenges can only be addressed through a judicious mix of policy measures. These measures may include

- **Direct capital grants**
  This will be meant to provide funding to overcome upfront capital expenditures. Currently nearly all the ongoing CCS/CCUS project received some form of capital infusion from the government in the form of grant. In India too, few initial projects of “First of a kind” nature may be supported with some form of capital grants similar to that provided under UK CCUS Infrastructure fund or EU Innovation fund. However, this cannot be a regular affair and has to be restricted to few initial projects only to avoid putting an enormous burden on the national budget.

UK CCUS Infrastructure Fund (USD 1.37 Bn) aims to develop four (4) carbon capture and storage hubs across UK. ETS Innovation Fund (USD 11.9 Bn- part of which will be dedicated to CCUS)- the fund aims to support low carbon technologies, including CCUS to achieve carbon neutrality in Europe. Similar dedicated funds have been allocated for low carbon technologies including CCUS/ CCS in Norway and USA.

- **Operational subsidies**
  This may include multiple form of benefits like tax credits, reimbursement of some operational expenditure to the operator or viability gap funding based on the difference between production cost and the market cost.
  An example of Tax credits is 45Q and 48A tax credits of USA. Where Industrial manufacturers that capture carbon from their operations can earn \$50 per metric ton of CO_2 if stored permanently or \$35 per metric tonne of CO_2 if the CO_2 is use, such as for enhanced oil recovery (EOR).
  In India for CCUS projects like CO_2 EOR, complete exemption from Cess & Royalty can be an option for initial projects. Also, tax credits in line with 45Q may be considered.

- **Carbon pricing mechanisms**
  This is mainly focussed on pricing schemes for CO_2 emission and incentive structure for its reduction. Currently two models of carbon pricing are in vogue, i.e, Carbon Tax and Emission Trading system (ETS).
  In Carbon Tax certain amount of financial penalty is imposed on emission. This is in operation in Scandinavian countries since 1990-91 and in mainland Europe since 2008 onwards.
  ETS also referred as “Cap and Trade” involves a cap on emission on large stationary sources and trading of emission certificates. ETS is in operation in EU, USA, China and few more countries. It started in 2005 in EU.

- **Regulatory requirements**

This involves making policy and regulatory framework not only amenable for creating an encouraging business environment for CCS/CCUS projects but also create some deterrent for emissions.

- **Low- Carbon products**
  Public procurement of low-carbon products from CCUS-equipped plants may be encouraged. This may not only generate a reliable and an early market for low carbon products but also facilitate advancement of technology and technical standards.

- Support for Research & Development in developing cost effective CCUS/CCS technologies for large scale commercial application in the medium to long term.

6.1 Critical factors for fast deployment of CCUS/CCS

The fast deployment of CCUS/CCS technologies requires some pragmatic and innovative policy initiatives catering to the national and sector-specific circumstances. For ease of understanding and implementation, the policy measures may be categorised into short, medium and long term in order to have a definitive pathway to attain the net zero goal by 2070.

6.2 Short Term (0-3 years)

- **Set net zero targets**
  Individual stakeholders of the upstream E&P value chain may be asked to set their individual net zero targets and roadmaps with a definitive timeline to achieve them. Also, the present emission figures of all companies may be recorded, and a robust mechanism may be devised to monitor the emissions from point sources of the upstream E&P industry.

- **Inclusion of CCS/CCUS in National Climate Action Plan**

  CCS/CCUS may be included in the National Climate Action Plan (NAC) as part of long-term strategy of mitigating climate change. Inclusion of CCUS in NAC shall bring focus to CCUS.

- **Create amenable conditions for investment**

  It is well understood that CCUS/CCS is highly cost intensive and a complex technology. Also, storage and transport involve a high degree of operational challenges and uncertainty. Already the cost of capturing CO2 worldwide is fairly high but the problem is compounded further in India due to the absence of any noteworthy transport network. In such a scenario it will be challenging task to bring investments. Therefore, tailormade policy, combining incentives with penalties needs to be formulated for India. For India the more prudent approaches are likely to be:

- ✓ **Provide financial support for feasibility studies for early-mover projects**
  A national level CCUS fund may be created by pooling funds from key stakeholder companies both from Public and Private sector which may then be utilized for funding/ aiding the development of CCUS/ CCS projects.
  Capital grants on achieving specific milestones may be given. [This could also be in collaboration with multilateral development banks (MDB)].

  Additionally, to garner support from International climate action supporting agencies in the form of grant, soft loan etc. negotiation may be initiated with assistance from the Government.

- ✓ **Establish and propagate Carbon markets:** The Government should aid the development of Carbon Markets to not only reduce emissions as well as pursue low carbon path, but also provide the required market support mechanism for adoption of new mitigation methods and technologies. However, the same should be cost effective, politically feasible and based on existing knowledge and experience in managing similar instruments in India and worldwide.

- ✓ **Provide tax credits to CCUS/ CCS equipment owners**

- ✓ **Provide Viability Gap Funding (VGF) for commercial projects at concessional rates**

- ✓ **Encourage procurement of lower emission products**

- **Provide funding to support capital and operating costs for early projects**
  Grant funding programmes can play a key role in supporting early CCUS/ CCS adoption. Therefore, support may be provided to a certain number of demonstration/ pilot projects. This may not only provide the necessary knowledge and experience but also help in alleviating the high capital costs and commercial and technical risks associated with such projects. As a strategy therefore, 5-10 demonstration projects with definitive timeline, may be taken up in the initial stages. The funding/ support may depend upon the CO_2 stored/ used resulting in reduction of overall emissions. However, a rapid scale-up of CCUS will necessitate a shift towards market-based measures that can complement grant funding and provide a stable and ongoing framework for CCUS facilities to operate over the long term.

- **Develop a geological CO2 storage atlas**
  Access to storage sites will pose a significant challenge to widespread deployment of CCUS/ CCS technologies. Capturing CO2 without the knowledge of sites where they could be sequestered is of very little relevance. Hence, there is an immense need for development of source and storage Atlas that will map the source as well as storage sites. Therefore, the Government geological surveys/ centres/ institutes should start immediately by undertaking pre-commercial CO2 storage assessments. Oil and gas companies will be important partners in this , as they already hold large amounts of data, notably on depleted oil and gas reservoirs.

- **Encourage and augment R&D**
  Support for R&D is vital for future development, deployment, and cost reduction of CCUS/ CCS technologies. Hence, a dedicated fund, which may also be set up in collaboration with some MDB, should be established to support/ fund innovative projects and projects related to R&D.

- **Develop and adopt norms for transparent and effective reporting, monitoring and verification**
  Rules and standard mechanism to report, monitor and verify the reduction in CO2 and GHG emissions should be set up. As a precaution, these rules and standards set up may first be tested in the pilot and demonstration projects before they can be made applicable for all projects.

- **Reinforce public awareness and enhance their participation**
  For CCUS/ CCS technologies to be adopted, it is imperative that the general public is made aware of the benefits and risks associated with those technologies. All-out efforts should be made to ensure that legitimate concerns of the people living in the proximity of storage sites are addressed. In fact, it is always advisable that the local community is consulted before deployment of such projects.

- **Set up a robust and transparent support system**
  Successful and effective deployment of CCUS/ CCS technologies requires the presence of independent transparent regulatory mechanism/ body with clearly defined roles and responsibilities. However, initially, to reduce administrative burden, the works of the proposed regulatory mechanism/ body may be looked after by an existing body.

6.3 Medium Term (3-10 years)

- **Allocate risks across the public and private sectors**
  To have impact on climate change mitigation, in the medium term CCUS/CCS needs to scale up to multiple commercial projects. This is only possible with

effective public private partnership. Successful operation of few initial Pilot/Demonstration projects mostly by public sectors could work as a confidence building measure for private operators to enter into CCS business. Apart from this, a viable and sustainable business model is imperative to attract private investment in storage operation. But for both public and private operators the long-term liability associated with CO2 storage, including the risk that the CO2 could migrate or leak out many years or decades after the operation is stopped, need to be addressed through proper policy measures. One option is to transfer the ownership of the stored CO2 back to governments after the injection is stopped and with assurances with evidence that the injected CO2 is behaving in a stable and predictable manner.

- **Target industrial hubs with shared CO2 infrastructure**

  The most pragmatic way to scale up CCUS/ CCS operations is through facilitation and creation of CCS hubs and cluster networks. These hubs will bring together and connect multiple emitters with multiple storage locations through common transportation infrastructure. This will not only reduce costs and risks but also facilitate and encourage greater volumes of CO2 capture. Bharuch district in Gujarat could be an ideal initial location for development of CCS hub considering the availability of multiple industrial CO2 source points as well as mature and depleted oil & gas reservoirs. Learnings from the project can greatly aid in identifying and developing new Hub sites.

- **Establish a legal and regulatory framework for safe and secure storage**

  The development of any CO2 storage resources either pure CCS or CCUS must ensure proper site selection and safe operation. Safe operating practices is a must to mitigate and manage risks at all stages of project operation and even in closure. It should also provide a legal basis for defining roles and responsibilities of ownership and liability for stored CO2. This can be in line with international standards that have already been developed/ implemented for CO2 storage (e.g. ISO/TC 265, ISO 27914).

- **Identify and encourage the development of CO2 storage**

  The importance of Pilot/Demonstration projects can never be overemphasized both in terms of learning and confidence building. Confidence in the safe and secure CO2 capture, transportation and storage is a prerequisite for investment in both transport and storage infrastructure and capture facilities. In India, significant assessment work is required in identifying realistic and bankable storage, where maximum amount of CO2 can ultimately be stored, the maximum rate of injection, containment of the injected CO2 and its migration in the formation and the risk of leakage.

- **Support public awareness and education**

  Any successful CCUS/CCS campaign needs the co-operation and involvement of multiple stakeholders. General public is one of the most significant of them. All the project of this nature needs the support and acceptance of the local community. With concerted efforts, the local community and the public at large needs to be sensitized about the significance and safety of permanent geological storage of CO_2. Communication and engagement should be a continuous affair throughout the project development to secure community support. Governments, non-governmental organisations and the scientific community, have significant role in communicating the value of CCUS in meeting the climate goals.

6.4 Long Term (10-15 years)

- **Encourage technology innovation to reduce capture cost & support novel technologies through R & D**

  One of the key challenges today is the high capture cost of CO_2. It requires innovation and persistent R & D efforts to develop methods and technologies to reduce capture cost exponentially. This can be a game changer in CCUS/CCS industry.

  Given that the world is still in the early stages of the CCUS revolution, India has a once in-a-generation opportunity to emerge as a global CCUS innovation hub. Key enablers to achieving this will include incentives and R&D subsidies for the private sector to help position India as a global tech and entrepreneurial hub. Also key will be the development of CCUS business incubators and R&D centres in close collaboration with universities, attracting innovative foreign businesses to establish or expand their presence in India.

  It is imperative to incorporate CCUS in the Academic curriculum to create a knowledgeable and skilled workforce to take up the challenge in near future. Also, Government needs to encourage and develop multiple R & D Institutes for CCUS related research.

- **Develop India as a CO_2 Storage hub**

  The long-term objective should be to develop India as a sustainable and viable CO_2 storage hub considering our huge spread of sedimentary Basins (both Offshore and Onshore). In addition to petroliferous basins, long term storage potential should encompass basalt storage in vast Deccan trap as well as saline aquifer.
  To achieve this objective, Government needs to create policies which are flexible, dynamic and evolving.

6.5 Dedicated Workforce for CCUS/CCS

India has a lot of scattered experience in CCUS and lacks a comprehensive direction to address the issue. A good beginning in this area has been already made with this UFCC taskforce that identifies enhanced oil recovery (EOR) and enhanced coal-bed methane recovery (ECBMR) as initial pathways for large scale implementation of India's CCUS strategy. A fundamental gap exists in the form of a knowledge pool on CCUS which can be rectified by mutually beneficial interaction of academia and industry with government bodies, international government community, and funding agencies such as Asian Development Bank and World Bank. The primary way forward could be a push towards knowledge sharing for verification and validation of potential storage capacities, development of feasibility and engineering projects on CCUS, collaboration between relevant stakeholders, capacity building for present and future endeavours, and manpower training to become better equipped for large-scale implementation. Strengthening the R&D infrastructure of the country for CO2-EOR to match up to the successful global examples will be key to India's rapid growth in CCUS.

Few initiatives have been taken by organizations in India to train individuals in CCUS. A series of workshops aimed at providing understanding of science & technology of Carbon Capture, Storage and Utilization and its growing importance in the energy industry have been conducted. Few institutes and universities have also carried out faculty development and capacity building programmes. IIT Bombay implements CCS in its academic curriculum with an advanced course on 'Geologic carbon sequestration and enhanced oil recovery' and has also launched a continuing education programme titled Climate Studies: Services and Solutions' which includes CCUS. The Centre for Oil, Gas and Energy at IIT Bombay is an MoPNG initiative that also has a programme designed for industry professionals on the 'Decarbonization of Industry' including the CCUS pathways.

An approach to engage manpower simultaneously from the participating industries as well as the knowledge partner institutions may be considered as follows:

In the first tier, dedicated working-level manpower in the industry would be identified for task-oriented capacity building, training and skill developments, and on-site engagement. A long term continued association of trained manpower attached with specific projects will ensure continuity of works. The second tier would have the management and business leadership such as the heads of the participating industries (e.g. HoI-IRS, HoI-COEES), that would finally be led by the topmost leadership in the industry together with the ministry of petroleum and natural gas.

Manpower from academic and R&D institutions would be important for development of capacity in India. Students at various undergraduate and postgraduate levels would benefit from learning about climate change mitigation, pathways for geologic carbon sequestration, carbon capture, transport and storage, and methods of enhancing petroleum recovery using captured CO2. The topics in CCUS may be adopted as part of the academic curriculum. The masters and doctoral degree students may engage in problems related to industry and be provided a task-oriented capacity building. Hands on training using laboratory facilities and simulation using field-specific data may provide dual benefit of mutual learning and filling in the gaps in deployment of projects. Members of faculty from various backgrounds relevant to CCUS along with the administrative research heads may constitute the supervisory group to align the directions of research as relevant to the country. Finally, the top management of the institutions may lead the vision of development in CCUS in close interaction with the industry partners and the Government.

India may develop cross-institutional capacity building programme, jointly with the industry to assimilate the developments in RD&D and deployment to present an experiential learning package to the student/young industry professional community.

Appendix-1

Carbon Capture and Utilization in Other Sectors

The emission of CO_2 in the atmosphere has skyrocketed in the last few decades due to the over-consumption of fossil fuels, deforestation, and over-expanded urbanization that leads to catastrophic climatic consequences. Urgent and immediate mitigation strategies are required to avert this issue and save the planet from apocalyptic repercussions caused by anthropogenic activities. The recently organized COP26 at Glasgow, saw leading emitters of CO_2 like India pledging to significantly lower CO_2 emissions in the coming decades. The onus has thus shifted to the science and associated technical community to formulate sustainable solutions that focus on CO_2 upcycling ensuring a circular carbon economy.

Recent advances in the field of biotechnology, supramolecular systems, nanoscience and technology have paved the way for a myriad of different catalysts to perform CO_2 conversion under variable conditions driven by electrochemical, photochemical, and thermo-mechanical pathways. These processes have led to the production of an array of industrially viable chemical products like carbon monoxide (CO), formic acid (HCOOH), methanol (CH_3OH), methane (CH_4), etc, which already have an existing market. CO_2 in its native form is thermally and kinetically stable. This particular feature resists the direct usage of CO_2 as a raw material for the majority of the chemical transformations. However, the rational usage of specific catalysts and regulated formation of reactive carbon intermediates have emerged as the way forward in this aspect. The above-mentioned CO_2-derived chemicals render value addition and increase its versatility to be deployed as an ingredient in various large-scale industries like pharmaceutical, paper and pulp, FMCG, cosmetics, paints, etc.

Among the different CO_2 downstream products, carbon monoxide (CO) is one of the preferred ones as it can be employed as a Syngas component during the Fischer-Tropsch reaction to synthesize high-value hydrocarbons. The reduction prowess of CO is a well-established feature in metallurgical processes for the metal purification process via the reduction of metal oxides to pure metals. CO gas is one of the prime reactants in the Monsanto-acetic acid process which manufactures million tonnes of commercially relevant anhydrides from alcohol.

Formic acid (HCOOH) is another important side product generated from CO_2 reduction. HCOOH forms one of the major reagents in the tanning and dye fixing process and it is also used as a neutralizing agent during the pH adjustment.

Apart from being one of the most common laboratory solvents, methanol (CH_3OH) is an important industrial raw material. It has a widespread usage as the starting substrate for the synthesis of various other chemical compounds like acids, anhydrides, and esters, used in adhesives, foams, paints, and polymers. Methane

(CH_4) is used as a fuel and biogas for household energy requirements and it can be manufactured in copious amounts from CO_2 with the help of industry-ready highly active heterogeneous hybrid catalysts. Apart from those chemicals, CO_2 can also be used to produce polycarbonates from cyclic epoxides. The end products of these reactions serve as the repeating template for various polymerization reactions and resin formation.

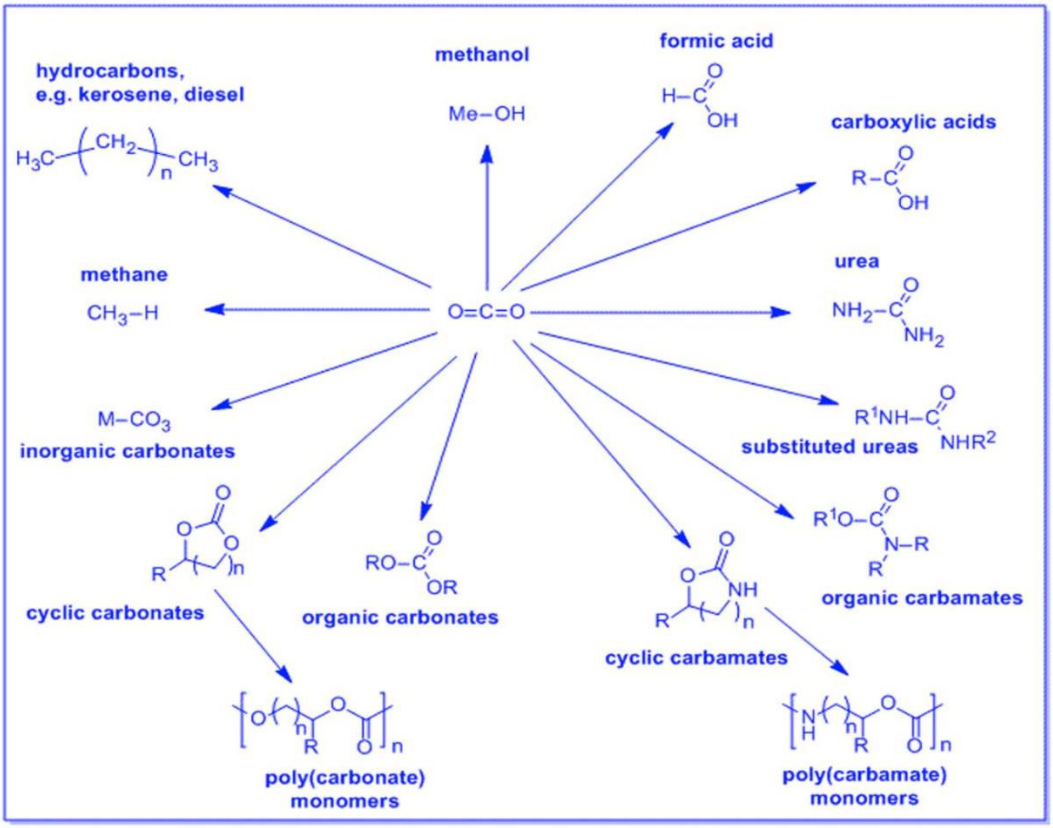


Figure 74 CO_2 conversion to versatile chemicals: A sustainable route for CO2 management (Source: Carbon Dioxide as Chemical Feedstock by Dr. Michele Aresta)

Hence, it is the need of the hour to encourage more research and innovation in the field of CO_2 utilization, which is reckoned as a key aspect of closing the loop of carbon biogeochemical cycle. This particular feature of CCUS technology allows a viable avenue for converting the otherwise waste CO_2 into highly valuable chemicals. Additionally, the revenue generated from these conversions ensures establishment of a cost-effective CCUS technology, which has emerged as the best bet for us to tackle the current CO_2 imbalance-driven climate calamity.

Soda ash, urea, polycarbonates, methanol, etc are essentials chemicals that are used either a feedstock or agricultural input (in case of urea). CO_2 is already used as a raw material in producing these products. CO_2 is already used in commercial processes, both in its pure form and as a feedstock in the synthesis of bulk chemicals such as urea. In the pure form, CO_2 is presently used in the food industry with uses as varied as carbonation of drinks to accelerated production of greenhouse vegetables. Likewise, large quantities are also used as solvents in processes such as dry fabric cleaning and decaffeination. If CO_2 is captured cheaply, efficiently and with high quality then it can act as an excellent method to replace carbon from these products.

Appendix-2

CCUS Global Overview

1 Global Perspective

Globally, there is a growing scientific consensus that Carbon Capture, Utilization, and Sequestration (CCUS) will likely play an important role in decarbonization efforts. Also, Carbon capture technologies can play an important role in reducing other kinds of emissions (eg., sulphur dioxide). Therefore, scaling up CCUS is an essential tool to achieve both climate change and net zero future. Several efforts have been made towards deployment of CCS/ CCUS technologies/ projects. The Global Status of CCUS facilities (large and pilot/demonstration facilities) which capture CO2 from industrial sources, power generation etc are explained in coming sections.

1.1 CCU & CCUS Projects in USA

CCUS already plays an important and valuable role in the U.S. economy. Currently there are 5,200 miles of dedicated CO2 pipelines. Around 52 million tons of CO2 were supplied to EOR for injection underground in 2019. Further, there are approximately 45 CCUS facilities in operation or in development in the United States today. Also, the costs of carbon capture have decreased by 35% between a first-of-a-kind power plant with carbon capture and the second facility using the same technology.

Apart from using CO2 for EOR applications, CO2 is used for producing economically valuable products like Ethanol, Dry Ice and for chilling, freezing, wastewater treatment, welding etc. Ethanol is the largest source (36%) of CO2 produced from industrial sources and used for commercial applications in the U.S.A.

Details of some of the major CCUS projects of U.S.A along with CO2 capture technology / methods are given below:

Table 27 Major CCUS Projects of USA (Source: Global Status of CCS 2020)

S No.	Project Details	Capacity (MMTPA)	Operational Status	CO2 captured from Industry / Facility	CO2 Capture Technology / Method
1	The Petra Nova Carbon Capture Project, south of Houston, Texas, USA	1.4	2017	Coal-fired power plant	KM-CDR Amine Solvent Technology
2	Great Palins Synfuel Plants, Beulah, North Dakota, USA	1.0	1984	Coal-to-SNG facility	Pre-Combustion
3	Air Products Steam Methane Reformer CCS	1.0	2013	Hydrogen Production	Amine based absorption technology &

	Facility, Port Arthur, Texas, USA				vacuum swing adsorption (VSA) technology
4	Illinois Industrial CCS in Decatur, Illinois, USA	1.0	2016	Ethanol plant	Alstom's amine process
5	Century Plant, USA	5.0	2010	Natural Gas Processing	Physical solvent-based capture
6	Shute Creek CCS Facility, LaBarge, Wyoming, USA	7.0	1986	Natural Gas Processing	Physical solvent-based capture

1.2 CCU & CCUS Projects in Canada

Canada's addresses the climate change via Pan-Canadian Framework on Clean Growth and Climate Change. Its main goal is a 30% reduction in national CO2 emissions from 2005 levels by 2030.

Several significant initiatives regarding CCUS have been taken in two provinces: Saskatchewan and Alberta. Both the provinces have new CCS regulations which came into effect in 2020 [10].

Details of some of the major CCUS projects of Canada along with CO2 capture technology / methods are given below [10]:

Table 38 Major CCUS Projects of Canada [10] (Source: Global Status of CCS 2020)

S No.	Project Details	Capacity (MMTPA)	Operational Status	CO2 captured from Industry / Facility	CO2 Capture Technology / Method
1	The Quest CCS projects, Edmonton, Alberta, Canada	1.2	2015	Crude Bitumen Processing Facility / Oil Sands Upgrading	Chemical solvent-based absorption
2	North West Redwater Sturgeon Refinery CCS Facility, Red Water, Alberta, Canada	1.2	2017	Hydrogen Production	Physical solvent-based absorption

3	Boundary Dam Carbon Capture Project, Estevan, Canada	1.0	2014	Coal-fired power plant	Cansolv's FGD technology
4	Huskey Energy Lashburn & Tangleflags CCS Facility, Saskatchewan, Canada	0.1	2012	Ethanol Production	Mitsubishi Hitachi Power Systems Amine Technology

1.3 CCU & CCUS Projects in Europe

Reducing carbon dioxide emissions is at the heart of the energy transition. There have been signs of the decoupling of emissions from economic growth, especially in Europe. In several European countries, CCUS has received more urgent attention. Presently, there are 13 commercial CCS facilities in operation or various stages of development across Europe.

Details of some of the major CCUS projects of Europe along with CO2 capture technology / methods are given below:

Table 49 Major CCUS Projects of Europe (Source: Global Status of CCS 2020)

S No.	Project Details	Capacity (MMTPA)	Operational Status	CO2 captured from Industry / Facility	CO2 Capture Technology / Method
1	Sleipner CCS Facility, Norway	1.0	1996	Natural Gas Processing	Chemical solvent based
2	Snohvit CCS Facility, Norway	0.7	2008	Natural Gas Processing	Chemical solvent based
3	Aberthaw Pilot Carbon Capture Facility, UK	Pilot Scale	2013	Power generation	Cansolv Integrated CO2 & SO2 removal System
4	Jerome CCS Facility, France	0.1	2015	Hydrogen Production	Cryogenic Separation
5	Acorn CCS Facility, UK	0.3	2020	Oil Refining	Direct Air Capture (DAC) technology
6	Air Liquide Refinery Rotterdom CCS Facility, Holland	2.5*	2024	Hydrogen Production	Combination of Adsorption and Cryogenics technologies

* 2.5 MTPA CO2 Storage Capacity

1.4 CCU & CCUS Projects in China

With a target to achieve carbon neutrality by 2060, CCS/ CCUS has gained considerable prominence in China. In addition to climate benefits, CCUS can create social and economic benefits, helping China to maintain economic growth, strengthen its market position in low carbon energy and secure energy supply. Deploying CCUS on this scale will require a range of new policies to commercialize CCS and help a CCUS industry to emerge.

CNPC's China Northwest hub, aims to lead the way for other hubs to emerge. If China can accelerate CCUS deployment at the scale needed to achieve carbon neutrality, it would catalyse the global CCUS industry.

China has completed 35 CCUS projects, but most are on a demonstration-scale and largely implemented by state-owned enterprises under the government's guidance, rather than as a commercial project.

One large-scale CCUS project is already in operation at CNPC's Jilin oilfield, five are due to start operation in 2021, and 10 are currently under consideration or in development, including China's first CCUS hub and three other CNPC-led hubs [12,13]. Together, these projects have the capacity to capture and store over 19 million tonnes of carbon dioxide per year.

Details of some of the major CCUS projects of China along with CO_2 capture technology / methods are given below:

Table 20 Major CCUS Projects of China (Source: OGCI Report September 2021)

S No.	Project Details	Capacity (MMTPA)	Operational Status	CO2 captured from Industry / Facility	CO2 Capture Technology / Method
1	Sinopec Zhongyuan Carbon Capture Utilisation and Storage, China	0.12	2006	Chemical production	Novel advanced solvent technology
2	Karamay Dunhua Oil Technology CCUS EOR, China	0.10	2015	Chemical & methanol production	AEA solution (An amine-based complex solution) based technology
3	CNPC Jilin Carbon Dioxide Capture and Storage Project	0.6	2018	Natural gas processing	MEA absorption capture technology
4	CRP Haifeng Project	1.0	2030	Power generation	Physical adsorption technology

1.5 CCU & CCUS Projects in Japan

Japan plans to become carbon neutral by 2050 by scaling up its use of renewables and hydrogen, as well as accelerating the research and development of key technologies, including CCUS. Japan is driving international activities to develop clean hydrogen production using CCS, and supply chains. Also, Japan has been supporting collaborations on CCS with numerous countries in the region.

Details of some of the major CCUS projects of Japan along with CO2 capture technology / methods are given below:

Table 21 Major CCUS Projects of Japan (Source: Global Status of CCS 2020)

S No.	Project Details	Capacity (MMTPA)	Operational Status	CO2 captured from Industry / Facility	CO2 Capture Technology / Method
1	Tomakomai CCS Demonstration Project, Japan	0.1	2016	Hydrogen Production	Solvent based absorption
2	Mikawa Project, Saga City, Japan	0.18	2020	Biomass power generation facility	Chemical absorption technology
3	Osaki CoolGen Project, Japan	0.1	2020	Power Generation	JGC promoted DDR-type zeolite membrane technology
4	Eagle Pilot & Demonstration Facility, Japan	Pilot Facility	2002	Power Generation	Chemical absorption method

1.6 CCU & CCUS Projects in Australia

Recently, the Australian Government has released several policy documents to establish a policy support mechanism for CCS projects. The government agreed to an industry consultation process on the development of a CCS methodology, under its Emissions Reduction Fund. Some CCUS facilities are in operation or in development stage in Australia today.

Details of some of the major CCUS projects of Australia along with CO2 capture technology / methods are given below:

Table 52 Major CCUS Projects of Australia (Source: Global Status of CCS 2020)

S No.	Project Details	Capacity (MMTPA)	Operational Status	CO2 captured from Industry / Facility	CO2 Capture Technology / Method
1	Gorgon CCUS Project, Australia	3.4	2019	Natural Gas Processing	Chemical solvent-based technology
2	Callide Oxyfuel Project, Australia	Pilot Facility	2012	Power Generation	Callide Oxyfuel combusti on technology
3	Hazelwood Carbon Capture & Mineral Sequestration Pilot Plant, Australia	Pilot Facility	2009	Power Generation	Ammonia based technology

1.7 CCU & CCUS Projects in South East Asia

Southeast Asia region with countries like Indonesia, Singapore, Malaysia, Thailand, Vietnam, Brunei is one of the fastest growing regions in the world. Its energy demand has increased more than 80 per cent from 2000, and hydrocarbon fuel (oil, coal, and gas) supplies more than 70 per cent of its energy.

Deployment of CCS can provide the region reliable, clean, and low-carbon power as well as decarbonize its large oil, gas, and manufacturing sectors. There are encouraging low-cost early mover opportunities for large-scale CCS projects in the natural gas processing and petrochemical sectors.

Southeast Asia region is also emerging as a key hub for CCUS projects. The region has a great variety of CCS pilot projects, which cover Natural gas processing, Fertilizer, Hydrogen production, Waste to energy, Iron/steel, Coal to chemical, Cement etc. Details of some of the upcoming CCUS projects of South East Asia are given below.

Table 63 Major CCUS Projects South East Asia [10] (Source: Global Status of CCS 2020)

S No.	Project Details	Operational Status	CO2 captured from Industry / Facility
1	Gundih Pilot CCS Facility, Indonesia	2021	Natural Gas Processing
2	PAU Central Sulawesi Clean Fuel Ammonia Production with CCUS Facility, Indonesia	2021	Fertilizer Plant
3	Petronas Kasawari Gas Field Development Project, Malaysia	Early Development	Natural Gas Processing

4	Repsol Sakakemang carbon Capture & Injection, Indonesia	2026	Natural Gas Processing

2 Global Sector-wise Technology

Industry produces about eight billion tonnes of direct CO2 emissions annually. Sectors like cement, iron & steel, and chemical sectors are responsible for about 70 per cent of these. If indirect emissions are added, industry accounts for almost 40 per cent of global anthropogenic CO2 emissions.

Demand for industrial products will grow further and growing affluence in developing economies, will see more industrial products.

Considering current commitments in Nationally Determined Contributions (NDCs) to limit emissions and improve energy efficiency, the IEA estimates that direct industry CO2 emissions will grow from eight to almost 10 billion tonnes per annum, by 2060. To achieve a climate outcome consistent with the Paris Agreement, these emissions should instead fall to 4.7 billion tonnes by 2060.

All the process emissions cannot be avoided using feasible production technologies. Multiple approaches will be necessary to cut emissions, including fuel switching, improved energy efficiency, and the deployment of current best available and future innovative technologies. The only feasible option for mitigation in many cases, is to remove CO2 after production, using CCS. Direct CO2 emissions in GtCO2 by various sectors globally are given below:

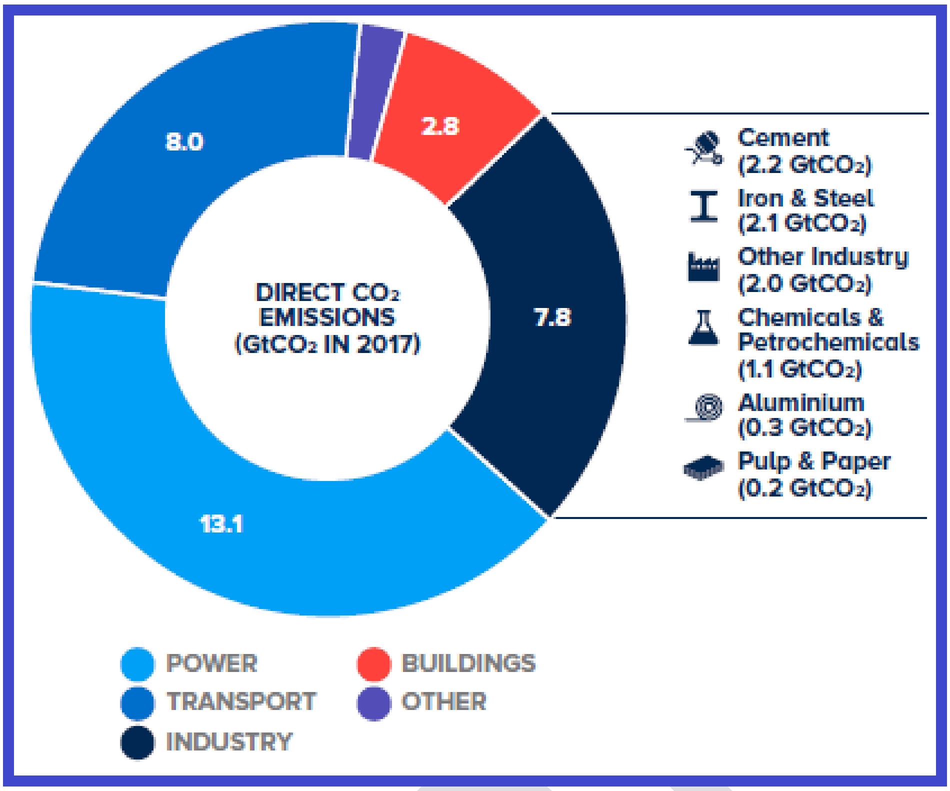


Figure 52 Global Industry Sector Wise Direct CO2 Emissions[10]
(Source: Global Status of CCS 2020)

2.1 Cement Industry

Conventional cement making involves exposing limestone (CaCO3), to intense heat in a rotating kiln, creating calcium carbonate (CaCO3) and CO2. Also, extra CO2 is produced by the combustion of fuels (coal or natural gas). The cement industry produces approximately eight per cent of global CO2 emissions with calcination representing around four per cent.

Addressing cement industry emissions is, therefore, essential for a net-zero world. Flue gases from cement kilns are good candidates for CCS.

Details of some of the CCUS projects implemented in cement industry along with capture technology is given below.

Table 74 CCUS Projects in Cement Industries (Source: Global Status of CCS 2020)

S No.	Project Details	Operational Status	CO2 captured from Industry / Facility	CO2 Capture Technology / Method
1	Norcem CCUS Pilot Facility, Norway	2014	Heidelberg Cement Plant	Proprietary based solvent technology

2	ITRI Pilot Facility, Taiwan	2013	ITRI cement industry	Calcium looping & solid sorbents technology
3	LEILAC Calix cement industry, Belgium	Under implementation	Calix cement Plant	Proprietary calcination reactor technology

2.2 Iron and Steel Industry

The iron and steel industry produces approximately 7% of global CO2 emissions. Considerable efforts are being made to reduce these through measures like steel recycling, energy efficiency programs, and early steps toward substituting fossil fuel for hydrogen. A large portion of GHG emissions can be addressed using CCS.

Details of some of the CCUS projects implemented in Iron & Steel industries along with capture technology is given below.

Table 8 CCUS Projects in Iron & Steel Industries (Source: Global Status of CCS 2020)

S No.	Project Details	Operational Status	CO2 captured from Industry / Facility	CO2 Capture Technology / Method
1	The Emirates steel plant CCUS Facility, Abu Dhabi	2016	Steel plant	Solvent-based CCS plant
2	Tata Steel, Ijmuiden CCUS Facility, The Netherlands	Early Development	Steel plant	The Hisarna process*

* The Hisarna process produces highly concentrated carbon dioxide from the reactor, so ideally suited for CCS without the need for gas separation

2.3 Natural Gas Processing Industry

The switch from coal to natural gas in industries reduces CO2 emissions. However, natural gas production and processing have significant emissions, both from the use of energy at processing facilities and from the way natural gas is produced. Around 150 Mtpa of high purity CO2 is released from gas processing plants around the world. As this CO2 is available at high purity, it typically only requires dehydration before it can be compressed and stored. This makes it a low-cost source to capture and store.

Details of some of the CCUS projects implemented in natural gas processing industries along with capture technology used is given below.

Table 95 CCUS Projects in NG Processing Industries (Source: USEA Technology Series, May 2019)

S No.	Project Details	Operational Status	CO2 captured from Industry / Facility	CO2 Capture Technology / Method
1	Shute Creek CCS Facility, LaBarge, Wyoming, USA	1986	Natural Gas Processing	Physical solvent-based capture
2	Sleipner CCS Facility, Norway	1996	Natural Gas Processing	Chemical solvent based
3	Snohvit CCS Facility, Norway	2008	Natural Gas Processing	Chemical solvent based
4	Petrobras Lula, Brazil	2013	Natural Gas Processing	Membrane-based
5	Uthmaniyah, Saudi Arabia	2015	Natural Gas Processing	Solvent-based
6	Gorgon, Australia	2019	Natural Gas Processing	Chemical solvent based

2.4 Power Industry

Electricity generation accounts for around a third of global CO2 emissions. Although, it is the largest source of CO2 emissions globally, higher demand for electricity is going to increase the emissions further. Hence, the rapid decarbonisation of power generation is crucial to achieving net-zero emissions. CCS equipped power plants will help ensure that the low carbon grid of the future is resilient and reliable.

Details of some of the CCUS projects implemented in power plants along with capture technology used is given below.

Table 106 CCUS Projects in Power Plants

S No.	Project Details	Operational Status	CO2 captured from Industry / Facility	CO2 Capture Technology / Method
1	The Petra Nova Carbon Capture Project, south of Houston, Texas, USA	2017	Coal-fired power plant	KM-CDR Amine Solvent Technology
2	Boundary Dam Carbon Capture Project, Estevan, Canada	2014	Coal-fired power plant	Cansolv’s FGD technology
3	Aberthaw Pilot Carbon Capture Facility, UK	2013	Power generation	Cansolv Integrated CO2 & SO2 removal System

4	CRP Haifeng Project	2030	Power generation	Physical adsorption technology
5	Osaki CoolGen Project, Japan	2020	Power Generation	JGC promoted DDR-type zeolite membrane technology
6	Eagle Pilot & Demonstration Facility, Japan	2002	Power Generation	Chemical absorption method
7	Callide Oxyfuel Project, Australia	2012	Power Generation	Callide Oxyfuel combustion technology
8	Hazelwood Carbon Capture & Mineral Sequestration Pilot Plant, Australia	2009	Power Generation	Ammonia based technology

2.5 Fertilizer Industry

Details of some of the CCUS projects implemented in Fertilizer industries along with capture technology used is given below.

Table 117 CCUS Projects in Fertilizer Industries (Source: USEA Technology Series, May 2019)

S No.	Project Details	Operational Status	CO2 captured from Industry / Facility	CO2 Capture Technology / Method
1	Enid Fertilizer, USA	1982	Fertilizer Plant	Pre-combustion
2	Coffeyville, USA	2013	Fertilizer Plant	Pre-combustion

2.6 Ethanol / Methanol Industry

Details of some of the CCUS projects implemented in Ethanol/Methanol industries along with capture technology used is given below.

Table 128 CCUS Projects in Ethanol & Methanol Industries (Source: Global Status of CCS 2020, USEA Technology Series, May, 2019)

S No.	Project Details	Operational Status	CO2 captured from Industry / Facility	CO2 Capture Technology / Method

1	Illinois Industrial CCS in Decatur, Illinois, USA	2016	Ethanol plant	Alstom's amine process
2	Huskey Energy Lashburn & Tangleflags CCS Facility, Saskatchewan, Canada	2012	Ethanol Production	Mitsubishi Hitachi Power Systems Amine Technology
3	Karamay Dunhua Oil Technology CCUS EOR, China	2015	Chemical & methanol production	AEA solution (An amine-based complex solution) based technology

2.7 Hydrogen Industry

Ninety-eight percent of current hydrogen is produced from coal via gasification and by steam methane reforming from natural gas. A very small portion (0.3 per cent) is produced from electrolysis of water, powered by renewable. Both the processes (coal & natural gas) produce significant CO2 emissions if abatement is not used. Both are well suited to economical CO2 emissions abatement with CCS.

A key low-emissions route for hydrogen production is SMR coupled with CCS. Today there are four industrial-scale SMR hydrogen facilities with CCS worldwide, producing a total of around 800,000 tonnes of low-carbon hydrogen per year [10,20]. One of these SMR with CCS facilities is Air Products' Port Arthur, Texas hydrogen plant, a two-train SMR facility which captures CO2 from its reformer units using vacuum swing adsorption.

Schematic view of SMR based Hydrogen plant is given below:

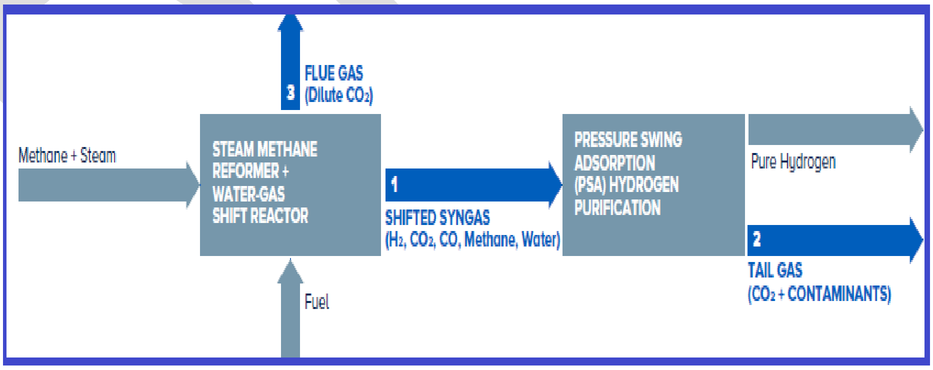


Figure 54 SMR based Hydrogen Plant (Source: Global Status of CCS 2020)

Details of some of the CCUS projects implemented in Hydrogen generation plants along with capture technology used is given below.

Table 139 CCUS Projects in Hydrogen Generation Units (Source:USEA Technology Series, May19)

S No.	Project Details	Operational Status	CO2 captured from Industry / Facility	CO2 Capture Technology / Method
1	Air Products Steam Methane Reformer CCS Facility, Port Arthur, Texas, USA	2013	Hydrogen Production	Amine based absorption technology & vacuum swing adsorption (VSA) technology
2	North West Redwater Sturgeon Refinery CCS Facility, Red Water, Alberta, Canada	2017	Hydrogen Production	Physical solvent-based absorption
3	Jerome CCS Facility, France	2015	Hydrogen Production	Cryogenic Separation
4	Air Liquide Refinery Rotterdom CCS Facility, Holland	2024	Hydrogen Production	Combination of Adsorption and Cryogenics technologies
5	Tomakomai CCS Demonstration Project, Japan	2016	Hydrogen Production	Solvent based absorption

Appendix-III

1. CO2 Transportation by Pipeline: World Scenario

Currently there is over 6,500km of CO2 pipeline in North America, Europe, the Middle East, Africa and Australia. Some of these pipelines have been operating for many years, mostly to transport CO2 for enhanced oil recovery (EOR) operations in the Americas. Some pipelines are linked to Carbon Capture and Storage (CCS) projects and a number of new pipelines associated with CCS are under development at the time of publication. Overview of some major pipelines in world has been depicted in figure-45.

2. Global scenario of CO2 pipelines: China, US, EU

- **China:** The People's Republic of China has no major CO2–EOR pipelines for transporting the CO2 and no regulations and standards for constructing such pipelines. In the early stages of CCUS development, pipelines for large-scale CO2 transport will consist of infrastructure built for other purposes without "open access." Initial investors in a dedicated pipeline have tried to minimize incremental cost by designing the pipeline specifically for its intended purpose, thereby limiting its accessibility to other potential future users (e.g., for CO2 transport). The lack of CO2 transport infrastructure further erodes the financial viability of early-stage CCUS projects in China.
  As the PRC moves into the 14th Five-Year Plan period, a common CO2 pipeline has been proposed to help reduce integration issues and facilitate the build-up of a cluster of CCUS projects. It has therefore been recommended that the associated CO2 pipeline network be developed and financed. The network operator should be an independent operator offering open access to CO2 capture plants through a common set of CO2 off-take agreements. This will strengthen investor confidence, improve economies of scale, and provide the CO2 supplier and oil field operators with operating flexibility. The CO2 pipeline network could be organized as a fully state-owned enterprise or as a public–private investment venture.
- **USA:** In the US, EOR has been the primary driver for CO2 pipeline infrastructure development. There are currently about 5,000 miles of CO2 transport pipelines in the United States. Economy-wide deployment of regional CO2 transport infrastructure in USA will require significant build out. The USA is planning to build 29,000 miles of CO2 transport routes to deliver around 300 million tons of CO2 in the near- and medium-term.
- **EU:** Most EU projects focus on CO2 storage within emissions reduction schemes. There are currently more than 1500 Km of CO2 transport pipelines in Europe. In order to meet decarbonisation targets, the EU Energy Roadmap estimates a total of ~32 GW of CCS is needed by 2035, rising to 190 GW by 2050, equivalent to 11,000 km and 20,000 km of CO2 pipeline infrastructure, respectively.

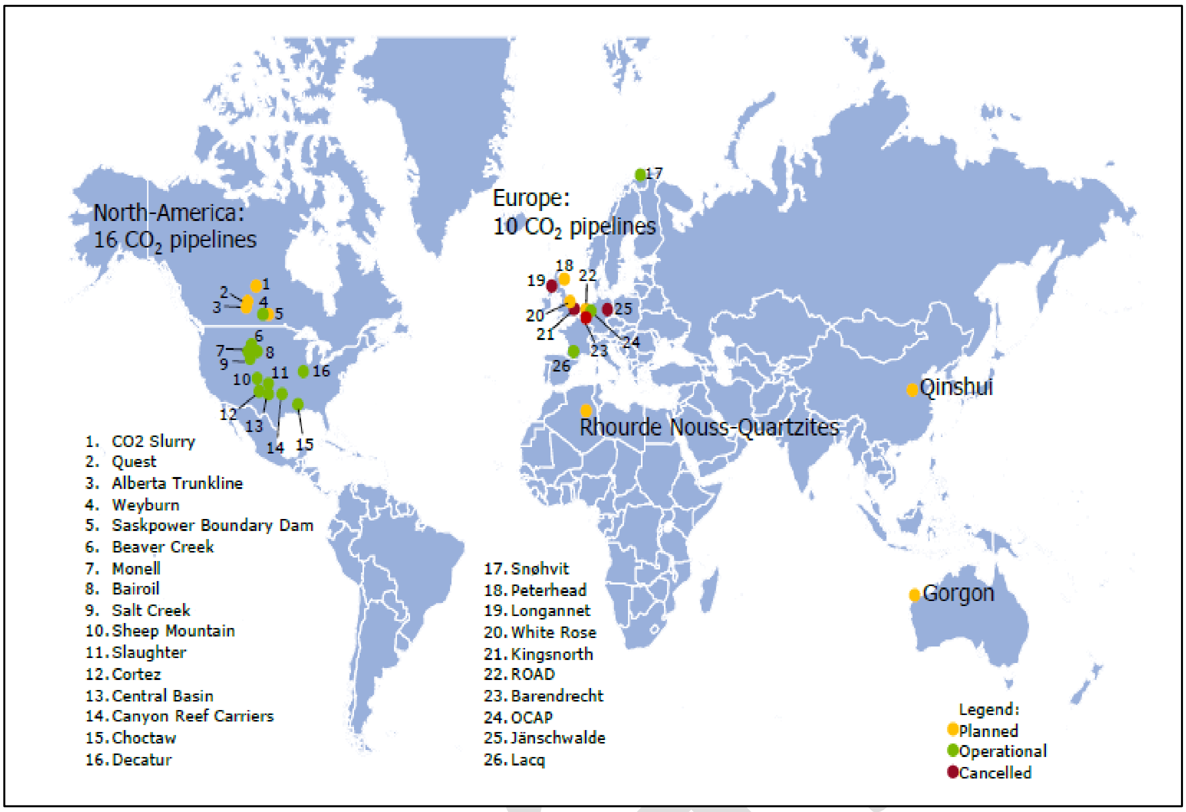


Figure 45 Overview of some major pipelines in World

Reference: IEA Environmental Projects Ltd. (IEAGHG) CO2 pipeline Infrastructure 2014

Abbreviations

ADB	:	Asian Development Bank
ASU	:	Air Separation Unit
AEE	:	Amino Ethyl Ethanol Amine
AL	:	Aluminium
BUR	:	Biennial Update Report
BOF	:	Basic Oxygen Furnace
BCM	:	Billions Cubic Meter
CO2	:	Carbon Dioxide
CCU	:	Carbon Capture and Utilization
COP	:	Conference of the Parties
CCUS	:	Carbon Capture, Utilization and Sequestration
Ca	:	Calcium
CaO	:	Calcium Oxide
CaCO3	:	Calcium Carbonate
CH4	:	Methane
CAP	:	Chilled Ammonia Process
CAGR	:	Compound Annual Growth Rate
CNPC	:	China National Petroleum Corporation
CEA	:	Central Electricity Authority of India
DAC	:	Direct Air Capture
DEA	:	Di-Ethanol Amine
DGA	:	Di-Glycol Amine
DRCF	:	Dual Refrigerant CO2 Fractionation
DRI	:	Direct Reduced Iron
DIPP	:	Department of Industrial Policy and Promotion
EAF	:	Electric Arc Furnace
EU	:	European Union
ECRA	:	European Cement Research Academy

FT	Fischer-Tropsch
FGD	Flue Gas Desulfurization
GHG	Green House Gases
Gt	Gigatonnes
GW	Giga Watt
GT	Gas Turbine
HDV	Heavy Duty Vehicles
IPCC	Intergovernmental Panel on Climate Change
IEA	International Energy Agency
ICE	Internal Combustion Engine
IRGC	International Risk Governance Council
ISP	Integrated Steel Producers
JGC	Japan Gasoline Corporation
LULUCF	Land Use, Land-Use Change and Forestry
LPS	Large Point Sources
MEA	Mono-Ethanol Amine
MDEA	Methyl-Di-Ethanol Amine
Mt	Metric Tonne
Mt CO_2e	Metric Tonne of CO_2 Equivalent
MBPD	Million Barrels Per Day
NOx	Nitrogen Oxides
NDC	Nationally Determined Contributions
NASS	Non-Aqueous Solvents
OMC	Oil Marketing Companies
O & G	Oil & Gas
PSA	Pressure Swing Adsorption
PCC	Post Combustion Capture
RES	Renewable Energy Sources
SPM	Suspended Particulate Matter
SOx	Sulphur Oxides

SMR	:	Steam Methane Reforming
SAIL	:	Steel Authority of India
TSA	:	Temperature Swing Adsorption
TERI	:	The Energy and Resources Institute
UN	:	United Nations
UNFCCC	:	United Nations Framework Convention on Climate Change
VSA	:	Vacuum Swing Adsorption

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Annexure

No.Exp-15022 (13)/24/2021-ONG-V (E-38731)
Government of India
Ministry of Petroleum and Natural Gas
(Exploration Division)

Shastri Bhawan, New Delhi
Dated 16th August, 2021

ORDER

Subject:- Upstream for Carbon Capture, Utilization and Storage (UFCC).

In order to provide opportunity for collaboration and knowledge-sharing to the industry and prepare a unified and practical strategy for development and implementation of Carbon Capture Storage/Carbon Capture, Utilization and Storage (CCS/CCUS) techniques in Upstream E&P in India, it has been decided to constitute a Committee with titled as " **Upstream for Carbon Capture, Utilization and Storage (UFCC)"** under Chairmanship of Additional Secretary (Exploration), MoPNG.

2. The composition of the Committee shall be as under:

(i)	Shri Amar Nath, Additional Secretary (Exploration), MoPNG	-Chairman
(ii)	Shri Asheesh Joshi, Director (Exploration), MoPNG	- Member
(iii)	Shri Sujit Mitra, IRS, ONGC	- Member
(iv)	Shri Atindra Roy choudhury, OIL	- Member
(v)	Shri Saloma Yomdo, OIL	- Member
(vi)	Shri Mukesh Sharma, IOCL	- Member
(vii)	Prof Vikram Vishal, IIT Bombay	- Member
(viii)	Shri Naresh Lalwani, JSW Steel	- Member
(ix)	Shri Jairam K Srinivasan, GEECL	- Member
(x)	Shri A. K. Bansal, Ex-ED, ONGC	- Member
(xi)	Shri O.P. Sinha, IRS, ONGC	-Coordinator
(xii)	Shri O.N. Gyani, ONGC –	-Alternate Coordinator

P-----/Contd.

-2-

3. The Terms of Reference (ToR) of the Committee shall be as under:-

(i) Assessment and evaluation of CO_2 storage potential in India.

(ii) Assessment of the opportunities available for re-purposing abandoned oilfields by Oil and Gas Companies and providing Carbon Capture and Storage services to other industries.

(iii) Review CCS/CCUS technologies used across the world and assess their feasibility for implementation in India

(iv) Identify suitable projects in the Upstream E&P sector where CCS/ CCUS can be implemented

(v) Develop policy and regulatory framework for CCS/CCUS

(vi) Develop financial framework for CCS/CCUS

(vii) Assess methods for improvement and Cost Reduction of Capture Technologies

(viii) Assess methods and way forward for development of CO_2 Transport Infrastructure

(ix) Create dedicated workforce for research and implementation of CCS/ CCUS in all Oil & Gas Companies

4. The Committee shall broadly work as per TOR mentioned in Para 3 above and shall be responsible for preparing "2030 Roadmap for Carbon Capture, Utilization and Storage" which shall provide necessary direction and guidelines for all Oil & Gas Companies in India to develop and scale up CCS/CCUS techniques.

5. The Committee can co-opt or associate any expert/stakeholders.

6. The Committee shall submit its report within a period of 6 month.

AKmehta

(Awdhesh Kumar Mehta)
Under Secretary to the Government of India
Tel: 011 23381984

To

(i) All Committee Members (ii)Chairman/CMDs/CEOs/Head of concerned Organisations	For information and necessary action.

Copy to:-

(i) PS to Minister (PNG) (ii) PS to MoS (PNG) (iii) PS to Secretary (PNG) (iv) Sr. PPS to Addl. Secretary (E), MoPNG	For information.

No.Exp-15022 (13)/24/2021-ONG-V (E-38731)
Government of India
Ministry of Petroleum and Natural Gas
(Exploration Division)

Shastri Bhawan, New Delhi
Dated 25th August, 2021

ORDER

Subject:- Upstream for Carbon Capture, Utilization and Storage (UFCC).

In continuation of this Ministry's Order dated 16.08.2021 (Copy enclosed) constituting a Committee with titled as "Upstream for Carbon Capture, Utilization and Storage (UFCC)", it is informed that it has been decided to co-opt/associate the following personnel in the Committee:-

i. Dr. Anand Gupta, ADG (Dev.), DGH
ii. Prof. Dalie Naidu Arnepalli, IIT, Madras

Encls.: As above

AKmehta

(Awdhesh Kumar Mehta)
Under Secretary to the Government of India
Tel: 011 23381984

To

(i) All Committee Members (ii)Chairman/CMDs/CEOs/Head of concerned Organisations	For information and necessary action.

Copy to:-

(i) PS to Minister (PNG) (ii) PS to MoS (PNG) (iii) PS to Secretary (PNG) (iv) Sr. PPS to Addl. Secretary (E), MoPNG	For information.