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DEPARTMENT OF
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सत्यमेव जयते

DST's R&D Roadmap to Enable India's Net Zero Goals through Carbon Capture, Utilization, and Storage (CCUS)

CCUS Technologies

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FOREWORD

Prof. Ajay Kumar Sood
Principal Scientific Adviser to the Government of India

India's long-term climate vision, rooted in the Panchamrit commitments of COP-26, reflects its responsibility to balance growth and sustainability. These commitments articulate a forward-looking framework for a clean and resilient energy future.

Climate change is among the most critical global challenges of our time, requiring both mitigation and adaptation. Carbon Capture, Utilisation, and Storage (CCUS) represents a key mitigation pathway, enabling the removal of CO_2 from hard-to-abate sectors while supporting continued industrial development. To advance this vision, the Government of India is finalizing a National Mission on CCUS, aimed at promoting technology development, strengthening national capacity through pilot projects and storage infrastructure, and accelerating large-scale decarbonisation.

The Department of Science and Technology (DST) has contributed to the development of India's CCUS landscape through consistent research support, innovation initiatives, and collaborative partnerships. By focusing on sector-specific priorities, DST has facilitated progress in technologies for CO_2 capture from major industrial sources and explored pathways for its utilisation in fuels, chemicals, construction materials, as well as options for secure geological storage.

To promote a structured, scientific, and forward-looking approach to CCUS in India, the Department of Science and Technology (DST) constituted a High-Level Task Force (HTF) to develop a comprehensive national R&D Roadmap. This Roadmap draws on expertise from academia, industry, policy, and funding agencies, and sets clear priorities for advancing CCUS technologies, overcoming economic and infrastructure barriers, and enabling coordinated investments across the value chain. Its focus on targeted funding mechanisms and accelerated technology deployment provides timely direction for scaling CCUS efforts.

The Roadmap serves as a valuable reference for policymakers and practitioners in shaping India's future CCUS efforts. By outlining clear priorities and pathways, it strengthens India's capacity to integrate CCUS into its broader climate strategy, ensuring that industrial growth is pursued in harmony with environmental responsibility. As India advances toward its climate goals, the Roadmap will guide coordinated action, foster collaboration, and enable investments that accelerate technology deployment. In doing so, it supports the reduction of the nation's carbon footprint and reinforces India's role as a responsible global partner, marking an important step toward a sustainable future aligned with the vision of **Viksit Bharat@2047**.

Ajay Kumar Sood

Principal Scientific Adviser to the Government of India **Prof. Ajay Kumar Sood**

FOREWORD

Prof. Abhay Karandikar
Secretary
Department of Science & Technology (DST)

As the world faces the escalating challenges of Climate Change, the need for innovative pathways to reduce Greenhouse Gas emissions has become more urgent than ever. For India, achieving Sustainable Development-balancing rapid industrial growth with environmental responsibility-remains a defining priority. At COP-26 in Glasgow, Hon'ble Prime Minister Shri Narendra Modi announced ***"India's Panchamrit"***, reaffirming the nation's long-term commitment to a sustainable future and setting the ambitious goal of achieving Net-Zero emissions by 2070. In this context, Carbon Capture, Utilisation, and Storage (CCUS) has emerged as a core technological pillar essential for decarbonising sectors where viable alternatives are limited.

Department of Science and Technology (DST) has been at the forefront of strengthening India's CCUS research ecosystem by promoting both fundamental and translational R&D through sustained extramural support. These efforts have been further bolstered by key multilateral and bilateral collaborations under Mission Innovation (MI), Clean Energy Transition Partnership (CETP), and Accelerating CCUS Technologies (ACT) initiative, ensuring India stays closely connected with global advancements.

Following India's Net-Zero announcement in 2021, DST established the country's first three National Centers of Excellence in CCUS-a major milestone that has accelerated national progress. These Centers foster coordinated research, promote academia–industry partnerships, and strengthen India's global linkages, enabling faster development and deployment of CCUS technologies across priority sectors.

DST has also taken a leadership role in supporting translational R&D through the creation of CCU test beds in real industrial environments, leveraging innovative public–private partnership models. These test beds focus on hard-to-abate sectors such as Power, Cement, and Steel-areas central to India's long-term decarbonisation trajectory.

The CCUS R&D Roadmap draws on nearly seven years of experience and the domain expertise of a High-Level Task Force formed thereafter. It provides strategic guidance on thematic priorities and funding pathways needed to accelerate CCUS development. The Roadmap balances advancing current technologies toward commercial readiness with supporting breakthrough science to drive next-generation solutions. Beyond technology, the Roadmap highlights the need for supportive frameworks-including skilled human capital, regulatory and safety standards, and early-shared infrastructure.

As India progresses toward its climate and economic goals, a blend of current state-of-the-art and next-generation technologies will be essential. DST is prepared to lead this emerging domain and empower Indian academia, research institutions, and industry to develop transformative CCUS solutions. The recently announced ₹1 Lakh Crore Research, Development & Innovation (RDI) Scheme will further strengthen private-sector-led innovation in Industrial Decarbonization, complementing the Roadmap's vision.

I am confident that this roadmap will play a crucial role in building national capabilities, fostering innovation across the CCUS value chain, and ensuring that India remains future-ready in a carbon-constrained global economy.

I extend my sincere appreciation to the members of the High-Level Task Force and the coordinating team for developing this impactful and visionary document. Their efforts will guide DST in driving a focused and strategic approach to advancing India's CCUS trajectory.

Prof. Abhay Karandikar

Secretary
Department of Science & Technology (DST)

FOREWORD

Dr. Ashish Lele
Director, CSIR-NCL, Pune
Chair, DST constituted High Level Task Force on CCUS

Carbon Capture, Utilisation, Conversion, and Storage (CCUS) has emerged as a critical pillar in India's pathway toward deep decarbonisation and sustainable industrial growth. As the country advances towards net-zero commitments, it is essential to strengthen the scientific, technological, and industrial capabilities required to deploy CCUS solutions at scale. This demands a coordinated effort to move beyond foundational research and accelerate translational work that directly supports deployment in real operating environments.

The roadmap is organized into six main chapters. While the first chapter provides important background information indicating the urgent need for adopting CCUS and the scale of the problem, the next three chapters outline the R&D requirements for the core components of CCUS namely, capture, utilization and storage. The fifth chapter focuses on financing and policy frameworks, emphasizing the mechanisms and investments needed from discovery to deployment of CCUS supported by enabling policies. The final chapter summarizes industrial sector-wise needs for CCUS, the challenges for integration of CCUS into existing technologies and the potential intervention strategies. A highlight of the roadmap is the recommendation of several enablers for accelerating large scale deployment of CCUS in India. These span across research, innovation, translation, collaborations, financing and policy.

The roadmap for foundational research in catalysis and materials research focuses on augmenting India's existing R&D capabilities by creating state-of-the-art Centres of Excellence where high through-put robotic experimentation combined with AI/ML platform and advanced real-time characterization tools can accelerate breakthrough discoveries. With regards translational science, the roadmap recommends leveraging India's strengths in process engineering, optimization and geological research to set up pilot facilities for rapid scale-up, demonstration and risk assessment of CO2 capture, transport and storage technologies. Further, the roadmap recommends setting up of industrial-scale test beds that would allow rigorous assessment of performance, reliability, safety, and cost-effectiveness of emerging CCUS technologies across diverse industrial sectors such as steel, cement, power, and chemicals etc. Recognizing that CCUS must become an integral part of industrial geography to enable real impact, the roadmap emphasizes the need to set up CCUS hubs and valleys wherein multiple CO2 emitters are connected with capture facilities, shared transport infrastructure, utilization plants and storage infrastructure.

The roadmap emphasizes on collaborative structures for accelerating the maturation of technologies from early conceptual stages to deployable systems. Suggested examples include thematic interdisciplinary clusters of excellence where experts from academia, R&D institutes and start-ups work together with industry partners and policymakers under unified mission-driven programmes. The roadmap specifically recommends India-specific storage site mapping and enhanced stakeholder engagement. It further highlights the importance of building international partnerships to enable access to storage corridors, and strengthen India's overall CCUS ecosystem.

The roadmap recognizes that successful development and deployment of CCUS will not be possible without an intelligent, multi-layered funding architecture. At the earliest stages, the roadmap recommends adequate investments in breakthrough research. Beyond this, translational R&D must be heavily supported through grants, pilot funding and semi-commercial testing platforms. At the highest level, large-scale deployment-such as cluster-wide CCUS hubs-must be created through viability gap funding, public-private partnerships and robust business models.

Financing alone is not enough. The roadmap supports the fact that a strong policy framework will be the backbone of CCUS deployment. Interventions such as operational subsidies for the capture, and capital subsidies for capture equipment, accelerated depreciation for downstream infrastructure, tax holidays for CCUS-enabled industries, and round-the-clock renewable power banking are urgently needed. The roadmap also recommends to exploit opportunities presented by international financing mechanisms such as the World Bank's Climate Investment Funds, IFC green financing, and Article 6.4-compliant carbon credit mechanisms.

India's growing renewable energy capacity combined with its engineering talent, its dynamic start-up landscape and the emerging carbon market places the country uniquely to become a global leader in CCUS technology and manufacturing. India can not only decarbonise its own industries but also export CCUS technologies, components and expertise to the rest of the world. There is an opportunity to build a new industrial sector that can create jobs, attract investment and strengthen India's global competitiveness.

The role of the Department of Science & Technology in accelerating CCUS deployment in India is pivotal. DST can serve as an anchor institution to support breakthrough research, fund translational science, enable pilot plants and industrial testing facilities, support start-ups, shape policy frameworks and foster international collaboration. DST is uniquely positioned to align the scientific community, industry stakeholders and multiple ministries. Through this alignment, CCUS can evolve from a research domain into a full-scale industrial ecosystem.

I commend all the members of the High-Level Task Force and the coordinating teams for their outstanding work in developing a comprehensive and future-oriented CCUS R&D strategy. I am quite hopeful that this Roadmap will play a decisive role in advancing India's climate ambitions and driving the nation's progress toward a more sustainable and thriving future.

Dr. Ashish Lele

Director, CSIR-NCL, Pune
Chair, DST constituted High Level Task Force on CCUS

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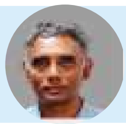

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EXECUTIVE SUMMARY

EXECUTIVE SUMMARY OF THE HIGH-LEVEL TASK FORCE ON CCUS

DST constituted a High-level Task Force (HTF) to develop a comprehensive R&D roadmap for India on carbon sequestration comprising Carbon Capture, Utilization and Storage (CCUS), thus covering all the pillars of the CCUS challenge. This report is the outcome of the deliberations of the HTF, consisting of experts from academia, research institutions, industry and their consortia members, on the roadmap on CCUS R&D for India.

The report is developed to capture the R&D needs in CCUS for India. It includes translational R&D that is necessary to scale up proven concepts from laboratory to pilot scale, demo scale and finally industrial scale. The report also includes fundamental R&D which is disruptive in nature and could considerably improve the viability of CCUS technologies. Few selected unique ideas can then be accelerated further to reach a higher maturity level through more concerted efforts. This report, therefore, strives to achieve balance by promoting the current state-of-art (SOA) technologies in CCUS to a commercially viable state and accelerating disruptive science in CCUS to take it to the next SOA level.

There are many CCUS reports in the national and international publication space. However, this report focuses specifically on how to leverage Indian R&D to solve India's carbon emissions problem. It dives into identifying the R&D needed to integrate the current SOA-CCUS technologies within the current tough-to-decarbonize industries, as well as suggesting new possibilities for integrating innovative CCUS technologies within hard-to-abate sectors to ultimately achieve improved viability. This approach will help de-risk the CCUS technological obsolescence as both the options of current and newer novel technologies will be available for adoption by the industry depending on the residual life of their assets needing decarbonization. For India's economic growth and our climate change obligations, the R&D approach proposed in this report gives an edge to the industries for quick implementation of CCUS and make our journey to net-zero by 2070 an achievable feat. Further, we have emphasized the importance and potent need for foundational R&D in new material synthesis and their scale-up in the report. The deep-dive into these domains calls for the use of state-of-the art tools such as high-throughput experimentation, AI/ML, and on-line characterization for high fidelity data generation, faster screening and evaluation and ultimate commercial material design.

In addition to the executive summary, the report includes five chapters. First three chapters highlight the R&D needs of the CCUS elements i.e. Capture, Storage and Conversion. Fourth chapter focuses on industrially relevant scaling up of proof of concept (POCs), and innovative integration of CCUS technologies with the existing facilities. Lastly, Final chapter is dedicated to financing such R&D to accelerate the India's march in CCUS for achieving net zero targets.

1. Key statistics

The highlights of fourth Biennial Updated Report (BUR) – December 2024 is reproduced below to set the context for needs of R&D in CCUS to meet India's net zero challenge.

India, one of the world's fastest-growing economies and home to nearly one-sixth of the global population plays a pivotal role in international development and in advancing the Sustainable Development Goals. Among the multiple challenges accompanying its development trajectory, climate change stands out as a key factor for ensuring long-term, resilient growth. Although India's historical contribution to global greenhouse gas emissions is relatively low, the country has committed to addressing climate change through strategic, low-carbon development choices aimed at achieving net-zero emissions by 2070. Recognising that climate change is fundamentally a collective action challenge, India remains firmly committed to multilateral approaches grounded in equity and the principle of common but differentiated responsibilities and respective capabilities (CBDR-RC), as articulated in the UNFCCC. In 2020, India's total GHG emissions amounted to 2,959 million tonnes of CO_2 excluding Land Use Change and Forestry (LULUCF), and 2,437 million tonnes of CO_2 when LULUCF is included.

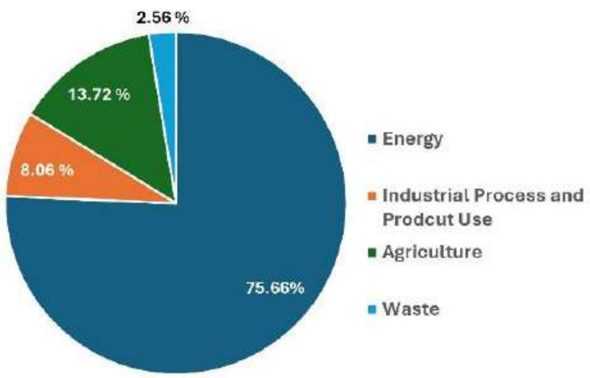
	Gases	Contribution		Sectors	Contribution
Emissions by Gases	**Carbon dioxide**	80.53 %	**Emissions by Sectors**	**Energy**	75.66 %
	Methane	13.32 %		**Agriculture**	13.72 %
	Nitrous oxide	5.13 %		**Industrial Process & Product Use (IPPU)**	8.06 %
	others	1.02 %		**Waste**	2.56 %

In 2020, India's forests, tree cover, and other land-use categories sequestered roughly 522 million tonnes of CO_2 offsetting about 22% of the nation's total carbon dioxide emissions for that year. The country has steadily advanced in decoupling economic expansion from greenhouse gas emissions. Forest and tree cover have shown continuous growth and now account for 25.17% of India's total land area. Between 2005 and 2021, these efforts have generated an additional carbon sink of approximately 2.29 billion tonnes of CO_2 equivalent.

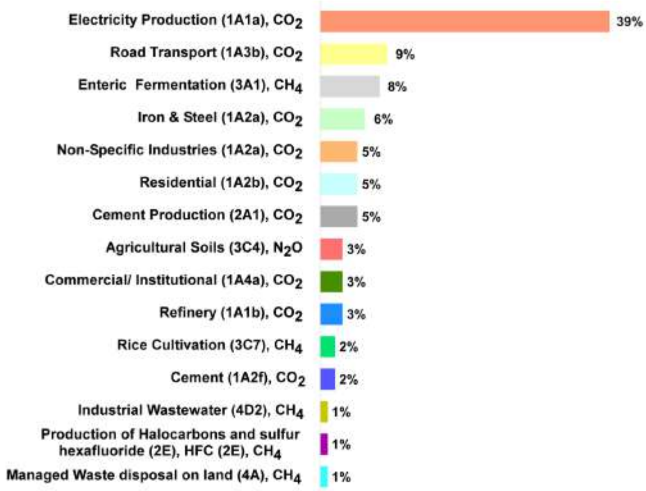
GHG sources & removals	CO_2 emissions	CO_2 removal	CH_4	N_2O	HFC 23	CF_4	C_2F_6	SF_6	CO_2 equivalent
Energy	2181012	NO	1523	82	NO	NO	NO	NO	2238409
IPPU	201044	NO	232	8	2	1	0.27	0.004	238556
Agriculture	NO	NO	14290	342	NO	NO	NO	NO	405983
LULUCF	9369	-532357	41	1	NO	NO	NO	NO	-521933
Waste	NO	NO	2726	58	NO	NO	NO	NO	
Memo Items	802846	NO	0.09	0.11	NO	NO	NO	NO	75641
Total Emission	2382535	-	18771	489	2	1	0.27	0.004	2958589
Net Emission	**2391904**	**532357**	**18811**	**490**	**2**	**1**	**0.27**	**0.004**	**2436656**

Abbreviation: NO- Not occurring

The energy sector contributed the most to overall emissions, 75.66 percent, followed by the agriculture sector, 13.72 percent, IPPU, 8.06 percent, and Waste, 2.56 percent.



Distribution of GHG emissions (GtCO2e) by sector, 2020

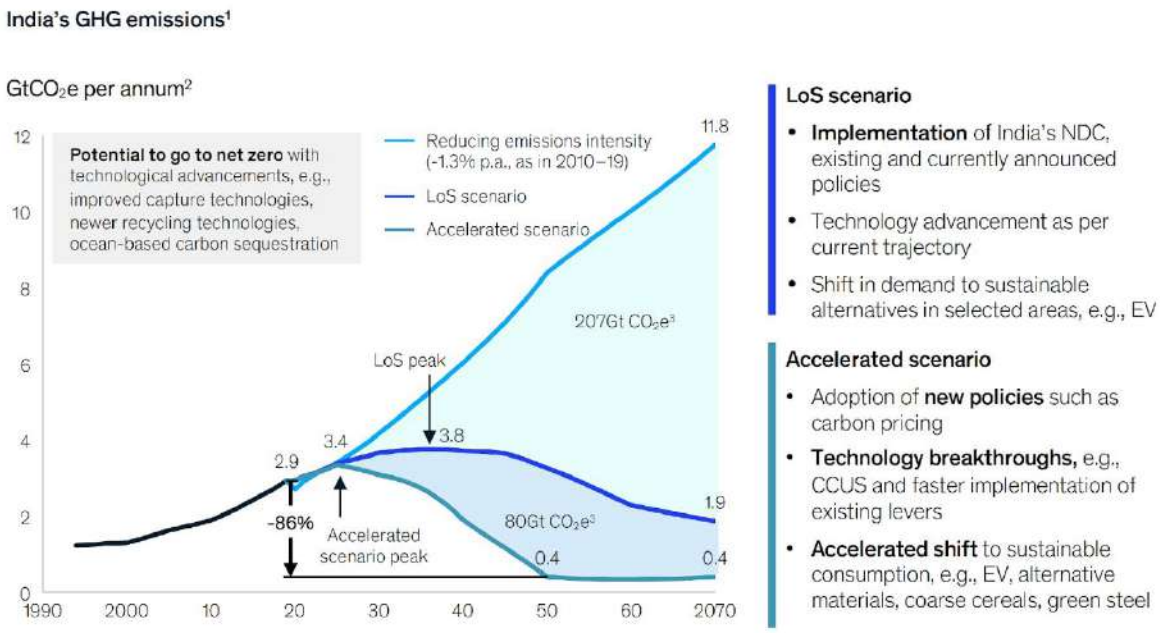


Percentage share of greenhouse gas emissions by category, 2020

The sectorial emissions presented in BUR reports bring clarity to the thrust areas which are essential for policy making. Power, cement, steel, refineries, transportation, wastewater treatment and chemicals are the sectors which need urgent attention to reduce their CO_2 emissions. Of these, it is necessary to prioritize CCUS from industrial sectors such as steel and cement due to the high growth in these sectors accompanied by stiff deadlines for meeting international regulatory measures.

2. R&D to push the CCUS lever

Indian economy is growing at a rapid rate being among the fastest growing economies in the world. It is anticipated that economy will bolster to reach a humongous size of 30 trillion US dollar by 2047 (Amrit Kaal). With the soft assumption of decoupled energy consumption and economic development (Kaya's identity), India's energy needs will race to 27,000 TWh from the current requirements of 8,500 TWh. The McKinsey report (Gupta et al. 2022) on Decarbonizing India – chartering a pathway for sustainable growth is elaborated here for better clarity. The report shows an increasing trend of the CO_2 emission trajectory in India for next few years (till 2034), though India's energy to GDP ratio will shrink due to improved energy efficiency and introduction of renewable energy (RE). The report also emphasizes the criticality of CCUS levers in our journey of net-zero. While the projected trajectory and numbers might have deviations, however, the overall trends will remain the same with respect to both line of sight (LoS) scenario and accelerated scenario.



India's current emissions of 2956 million tons (MT) per annum of CO_2 will grow to 3800 MT by 2034, and subsequently, it will start showing a downward trend depending on how quickly India develops and deploys the energy transition technologies. The McKinsey report is indicative of two challenges:

1. By 2070, it is incumbent upon us to capture about 11.4 GtCO2e cumulatively from industrial sectors (steel, cement, refineries and chemicals) by CCUS. Most of this CO_2 mitigation could be addressed by capturing and storing CO_2 from point-source emissions.

2. In the LoS scenario, there will be residual annual emissions of 1.4-1.9 GtCO2e/y by 2070. Addressing these emissions will necessarily require CCUS, preferably by targeting point source emissions.

Typically, CO_2 concentrations in industrial emissions range from 50-90% flue gas for high-purity point source to 5-15% flue gas for low-purity point source. These are far higher than the 400 ppm CO_2 concentration in atmospheric air. Thus, it is generally advisable to focus CCUS efforts on point source emissions in short to medium term.

As of today, negligible amount of CO_2 emissions in India can be mitigated by CCUS technologies because of insufficient maturity of these technologies. Thus, the aforementioned targets convey the sheer magnitude of the problem and the limited timeline available to solve it. This underscores the need for R&D to build scales at an unprecedented speed. It is necessary to understand the challenges likely to be faced during scale up and industrial adoption before we embark on any of R&D pathways. In terms of complexity, net-zero target is no less than a moonshot and how multiple disciplines and societal arms have to come together to deliver the required goal.

The second biggest challenge of CCS is the prohibitive cost along its entire value chain. It is to be noted that the cost of capturing is significantly higher, accounting for 80% of the total cost compared to 12% and 8% for transport and storage respectively of overall total cost for CCS. In the case of CO_2 conversion, the cost of converted products is mostly controlled by the cost of CO_2 capture and the cost of green hydrogen. The use of hydrogen is invariably required for transforming CO_2 into value-added products. Therefore, economic viability of converted "green (or blue)" products is presently contingent upon the existence of regulatory measures that may fetch higher price compared to the equivalent "grey" products. Thus, R&D is critical to drive down the cost of CCUS, thereby reducing regulatory penalties.

2.1 R&D strategy for CCUS in India's net zero ambition

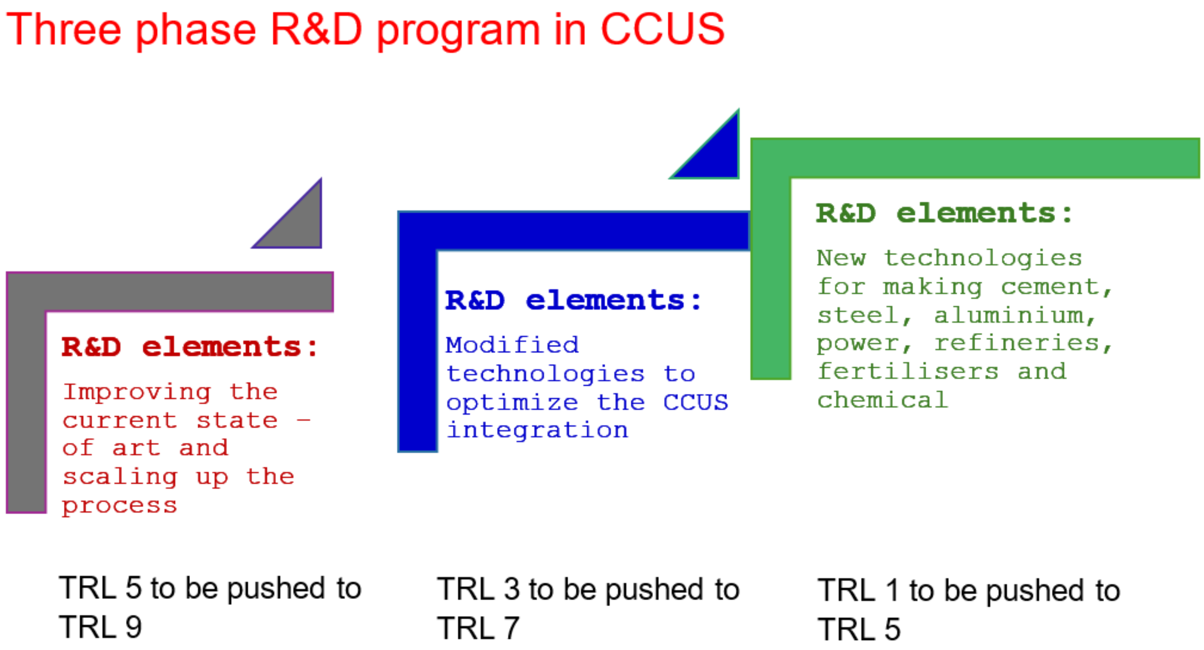
Developing the robust R&D strategies for achieving India's net zero ambitions require careful consideration for three other dimensions of nation and economy: (1) overall India's growth strategy, (2) the nature of our hard-to-abate industries over their entire life-cycle, and (3) dependency on coal for energy security. To this end, three separate verticals are developed as a part strategy for achieving net zero. These verticals are designed to take care of speed of deployment, to implement disruptive innovations, and to balance economic growth and emissions.

Strategy # 1: Integration of the current state-of-the-art CCUS technologies and/or of their improved versions as ***End-Of-Pipe*** **(EOP)** solution in the existing CO_2 emitting industries.

Strategy # 2: Integration of advanced state-of-the-art CCUS technologies in new industrial manufacturing plants using ***CCUS Compliant Design*** **(CCD)**.

Strategy # 3: Integration of emerging CCUS technologies such as photo-bio-electro-catalytic conversions as ***CCUS in One Pot*** **(COP)** strategy in new low-emission industrial manufacturing technologies.

This R&D strategy is suitably illustrated in the scheme presented below. All of the above strategies are focused on mitigating point source emissions, which as mentioned earlier are relatively easier than DAC. In our view, the successful adaptation of these strategies will allow us to reach our own net zero target. It will also help us establish as a global beacon of innovations in this domain by transferring advanced CCUS technologies to the world and more specifically to a number of less developed countries that are aspiring to grow as well as meeting the climate change challenge.



2.2 Methodology under each R&D strategy

R&D for End-of-Pipe solutions (EOP):

India has built its current 4 trillion USD economy on the foundation of strong manufacturing and energy sectors comprising of cement, steel, aluminum, refining, fertilizers, chemicals and power plants. However, all of these technologies are predominantly dependent on fossils (oil, gas and coal) mediated technologies. Additionally, there is heavy dependency on coal as a dominant fossil fuel source for India that results in relatively higher emissions from the industrial and power sectors compared to those nations that run on natural gas. These existing plants still have a residual life of more than 20-40 years left in them. It is the concerted efforts on energy efficiency measures pursued for last few decades that helped India to reduce the energy intensity by an average of more than 25% in major fossil guzzling industrial plants. These steps have brought down CO_2 emissions nearly by a similar percentage. The best way to make these plants net zero will be to add the CCUS island as end-of-pipe (EOP) solution i.e., downstream of the emission stack.

However, a key challenge here is to ensure that an EOP solution does not result in net emissions. To illustrate this, consider the following example. The Indian cement industry has demonstrated strong performance across key sustainability metrics, achieving some of the lowest specific energy consumption levels globally - thermal energy use at just 3084 MJ/ton of clinker and electrical energy at 276 MJ/ton. These improvements have brought down emissions to about 800 kg CO_2 per ton of clinker, reflecting two decades of consistent progress in energy efficiency and process optimization. In such a scenario, adopting current state-of-the-art (SOA) amine-based post combustion carbon capture technologies would impose an additional energy penalty of approximately 3360 MJ/ton of clinker. If supplied through coal, this would emit an additional 840 kg CO_2 per ton, potentially nullifying the hard-won efficiency gains. This highlights the critical importance of advancing innovative low energy carbon capture technologies that support, rather than compromise, the industry's sustainability achievements.

Indeed, EOP integration of CCUS in the existing infrastructure needs to dwell deep into the field of process intensification and integration of existing solvent-based technologies with that of flue gas from the plants. Following is suggested directions for R&D in EOP solutions:

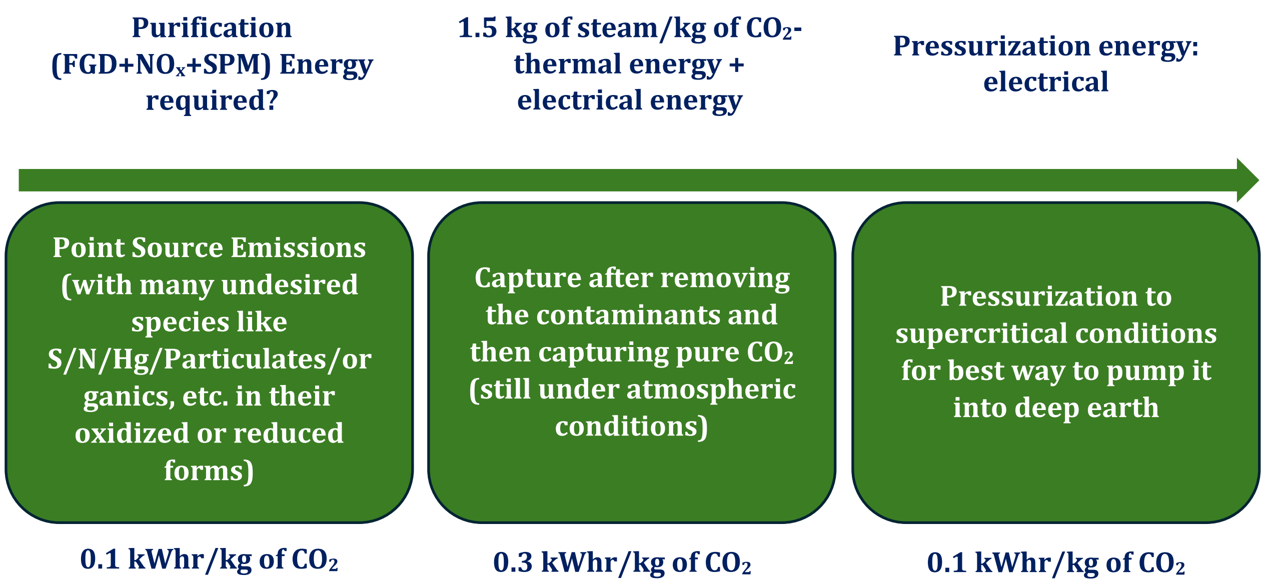
- Intensify processes to minimize the energy demand for CO_2 capture by multiple levels of intervention like better solvents, dual solvents, staging in the stripper design, maximum heat recovery between absorber and stripper, enhanced mass transfer and use of rotating packed towers. This would need R&D in basic process design, heat exchangers, complex system integration, use of RE as thermal energy and AI/ML tools in selection of the best solvents to reduce energy requirements.

- Valorize the residual energy in flue gas by using state-of-the-art heat pump technology and integrate with renewable heat and electricity sources.

- Deploy comprehensive pre-cleaning process to remove contaminants like SO_x, NO_x, oxygen etc, from the flue gas since they tend to degrade the solvents/ adsorbents.

- Use solvents that have higher stability in presence of the flue gas contaminants and ensure appropriate technology for the removal of Heat Stable Salt (HSS).

These R&D measures should reduce energy and solvent demand from the current state of art. The proposed target of energy requirement in the capture process should be 0.5 kWh as compared to the current 1.5 kWh.



2.3 R&D for CCUS Compliant Design (CCD)

This mid-term R&D strategy may support new industrial plants (steel, cement, refining, chemicals, etc.) to be designed with consideration for potential future CCUS integration, contingent on technology readiness, economic feasibility, infrastructure availability and policy support. It is expected that substantial modifications will be needed in these plant designs to accommodate CCUS. At the same time, R&D is required to adapt CCUS technologies so that they can integrate optimally in the modified designs.

Some suggested R&D directions are:

- In a typical current state-of-art CCUS technology adopted in an EOP solution, the concentrated CO_2 emissions from the manufacturing plants are diluted with external ambient air, cooled down and pre-treated before the CO_2 is captured and concentrated again. As against this, in a CCD process, it is suggested that the tap-off point be smartly chosen upstream of EOP to ensure that the CO_2 in the flue gas is not diluted. This strategy has the potential to substantially decrease the footprint, capex and opex of the CCUS process. For instance, capturing CO_2 at an early tapping point where the concentration is three-fold higher can result in more than two orders of magnitude reduction in the steam required for CO_2 stripping. Further reduction is possible when the stripper is designed with energy intensification designs such as two stage strippers, and mechanical compact heat exchanger designs. The aim is to ensure that the waste heat in the flue gas from which CO_2 is to be captured is enough to be used for stripper operation so that net use of energy is zero. However, upstream CO_2 captures present several challenges. For instance, since most of the plants have their emissions at 130-250°C and since the flue gas contains many contaminants like SPM (suspended particulate matter), SO_x, NO_x, Hg etc., the capture process would require adsorbent materials capable of adsorbing at higher temperature such as hydrotalcite or MOFs. The process operations will require specially designed material of constructions to tackle corrosion and wear resistance.

- Develop pre-combustion technologies so that CO_2 can be captured before the energy is extracted. For example, integration of coal gasification with direct iron ore reduction allows use of high-pressure synthesis gas for steel making, thereby reducing overall CO_2 footprint and the energy intensity of CO_2 capture.

- New CCUS technologies where conversion of CO_2 can happen during capture. This would mean doing mineralization or hydrogenation process during the process of CO_2 absorption. This would enable removing the most energy swapping stripper (desorption) in the CCUS.

Both EOP and CCD strategies as described above are essentially focused on capturing CO_2 emissions, which subsequently must be transported and stored. The R&D needs for storage of CO_2 are summarized later. The third CCUS strategy namely, COP is described below.

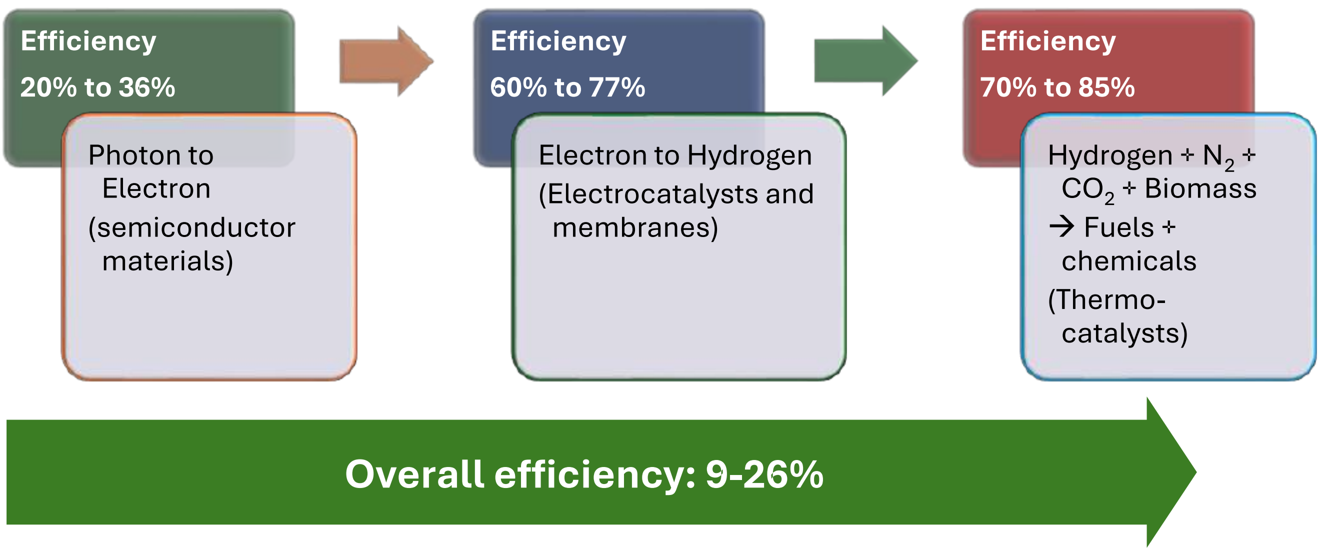
2.4 R&D for CCUS in One Pot (COP)

The long-term strategy for net zero would involve next generation plants producing steel, cement, aluminum, ammonia, and chemicals, which are likely to use new technologies where CCUS can be done in a single pot. Few examples are described below:

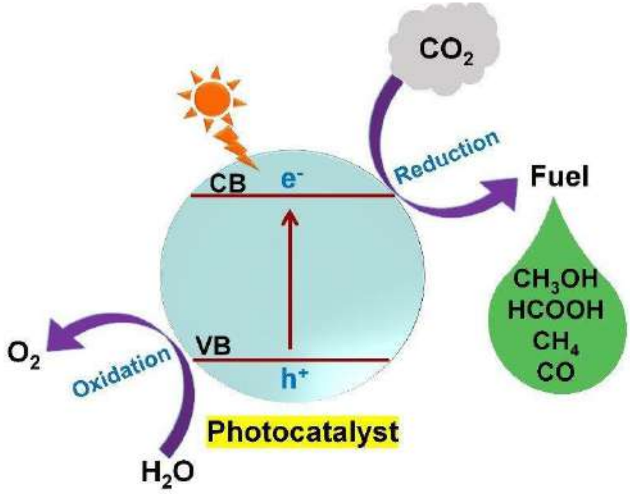
1. Pyrolyze fossil fuel into hydrogen, which will be the primary reducing agent for manufacturing steel, aluminum, ammonia, etc. In the pyrolysis process, carbon is produced as a by-product that can be valorized without burning. The cumulative CO_2 footprint of the pyrolysis process and the subsequent material manufacturing processes is much lower than conventional processes.

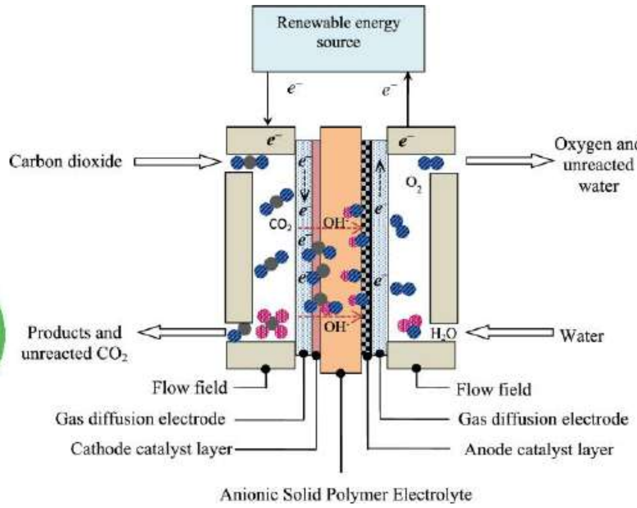
2. Use new processes like e-clinker, green hydrogen-based steel BF or DRI, e-steel, e-fertilizers, inert electrode-based aluminum smelter, etc. Such technologies will use renewable energy options for manufacturing of bulk materials so that conventional fossil guzzling plants are replaced by low carbon footprint renewable electricity–thermal hybrids.

The flow sheets for these new manufacturing processes should include emerging CO_2 conversion processes such that the relatively small amounts of CO_2 emissions from the manufacturing processes can be directly converted into usable chemicals and fuels using RE. The following example illustrates the strategy: Current CO_2 conversion technologies require green hydrogen, which is typically produced using RE based water splitting. The overall efficiency of this CO_2 conversion is rather low as shown below.



As against this, the envisaged one pot process would involve direct photocatalytic or photo-electrochemical or biological conversion of CO_2 into fuels or chemicals, such as schematically shown below.





Most of these technologies are in the early stage of ideation and research. Thus, the R&D needs for these CO_2 conversion technologies are vast. The main effort here is to reduce the cost of conversion by developing high efficiency process. For instance, the current approx. 1% efficiency for direct Solar to Fuels (STF) technology should be increased to >25% efficiency to achieve the desired cost of fixing CO_2 either as chemicals or as fuels.

3. CO_2 storage

As stated earlier, India's net zero target would require sequestering 11.4 $GtCO_2e$ cumulatively till 2070. The conversion of captured CO_2 might take care of a fraction say 10-20% of the total requirements. The rest of the CO_2 needs "bio and geo sequestration". For instance, well cultivated agroforestry strategy could be used to fix CO_2 biologically. However, this should not happen at the expense of natural forests, else there may be a real danger of loss of biodiversity and aggravation of human-forest conflict. There are also immense possibilities of developing synthetic biology routes to accelerate CO_2 sequestration into bio-space.

Geological sequestration is another tool available if only we can unravel the long-term impact of CO_2 with the rocks and aquifers. It is still a developing technology, which will be subjected to many regulatory demands. India is a land starved nation and may have relatively fewer risk-free sedimentary rocky reservoirs that could be available for geological CO_2 sequestration.

R&D in geological sequestration requires special attention to establish a sound basis for sequestering CO_2 in the geological formations in India, develop confidence and establish risk mitigation strategies. While there are limited studies, the need of the hour is to conduct detailed geological studies at a few identified sites having different geology. This should include geophysical, geo-chemical, geo-mechanical, simulation and experimental including core analysis - both routine and special core analysis (RCAL and SCAL). Further, this needs to be followed up with pilot scale injection and scientific monitoring of the CO_2 plume. This may need further review of the geological data available in the country such as investigation on injectivity and cap rock integrity.

While it is technologically possible to identify the actual usable storage capacity, injectivity, cap rock integrity and monitoring of CO_2 plume movement, the real challenge lies in resolving issues related to post-injection liability, CO_2 ownership, CO_2 accounting, etc. We will need to develop enough confidence by bringing a high-level geological model with pilot plant injection campaigns. Global collaboration is needed here at the demonstration scale.

4. Funding of the R&D program for India

There are three levels of funding needed to boost CCUS R&D in India so that faster and deeper penetration happens in the eco-system. These levels are described below. A desirable total cost of CCUS (say, not more than 5-10 Rs/kg of CO_2 i.e., about 60-120 USD/ton-CO_2) is the one that will minimally add to the manufacturing cost of commodities, keeping it affordable. The CO_2 tax should be within the global purview. The R&D roadmap should be aligned with this cost trajectory.

EOP R&D: The R&D need in this space is mainly for building pilot plants (TRL 6) with back-end research in improved solvents, heat integration, modified stripper design, new mass transfer equipment and integrating heat stable salt recovery designs. R&D schemes in this area must be designed to catalyze the triple helix model of industry-academic-government collaborations. The aim of R&D efforts is to reduce the energy demand for CO_2 capture to less than 0.5 kWh, solvent make up loss less than 0.5% per year and the entire capital cost of the system under 1 Cr/ton per day of CO_2 when the scale of capture is in million tons per annum.

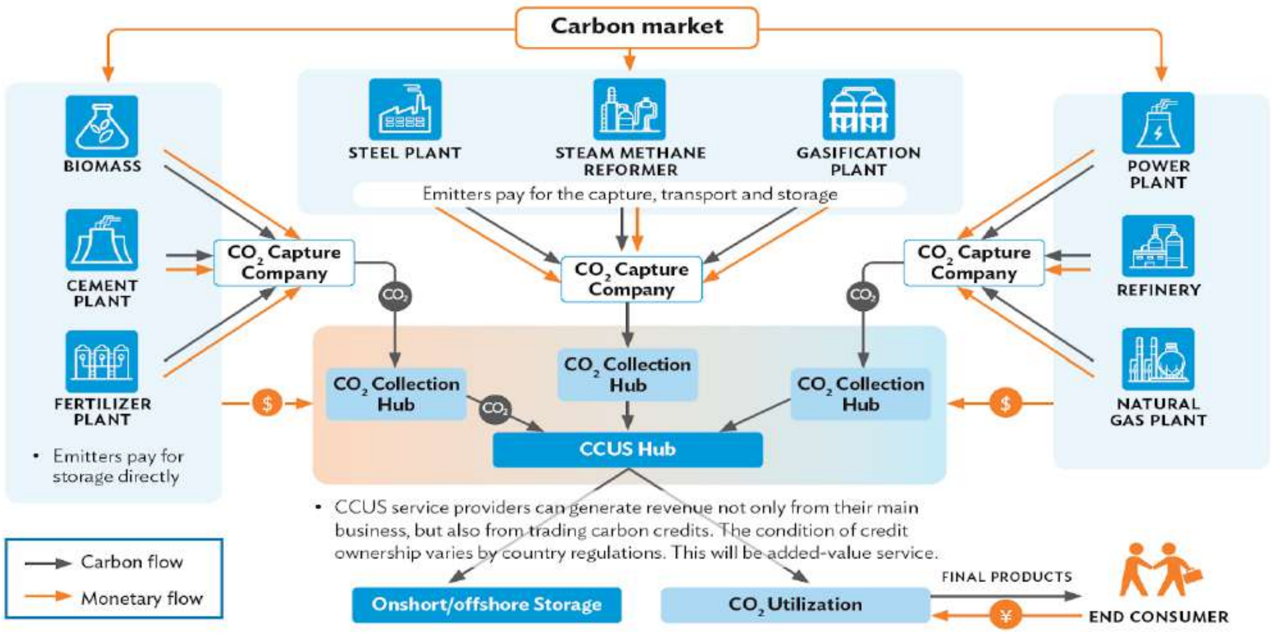
EOP will also include the CO_2 conversion technologies currently based on thermo-catalytic principles. The R&D focus in this domain would include the development of improved catalysts, optimized reactor designs, and better heat integration. Direct mineralization options at the EOP solution are emerging to be attractive. Sugar industry, which usually has ample amounts of nearly pure CO_2, presents a low hanging fruit to improve CO_2 conversion technologies.

The activities in this space of developing EOP solutions must be on a pilot scale supported by back-end R&D and fast-tracked delivery. It is recommended that the funding allocation will have to be 50% of the overall funding allocated to CCUS R&D.

Preliminary estimates indicate that each pilot plant of approximately 1.0 TPD scale will require a funding of 25 Cr including the R&D cost on catalysts, amines and other materials. If we choose 7 key sectors such as cement, steel, aluminum, power, refinery, fertilizers and chemical, and installation of 3 CCUS demonstration plants per sector, then total funding requirement will be of the order of 525 Cr over next 24 months as capital cost grants. The operating costs will be another 1500 Cr for operation for the next five years.

As technological maturity improves, there will be a need for at least seven semi-commercial or demo scale plants (TRL 8) to be built under each sector, which will be at least 100X the pilot plant size. The creation and operation of such high-capacity plants will need viability gap funding of about 2000 Cr in total. These can be funded and operated in Public-Private Partnership (PPP) mode jointly by the

DST and industrial partners through schemes such as CCUS hubs or clusters, in which several aspects of the CCUS value chain namely, capture, storage, transportation, conversion and sequestration can be demonstrated and validated for techno-economic viability, life cycle assessment, risk management and mitigation, among others. Hubs and/or clusters can play a vital role in accelerating the development and deployment of CCUS technologies in India. They will also enable hands-on skill development for CCUS. The Indian CCUS hubs/clusters can also collaborate and partner with similar projects outside India to enhance capabilities and accelerate the deployment. These facilities can also offer industrial-scale testbeds for validating CCUS technologies in real-world conditions (Living Labs).



CCUS = carbon capture, utilization, and storage; CO_2 = carbon dioxide.
Source: Adapted from Integral. The CCUS Hub: An Essential Business Model to Reach Carbon Neutrality in China. https://www.integralnewenergy.com/?p=38364.

Carbon Capture, Utilization, and Storage Hub Mode (in future commercialized phase)

CCD R&D: There is a deeper R&D need in this space. The effort here will be focused on taking already known scientific research from TRL 3 (POC) to TRL 5 (lab mini-pilot scale). Exciting developments such as new materials for CO_2 capture at high temperatures or alternative ways of using fossil fuels in a pre-combustion oxy-fuel mode, which have been demonstrated at POC level, should be converted into mini-pilot plants. These facilities should be set up in industrial R&D labs of some potent sectors such as steel, power and cement. We anticipate that this might need an investment of approximately INR 1500 Cr over next 36 months.

COP R&D: This is the ultimate holy grail where CO_2 is directly converted to fuels, chemicals, and minerals. A differentiated approach can be taken to achieve the targets firstly through two pot processes and then converging to a single pot process. The R&D to develop the viable solution in this domain begins with accelerating new molecular/materials discovery using AI-ML driven high-throughput experimentation facilities on the one hand and process intensified reactor designs on the other.

In summary, the total R&D funding required for developing and deploying EOP, CCD, COP solutions for carbon capture and conversion including pilot scale facilities would be approximately INR 4500 Cr over next 2-5 years. Another tranche of funding of approx. INR 2000 Cr will be required for demo-scale hubs/ clusters. Further, it is estimated that the R&D needs of geological storage including basic R&D and pilots would be approximately 3000Cr.

Sr No	Funding Domain	Pilot plant CAPEX	Pilot Plant Opex	Basic R&D
		(Fund requirements in INR, Crores)		
1.	EOP in CCU	525	1000	500
2.	CCD CCU	300	700	500
3.	COP in CCU			1000
4.	Geological Sequestration	1000	1500	500

Research & Developmental Roadmap

In a nutshell, following is the suggested R&D roadmap for CCUS in India:

Phase 1 (2025–2030)

Translational Research, Development, & Innovation (RDI) and Breakthrough Foundational Work

- Support breakthrough research programs for materials discovery related to all aspects of CCUS. To accelerate this, it is necessary to support the creation of a few critical research facilities (for example, AI-ML coupled with High Throughput Synthesis, Evaluation and Screening platforms) for the discovery of novel absorbent/adsorbent materials and novel catalysts for efficient and viable CO_2 capture and conversion.

- Support pilot-scale projects for demonstration and validation of innovative and laboratory proven capture and conversion technologies, especially for EOP and CCD strategies including direct air capture (300-3000 t/y of CO_2). Target capture cost reduction should be aspirational i.e. < $ 40/t of CO_2.

- Support FEED studies for setting up two demonstration scale CCU testing and validation facilities (of the order 50,000 t/y CO_2) to check the techno-economic feasibility of capture and conversion technologies at this scale.

- Support development and demonstration of advanced monitoring technologies (e.g., seismic, satellite, and fiber optics) for CO_2 leakage from storage sites.
- Support selected programs for undertaking detailed India-specific storage site mapping (Cambay, Mahanadi, and Cauvery Basins).
- Support research on basalt-based CO_2 mineralization in Deccan traps.
- Catalyze stakeholder discussions and public engagement on critical issues related to large scale CO_2 storage.
- Catalyze consortium mode thinking around creating international partnerships for the development of hubs and CO_2 shipping corridors along with access to storage sites.

Phase 2 (2030–2035)

Demonstration and Industry Integration

- Initiate implementation of a hub and cluster model in regions such as the Krishna Godavari basin, and Northwest India (Rajasthan).
- Draft national CCS regulations and legal framework covering the entire CCUS value chain focusing on CO_2 ownership, liability for transport and post-injection, and carbon accounting.
- Support pilot-scale CCS injection projects at selected storage sites (small, <30,000 t/y).
- Accelerate mineralization projects (e.g., basalt formations in Karnataka, Deccan Traps).
- Support pilot-scale projects on DAC collocated with renewables.
- Support focused research on the development of India-specific techno-economics models for CO2 capture + transport + storage for industrial clusters.
- Support creation and operation of two demonstration-scale (i.e., semi-commercial) CCU technology testing and validation facilities as public-private partnerships in which the assets are created through public funding and owned by the government, while the facilities are managed and operated by private parties.
- Initiate FEED studies for creating two semi-commercial scale CCS hubs in industrial clusters which showcase EOP solutions for capture (>500,000 t/y), transportation and storage.
- Create carbon market linkages (Carbon Contracts for Difference, VCMs, CCTS).

Phase 3 (2035–2045)

Commercialization and Scale-Up

- Develop two commercial scale CCS hubs (>1 Mt/y) in industrial clusters comprising hard-to-abate industries for demonstrating full-chain EOP and/or CCD solutions for capture, transportation and storage projects. This will include multi-million t/y CO_2 storage hubs (offshore & onshore). This could also include shipping of CO_2 to international storage sites developed through bilateral/ multilateral agreements.

- Integrate CCS with India's hydrogen economy initiatives (blue hydrogen + CCS).
- Complete regulatory frameworks for CCS commercialization and public acceptance.

At the higher level, the R&D roadmap presented here will have to feed into the national CCUS implementation strategy, which should include policy research on issues such as carbon trading, CO_2 tax and CO_2 financing, regulatory issues such as monitoring, measurement and validation techniques (MMV), and public acceptance.

The expected strategic outcomes of the phased R&D approach are:

- Reduction in CO_2 capture cost (< 40 $/ton)
- Translate indigenous innovative CCUS solutions from lab to commercial scale
- Operationalize industrial scale CO_2 storage hubs in 3-4 regions
- Full-chain CCS commercialization in hard-to-abate industrial sectors
- Enabling India to lead global CCS innovation suited for developing economies

Following is a suggested Priority Technology Table for CCS R&D in India indicating technologies to prioritize funding for maximum impact:

Technology Area	Best Bets for India	Why Important
Capture	❑ Improved amines (low regeneration energy) ❑ Solid sorbents (zeolites, MOFs) ❑ Calcium Looping (for cement kilns)	Capture cost dominates total cost. Industrial sources need customized solutions.
Transport	❑ Small pipelines in clusters ❑ Ship transport for coastal hubs	Cheaper to cluster the emitters. Ships flexible for offshore storage.
Storage	❑ Deep saline aquifers ❑ Depleted oil & gas fields ❑ Coalfields ❑ Basalt mineralization (Deccan Traps)	Large storage capacities, long-term permanence.

Monitoring (MRV)	❑ Fiber optic sensing ❑ Satellite monitoring (GHGSat-type) ❑ In-situ pressure monitoring	Regulatory compliance and public assurance. Essential for scale-up.
Utilization (CCU)	❑ CO_2-to-methanol (with green hydrogen) integrated with downstream processes (e.g., methanol-to-olefins, MTO) for value addition or with committed off-takers (e.g., green digital shipping corridor, GDSC) ❑ Concrete carbonation (building materials) ❑ Enhanced Oil Recovery (EOR) in NE India	To create early markets for captured CO_2, improving project economics.
Policy and Business	❑ Carbon contracts for difference (CCfDs) ❑ Carbon pricing integration ❑ CCS finance mechanisms (National CCS Fund)	To de-risk projects financially and attract private investment.

Some of the key industrial and geological clusters where CCUS hubs can be considered are:

- Gujarat coast (Refineries, Chemicals, Cambay Basin)
- Odisha-Jharkhand Belt (Steel, Cement, Mahanadi Basin)
- Tamil Nadu (Fertilizers, Chemicals, Cauvery Basin)
- Maharashtra-Konkan region (Refineries, Off-shore Arabian Sea storage)
- North-East India (Oil & Gas, Assam Shelf)
- Krishna Godavari basin (Refineries, Cement, Steel)
- Northwest India (Rajasthan)

To conclude, this is a great moment for India to showcase for its knowledge prowess to the world. India occupies a unique position in the development spectrum straddling the needs of both the developed and the developing world. As such, the country must navigate the complex task of sustaining a substantial base of existing industrial assets, many of which will require near-term decarbonization through CCUS technologies while simultaneously investing in and constructing new, future-ready infrastructure built on advanced low carbon technologies. India has well demonstrated its technological abilities in almost all fields, which makes us abundantly confident of our capacities to nurture and take the lead in CCUS technologies for which a nurturing R&D ecosystem should be prioritized. International research and development efforts provide valuable insights that can significantly enhance our strategies. It is, however, even more crucial to focus on strengthening domestic R&D capabilities. Developing and nurturing indigenous innovations ensures that new technologies are effectively transferred to and adopted by domestic industries. Prioritizing this approach both in the present and looking ahead to the future will help build a resilient innovative ecosystem that benefits our industry, workforce and overall competitiveness on a global scale.

CHAPTER 1

BACKGROUND & INTRODUCTION

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Greenhouse Gas (GHG) emissions in the atmosphere are monotonically increasing to meet the needs of modern lifestyle of mankind, such as energy, construction, mobility, and consumption. Climate change, driven by the relentless increase of GHGs in the atmosphere, poses a potential threat to earth's ecosystem and ecological balance. Among these gases, Carbon Dioxide (CO_2) is one of the most prevalent GHGs that requires immediate attention to alleviate the challenges of climate change. The ubiquitous use of fossil fuels is the main contributor of CO_2 emissions, along with other large anthropogenic sources such as steel and cement production, deforestation, and biomass burning, leading to global warming and triggering widespread environmental disruptions. To this end, the global community has realized the urgent need to address rising CO_2 levels at the national and international levels to mitigate the severe impacts of climate change and ensure a sustainable future.

In the wake of a rapidly changing global climate landscape, India has taken significant steps to redefine its environmental commitments and proactively address the challenges posed by climate change. The Hon'ble Prime Minister of India has presented a roadmap for a sustainable future to address climate change by introducing "India's Panchamrit Tatva" at COP26 in Glasgow, Scotland. In line with this vision, the Indian government has committed to reaching a carbon-neutral economy by 2070. The "Panchamrit" of India's climate action outlines an extraordinary path, blending innovation with responsibility, as the nation embarks on a transformative journey. The following key components of this commitment encompass both immediate and long-term strategies, addressing the intricacies of carbon mitigation and sustainability:

India's Panchamrit Tatva

Phase I	Phase II	Phase III	Phase IV	Phase V
500 GW non-fossil energy by 2030	50% of energy requirement from renewable energy by 2030	Reduction of 1 billion ton of total projected carbon emission by 2030	Reducing the carbon intensity of its economy by less than 45%	Net zero by 2070

As India stands at the forefront of climate action, the dynamic commitments encapsulated within the "Panchamrit" serve as a beacon of hope and a testament to the nation's resolute determination to address climate change. As a fast-growing emerging economy and the third-largest CO_2-emitting country in the world, India's GHG emissions are projected to increase in the future. Given the commitment to mitigate climate change, India has voluntarily committed to reduce the GHG intensity of its economy. In this regard, Carbon Capture Utilization and Storage (CCUS) has become increasingly important for both nationally and globally, as it aligns with broader Net Zero goals.

Carbon capture combined with either permanent storage or the utilization of captured CO_2 is a crucial approach for lowering emissions, demanding coordinated action to address climate change. Although Carbon Capture and Utilization (CCU) is an important component of long-term strategies, Carbon Capture and Storage (CCS) is essential for achieving large-scale CO_2 reductions more rapidly. Converting CO_2 into value-added products through chemical processes under CCUS can also enhance the diversity and flexibility of energy supplies, thereby strengthening energy security that is a rising priority for governments globally. Moreover, CCUS provides viable pathways for deep decarbonization in several hard-to-abate sectors, including iron and steel, cement, and chemicals.

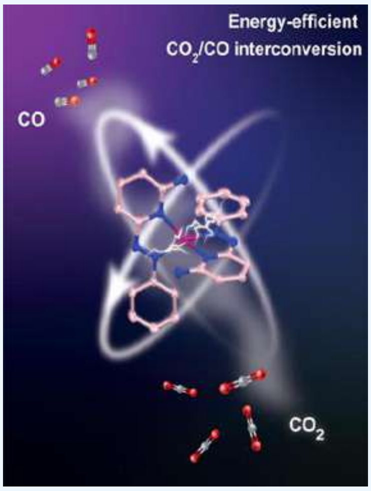
The Department of Science and Technology (DST), India, aims to foster joint research efforts for technological advancement by leveraging the existing infrastructure, and enhancing capacity building across the country in the decarbonization and clean energy domain. For example, multipronged approaches can be seen in areas such as CCUS, Hydrogen, E-mobility, Clean Coal Technologies, Solar Energy Systems, Energy Storage, and Building Energy Efficiency, that align seamlessly with the Hon'ble Prime Minister's vision of achieving net-zero goals by 2070.

The DST India, has pioneered CCUS R&D at the national level and has been consistently contributing to establish a robust CCUS ecosystem in the country. Through a series of DST's interventions at national and international levels in the past three years, a widespread network of academia, research groups, industries, and start-ups has been created through direct engagement with DST or its supported interventions in the specific thematic areas of CCUS.

To promote a unified strategy and accelerate progress toward net zero, the DST has established three National Centres of Excellence (CoE) in the field of CCUS at the Indian Institute of Technology (IIT) Bombay, the Jawaharlal Nehru Centre for Advanced Scientific Research (JNCASR) in Bengaluru, and CSIR–National Environmental Engineering Research Institute (NEERI) in Nagpur. These centres aim to support the mapping of ongoing R&D and innovation activities related to CCUS and to build networks among researchers, industries, and stakeholders by encouraging collaborative research across partnering groups and institutions. They serve as focal points for advancing multidisciplinary collaboration, capacity building, and cutting-edge, application-driven research in the CCUS domain.

DST Supported

National Centres of Excellence



IIT Bombay, with support from DST, carried out a comprehensive, large-scale national study to evaluate the potential for CO_2-enhanced oil and natural gas recovery across major sedimentary basins in India. Additionally, a unique class of bio-inspired catalysts has been also developed by this DST-National Centre of Excellence (NCoE -IITB) that exhibit CO_2 capture in aqueous solution. NCoE-IITB has also developed promising technology for CO_2 to CO conversion with potential application in Steel sector. A start up ***Urjanova C*** has also emerged from the activities of the NCoE -IITB.

The DST's NCoE at JNCASR, Bengaluru, has created integrated technologies for converting CO_2 into value-added products including methanol, ethanol, formic acid, olefins, and higher hydrocarbons & thereby helping to decrease reliance on conventional fossil fuel resources. A facility has also been established at a 280 kg/day capacity for CO_2 to methanol conversion from the NCoE activities. A start-up, Breathe India Ltd, has also emerged from the activities of the NCoE -JNCASR Bengaluru.

Facility for CO_2 conversion to Methanol at JNCASR, Bengaluru

DST, India has participated in the transnational platforms like Accelerating CCUS Technologies (ACT), Mission Innovation (MI), and Clean Energy Transition Partnership (CETP), to support 23 national and multilateral consortia projects in the area of CCS and CCU. These projects engage both premier research institutions and industries to accelerate CCUS technologies to higher TRLs (Technology Readiness Levels). Some of these projects are enumerated below.

- DST has funded a project at the IIT Delhi to develop a hierarchical, novel catalyst for the one-pot conversion of CO_2-rich synthesis gas into Dimethyl Ether (DME), along with scale-up assessments. The IIT Delhi team has successfully developed an innovative and cost-effective catalyst that achieves higher conversion rates of CO_2-rich syngas, and this technology has already been implemented at the field level.

Facility for one pot Conversion of CO_2 rich synthesis gas to DME at IIT Delhi

- With DST's support CSIR-IICT, Hyderabad, has developed a dual operational fixed cum fluidized bed reactor (FBR) system and sorbent catalyst materials (CSCM) for CO_2 capture.

- The CCUS project, supported by DST at IIT Bombay, has developed a workflow for calculating estimates of CO_2 storage capacities through CO_2-EOR, CO_2 ECBMR, in saline aquifers, and basalt (**Figure 1.1**). Furthermore, a CO_2 resource-reserve pyramid has been developed to quantify theoretical, effective, and viable potential for CO_2-EOR-associated storage in key oil-producing basins.

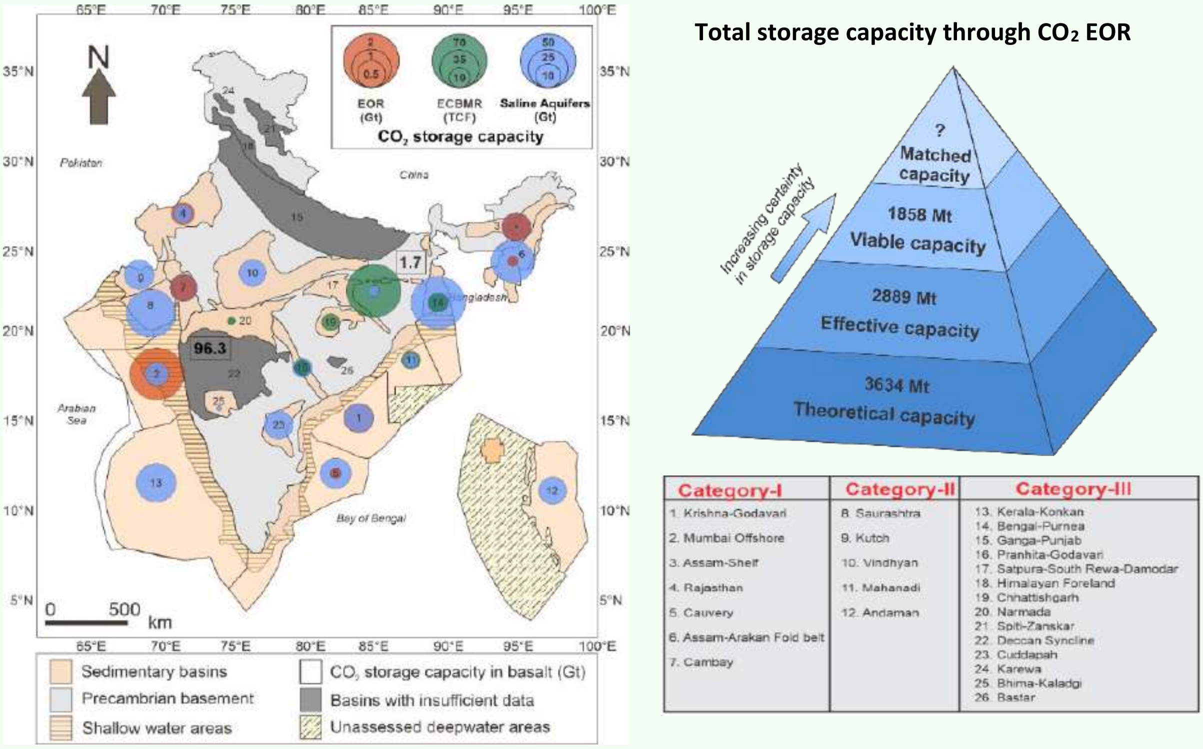
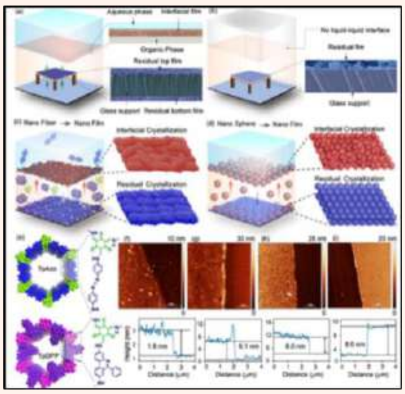


Figure 1.1: Geological CO_2 storage potential of different sedimentary basins in India

- The CCUS project, supported by DST at IISER Kolkata, has synthesized hierarchical covalent organic nanosheets and nanosheet-based hybrid membranes for effective and selective CO_2 capture.



Schematic illustration of COF thin-film formation at liquid–liquid and solid–liquid interfaces through interfacial and residual crystallization.

CCUS Technologies

- BITS, Goa, developed an Unmixed Combustion (UMC) test rig for converting CO to CO_2 with DST's support. Combustion of fuel, such as CO, results in pure CO_2 and water, offering advantages like no NO_x formation and simplified CO_2 capture.

UMC Test Rig

- IIT Madras has designed and developed bench-scale unit for conventional CO_2 capture for sono-assisted solvent regeneration / CO_2 stripping process. This technology can be integrated into existing solvent-based post-combustion CO_2 capture facilities with support from DST.

Bench Scale Unit for Conventional CO_2 Capture Process Test Rig

- The CCUS project supported by DST at IIT Delhi, has developed Lab-scale batch slurry phase reactor which has been successfully installed and demonstrated with integrated CO_2 Capture and Conversion Technology for CO_2 to Methanol using innovative catalysts.

- In a significant step towards sustainable construction, researchers from the Indian Institute of Science (IISc), Bengaluru, funded jointly by DST under the Trans-national platform of accelerating CCUS Technologies, have pioneered breakthrough materials and processes that could enhance the building industry's impact on carbon emissions. The Centre for Sustainable Technologies in IISc Bengaluru has utilized 3D printing technology for carbon sequestration under this project.

- In a study led by CSIR-NGRI Hyderabad, and supported by DST, methods have been developed to monitor the presence and movement of CO_2 in the sedimentary reservoirs. Another study has been undertaken by CSIR-NGRI Hyderabad, to demonstrate the feasibility of permanent CO_2 sequestration in Deccan flood Basalt.

- Through a recent initiative, DST has provided support for two Technology Deployment Test Beds to be executed by Industry Research Consortia, specifically IIT Delhi with Thermax Ltd., and CSIR-IICT Hyderabad with Bharat Heavy Electricals Limited (BHEL). These efforts aim to establish pilot-scale demonstrations in coal gasification plants for producing Methanol and DME, with industry partners serving as solution providers alongside technology designers (knowledge partners) to implement CCU in hard-to-abate sectors such as thermal power.

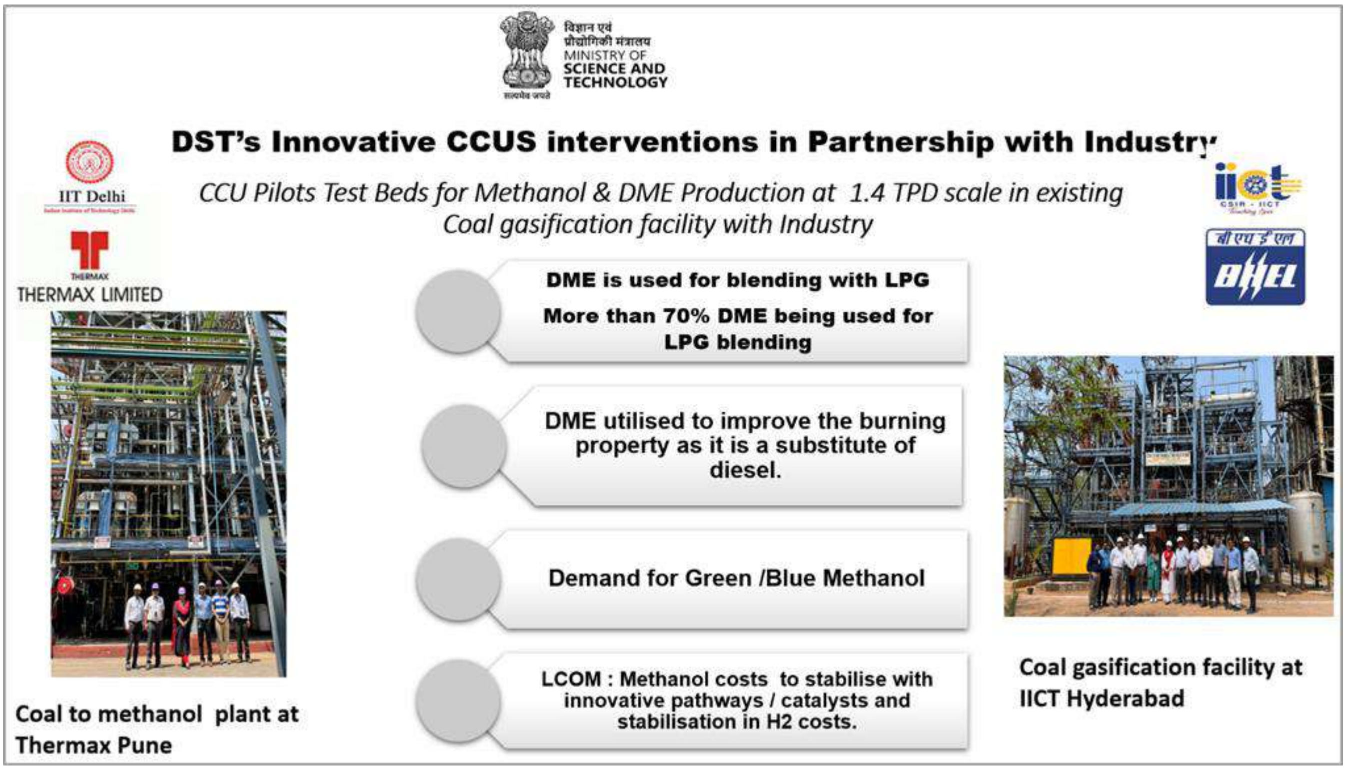


Figure 1.2: CCU pilots test beds for Methanol & DME production

- IIT Delhi – Thermax Pvt. Ltd. Consortia aims to develop and integrate CCU technology for both pre-combustion and post-combustion in the existing coal-to-methanol pilot plant at a capacity of 1.4 TPD Methanol in Pune (**Figure 1.2**).

- In the other pilot, CSIR-IICT Hyderabad – BHEL Consortia envisages to erect a facility to indigenously demonstrate CO_2 capture at 0.5 TPD scale from coal gasification facility and convert it through direct catalytic conversion to Dimethyl Ether (0.18 TPD) in Hyderabad.

- These initiatives are in line with national missions like Atmanirbhar Bharat and Viksit Bharat that aim to foster technological self-reliance in Methanol and DME production in India and support the Government of India in achieving its net-zero targets.

Accelerating industrial CCUS is essential for reducing the footprint of CO_2 in existing industries, and subsequently creating opportunities for green industries of the future. Transforming hard-to-abate sectors such as steel, cement, power, oil and natural gas, and chemicals into comparatively greener sectors requires their concerted efforts to decarbonize their production processes and transition to cleaner practices. These initiatives involve capturing industrial emissions, converting them into value-added products, and managing the transport and subsurface storage of CO_2. Therefore, there is a palpable need to drive the upstream and downstream value chains of CCUS.

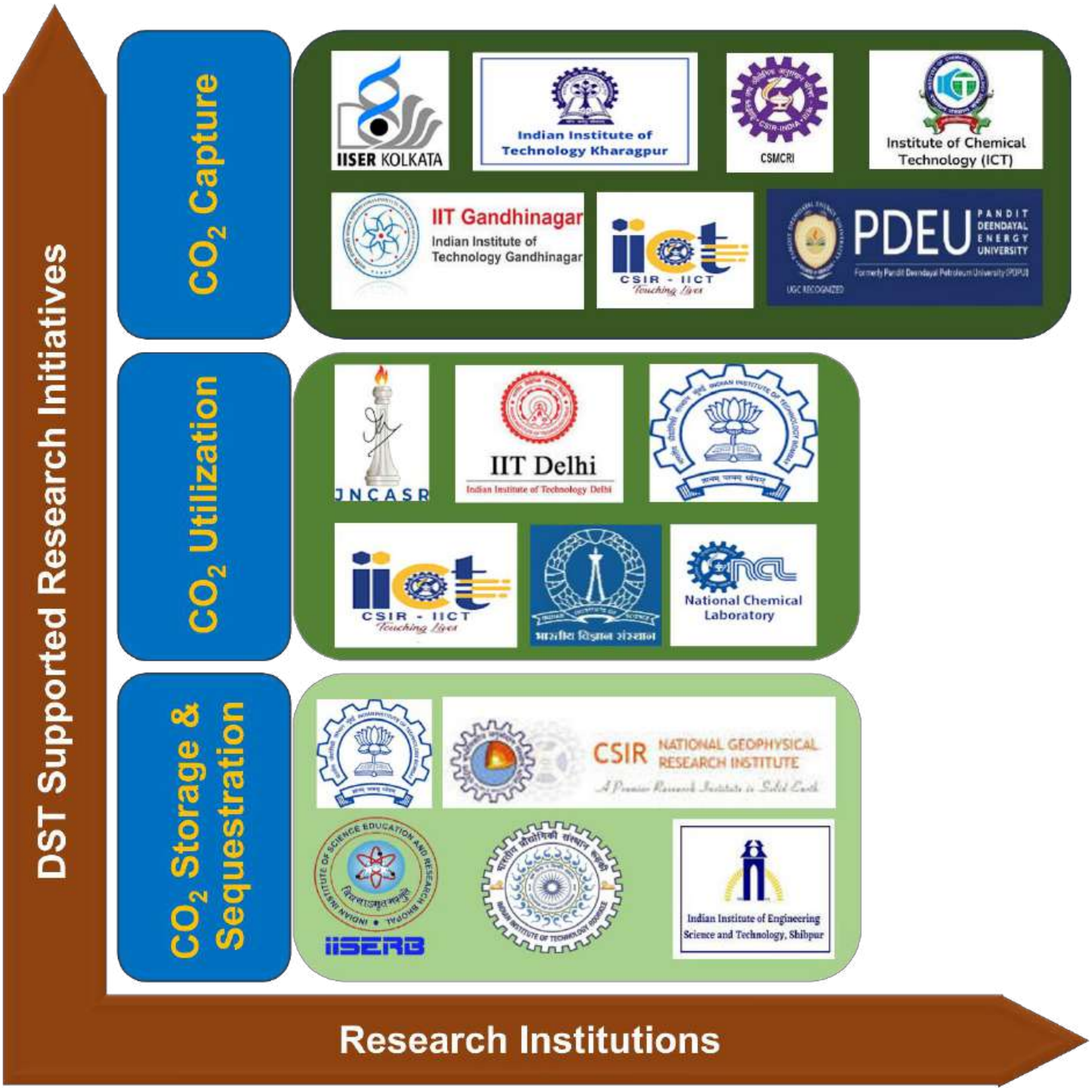


Figure 1.3: Major organizations involved in accelerating CCUS technologies with DST's support.

Creating the green industries of the future involves not only promoting green business models that drive demand for CCUS solutions but also pioneering the development and deployment of cutting-edge CCUS technologies through advanced R&D and international partnerships. Governments play a critical role in ensuring that the right enablers are in place to accelerate the development and deployment of CCUS technologies. To reinforce the CCUS value chain across its TRL progression and secure essential last-mile linkage for advancing technologies toward high-TRL deployment and market readiness, DST has been actively collaborating and consulting with experts and representatives from key industries, PSUs, research institutions, academia, government bodies, and policymakers (**Figure 1.3**).

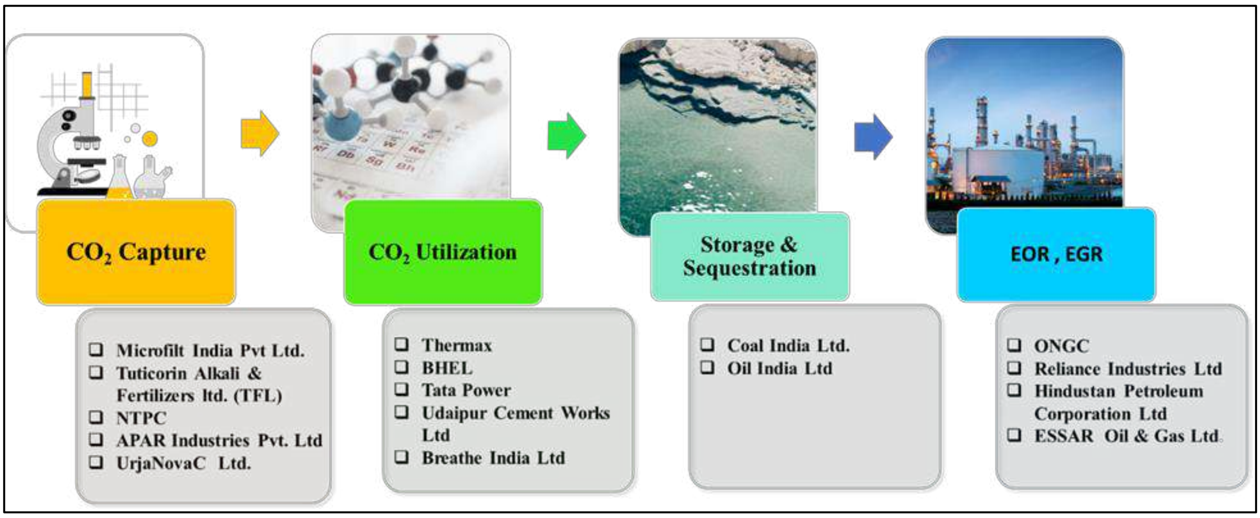


Figure 1.4: Major industries/start-ups interacting with DST for advancing CCUS technologies.

To further streamline the direction and bring coherence in its efforts to meet Net Zero targets, DST, India has constituted a High-Level Task Force to develop DST's CCUS Roadmap to capture the collective vision and ideas from experts and think tanks representing policymakers, academia, research groups, industries, consortiums, funding agencies, and associations. This Task Force is entrusted with integrating diverse perspectives and innovative ideas from a broad range of stakeholders. The goal is to create a comprehensive and collaborative strategy that effectively addresses the challenges of carbon capture, utilization, and storage, ensuring a unified and strategic approach towards achieving India's climate goals. It is anticipated that this collection of visionary directions of the roadmap will assist DST, India, in streamlining efforts and ensuring a well-coordinated and focused approach to addressing the immense challenge of CCUS domain (**Figure 1.4**).

1.1 Need for DST's Roadmap

DST's CCUS Roadmap is essential for navigating the complex landscape of CCUS technologies through breakthrough and translational research. As India commits to ambitious climate goals, including achieving Net Zero emissions by 2070, the CCUS Roadmap becomes an essential strategic tool for guiding the country's innovation efforts in this critical domain. This roadmap provides a strategic framework for identifying and prioritizing key research areas, ensuring efficient allocation of resources, and setting realistic timelines for technological advancements. By establishing clear priorities and directing investments towards the most promising areas, the roadmap envisages to maximize the impact of technological, financial, and human resources. Ultimately, the DST's CCUS Roadmap will be a critical tool for accelerating technological innovation for CCUS in India and effectively moving towards achieving India's net-zero targets. The needs and intangible outcomes of the roadmap can be categorized into the following broad areas:

Strategic Planning	**R&D Priorities**	The CCUS Roadmap is crucial for identifying R&D priorities, funding requirements, and timelines. This prioritization includes determining the required funding levels and setting realistic timelines for achieving milestones.
	Resource Allocation	The roadmap will pave the direction for allocation of resources, ensuring that investments are directed towards the most promising and priority areas. Effective resource allocation is vital for the success of any large-scale initiative, ensuring that technological, financial, and human resources are utilized optimally.
Technological Advancement	**Innovation and Development**	Promoting the development of emerging, disruptive and sustainable CCUS technologies that are more efficient and cost-effective. This involves supporting research initiatives, providing funding for experimental projects, and encouraging collaboration between academia, industry, and government bodies to drive technological advancements.
	Deployment and Scaling	The roadmap will outline strategies for transition from laboratory to pilot scale and eventually to large-scale industrial applications.
Climate Change Mitigation	**Curtailing Greenhouse Gas Emissions**	One of the major objectives of CCUS is to significantly reduce GHGs emissions. The roadmap will set out a clear pathway for the implementation of CCUS projects that can contribute to substantial reductions in national and global CO_2 emissions.
	Meeting International Commitments	A structured roadmap can help in reducing carbon emissions and achieving net-zero targets, thereby fulfilling international climate commitments.
Economic Benefits	**Job Creation**	Development and deployment of CCUS technologies can create jobs in research, engineering, and manufacturing. By fostering a robust CCUS ecosystem, the roadmap can stimulate job growth and provide new employment opportunities, thereby supporting economic development and workforce diversification.
	Economic Growth	Innovation in CCUS can stimulate economic growth through the development of new startup/industries and markets. The development of new technologies and industries centered around CCUS can lead to the creation of new markets and business opportunities.
Energy Security	**Sustainable Energy**	JSET (Just Sustainable Energy Transition) is the need of the hour. We need to pursue an energy transition but not at the cost of development. Coal dependence will continue to be a reality in the near future. Integrating CCUS with renewable energy sources can enhance energy security by providing a steady supply of low-carbon energy.
	Resource Utilization	Utilizing captured CO_2 in various industrial processes and manufacturing pathways can lead to better resource efficiency. This approach not only provides a value-add for captured CO_2 but also reduces the demand for raw materials, contributing to a robust circular economy. The roadmap will identify and promote opportunities for integrating CO_2 utilization into existing industrial processes, enhancing overall resource efficiency and sustainability.

1.2 Gaps in CCUS

CCUS technologies face several gap areas and challenges, including the need for ongoing research to enhance efficiency, cost-effectiveness, and sustainability. Key areas requiring attention are improving partnerships between academia, industry, and government, advancing both fundamental and translational research, and devising diverse funding mechanisms through Public-Private Partnerships (PPPs) to bridge the gap between laboratory innovations and commercial deployment. Integrating multiple CCUS technologies into tailored solutions could further optimize efficiency and address broader CO_2 capture and storage challenges. The gaps in CCUS can be broadly categorized as follows:

1.2.1 Research and Development Gaps

- **Ongoing Research:** Consistent R&D interventions are essential to develop innovative CCUS solutions that are more efficient and cost-effective. This includes accelerating current technologies and creating new pathways to capture, utilize, transport and store CO_2.

- **Enhanced Partnership:** A coordinated approach involving academia, industry, and government is vital to accelerate research and development efforts. Collaborative projects can leverage the strengths and resources of each sector, leading to more significant advancements in CCUS technologies. Joint initiatives can also facilitate the sharing of knowledge and best practices, fostering an environment where innovative solutions can be rapidly developed and implemented.

- **Fundamental and Translational R&D:** There is a pressing need for both fundamental and translational research in the CCUS field. Fundamental research explores breakthrough scientific principles and mechanisms, while translational research focuses on applying these principles to develop practical solutions. To facilitate these efforts, a variety of funding mechanisms need to be devised, including PPPs. These mechanisms will serve to close the gap between theoretical research and practical, real-world applications.

1.2.2 Technological Gaps

- **Efficiency and Cost-Effectiveness:** Improving the efficiency and reducing the cost of CCUS technologies are critical for their viable and sustainable upscaling.

- **Integration with Industrial Setups:** Integrating CCUS technologies within existing hard-to-abate industrial setups, such as thermal power plants, cement, steel, and chemical/fertilizer sectors, pose significant challenges. Integrating interventions need to be mounted to focus on retrofitting these sectors with appropriate CCUS technologies in a way that minimizes the emissions and maximizes efficiency as well as sustainability.

- **Upscaling and Integration:** The transition from small-scale demonstrations to semi-commercial scale applications requires significant technological advancements. Upscaling involves overcoming engineering and logistical challenges, while integration requires developing systems that can work seamlessly with existing industrial pathways.

1.2.3 Economic and Financial Gaps

- **High Initial investment and operational costs:** The high initial capital investment and operational costs associated with CCUS projects are major barriers to their widespread adoption. Financial models and incentives are needed to make these projects economically viable.

- **Insufficient Funding:** There is often insufficient funding for research, development, and deployment of CCUS technologies. Increasing funding from both public and private sources is crucial to support the entire lifecycle of CCUS projects, from initial research to full-scale deployment.

- **Lack of Economic Incentives:** The absence of strong economic incentives or carbon pricing mechanisms hinders the adoption of CCUS technologies. Implementing policies such as carbon taxes or cap-and-trade systems can provide financial motivation for industries to invest in CCUS.

1.2.4 Infrastructure Gaps

- **Transport Infrastructure**: The lack of infrastructure for transporting captured CO_2 to storage or utilization sites is a significant barrier. Developing a network of pipelines or alternative transport methods is essential to connect point sources of CO_2 emissions with storage or utilization sites.

- **Hotspots and Enabling Ecosystems:** Identifying viable hotspots with mapped sites and point sources is necessary to create an enabling ecosystem for CCUS hubs and clusters. This involves detailed geological surveys and assessments to pinpoint suitable locations for CCUS deployment.

- **Geological Storage Sites:** Identifying and developing suitable geological storage sites for CO_2 is critical. This includes conducting extensive geological assessments to ensure the safety and suitability of potential storage sites.

1.2.5 Regulatory and Policy Gaps

- CCUS in India has to be a mix of government policies on incentivization, carbon tax and superior technologies that offer low cost, high life cycle, and low environmental impact.

- **Regulatory Frameworks:** Incomplete or unclear regulatory frameworks for the deployment and monitoring of CCUS projects pose significant challenges. Clear and comprehensive regulations are needed to ensure the safe and effective implementation of CCUS technologies.

- **Policy Support and Incentives:** Stronger policy support and incentives are required to drive research and adoption of CCUS technologies. This includes policies that encourage investment, provide financial incentives, and remove regulatory barriers. Government initiatives and international collaborations can also play a crucial role in promoting CCUS development.

- **Carbon Market Mechanism:** There is also a need for a well-designed carbon market mechanism that could attract international investments and partnerships, facilitating technology transfer and knowledge sharing. Ultimately, the establishment of a working carbon market mechanism in India would not only drive the growth of CCUS activities but also contribute to the country's efforts in mitigating climate change and achieving its sustainability goals.

1.2.6 Immersive Enablers

- **Capacity building, Training and Outreach programs:** Capacity-building initiatives are essential to equip the workforce with the necessary skills and knowledge to implement and manage CCUS technologies. Public awareness and outreach programs will be devised to play a crucial role in raising understanding and support for CCUS technologies, engaging communities, policymakers, and stakeholders through seminars, conferences, and informational campaigns. International collaboration can enhance these efforts, involving exchange programs, joint research initiatives, and sharing best practices.

- **Life-Cycle Assessment (LCA):** LCA is a key tool for evaluating the environmental impacts of CCUS technologies across their entire lifecycle. Studies related to LCA of CCUS technologies will be included to assist in identifying suitable and sustainable decarbonization pathways.

- **Techno-Economic Assessment (TEA):** TEA is another crucial tool to assess CCUS pathways, as it identifies cost hotspots and potential areas of improvement, which can help in evolving appropriate strategies to ensure sustainability and accelerate commercialization.

- **Risk Assessment:** Risk assessment comprises of risk identification, analysis, and assessment. In this regard, crucial studies will be supported and conducted for identifying and evaluating potential risks associated with CCUS technologies related with operations and infrastructure. These studies help in course correcting novel approaches towards more practical directions.

- **Inventory Assessment:** One of the major challenges impending the development of effective solution to contain CO_2 emissions, is the absence of high-quality detailed data with topological, and sectorial distribution. Moreover, the detailed analysis is also missing due to the absence of collated data providing information about the chemical composition and actual quantities of emissions from unit operations in different sectors. Monitoring studies for inventory assessments need to be undertaken to collect all the relevant data from various point sources and quantities of CO_2 emissions for targeted capture and storage.

- **Tools and Methodologies for Emission Monitoring** will be developed for accurately monitoring and reporting CO_2 emissions.

- **Risk Forecasting:** Suitable models need to be developed to predict future risks and uncertainties in the deployment of CCUS technologies. It will be an important aspect for both environmental impact assessment and social viability.

1.2.7 India's Energy Landscape and Carbon Footprint

Total Emission Trend in India

India's CO_2 emissions have been on the rise, primarily driven by increased industrial activities and energy demand in a rapidly growing economy. The line chart illustrates the annual change in India's CO_2 emissions from 1970 to 2023. The data (**Figure 1.5**) reveals a general upward trend in emissions, with significant increases around the early 1980s, early 1990s, and late 2000s to mid-2010s. Notable peaks in emission growth occurred in 2012, 2015, and 2016, with increases close to 100 $MtCO_2$ in some years. The financial year 2019-20, highlighted in red, marks a significant decrease of approximately 30 $MtCO_2$ (1.4%), breaking a four-decade trend of rising emissions. This reduction could be attributed to economic slowdowns, policy changes, or shift towards renewable energy sources, indicating potential efforts toward carbon management strategies. Overall, there has been considerable increase in CO_2 emissions that requires holistic approach to mitigate the impending aftermath effects.

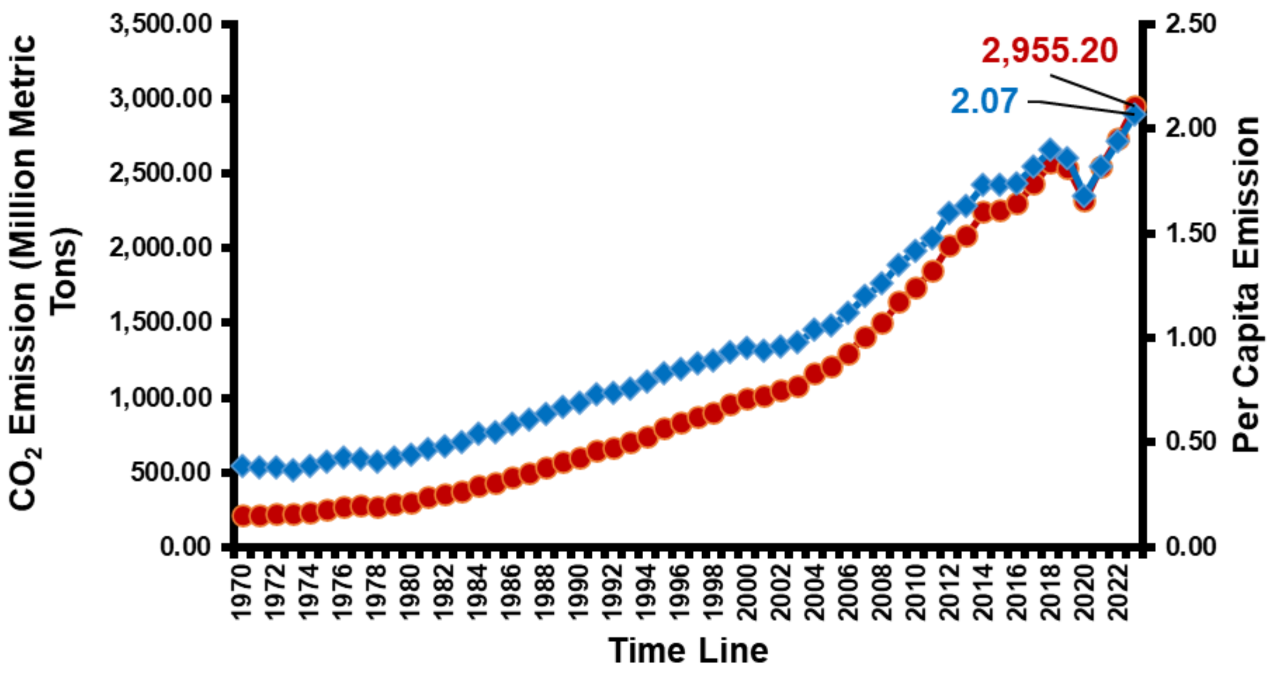


Figure 1.5: India's total and per capita CO_2 emissions over a period of 1970-2023 (Red line indicate- CO_2 emissions (million metric tons) and Blue line indicate- per capita emission) (Source: Expert(s) (Crippa et al. (2024)); EDGAR/JRC; European Commission; IEA).

Intertwined India's Growth and CO_2 Emission: The upward trajectory of total CO_2 emission in India has to be seen in the context of growth of developing economy. India's demography is young and aspirational and there are concerted efforts from the government to achieve the status of developed economy. The PwC projection suggests that India will grow by 15% to become the 2nd largest economy in the world as depicted in **Figure 1.6.** To achieve the higher standard of living as a developed economy, we are bound to see increased demand for energy, and construction materials such as cement, iron & steel as a marker of growth. Here, we present the projected growth of energy and construction material under different scenario as shown in **Figure 1.6**. Energy demand is anticipated to increase by 90 % and 21% under current trajectory and net zero scenario respectively. The installed capacity for cement in India is projected to increase substantially, rising from about 700 MMT in FY2025 to around 1,000–1,050 MMT by 2030, representing a growth of roughly 43–50% within just five years. By 2050, demand is expected to reach 2,600–2,700 MMT, implying an overall increase of nearly 270–285% from current levels to meet the expanding infrastructure and housing requirements. The highest growth will be observed in crude steel demand with an increase of 260% by 2050 compared to 2022 as the base year. To meet these demands, the new production units have to be installed, and existing facilities need to revamped. Notably, these are hard-to-abate sectors for CO_2 emission. This will result in the overall increase in the total CO_2 emission that requires acute attention to implement the CCUS intervention for sustainable growth. The potential growth of economy presents both opportunity and challenges for the future. Notably, it is implicit that we need to understand the underpinning of different sectors contributing to CO_2 emissions and requires differentiated approach to tackle the challenge of climate change owing to GHG emissions.

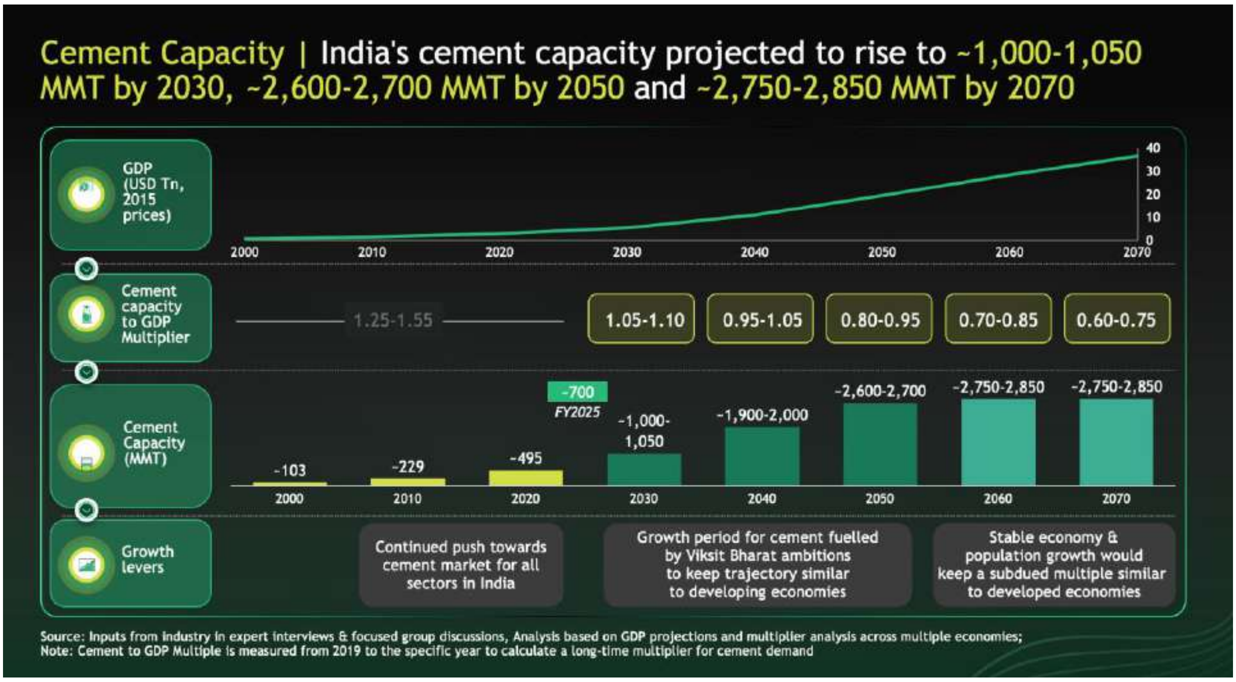


Figure 1.6: India's projected economic growth and potential subsequent growth in energy, cement and crude steel Industry (Sources: CMA-BCG Decarbonisation Study on Cement and Concrete 2025 (forthcoming).

Sectorial Mix of CO_2 Emission: The overall CO_2 emissions exhibited a pronounced upward trend from 1970 to 2023 as shown in **Figure 1.5**. A closer look at the sector-specific contributions can be illuminated from the histogram represented in **Figure 1.7**. It is clear that power industry is the highest contributor to the total emissions with ever increasing energy demands. This is in line with increasing demand for power for better standard of living of Indian population. The second-highest contribution is coming from the industries with significant contribution coming from cement and iron & steel industries, along with others. Moreover, there is progressive increase in CO_2 emissions from the transport sector, which can be attributed to increased mobility of population with enhanced infrastructure, and better economic perspective. While these have been major contributors of CO_2 emission, there are marginal contribution from agriculture, residential and other activities.

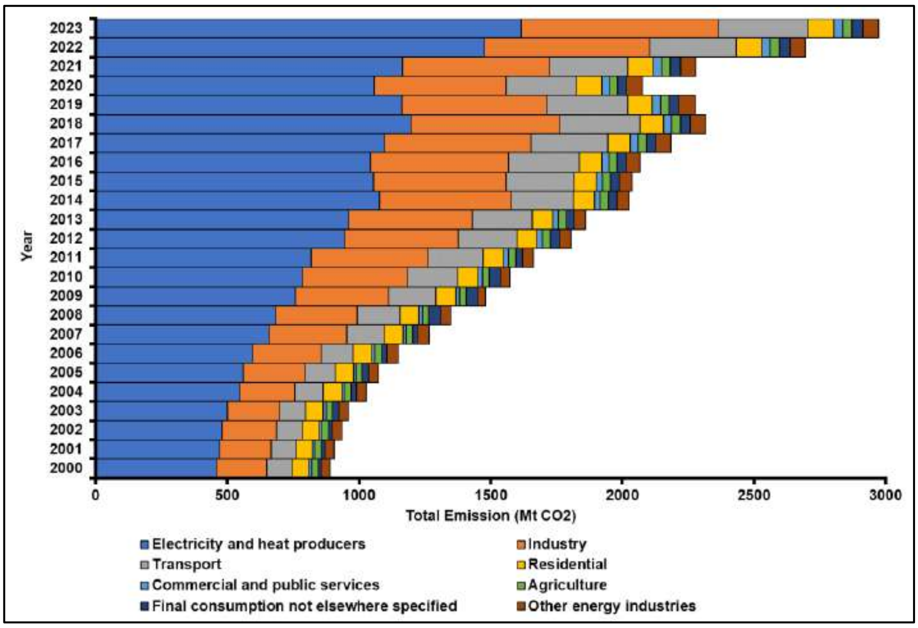


Figure 1.7: Sectorial contribution of CO_2 emissions in India from 2000 to 2023 (International Energy Agency).

A Closer Look at Hard-to-Abate Sectors: Evidently, power will continue to remain the main contributor of CO_2. It is important to have a detailed perspective to understand the underpinnings of energy distribution. The International Energy Agency (IEA) data offers a comprehensive overview of India's energy landscape. To the total energy mix, coal has the highest contribution close to 45 %, followed by oil. This might be attributed to the fact that India is one of the major producer of coal with heavy dependence on imports for oil. Evidently, majority of the indigenously produced coal is consumed in electricity production (71.5%) as shown in **Figure 1.8**. This suggests a strong case for imbibing CCUS technology in power sector to have appreciable changes in overall CO_2 emission. Coal and biofuels are the major source of energy production, with a contribution of approximately 49.7% and 33.4% respectively. There is a critical need for diversification of fuel sources, along with efficient and cleaner utilization of coal in thermal power plants.

Figure 1.8: Distribution of fuel usage across the India's energy landscape and CO_2 emissions trends by fuel (IEA).

Based on the prior analysis, it is evident that certain hard-to-abate sectors require focused attention. Here, we looked into three sectors, namely: 1) Power, 2) Cement, and 3) Iron & Steel. A detailed perspective of the power sector has been discussed earlier. **Figure 1.9** shows that Cement consumption is projected to rise steadily, reinforcing the sector's critical role in supporting India's growth trajectory. India's possible cement demand is projected to grow from 450 MMTPA in FY2025 to 650-700 MMTPA by 2030. In FY 2025, production of around 450 million tonnes of cement resulted in roughly 288 million tonnes of CO_2 emissions. If the Indian cement industry maintains its current trajectory of emissions intensity at 0.64 tCO_2/Cement without further policy support and industry innovation, emissions could continue to rise significantly, with total annual emissions expected to grow from about 288 MMT today to nearly 1.34 billion MT by 2070. However, if the best available technology in 2021 is applied, we expect that the trajectory might show a dip in overall CO_2 emissions. It should be noted that there might be emerging better technologies that can have an even higher effect in curbing the CO_2 emission.

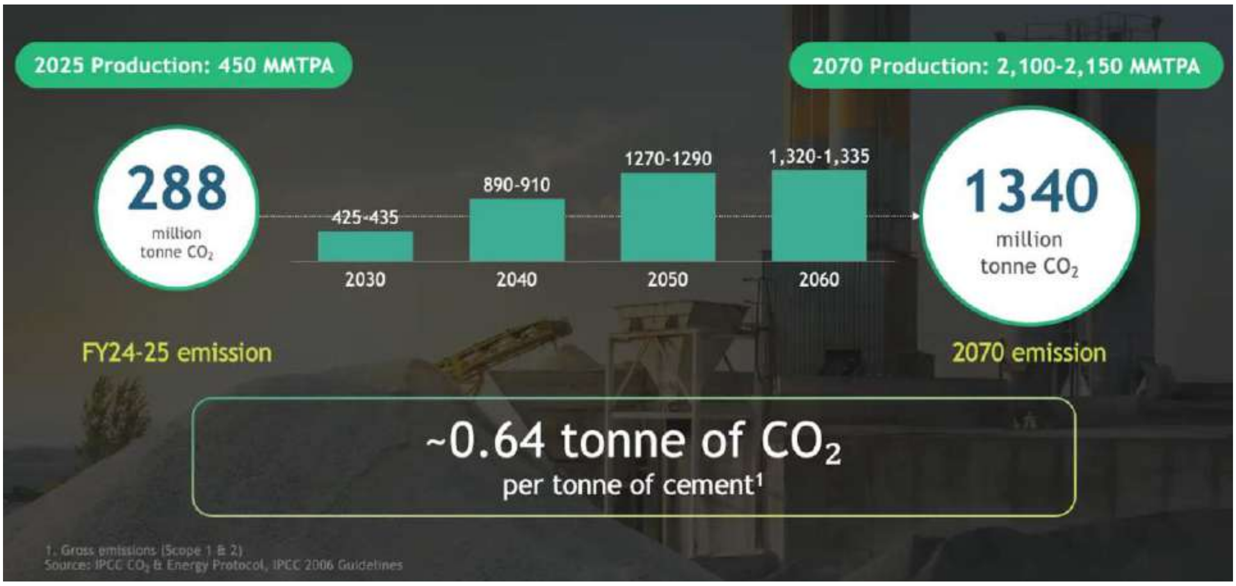


Figure 1.9: Emission projections from the CMA-BCG Decarbonisation Study on Cement and Concrete. (Source: CMA-BCG Decarbonisation Study on Cement and Concrete 2025 (forthcoming).

Potential Climatic Impact of Temperature Rise Due to GHG Emission: The latest assessment from the International Panel on Climate Change (IPCC) highlights the perilous trajectory of climate change, largely driven by human-generated greenhouse gas emissions, especially CO_2.

1.3 Challenges and Opportunities for CCUS Technologies in India

There are various challenges and opportunities associated with CCUS Technologies in India, which have been elaborated as follows:

1.3.1 Challenges

- **High technological costs:** CCUS technologies face significant challenges in India primarily due to high costs. Initial capital investments for infrastructure, such as capture facilities and transportation networks, are substantial. The operational processes are energy-intensive and require regular maintenance, adding to costs. In addition, small-scale projects do not benefit from economies of scale, and the lack of robust carbon pricing mechanisms and uncertain markets for utilized CO_2 hinder economic viability. Insufficient policy support, regulatory hurdles, and the need for localized research and development further complicate implementation. Addressing these challenges requires government subsidies, international collaboration, carbon pricing, public-private partnerships, and scaling up projects to achieve cost efficiencies and support CCUS deployment in India [1,2].

- **Limited scalability:** The limited scalability of the current CCUS technologies can be attributed to the insufficient infrastructure and geographical constraints in India. India lacks the extensive pipeline networks and storage facilities required to transport and store captured CO_2 on a large scale. Suitable geological formations for CO_2 storage, such as saline aquifers or depleted oil and Appropriate geological formations for CO_2 storage such as saline aquifers or depleted oil and gas reservoirs are unevenly distributed throughout the country. In addition, uncertain CO_2 utilization markets for products derived from CO_2 utilization, such as chemicals, fuels, and building materials, are still developing and do not yet provide reliable revenue streams [3].

- **Incentives and policy interventions:** India's adoption of CCUS technologies is hindered by major challenges, primarily due to the lack of adequate incentives for industries. High initial and operational costs, coupled with limited government subsidies and the absence of robust carbon pricing mechanisms, deter investment. Policy and regulatory uncertainties, along with insufficient R&D funding and technological readiness, add to the barriers. To overcome these challenges, India needs to implement carbon pricing, increase government support and establish clear policies, creating a conducive environment for CCUS adoption [4].

- **Barriers to retrofitting and deployment:** Retrofitting existing industrial facilities, especially older coal-fired power plants and industrial units, with CCUS technologies poses significant technical and financial difficulties. Many CCUS technologies are still in development or pilot phases, complicating their seamless integration into existing systems without major modifications. Additionally, capturing and compressing CO_2 is highly energy-intensive, resulting in increased overall energy consumption for retrofitted facilities. These factors make the technical implementation of CCUS both challenging and costly [2].

- **High capital investment for CO_2 capture, storage, and related infrastructure:** Implementing CO_2 CCUS technologies in India involves significant capital investments. The initial costs are primarily driven by the need for advanced technology and infrastructure development. Capturing CO_2 from industrial sources or power plants requires sophisticated equipment such as amine-based solvents, pressure swing adsorption systems, and advanced cryogenic processes, which are costly to procure and maintain. Moreover, the need for extensive pipeline networks to transport captured CO_2 to storage sites or utilization facilities adds to the overall financial burden. These pipelines must be constructed to meet stringent safety and environmental standards, further increasing the capital expenditure. Additionally, the construction of injection wells and monitoring systems to track the movement and stability of stored CO_2 involves significant costs. The need for long-term monitoring and maintenance to prevent leaks and ensure environmental safety also adds to the financial demands of these projects. Financial incentives and government support are critical to overcome the high capital investment barriers associated with CCUS in India. Encouraging public-private partnerships can leverage the strengths of both sectors to share the financial risks and benefits [5].

- **Low public awareness of CCUS benefits and potential risks:** A successful CCUS initiative depends on the participation and collaboration of numerous stakeholders, with the public being most important. Support and acceptance from local communities are essential for projects of this kind. It is important to educate and raise awareness within these communities about the significance and safety of permanent geological CO_2 storage. Continuous communication and engagement throughout the project's life-cycle are key to building and maintaining public trust. Governments, NGOs, and the scientific community all play an important role in articulating the importance of CCUS in meeting climate targets.

- **Uncertainty surrounding long-term ownership and liability for stored CO_2:** The uncertainty surrounding long-term ownership and liability for stored CO_2 in India poses significant challenges for the deployment of CCUS technologies. Currently, there is a lack of clear legal frameworks and regulatory guidelines defining who owns the stored CO_2 and who is liable for its safety and maintenance over time. This ambiguity creates risks for investors and operators, as they may face unforeseen legal and financial responsibilities. Establishing well-defined policies and liability mechanisms is crucial to ensure long-term security and to encourage private sector investment in CO_2 storage projects [7].

- **Cost-effective methods for long-term CO_2 storage site monitoring:** Monitoring long-term CO_2 storage sites in India effectively requires a combination of innovative methods to ensure environmental safety and regulatory compliance. Key approaches include using remote sensing technologies such as satellite imagery and drones for extensive coverage, geophysical monitoring with seismic surveys to track CO_2 movement, and in-situ tools like downhole sensors for real-time data on storage conditions. Additionally, microbial monitoring of environmental changes can indicate CO_2 leakage, and integrating data from various methods into predictive models enhances monitoring accuracy.

Engaging with regulatory bodies to establish clear guidelines and involving local communities in monitoring activities can enhance transparency and trust, facilitating smoother project implementation. By leveraging these methods, India can develop a robust, cost-effective monitoring system for long-term CO_2 storage sites, promoting the widespread adoption of CCUS technologies while ensuring environmental safety and regulatory compliance [7].

1.3.2 Opportunities

- **Long shoreline in India:** India's long shoreline, extending over 7,500 kilometres, presents significant opportunities for CO_2 storage, particularly through offshore geological formations. These formations, such as depleted oil and gas fields and deep saline aquifers, can potentially store large quantities of CO_2. Offshore storage minimizes the risk of CO_2 leakage into populated areas and can leverage existing oil and gas infrastructure for transport and injection. Additionally, coastal and marine environments can support the development of CCUS projects by providing access to deepwater storage sites, thereby enhancing India's capacity to manage and mitigate carbon emissions effectively [1,2].

- **Transforming CO_2 into valuable products:** India is actively exploring the transformation of CO_2 into valuable products through various research initiatives. Key areas include chemical conversion to produce methanol, formic acid, and polymers, bio-conversion using microorganisms and algae to create biofuels, and mineralization processes to produce construction materials. EOR utilizing CO_2 is also a significant area of focus [8].

- **Creating New Industries and Jobs in the CCUS Sector in India:** The development of CCUS technologies in India presents significant opportunities for creating new industries and jobs:

Job Creation and Skill Development

- Industry Growth: Establishing CCUS plants and facilities can spur the growth of related industries, such as manufacturing of capture equipment, pipeline construction, and CO_2 utilization products.

- Research and Development: Increased funding for CCUS research can create positions for scientists, engineers, and technicians. Hiring PhD students for specific CCUS projects will advance the technology and provide skilled graduates for the industry.

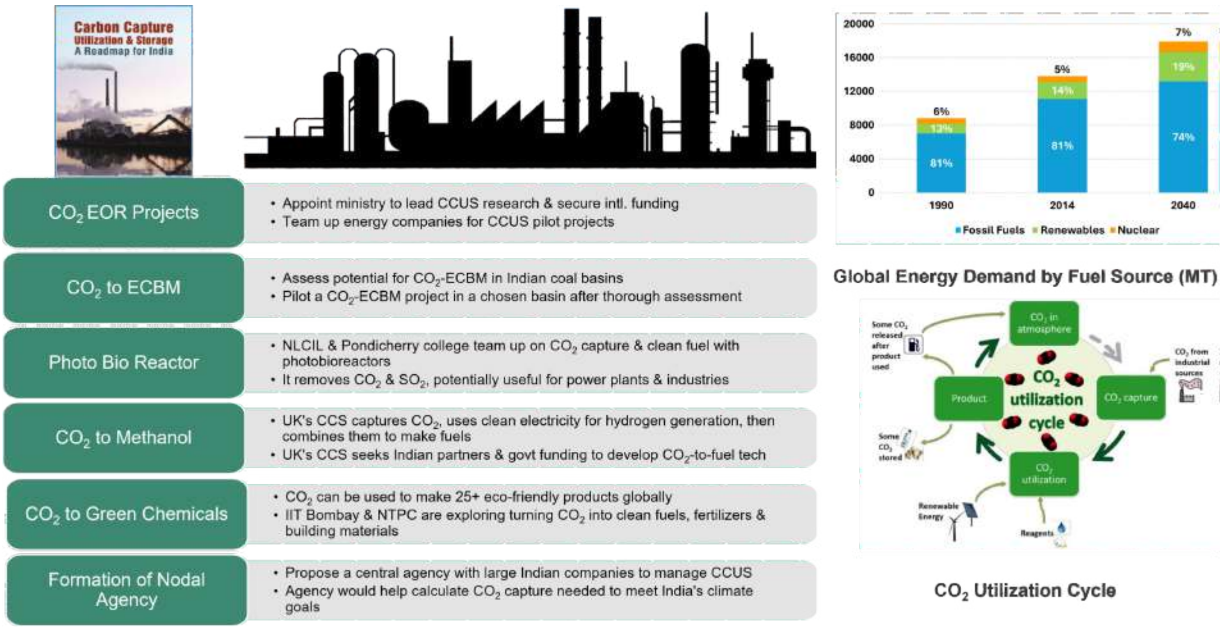
- Operational Roles: Operational jobs in CCUS facilities include roles in engineering, maintenance, safety, and environmental compliance, providing a wide range of employment opportunities.

- **Reducing reliance on imported fuel:** Reducing reliance on imported fuels in India can significantly boost the CCUS sector by promoting energy security and domestic innovation. As India shifts towards self-sufficiency, investments in indigenous energy sources, including coal, oil, and gas, can be complemented by robust CCUS technologies to mitigate associated emissions. This transition can enhance technological expertise, reduce energy costs, and support India's climate goals, fostering a sustainable and resilient energy landscape [8,9].

1.3.3 Previous roadmaps to CCUS

- **Technology Information, Forecasting and Assessment Council (TIFAC), DST**

  The TIFAC DST roadmap for CCUS technologies in India outlines several strategic initiatives. These include appointing a suitable agency to lead research and secure international funding for CO_2 EOR projects, assessing and piloting CO_2-enhanced coalbed methane in Indian coal basins, and developing photobioreactors with Neyveli Lignite Corporation India Limited (NLCIL) and Pondicherry College for CO_2 capture and clean fuel production. It also emphasizes collaborations with UK's CCS for CO_2-to-methanol technologies, exploring CO_2 utilization for eco-friendly products with IIT Bombay and NTPC, and proposing a central nodal agency to manage CCUS efforts and meet climate goals.



Scheme 1.1: Roadmap to CCUS by TIFAC DST.

- **CMA-BCG Decarbonisation Study on Cement and Concrete 2025 (forthcoming)**

The Indian cement Industry envisages significant potential in utilising captured carbon to create value added products, particularly within the building material sector and through carbon mineralisation. This approach offers a circular economy pathway, turning the CO_2 back into useful fuel resources.

Carbon Mineralisation into Building Materials- This is a highly promising avenue where captured CO_2 can be chemically reacted with alkaline industrial by products (like slag, fly ash, or even demolition waste) or natural minerals to form stable carbonates, effectively permanently sequestering CO_2 within construction materials. Examples include producing CO_2 cured concrete blocks, aggregates or precast elements. This not only sequesters CO_2 but can also enhance the properties of the materials and reduce the need for virgin raw materials.

Specific Challenges

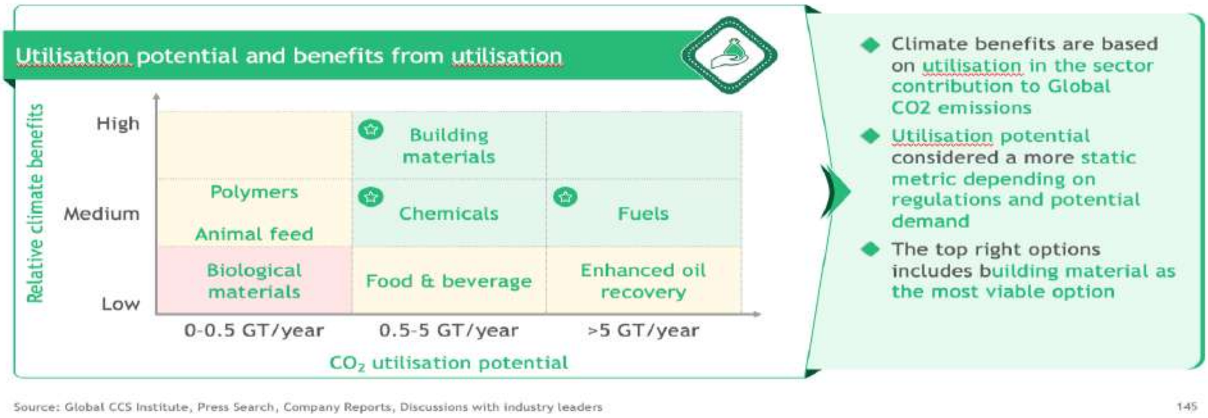
i. **Scalability and Cost:** While lab and pilot scale successes are emerging, scaling these processes to industrial levels is capital intensive. The cost of CO_2 capture and the energy required for accelerated mineralisation processes remain significant hurdles.

ii. **Reaction Kinetics:** Achieving optimal and consistent reaction rates for mineralisation, especially with varied industrial wastes, requires precise control over temperature, pressure, moisture content and CO_2 concentration.

iii. **Material Properties and Standards:** Ensuring that CO_2 mineralised products meet existing building codes and performance standards (e.g., strength, durability, fire resistance) requires rigorous testing and the development of new, relevant standards.

iv. **Availability of Alkaline Feedstocks:** While industrial by products are promising, their consistent availability and optimal physical and chemical composition for mineralisation need to be ensured across different regions.

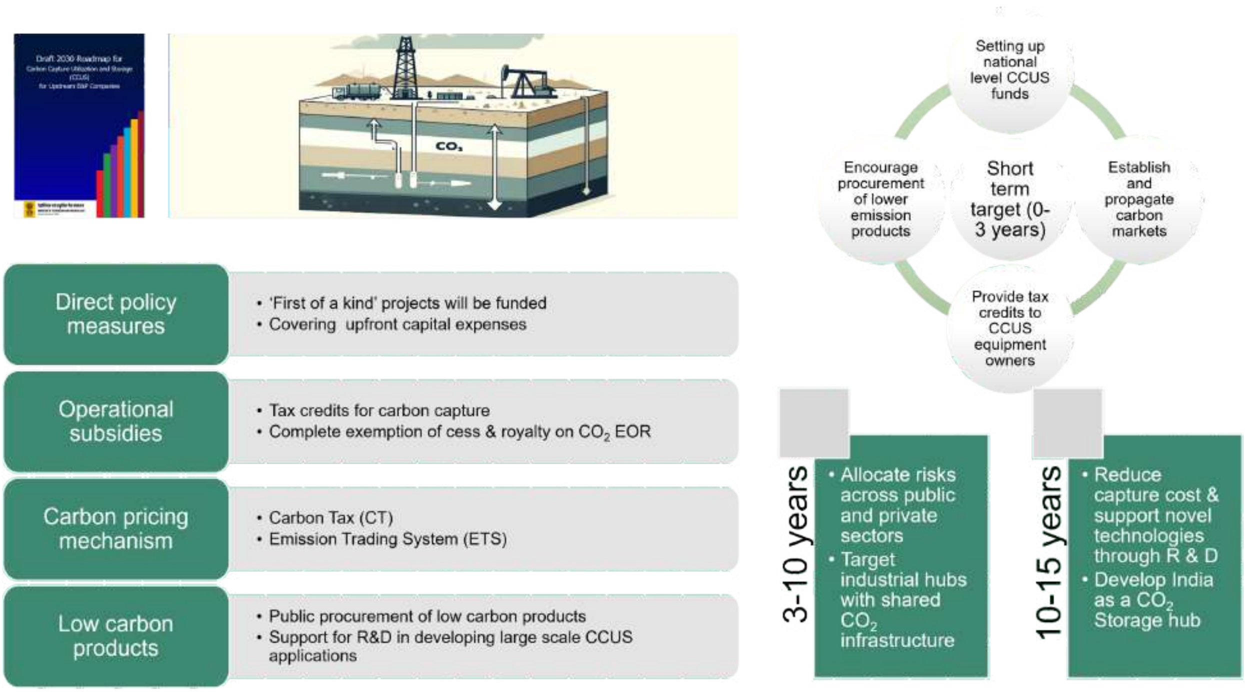
v. **Purity of Captured CO_2:** The purity requirements of captured CO_2 for mineralisation processes can vary, impacting the cost of upstream carbon capture.



Scheme 1.2: Utilisation potential and benefits from utilisation (Source: CMA-BCG Decarbonisation Study on Cement and Concrete 2025 (forthcoming)

- **Ministry of Petroleum and Natural Gas (MoPNG)**

The draft roadmap to CCUS technologies prepared by MoPNG, India, includes several strategic initiatives aimed at achieving short-term targets (0-3 years). These include setting up national-level CCUS funds, establishing carbon markets, providing tax credits to CCUS equipment owners, and encouraging the procurement of low-emission products.

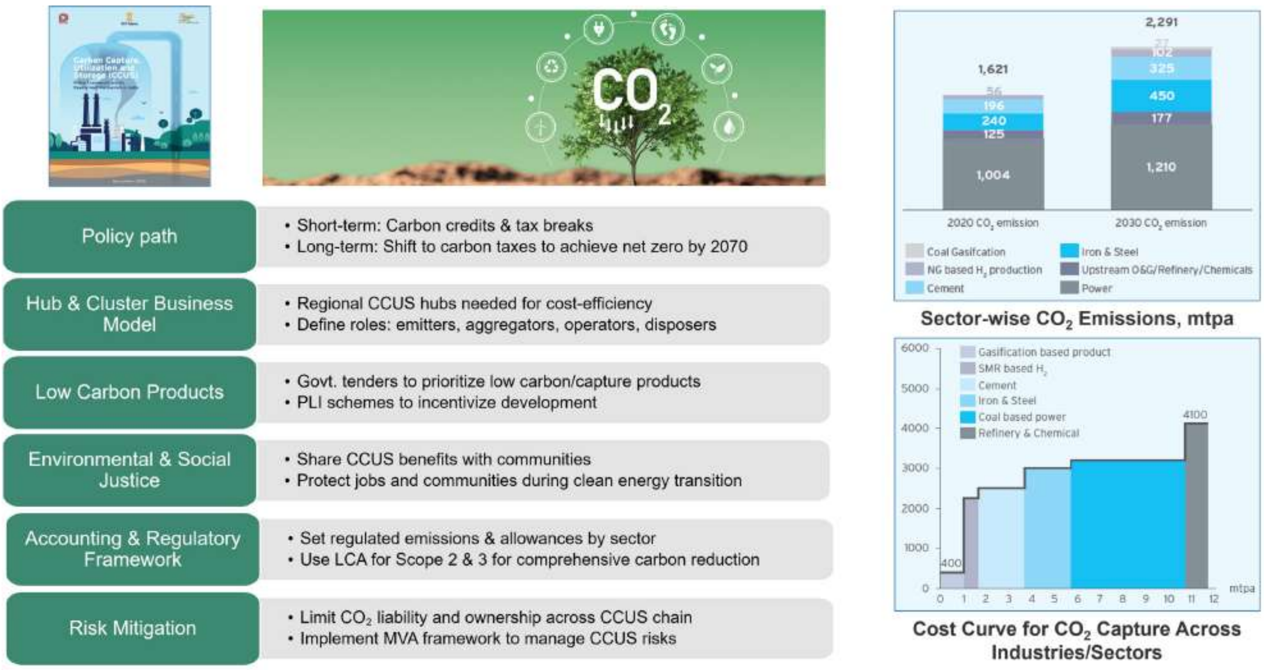


Scheme 1.3: Roadmap to CCUS by ADB - Dalmia Industries

Medium terms goals (3-10 years) involve allocating risks between public and private sectors, targeting industrial hubs for shared CO_2 infrastructure, and supporting R&D to reduce capture costs. In addition, long term goals (10-15 years) include introducing policy measures include funding "first of a kind" projects, providing operational subsidies, implementing carbon pricing mechanisms, and promoting public procurement of low-carbon products [6].

- **NITI Aayog**

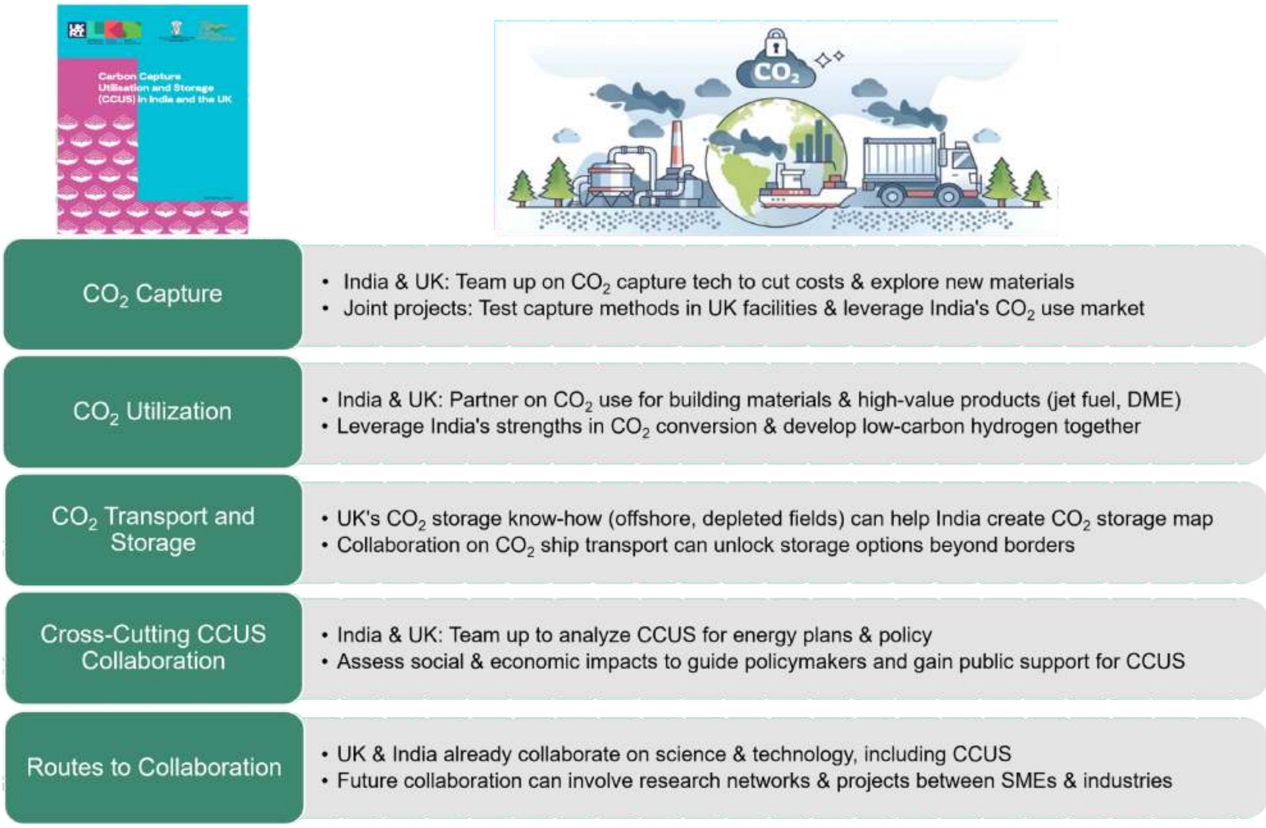
The roadmap to CCUS technologies by NITI Aayog, India, emphasizes several key initiatives. The policy path includes short-term carbon credits and tax breaks, with a long-term shift to carbon taxes to achieve net zero by 2070. Establishing regional CCUS hubs for cost-efficiency and defining roles within the CCUS chain are essential. Government tenders and Production Linked Incentive (PLI) schemes will prioritize low carbon products. Ensuring environmental and social justice involves sharing CCUS benefits with communities and protecting jobs. The regulatory framework will set emissions allowances by sector, and risk mitigation strategies will manage CO_2 liability and ownership.



Scheme 1.4: Roadmap to CCUS by NITI Aayog

- **DST - UK Research and Innovation (UKRI)**

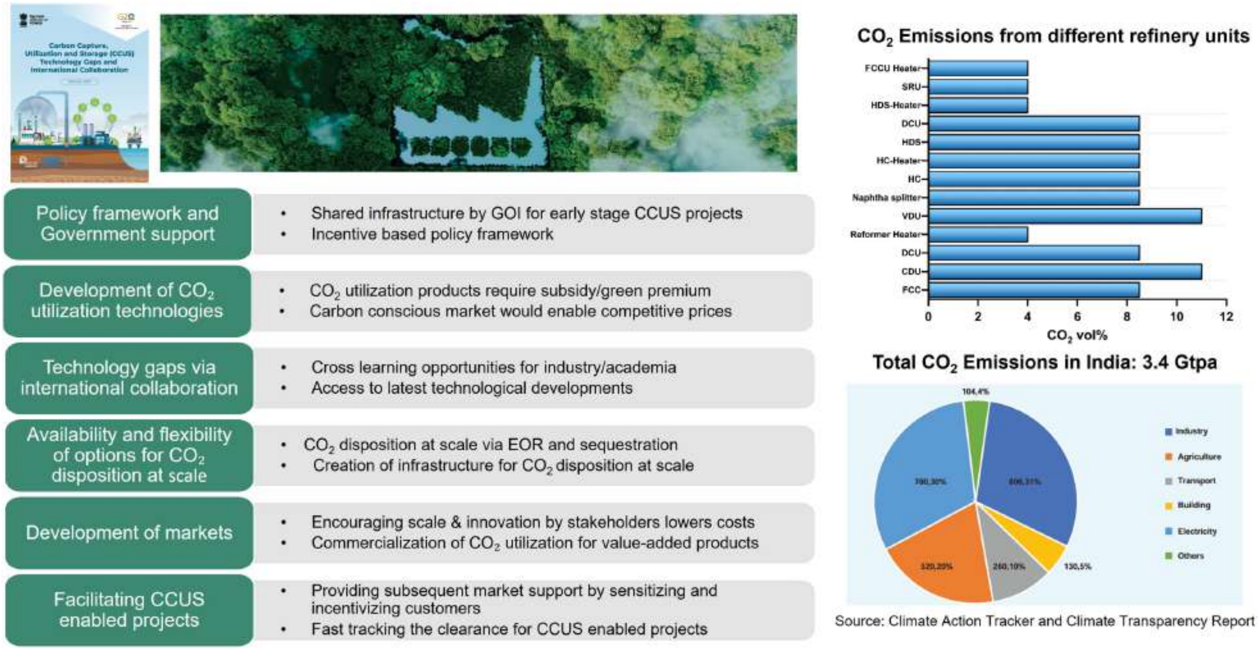
The roadmap to CCUS technologies by UKRI and DST India outlines collaboration areas between India and the UK. For CO_2 capture, both countries aim to team up on technologies to reduce costs and explore new materials, with joint projects testing methods in UK facilities and leveraging India's CO_2 market. For CO_2 utilization, the focus is on using CO_2 for building materials and high-value products like jet fuel. CO_2 transport and storage will benefit from the UK's offshore storage expertise and ship transport collaboration. Cross-cutting collaboration involves analyzing CCUS for energy policies and assessing social and economic impacts. Existing collaborations in science and technology will expand to include research networks and projects between Small and Medium Enterprises (SMEs) and industries.



Scheme 1.5: Roadmap to CCUS by DST – UKRI.

- **Ministry of Power (MoP)**

The Ministry of Power (MoP), India's roadmap for CCUS technologies emphasizes creating a supportive policy framework with government incentives and shared infrastructure. It highlights the need for subsidies and a carbon-conscious market to develop CO_2 utilization technologies. Addressing technology gaps through international collaboration and cross-learning opportunities is crucial. The roadmap calls for developing infrastructure for large-scale CO_2 disposition via EOR and sequestration. Encouraging market development, innovation, and commercialization of CO_2 products is vital, along with fast-tracking project clearances and providing market support to incentivize customers.



Scheme 1.6: Roadmap to CCUS by Ministry of Power.

1.4 Summary

The Government of India has outlined an ambitious trajectory for accelerated economic growth, aiming to transition the country into a developed nation in alignment with the aspirations of its citizens. While growth is both inevitable and essential, India philosophy has long emphasized a sustainable path to achieving a higher standard of living. This requires that the engines of growth must evolve, encompassing sustainability as a core principle. The key sectors that will see strong growth are the power and infrastructure building sectors, such as cement and iron & steel. The capacity building of these hard-to-abate sectors will inevitably lead to increased greenhouse gas emissions, particularly CO_2. Anticipating these challenges, the Hon'ble Prime Minister of India, Shri Narendra Modi, introduced the *Panchamrit Sutra*, a strategic framework to combat climate change with a vision to achieve net-zero emissions by 2070.

The DST has made commendable strides in advancing this vision. A wide array of initiatives has been launched to bolster both fundamental and translational research focused on establishing a comprehensive CCUS framework. Several national, international, and bilateral research proposals have been sanctioned to accelerate the development of technological solutions. These efforts have catalyzed multi-institutional collaborations, fostered capacity building through manpower training, and facilitated knowledge sharing across academia and industry. A key milestone includes the establishment of three DST-funded Centres of Excellence, which have served as incubators for innovation, spawning start-ups and fostering applied research. Furthermore, India's active participation in transnational platforms such as Accelerating CCUS Technologies (ACT), Mission Innovation (MI), and the Clean Energy Transition Partnership (CETP) reflects its growing role in the global sustainability dialogue. Importantly, industrial engagement underscores the resolve to translate research into commercially viable solutions.

While DST-India is making significant progress in addressing this mammoth challenge, a structured roadmap is essential for strategic prioritization and optimal resource allocation. This roadmap aims to provide guidance on R&D priorities, technology deployment strategies, scale-up potential, and alignment with international commitments. Several critical challenges must be addressed to realize these goals. The availability of economically viable and scalable CCUS technologies remains limited. There is a pressing need for accelerated R&D efforts to improve technological maturity. Financial and economic constraints continue to pose significant barriers to large-scale implementation. Infrastructural inadequacies, particularly in relation to CO_2 storage and transport, require focused attention. The regulatory landscape and policy frameworks are yet to fully evolve to support widespread deployment. Moreover, the enabling ecosystems necessary to facilitate the adoption and integration of CCUS technologies are still evolving.

Technological deployment encounters further challenges. Most current technologies remain in the early stages of development and are linked to high capital costs. While some have progressed along the TRL ladder, their implementation remains resource-intensive and relies on government support and subsidies, for which frameworks are being developed. Integrating these technologies into existing industrial setups is complex and requires cost-effective retrofitting. Many of these solutions also demand significant investment in CO_2 storage and transportation infrastructure. From a societal standpoint, community acceptance is still low. Public awareness is limited, which requires a campaign to generate greater acceptance. Additionally, determining the accountability for monitoring and assessing CO_2 storage over a long period needs to be established.

Nonetheless, these challenges must be viewed as opportunities for innovation and development. Emerging methodologies for CO_2 valorization have the potential to reduce energy dependence, stimulate infrastructure growth, enhance climate resilience, and generate new employment opportunities. Ultimately, these initiatives represent a collective step toward building a peaceful and sustainable future by mitigating the adverse effects of climate change.

This chapter provides a comprehensive overview of the current challenges and DST's multifaceted approach to addressing them through strategic funding, knowledge exchange, pilot-scale implementation, and the establishment of Centres of Excellence. It also underscores the gaps that require coordinated and strategic interventions to meet India's net-zero target. The first three chapters of this roadmap delve into the technological dimensions of carbon capture, carbon utilization, and carbon sequestration, exploring potential solutions, implementation pathways, and broad guidelines for the development of viable technologies. The subsequent chapter focuses on the financial models and policy interventions needed to accelerate research and technology translation, offering recommendations to optimize resource allocation and funding strategies. The penultimate chapter examines the challenges posed by hard-to-abate sectors, identifying specific pain points and proposing tailored solutions for industries with high emission intensities.

Overall, DST-India's proactive efforts in developing and deploying CCUS technologies are both timely and critical. This roadmap represents a pivotal step toward consolidating these efforts and addressing the interlinked technological, financial, infrastructural, and policy challenges. In doing so, it lays the groundwork for a more systematic and strategic rollout of CCUS platforms, thereby contributing to India's long-term sustainability and climate commitments.

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CHAPTER 2

CARBON DIOXIDE CAPTURE

CARBON DIOXIDE CAPTURE

The reduction of anthropogenic CO_2 emissions has taken centre stage owing to the potential threat of climate change. The global community is approaching to resolve these problems through two major strategies: (1) continuous implementation of renewable energy sources with relatively lower carbon footprint, and (2) reduction of CO_2 emissions from conventional fossil-based processes (typically hard-to-abate sectors). While the former approach is not under our purview, the latter approach can be implemented through Carbon Dioxide Capture, Utilization, and Sequestration (CCUS). This three-step approach mainly includes; (1) the separation of CO_2 from associated gases such as N_2, NO_x, SO_x, and H_2S, (2) the partial conversion of purified/captured CO_2 in value-added chemicals in hydrogen or hydrogen-rich environment, and (3) the transportation and sequestration of the remaining CO_2 underground, undersea or above the ground making it immobile via mineralization, solubilization, or hydrate formation. A holistic approach of synergizing contributions from CCUS implementation, renewable energy utilization, and green hydrogen production, among other efforts would help reduce the global CO_2 emission which is currently pegged around 40 billion tons per year. The carbon budget for the +1.5°C scenario is roughly 250 billion tons which offers 5-6 years before hitting the limit under business-as-usual circumstances. The best-case scenario is to target a +2°C scenario and develop a robust roadmap encompassing the identification of effective research, development, and deployment targets for India for the next two decades. This chapter discusses inherent challenges and opportunities concerning CO_2 capture in terms of fundamental research and translation research for the deployment of demonstration and commercial plants. The focus of discussion in this chapter is to identify key bottlenecks and suggest potential pathways for RD&D of CO_2capture.

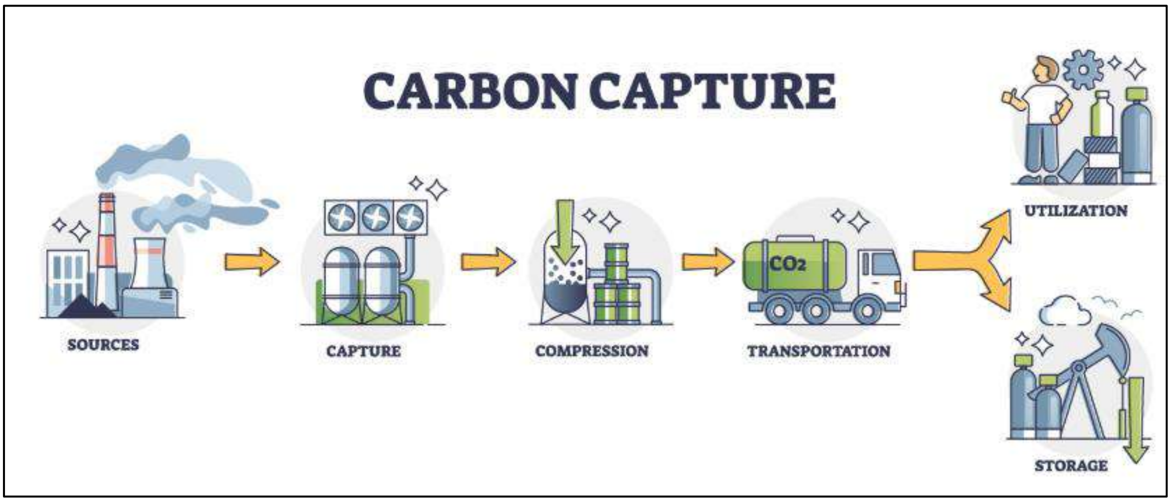

Figure 2.1. Complete value-chain of carbon dioxide capture under CCUS strategy.

The capturing of CO_2 is a classic chemical engineering problem of gas separation. The design and technology choice for separation will be strongly dependent on the chemical composition of source gases. For instance, ambient air contains less than 1% of CO_2 whereas biogases can contain up to

40-50% of CO_2. For any separation and capture technology, it is pertinent to identify or design a suitable solvent (absorbent) or nanoporous solid framework with a high internal surface area (adsorbent). This calls for strong research on the synthesis of novel materials, a detailed study of thermodynamic properties, and performance evaluation in terms of capture efficiency, kinetics, and recyclability. Among many challenges, the scale-up of technologies for commercial rollout faces a major hurdle of poor material robustness. Under dynamic conditions, separating medium must be regenerated multiple folds for long-term use and economic viability of commercial processes. Moreover, regeneration is an energy-intensive step that further limits the viability which can be circumvented by integrating with renewable sources of energy. Herein, we will discuss the potential options to accelerate the efforts toward carbon capture and suggest a way forward for the future. We will categorically try laying out the roadmap for CO_2 capture by discussing the questions enumerated below:

1. What are the possible sources of CO_2 mixture?
2. What are the technologies available for the separation of these CO_2 compositions?
3. What are the new directions moving forward?

Sources and Nature of CO_2 Mixture

- **Post-Combustion capture systems:** Most of the carbon dioxide capture steps which are projected to be retrofitted, come under post-combustion capture wherein CO_2 is separated from a flue gas stream generated due to fuel combustion in the air. This is denoted as end-of-pipe (EOP) solution for carbon capture. The flue gas is typically lean in CO_2 (~10%) containing predominantly unreacted N_2 and O_2. Depending on the fuel and nature of combustion, it can contain varying amounts of NO_x, SO_x, and H_2S. Major efforts in research for post-combustion separation technologies are focused on developing advanced solvents, adsorbents, membranes, and calcium looping systems. Many novel concepts are developed by hybridizing the multiple technologies to seek the benefits through cost reduction and reduced energy penalty. The use of amines as solvents has been successfully implemented commercially for post-combustion capture technologies around the world. Details of amine-based processes are discussed later in this document. The next three technology options belong to the CCUS compliant design (CCD) category.

- **Pre-Combustion capture systems:** Pre-combustion capture is characteristically different from post-combustion capture. Unlike the post-combustion process, fossil fuels are gasified or liquified before combustion. Subsequently, as-obtained fuel can be combusted in stoichiometric ratio or limited supply of air resulting in CO_2-rich flue gas. This approach requires greenfield projects under clean coal programs. Currently, there exists no such industry-scale facility operating in India. This is an area that requires more focused attention. Additionally, it should be noted that post-combustion capture poses more stress on the separation medium owing to high reactive impurities, unlike pre-combustion capture.

  In integrated gasification combined cycle (IGCC) plants, pre-combustion capture systems are configured to remove CO_2 prior to complete fuel combustion by separating it from the hydrogen-rich syngas generated in the gasifier. To enhance carbon capture efficiency and increase hydrogen yield, the syngas undergoes a water–gas shift (WGS) reaction, which converts carbon monoxide into CO_2 while producing additional H_2. Current R&D in pre-combustion capture focuses on advanced solvents, solid sorbents, and membrane technologies for hydrogen separation, with particular attention to high-temperature and novel materials, process intensification, and nanomaterial-based systems. While chemical and physical solvents are already commercially deployed, membrane technologies remain at the laboratory evaluation stage.

- **Oxy Combustion / Oxyfuel Combustion:** The third approach is oxyfuel combustion which is not used extensively in industrial processes. This approach uses pure oxygen for combustion instead of air. This requires the separation of oxygen from the air before using for combustion. This results in the release of a flue stream rich in CO_2 concentration. Subsequently, CO_2 needs to be captured from the mixture of flue gas containing CO_2 and O_2. The high concentration of CO_2 simplifies the capture process. Capture can be conducted using a physical process instead of a chemical route. It results in better regeneration of the solvent without much degradation. These routes facilitate the lower operational cost for CO_2 capture. However, the viability of this process has to be evaluated accounting for both steps, the separation of oxygen from air and post combustion separation of oxygen from CO_2. Recent studies suggest that the cement industry may benefit from oxyfuel combustion which is presented later in this report.

- **Chemical looping:** This technology uses metal oxides for combusting the fossil fuel resulting in highly concentrated CO_2 release. High CO_2 concentration results in better capture efficiency. For example, calcium looping is one such approach that is specifically suitable for the cement industry. Calcium Looping involves using calcium oxide (CaO) as a sorbent to capture CO_2. In the first stage, CO_2 reacts with CaO to form calcium carbonate ($CaCO_3$). In the second stage, $CaCO_3$ is heated to release the CO_2 and regenerate CaO. This process can be integrated into cement production to capture CO_2 and improve efficiency.

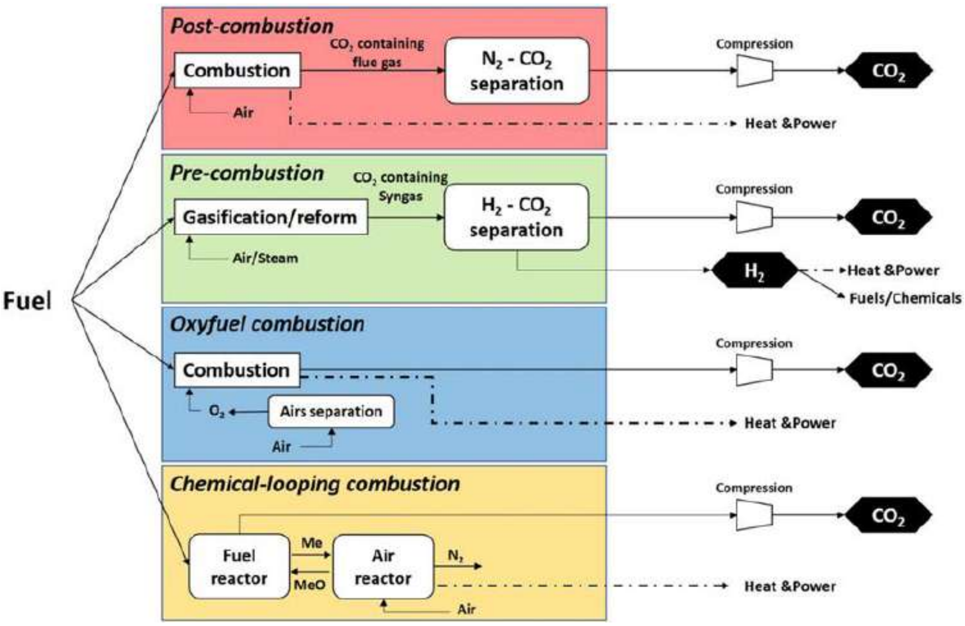

Figure 2.2. Schematic of CO_2 capture system. (Source: Adsorption of Carbon Dioxide for Post-combustion Capture: A Review; Energy Fuels 2021, 35, 12845–12868)

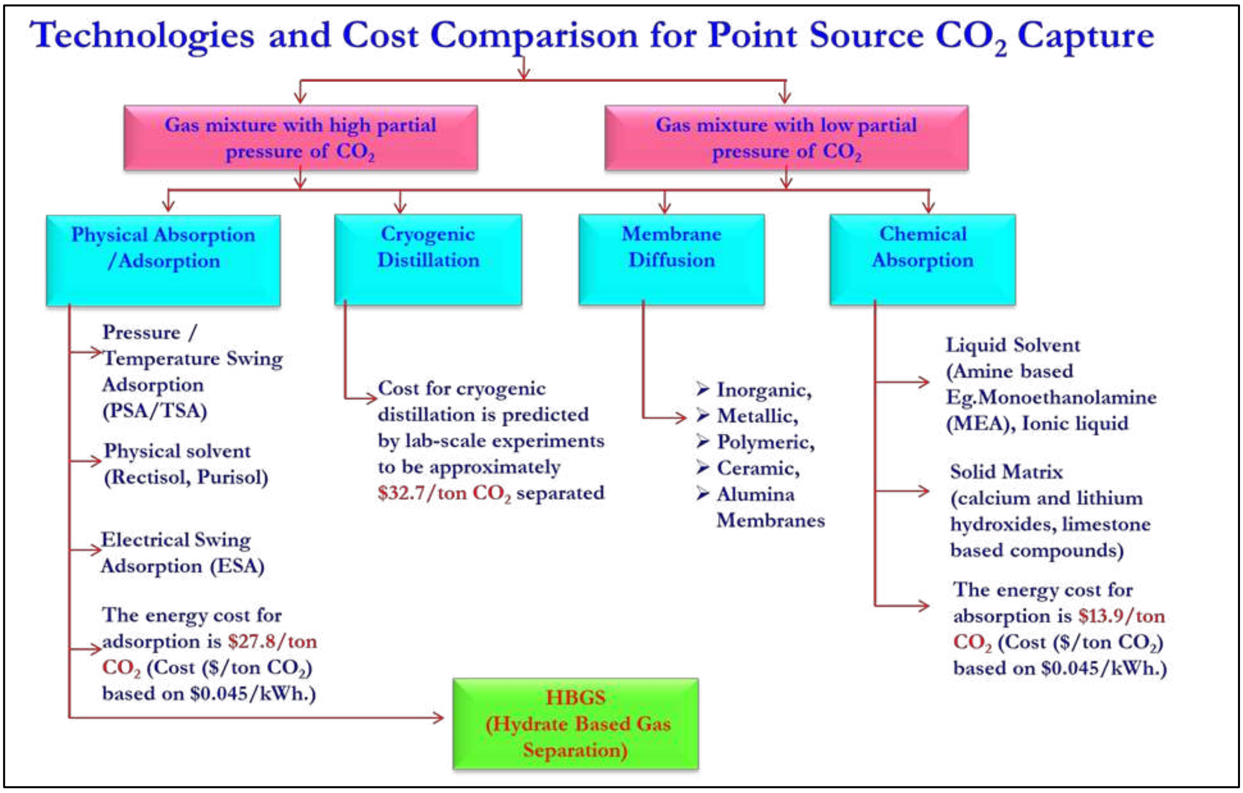

Figure 2.3. Schematic of technologies and cost comparison for point source CO_2 capture.

Figure 2.3 sketches the comprehensive picture of different CO_2 capture processes that are strongly dependent on the concentration and partial pressure of CO_2 in flue gases. It demarcates the separation approaches based on the concentration. Physical processes are suitable for flue gases rich in CO_2 compared to chemical approaches which work better for flue gases lean in CO_2. Broadly, the CO_2 capture approach can be segregated into three major categories:

- **Conventional amine-based approaches:** Research and development of novel amine molecule is highly desirable in order to achieve higher market readiness. These efforts should be aimed at improving absorption capacity, higher regenerability, lower energy consumption for regeneration, and facile phase change amine solvents, among others.

- **New and upcoming point source capture:** There are emerging trends in various novel technologies and materials that require a dedicated and targeted approach to accelerate better capture technologies. To name a few, focused attention is required on advanced membrane technologies, amino acids, ionic liquids, gas hydrates, different alcohol derivatives, eutectic mixtures, zeolites, MOF, COF, ZIF, etc.

- **Direct Air Capture or Direct Sea Capture:** DAC and DSC have drawn a lot of attention for capturing CO_2 from ambient air and oceans at low concentrations. However, it suffers from the major challenge of high cost and high energy requirements. The integration of such processes with renewable energy, process optimization for reduced cost, overall CO_2 footprint evaluation, etc. are critical for technology acceleration.

Solvent-based (Chemical/ Physical)

TRL 8-9

a. Chemical solvent: Traditional amine solvents, developed by Fluor, Shell, Dow, Kerr-McGee, Aker Solutions, etc., are widely used in various industries such as fertilizer, soda ash, and natural gas processing plants (such as Sleipner, Snøhvit, and Tuticorin). A new class of sterically hindered amines was developed by organizations such as MHI, Toshiba, and CSIRO. The technology was demonstrated in a commercial plant, namely, Petra Nova carbon capture.

b. Physical solvent: Selexol and Rectisol are two physical solvents that have been commercially used by UOP, Linde, and Air Liquide. These approaches are widely used in natural gas processing and coal gasification plants.

c. The chilled ammonia process was developed by Alsthom & GE. A pilot test was conducted for the demonstration plant for feasibility studies.

TRL 1-4

a. Water-lean solvent technologies have been developed by various vendors such as Ion Clean Energy, CHN Energy, and RTI. Pilot test and commercial scale studies were done at CHN Energy's Jinjie pilot plant.

b. Phase change solvents have been developed by IFPEN/Axens. Using this platform, DMX™ demonstrations have been explored by Arcelor Mittal.

c. Amino acid-based solvent/precipitating solvents have been explored by Siemens, and GE at the lab level for conceptual studies.

d. Other interesting examples include encapsulated solvents and ionic liquids that are still at the lab scale.

Solid Absorbent /adsorbent

a. Pressure Swing Adsorption/Vacuum Swing Adsorption has been around for many years. These technologies have matured over the years and have been commercialized for multiple applications by Air Liquide, Air Products, UOP, etc.

b. Temperature Swing Adsorption (TSA) has been developed by Svante and has been demonstrated at TRL 7 and further to feed studies and large commercial tests.

c. Enzyme-catalyzed adsorption has been demonstrated by CO_2 solution at TRL-6 at pilot-level demonstrations.

d. Sorbent-Enhanced Water Gas Shift (SEWGS) is specifically suitable for gasification processes.

e. Electrochemically Mediated Adsorption using ZIF/MOF etc. is still at R&D level with market readiness from 1 to 3.

Membrane Gas Separation

a. Membrane for natural gas processing, which typically has high CO_2 concentrations, has been developed by UOP, and Air Liquids. It has been demonstrated at multiple sites at TRL-9. The most prominent example is at Petrobras Santos Basin Pre-Salt Oil Field CCS.

b. Polymeric Membranes (mostly polyamide) have been developed by MTR for front-end engineering designs for large pilot plant studies.

c. Electrochemical membrane has been integrated with Molten Carbonate Fuels Cell by FuelCell Energy. It was demonstrated at a large pilot scale at Plant Barry.

d. A hybrid approach of polymeric membranes combined with cryogenic separation has been demonstrated by Air Liquide, Linde Engineering, and MTR at pilot scale at TRL level 6.

e. Polymeric membranes and the solvent hybrid process was demonstrated by MTR in collaboration with the University of Texas at TRL-4 at room temperature.

f. Ionic Liquid Membranes at room temperature have also been tested at lab scale.

Calcium Looping

Calcium Looping (CaL) and Chemical Looping Combustion were demonstrated by Carbon Engineering and Alstom respectively at TRL level 5-7. These studies delved into feasibility assessment /cost studies for commercial scale.

Since most of the processes are integrated into thermal energy obtained by the combustion of coal or other fossil fuels, CO_2 capture from post-combustion is the most studied and explored option for CCS technologies. This is evident from the research activities, pilot/demonstration plants, and patent filings every year. The post-combustion technologies, particularly the reference technology i.e. monoethanolamine (MEA) based solvent for CO_2 capture, are assessed as an easier retrofit than other integrated technologies. It is possible because of the higher degree of maturity of this technology, which has been used in the oil and gas industry for decades. This process is simple and flexible enough to suit individual process requirements.

The use of amines (chemical absorption) is a well-known process and is proven at the large industrial scale for CO_2 capture. However, it has its limitations in terms of energy requirement and solvent degradation/regeneration. Further, extensive research is required to develop newer and novel solvents with improved physicochemical properties. For example, the mixture of Ionic Liquids (ILs) with traditional amines is gaining huge interest from the research community. Similarly, many other scientific interventions are possible in designing propriety chemicals that could be used for CO_2 capture from flue gases. The following are the targeted focus for designing the novel solvent:

a) Higher reactivity to ensure faster kinetics.

b) Better resistance from trace impurities in flue gases including particulate matter.

c) Low volatility of solvent.

d) Higher recyclability at temperatures close to 100°C.

e) Solvent with a lower CO_2 footprint. For example, MEA manufacturing has a significantly large CO_2 footprint when produced from using fossil fuels as an energy source.

Concerted research is required with special emphasis on patenting activity in developing adsorbent materials such as amine-modified adsorbents/polymers, activated carbon, microporous organic polymers, metal-organic frameworks, zeolites, alkali metal carbonates, layered double hydroxides, and calcium-based adsorbents. Optimization is required to improve the efficiency of adsorption processes such as temperature swing adsorption (TSA), pressure swing adsorption (PSA), vacuum and temperature swing adsorption (VTSA), and vacuum and pressure swing adsorption (VPSA). Solid adsorbents have the added advantage of cleaner operations compared to liquid amine-based solvents. However, efficient utilization of solid adsorbents requires a better reactor design to circumvent the heat and mass transfer limitations in a packed bed arrangement. Technology advancement in this domain may come with the following attributes:

a) Extremely large surface area of solid adsorbent with optimized pore diameter which results in better mass transfer without compromising on heat transfer characteristics.

b) Higher loading capacity of active ingredient or functionalization.

c) Magnetically or electrically controlled capture and regeneration cycles.

d) Proper integration of vacuum and temperature cycles for optimized operation.

Direct capture for CO_2 from air or sea/ocean becomes a necessity because the CO_2 concentrations in the atmosphere are expected to reach 450 ppm shortly. This level of CO_2 cannot be brought down by capturing CO_2 from the point source as discussed earlier. DAC could be installed ubiquitously in non-usable spaces such as rooftops, public parks, indoor stadiums, and others. As the technology matures and integration with renewable sources is introduced, this might be the future of CO_2 capture in the next 10-15 years. However, the cost of this technology and the availability of green power remains a challenge as of now.

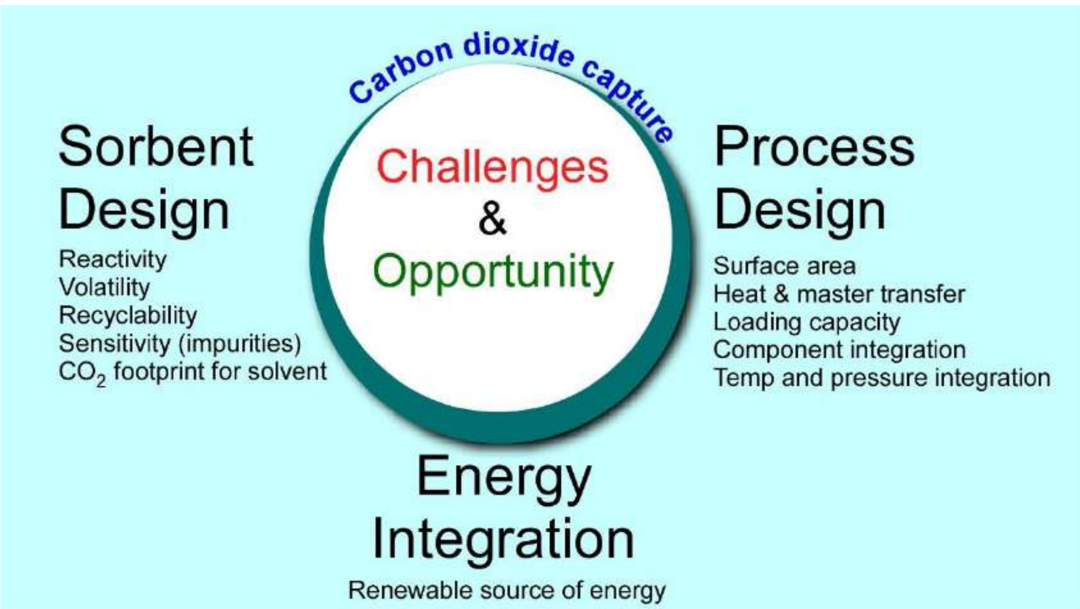

Figure 2.4. Schematic describing the challenges and opportunities for CO_2 capture system.

2.1 Fundamental Challenges Associated with CO_2 capture

2.1.1 Thermodynamic Challenges

Depending on the CO_2 concentration in the source, there can be different approaches for CO_2 capture. Each approach poses different thermodynamic challenges that have to be navigated differently. There exist three major scenarios as described below:

I) Capturing CO_2 from ambient air at a low concentration of 420 PPM from associated gases such as N_2 and O_2 is relatively easy from the perspective of less exposure to corrosive gases such as SO_x and NO_x. Additionally, separating medium do not get exposed to too much particle matter, thereby, maintaining high capture capacity for a longer duration. However, there are many disadvantages that need careful evaluation. Primarily, the cost of separation of CO_2 at such low concentration is high owing to thermodynamic challenge. Thermodynamic challenge alludes to the fact that the theoretical minimum energy needed for separation of 420 PPM CO_2 from air is given by the Gibbs free energy of separation.

$$\triangle G = RT \sum_{i=0}^{n} (X_i \ln X_i)$$

where R is the ideal gas constant, T is the temperature, and X_i is the mole fraction of each component. Because the mole fraction of CO_2 in the atmosphere is so small, the thermodynamic minimum work required for separation is much higher than for flue gas. Further, any practical systems will always exceed this minimum due to irreversibilities which is further compounded due to high energy cost for regeneration of the material which is used for such separations. The thermodynamic challenge dictates that the material for CO_2 capture has to be synthesized in large quantities and regenerated. The carbon footprint for the synthesis of materials should be evaluated carefully if they degenerate or loose partial functionality after each cycle of capture and regeneration.

ii) CO_2 can be captured more efficiently from the point sources (when compared to direct air capture) such as flue gas stacks of power plants, cement, and steel. The minimum work required to separate a component from a mixture is a function of its concentration (as discussed above). These point source streams are relatively rich in CO_2 (10-15% for flue gas from coal fired power station), a higher concentration requires less energy for separation. However, these point source flue gases contain significantly high concentrations of deleterious gases such as SO_x, NO_x, O_2, and particulate matter as well. These impurities are highly detrimental during the regeneration cycle as they react with solvent to form products that cannot be regenerated. The advantage however comes from relatively richer CO_2 concentration compared to DAC. This allows one to choose a material that does not interact very strongly with CO_2, which in turn results in lesser regeneration costs. There are other advantages of this process like efficient process integration, reduction in utilities cost, better integration with renewable energy, easy accessibility to utilization sites, and scale-up operational benefits. These advantages result in relatively lesser cost of operation and lower carbon footprint of the process. The typical cost for CO_2 capture from point source is 30-50

USD per ton which is an order of magnitude lower compared to DAC. However, innovation is required to further reduce the capture cost and seamlessly integrate the processes with renewable energy with a lower carbon footprint.

iii) There are many applications where the emitted gaseous mixture has a CO_2 concentration of more than 30%. For example, sour natural gas is highly rich in CO_2 concentration that has been handled by oil and gas industries for many decades. Amine-based processes can be used for CO_2 capture for such gases, however it is not necessary to use a chemical absorbent when the CO_2 concentration is higher in the gas mixture, in many such cases where CO_2 concentration is higher like in natural gas stream, in bio-gas stream in coal gasification stream the total pressure is also high, in such cases CO_2 separation could be achieved by physical adsorbent and thus results in lower regeneration losses as well as energy cost. For example, at high concentrations of CO_2, alcoholic molecules and zeolites can also be used that are mediated through physical interactions rather than strong chemical bonds. These sorbents have the inherent advantage of lesser operating cost and better recyclability of the material during CO_2 capture.

All of the above are examples of End of Pipe (EOP) technologies as mentioned earlier in the Executive Summary.

2.1.2 Kinetic Challenges

The biggest challenge in developing a commercial-scale plant is the rate at which CO_2 is captured in the sorbents. Typically, one interacting site will hold one CO_2 molecule through molecular interactions. For example, in the DAC process, sorbent material gets to interact with one CO_2 molecule for every 2500 non-CO_2 molecules. This mandates the creation of novel material with a very high surface area. This makes the CO_2 footprint high for synthesizing such material. Alternatively, we can recycle the air through the material multiple times to increase the probability of interaction with sorbent but that leads to increased energy consumption because of handling of high gaseous volume. The advantage, however, is that one need not match the rate of generation with the rate of capture. One approach, which may work in the long run, is capturing during the non-sunshine hours (capture at relatively cooler ambient temperature) and regeneration during the sun-shine hours (solar thermal or PV-based process to achieve higher regeneration temperature). In the case of point capture, 100% of the CO_2 from a coal-powered power plant has to be captured. The rate of capturing CO_2 should be equal to the rate of regeneration for retrofitting in existing plants. The storage of flue gas will be challenging as a huge quantity of CO_2 is released every minute of operation. Complete CO_2 capture (~100%) without releasing any flue gas is going to be difficult to implement. This requires identifying a process with very high kinetics. One way to increase the capturing kinetics is to use a material that has a strong affinity to CO_2. However, the strong affinity also has a detrimental effect of high regeneration cost. Thermal degradation of sorbents is always a challenge. The limitations associated with mass and heat transfer are always part of any multiphase process design for ensuring uniform temperature distribution.

2.1.3 Catalyst design challenges for better regeneration efficiency (energy as well as recyclability)

The catalyst should allow the regenerability of the material at a lower temperature (compared to no catalyst regeneration). One innovative design, which seems feasible, is a catalyst embedded in the packing material which remains inactive during the CO_2 capture step (due to the low-temperature absorption step) and gets activated during the material regeneration step (relatively high-temperature stripping step). The other option could be to use the catalytically active packing in the stripping section if the product after CO_2 capture still flows.

2.1.4 In principle, a few suitable interventions for a green field project, which has good potential for success in India, are as follows:

- Utilization of coal in green field projects through gasification which is also called pre-combustion capture. This route ensures significantly higher efficiency in energy generation and significantly lower cost of CO_2 capture (through IGCC).

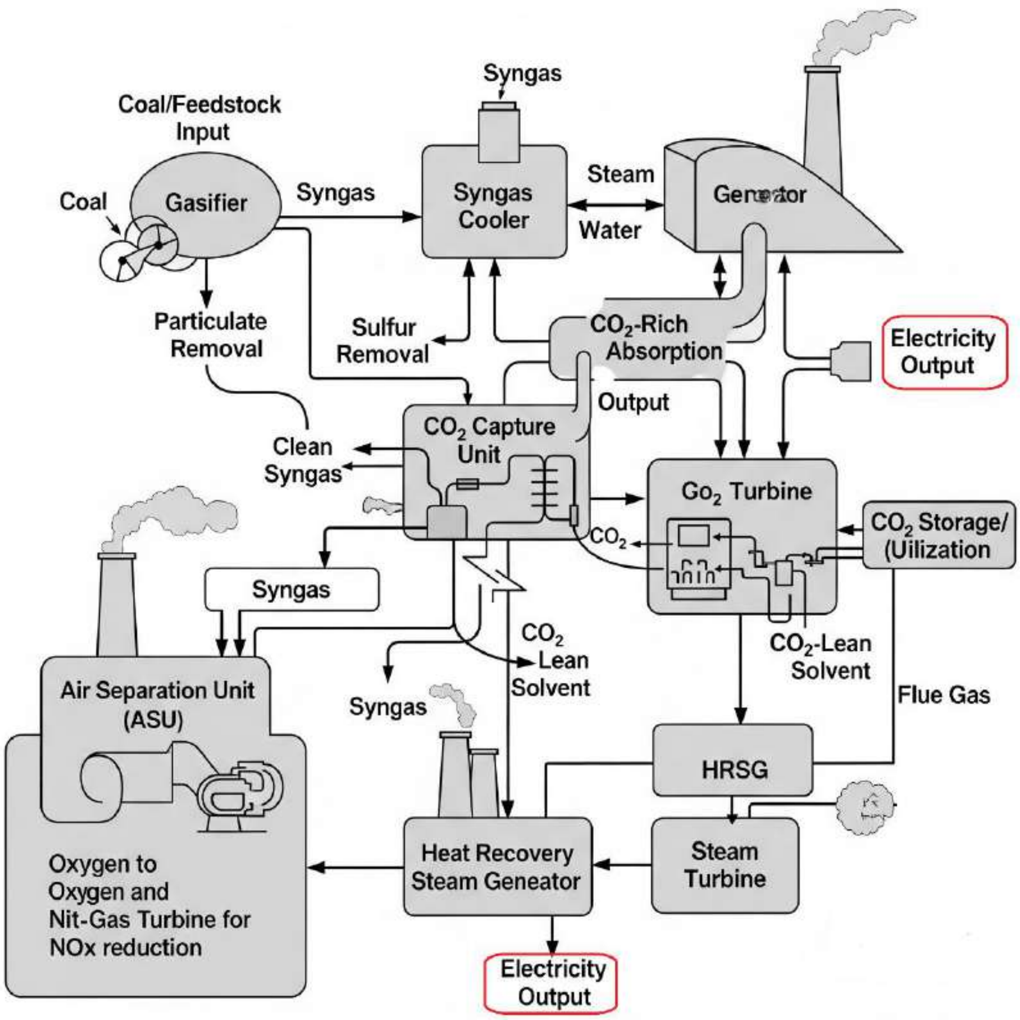

Figure 2.5. A Typical IGCC Plant Generated by Using Web-based AI Software Tool, notice multiple electricity generation points which makes the process very efficient.

This route also allows integration with bio-energy in a better way (Further using). Using the carbon that is above the earth (i.e. capturing the CO_2 from the air) is much more expensive than utilizing the carbon from under the earth and sequestering the CO_2 back into the earth. This route is more suitable for electricity generation than the combustion route which is currently followed in India.

- For industries like cement and steel, one may look for oxy-fuel combustion, as separating O_2 from N_2 may turn out to be better compared to the separation of CO_2 from flue gas (NO_x is not a problem in oxyfuel combustion, CO is less of a problem). This route has been predicted to be suitable for the cement industry. However, these technologies though feasible has not been demonstrated at large scale. Further, this is more suitable for a greenfield project. Converting an existing plant to oxyfuel is not trivial and comes with significant cost, integration and feasibility constraints. The IGCC and oxy-combustion routes are examples of CCUS Compliant Designs (CCD) as described earlier in the Executive Summary.

- When it comes to post-combustion CO_2 capture, amines seem to be the simplest process, and identifying a new material that has lower regeneration cost is the need of the hour. As discussed, the use of phase change solvent is one such intervention. It may work, as a separation of non-converted (mostly liquid) amines from the converted (solid mass) is possible and the separated liquid could be recycled back to the absorption tower (thus reducing the heating requirements). The exhausted solid amines can be regenerated in the stripping section exclusively.

- However, there are other innovative and newer processes. One such process is the chlor-alkali route which has shown some potential. In this process, solar energy can be used for the electrolysis of salt water generating hydrogen, chlorine, and caustic soda. Except for electrolysis, all other reactions are energetically self-sufficient and may not require a lot of energy input. Caustic soda can be carbonated to sodium carbonate which is a facile reaction. Throughout the process cycle, there is no need for regeneration, and accounts for CO_2 capture and utilization. The CO_2 used here needs to be captured separately and may be part of (or greater than) the emissions associated with the electrolysis process. Tuticorin plant has been running this process successfully for several years, which gives a lot of confidence for others to implement this approach.

2.1.5 Advanced Research Requirement for Carbon Capture

Given the recent advancements in CO_2 capture technologies, a gap analysis is necessary to identify the research requirements for further progress.

- **For improving the absorption performances in terms of stability, energy, and capture efficiency –** Utilisation of ionic liquids, use of nanoparticles (e.g. SiO_2 or carbon nanotubes) microencapsulation, phenoxides, etc. Stability refers to the regeneration losses which typically happens due to higher temperature, oxidation etc. All the three parameters discussed above benefits from identifying materials which could regenerate at lower temperature, a typical number could be closer to 100°C. Literature suggests that per ton of CO_2 captured and regenerated may lead to 2 kg of amine loss, this number should be brought down to 0.2 kg amine loss/ton of CO_2 captured.

- **For improving CO_2 absorption capacity, low energy consumption, and reduced space requirements –** Developing advanced material for membranes using polymer, ceramic, composite metals, Metal-Organic Frameworks (MOFs), zeolites, mixed matrix, graphene oxide, polyimide, and doping of membranes with ionic liquids and nanoparticles. Current energy requirements ranges from 3.6 GJ – 4.0 GJ per ton of CO_2 captured and material regenerated using simple amines. If one uses a combination of these technologies, the reported numbers are 2.5 GJ/ton, however, these are not sufficient and it should certainly come down to 1-1.5 GJ range. Absorption capacity is less important, however, rate of absorption is very crucial which clearly connects to reduced space requirements for a full scale plant.

- **Low-cost renewable energy sources –** These sources of energy can be used for the manufacturing of commercially valuable compounds like formic acid, propanol, methanol, ethylene, methane via electro-chemical reduction during capture step. Many lab-scale studies and some pilot systems have demonstrated Faradaic efficiencies in the 80-90% range for single products like carbon monoxide (CO) or formic acid (HCOOH). One should target more than 95% at a rate which ensure scalability. The overall energy consumed per unit of product, is a crucial economic metric, it is directly related to the cell voltage and the Faradaic efficiency. One should target for the total cell voltage (the sum of the thermodynamic potential, overpotentials, and ohmic losses) of **< 3 V**, and ideally **< 2.5 V**, current state of the art is 3V to 4 V. This would integrate CO_2 capture and utilization i.e., the CCUS in One Pot (COP) as mentioned in Executive Summary.

- **Developing a non-thermal plasma and new types of plasma generation –** New mechanisms such as dielectric barrier, microwave, corona, radio frequency, glow, and nano-second pulse discharge options need to be explored. These could be used for the reduction of CO_2 to carbon nanoparticles. Production of solid carbon nanoparticles, graphene, carbon quantum dots, has applications in catalysis, energy storage, flexible electronics, polymer composites etc.

- **Optimization of algae culture conditions, design and optimize novel photobioreactor –** Optimization to increase the efficiency of photosynthesis for algae as a source for biofuels and other bio-products and crop cultivations is required. The high cost of cultivation, harvesting, and processing of algae is the primary barrier to commercialization. Per ton capture cost through algae route is roughly around 300 USD. Which when combined with low market value of bio-fuels may not make commercial sense.

- **Greener solutions –** Developing carbonic anhydrase enzymes as catalysts dispersed in the liquid phase would prove to be a greener alternative with a lesser CO_2 footprint. Key feature however is the incredible rate at which CO_2 capture happens having a turnover ratio of 10^6 molecules per second. One may just add certain amount of these enzymes in the conventional process and improve the kinetics at ambient conditions. However, its inherent thermal and chemical instability is a major hurdle. By finding robust enzymes in nature and/or through advanced bioengineering techniques, one may target an application where CO_2 capture needs to be done at temperature close to 80-90°C.

- **Direct Air Capture (DAC)** involves removing CO_2 directly from ambient air, with the captured carbon either permanently stored in deep geological formations or utilised in producing fuels, chemicals, building materials, and related products. Although DAC is not specifically targeted at capturing emissions from industrial stacks, it may be valuable in situations where retrofitting an existing facility is not feasible. At present, 15 DAC plants operate globally, collectively capturing over 9,000 tonnes of CO_2 per year. Ongoing R&D efforts aim to advance DAC technologies through the development of novel materials and structured adsorbents to further reduce capture costs.

- **Lowering regeneration cost –** Energetic cost for CO_2 regeneration from sorbents is between 2.4 to 4 GJ per tonne of captured CO_2. Some innovations have been reported on catalytic regeneration as well as using carbonated amine as the electrolyte to generate electricity during regeneration (capacitive cells). This energy cost should come down to 1.5 GJ per ton.

- **Catalytic regeneration** adds one additional layer of complexity. Apart from the solvent, the catalyst needs to be regenerated as well. The desired temperature target for capturing CO_2 is 60-80°C and 80-100°C for catalytic regeneration.

- All recyclability must be in tune with the CO_2 footprint of the process. This is why the mixture of amines and ionic liquids has drawn great interest.

- Another focus area could be amine-impregnated solid adsorbent which synergizes the best attributes of both classes of material. This approach has the potential to reduce the regeneration cost below 2.4 GJ/ton of captured CO_2.

- **Electro-swing adsorption** could be a low-voltage electric current process that goes well with the surge of photovoltaics system. Efforts should be made to illustrate a bench-scale proof of concept.

- **TSA and PSA** (or a combination of both PTSA) are the classic adsorption processes. Solid adsorbents such as activated carbon, mesoporous silicates, alumina, zeolites, and metal oxide are commonly used. ZIFs and MoFs present a unique opportunity. Many ZIFs have already been commercialized. A recommended target would be to demonstrate a100 Kg/hr demo pilot and perform technoeconomic analysis for the same.

- **Molecular sieves, membranes (inorganic/organic/combined with chemical absorbents).** A recommended target would be to demonstrate a 100 Kg/hr demo pilot and perform techno-economic analysis for the same.

2.1.6 Problem Statements for Scientific and Technological Advancement on CO_2 Capture Material

Because the regeneration cost is directly proportional to the strength of interaction between the material and the CO_2, there is a need to identify a material that reacts strongly with CO_2 (when the mixture is lean) and reacts weakly with CO_2 when the concentration is rich. Typically, this contradiction is a challenge and a practical approach is going for physical absorption/adsorption when the CO_2 concentration is high and using chemical absorption/adsorption when dealing with lean CO_2 mixtures. Some of the key issues and corresponding problem statements are listed below.

These could form the basis of focused R&D programs:

- The volume of CO_2 that needs handling is huge. These streams contain multiple impurities which results in deterioration in material quality. A recommended R&D focus should be on the recyclability of the material rather than increasing the capture capacity.

- In each carbon capture R&D program it is critical to identify the CO_2 footprint of the proposed capture process through a proper LCA or mass and energy. For brevity, less than 1 mole of CO_2 should be emitted for capturing 1 mole of CO_2 and subsequent regeneration of material. Thus, the entire capture and regeneration cycle should be CO_2-neutral. The medium to long-term target for the CO_2 footprint should be 0.5 moles of CO_2 emitted per mole of CO_2 captured and regenerated.

- For an R&D progam on pre-combustion CO_2 capture such as IGCC, a complete cost analysis of a green-field plant with CO_2 capture vs. a conventional plant with CO_2 capture should be included.

- In the case of R&D program on oxy-fuel combustion, it is necessary to present a comprehensive picture through careful mass and energy balance for estimating CO_2 footprint. It should include CO_2 emission for O_2 separation from the air, and then compare the same for CO_2 capture from N_2 (in comparison to post-combustion capture). Further, additional challenges such as controlling flame temperature, use of the right MOC, recycling of flue gas during combustion, etc need to be addressed.

- For R&D programs on DAC, thermodynamic calculations for estimating the energy requirement for capturing CO_2 from a 450-ppm gas mixture which primarily contains N_2 and O_2 are required. Various questions that require detailed evaluations are: What are the best models to supply this huge energy (comparison of various RE options as a distributed system should rely on solar/wind etc.)? and which locations are the prime target for such implementations? A suggestive innovative design could be the use of a solar concentrator for regeneration. The regeneration can be done during the daytime and the capture of CO_2 can be done during the nighttime as a new strategy. The LCA for identifying CO_2 footprint to know exactly when a DAC unit would start becoming CO_2 neutral. Additionally, the development of materials with large surface area for CO_2 capture for direct air capture is required. It should also show a very strong interaction with CO_2.

- When it comes to CO_2 capture from sea, (i.e., an R&D program on Direct Sea Capture), a calculation for cost and energy requirements for this process vs DAC is required. Further, concerns pertaining to environmental and ecological challenges associated with direct sea capture should be addressed.

- In the case of R&D programs on point source capture and regeneration of materials (recyclability of material), the focus has to be on identifying a material that has a high capture rate. Thus, one should aim at strong binding energy between CO_2 and the material. However, one would have to rely on a catalyst to bring down the regeneration temperature which would reduce the energy cost and water wastage.

- Water wastage is a huge problem which has not got much attention. The cooling towers are operated to cool the CO_2 gas that comes out of the stripper at 120-140°C. It results in significant water loss which makes the process challenging to operate at commercial facilities. An R&D program that proposes process intensification of the process to reduce water usage would be valuable.

- A suggested R&D approach for improving the energy efficiency of the regeneration is the use of phase change material. This allows the solid product from the capture cycle to be separated and regenerated separately. The non-converted base material is recycled without going through the regeneration step. It ensures better energy efficiency but also results in lower losses during the regeneration process.

2.2 Integrated Upscaling / Retrofitting

CCUS has gained global attention recently, but it is not a new technology. There are more than 45 commercial and demonstration plants in the USA and Europe with a total capture capacity of close to 50 Mt CO_2 annually (source: www.iea.org). Some of these facilities are large-scale demonstration plants having a capture capacity of at least 100000 tCO_2/year. Also, some of the facilities capture CO_2 directly from the air. The largest one is ORCA in Iceland with a capturing capacity of 4000 tCO_2/yr. Another start-up venture, Heirloom and Global thermostat's is capturing 1000 tCO_2/yr in the United States. While ORCA uses amine-loaded mesh for CO_2 capture from air, and Mosaic Materials has deployed metal-organic frameworks-based material for both DAC and point-source carbon capture. Despite the high cost of DAC compared to point source capture, it is a necessary technological tool for two reasons: (1) mitigation of unavoidable CO_2 emissions from anthropogenic sources or the transportation sector, (2) containment of legacy emissions released in the past.

In the case of point source (EOP) capture, the choice of chemical has been primarily amine-based solvent. Some of the large plants for bioethanol production have been listed as CO_2 capture units by IEA. Blue Flint ethanol project is one such endeavor. This plant produces bioethanol from corn by utilizing waste heat from a coal-fired plant. Linde Clear Lake capture facility is another large-scale unit that produces blue hydrogen through the gasification of coal and captures the CO_2 from the mixture containing CO and H_2 using an amine-based solvent. Captured CO_2 is later converted into methanol by Celanese. Linde with BASF also has a propriety chemical called OASE® blue solvent which they claim to be more energy efficient. Another remarkable project worth mentioning is the Petra Nova carbon emissions reduction system based on amine-based sorbent. The process was partly developed by Mitsubishi Heavy Industries which can capture CO_2 from the coal-fired power plant through absorber-stripper route using a mixture of amines. Captured CO_2 gas is compressed and sent 82 miles through a 12-inch diameter pipe for EOR application.

The Norwegian government has shown significant commitment through many installations in the country. "The Longship Project" is one such project that was conceptualized to showcase full-scale CCS solutions in Norway. It will be available for other European countries for usage and demonstration. Another unique setup is the Northern Lights. It is engaged in CO_2 capture, transport, and storage. This facility is open for third parties for demonstration as an open-source infrastructure network for CO_2 transport and storage. European countries can use this network to store their CO_2

safely and permanently underground. It boasts a storage capacity to the tune of 1.5 million tonnes of CO_2 per year. This project was initially conceptualized for decarbonizing the cement industry but today it finds varied usage.

Zero-Carbon Humber in the UK is another ambitious project that works in consortia mode. This project uses Shell's propriety mixture of amine solvent CANSOLV for CO_2 capture from flue gases. Captured CO_2 will be transported via a newly constructed 55 km onshore underground pipeline to be permanently stored in depleted gas fields of the southern North Sea. As an expansion of this facility, it is planned to produce 170,000 tonnes of “blue hydrogen” per year. Other CCS plants in the USA are stationed in Louisiana, Houston, etc.

Another CCS project worth mentioning is Scotland's advanced CO_2 transport & storage network which promises to permanently lock captured CO_2 emitted from industries in rock formations deep below the North Sea. This project is expected to start operating by 2025 and will use geological sites 100 km off the north-east coast of Aberdeenshire, and 2.5 km below the North Sea bed. A few other similar projects in the UK include Net Zero Teesside, which is also a green field cluster project that produces green electricity through a natural gas power plant with CCS. H21 North of England, UK is a blue hydrogen production facility that plans to replace natural gas with hydrogen to reduce carbon emissions. It is in the early stages of feasibility studies and trials. This also falls in the category of CCS. Dartagnan Dunkirk in the Netherlands is also another CCS facility under commissioning, to be operated from 2025. Axe Seine is a power generation and manufacturing organization in France's Normandy region that will operate a CCS pipeline from 2030. Antwerp@C is a consortium in Belgium that plans to provide transportation infrastructure to decarbonize the integrated energy and chemical sector through liquefaction, storage, transportation, and sequestration. In short, most of the European projects are CCS facilities that are trying to capture low-hanging fruits for achieving a net zero target by 2040-2050. Many other significant efforts are made that will have direct and indirect effects such as project Aramis and Porthos in the Netherlands for CO_2 transport and storage, H-Vision in Netherlands for usage of residual gas for heating and hydrogen production, Equinor's Hydrogen 2 Magnum (H2M) project to produced low carbon hydrogen with CCS, H2morrow feasibility study for supplying blue hydrogen to steel plant in Germany CCS plants in Germany, and Ravenna hydrogen in Italy, etc. In Saudi Arabia, Jubail has one such CCS plant under commissioning which is set to be operated from 2027. Various other countries are developing CCS with varying timelines such as the CCS hub in Jurong Island in Singapore (2030), the RIO DE JANEIRO CCS HUB in Brazil, and the SEA CCS hub in Australia.

China alone has around 40 CCUS demonstration projects in operation or under construction, with a total annual capture capacity of around 3 million tonnes per year. Some of the large plants, such as the Jiling Petrochemical CCUS facility, capture CO_2 from natural gas production (22% CO_2 in the natural gas mix from Changling Gas Field) and transport the same to nearby oil fields for enhanced oil recovery along with storage in exhausted fields. China National Offshore Oil Corporation (CNOOC) Enping oil field is another such project that demonstrates the CCS route, CO_2 produced from the oil and gas field is first captured and later injected into the saline water layer at a depth of around 800 meters under the seabed. CNOOC Limited claims that they have a complete set of technology and equipment systems for the capturing, processing, injection, sequestration, and monitoring of carbon dioxide at offshore oil and gas fields. The project currently stores over 1.5 million tons of carbon dioxide under the sea. China Energy Taizhou power plant promises to capture 500,000 tonnes of CO_2 every year. This is an amine-based capture unit with a 90 KWh requirement per ton of CO_2 captured. This plant currently stores the captured CO_2 in liquid form and they are testing long-term stability etc. There are multiple CCS plans underway, the one in Northwest China is getting operational in 2025. In East China and South China, two additional projects are in the development and feasibility studies phase.

In India, one of the largest demonstration units based on amines is in Vindhyachal Super Thermal Power Station, MP. This is a 20-ton-per-day CO_2 capture unit which is based on propriety amines from Carbon Clean Inc. They propose to convert the captured CO_2 into value-added chemicals like methanol/ethanol, however, the conversion unit has not been commissioned yet. Tata Steel in Jamshedpur also runs an amine-based unit for CO_2 capture which could be considered a first-generation capture plant. Another effort made by Coal India is the coal-to-methanol plant at the Dankuni plant which is planned for commissioning in 2025-26. Another unit that has been running for the last several years is in Tuticorin which utilizes the captured CO_2 in the chlor-alkali process. This plant essentially is not a proper CO_2 capture plant as the feed to the amine unit is largely free of SO_x, NO_x, etc. due to the process from where it comes.

Perhaps the first effort in India on decarbonisation was done in 2010 by an alliance of two government-owned businesses, BHEL and NTPC. Together, they were instrumental in testing an oxy-fuel system. These projects were done under clean coal technology initiatives in which DST, CSIR, and other PSUs conducted multiple tests. CFRI and IICT tested multiple coal combustion routes, including FGD, circulating fluidized bed for coal combustion, IGCC, coal liquefaction, etc. in consortium mode. Similarly, two high-ash Indian coal gasification pilot plants set up by CSIR-CIMFR and Thermax-IIT Delhi have demonstrated the technological viability of pre-combustion CCUS. Dalmia Cement along with Carbon Clean Inc. is planning to implement an amine-based capture in their cement manufacturing plant in Tamil Nadu, 500000 tons per year capacity. A small pilot project was taken up in Hazira and Surat for algae-based carbon capture. Similarly, seagrass and algae have been cultivated to study the potential of carbon capture through natural means in many places in Tamil Nadu, Kerala, and Odisha. Reliance Industries Ltd has demonstrated India's largest algal based CCUS process at pilot scale in Jamnagar.

2.2.1 Disruptive inventions at TRL 2/3 that may be worth scaling to TRL 4/6

Disruptive technologies in this domain are probably those that claim to capture and convert CO_2 to useful products in a single step (COP), along with regeneration of the chemicals that didn't participate in the product. One such process is the chlor-alkali process for CO_2 capture and utilization. In this process, highly concentrated brine is converted to sodium hydroxide and hydrochloric acid. The first step gives HCl (or H_2 gas and Cl_2) and sodium hydroxide. In step 2, sodium hydroxide is reacted with calcium carbonate to produce calcium hydroxide and soda ash (which is also a valuable product). In step 3, the calcium hydroxide is used to capture CO_2, which produces back the limestone that is used in step 2. The beauty of this process is that the CO_2 is directly mineralized thus it is captured cum sequestration/utilization.

This route of caustic production is an energy-intensive route and uses both electricity and heat energy through the conventional chlor-alkali route. Energy usage is one of the most important factors and makes up a significant portion of the variable cost. A recently published disruptive innovation comprises direct electrosynthesis (DE) or through an alternative route which is termed bipolar membrane electrodialysis (BMED). In the above two routes, both electricity requirement and heat energy requirement are lesser than that of the conventional chlor-alkali process which currently produces 99.5% of all the caustic soda production worldwide. A mature DE route or the BMED route could potentially run 100% via electricity produced from PV solar panels which essentially will cut down the carbon footprint of the CO_2 capture process. This process will also produce hydrogen and chlorine both of which are important chemical feedstock. In addition, the soda ash produced from the process is essentially a value-added product of captured CO_2. Another innovation in this process could come from adapting the soda ash in geopolymer synthesis. This innovative work promises to use a mix of 32 wt% soda ash along with fly ash and copper slag to produce geopolymer which has significantly large compressive strength and may potentially replace natural materials which are becoming scarce.

2.2.2 Challenges for hard-to-abate sectors like Cement, Steel as well as Thermal Power or Chemicals

CO_2 capture based on amine is known to be a mature technology and sector agnostic to a large extent. In comparison, adsorption material like MOF has been identified to have scale-up challenges, and the focus should be on pilot scale demonstrations. There are certain reported ZIF in literature with huge promise and are explored in decarbonizing the cement industry in Canada. Tata Steel and GAIL India Limited in collaboration with academia have tested multiple MOFs for similar applications. Better coordination with different agencies (such as NTPC and Tata Steel) would ensure better learning and speedy implementation of suitable solutions to overcome teething challenges. Continuous operations of such large-scale units would also ensure better identification of challenges and their potential solutions.

For CO_2 utilization, the best-case scenario is CO_2 to polymer or diamonds, etc. which brings either volume or value. However, one should be aware that converting 1 Kg of captured CO_2 into a useful chemical should happen by releasing less than 1 Kg of CO_2 back into the atmosphere. This could be a challenge currently. This mismatch in CO_2 utilization Vs CO_2 production (through a chemical process) means real net zero may only be achieved by CO_2 sequestration. This is primarily one of the reasons why Europe has been investing heavily in the CCS approach.

2.2.3 Problem Statements for Scientific and Technological Advancement on CO_2 Capture Material

Deploying CCUS at scale requires the smooth alignment of many different stakeholders. Main stakeholders include; (i) CO_2 emitters: fossil fuel-powered electricity generation, cement, and steel production units (ii) CO_2 consumers: chemical processes like ethanol, urea, polymers, etc. It further requires integration with technology providers with strong expertise in the separation and capturing of CO_2. Next, they would also have to integrate with logistic providers to ensure the transportation, processing, and compression of captured CO_2 through trucks or pipelines.

In case there is an excess supply of captured CO_2 beyond the utilization capacity, the technology and expertise for injection, storage, and long-term monitoring of the underground CO_2 will be required. A policy and mechanism to bear the cost of CO_2 monitoring between key stakeholders will have to be worked out. Integration of all these different stakeholders is easier to implement at the pilot plant scale, however, at the commercial scale the capital expenditure and cross-project risks across the entire value chain would be too great for any one entity to take onto its balance sheet. This is where active support of government will be necessary. Particularly, jurisdictions and regulations covering the geological storage of CO_2 have to be identified and developed. As discussed in this chapter, many countries have established the infrastructure for CO_2 sequestration with government funds and support. Similarly, in case of CO_2 utilization also, government support in creating clusters is essential. These clusters should be planned at a location where large CO_2 producers and consumers are located nearby and trucking the captured CO_2 is a possibility. A few specific enablers for setting up integrated CCUS clusters are as follows:

1. Pipeline infrastructure development for transporting CO_2 is necessary for those large producers where no consumers exist nearby. Thus, one such mapping exercise will have to be conducted.

2. In addition to the specific CCUS implementation challenges, which are unique to the commercial scale, there is skepticism about CCS amongst the public. Leakage of CO_2 from transport pipelines, explosion, seismicity resulting from CO_2 injection, and eventual loss of stored CO_2 to atmosphere requires proper addresal mechanism and awareness programs.

3. Among CCUS enablers, the first intervention should be the availability of high-concentration CO_2 gas streams. The techno-economic viability of creating a CO_2 bank may allow the CO_2 consumers to get supply at fixed cost.

4. Providing seamless access to high-quality CO_2 geological storage sites connected through a network of CO_2 pipelines would be a critical enabler for creating CCS clusters. The availability of such an ecosystem reduces the cost and associated complexity which promotes effective utilization and sequestration of CO_2.

5. Most of the CCS facilities that are operational today, partially monetize their investment in infrastructure through the existing EOR ecosystem. Such ecosystems create a long-term secure revenue stream. Policy intervention required to ensure such ecosystems in India is critical. In addition, clarity about tax benefits/credits would provide the necessary impetus by ensuring alternative revenue sources. A suitable and timely regulation would play a key role in incentivizing investment in CCS. In the US and EU countries, this has become an important enabler for the multiple CCS ecosystems. For example, a carbon tax introduced in Norway in 1991 was instrumental in incentivizing the development of the Sleipner projects. Regulations have also played an important role in India for reducing emissions. For example, Bharat Stage certification for vehicular emission control has shown success. Currently, India is running through the BS6 stage which progressed from BS-I in phase phase-wise manner. Similarly, introduction of suitable regulations for CCS would catalyse the ecosystem in India. An independent agency is required which would identify projects eligible for such tax benefits/credits.

6. Finally, the development of a central database for CO_2 storage with seamless access to the stakeholders will be a critical enabler. The database can provide information about emission quality and quantity, pore space, relevant storage conditions, and total capacity for the geological storage potential of CO_2. One agency would be required for streamlining the legal and regulatory framework that could identify the potential liabilities and responsibilities of stored CO_2. This agency could also enable PLI-based funding for CO_2 sequestration. The grants for capital and operational expenditure seem to have worked for entities in various countries. In some cases, a low-cost loan has been shown to deliver desired results in hard-to-abate sectors.

2.2.4 Cost Reduction for CO_2 Capture

One of the most important variables that affect the cost of CO_2 capture is the partial pressure of CO_2 in the source gas mixture and the gas stream pressure.

- In power plants, either the power production is happening through a Natural Gas Combined Cycle or a coal-fired or biomass/waste-fired unit. The CO_2 partial pressure is in the range of 3 to 15 kPa. This means one has to use a chemical solvent for better kinetics of separation.

- Industrial heat and petroleum complex also produce CO_2 with a partial pressure in the range of 3-15 kPa. In the petroleum complex, however, a significant portion of CO_2 is also available from steam reforming which is primarily used for hydrogen production. The CO_2 partial pressure in such streams is in the range of 300-700 kPa and the gas stream pressure is 2000-3000 kPa. Ethylene plants in such complexes produces CO_2 at a partial pressure of 100 kPa and above.

- Paper and pulp industry and cement industry have CO_2 partial pressure in the range of 30 kPa. Depending upon the process of aluminum and steel making, the CO_2 partial pressure range is from 1 kPa to 30 kPa with the gas stream pressure at atmospheric pressure.

- Fertilisers, bio-ethanol, and natural gas processing have significantly higher CO_2 partial pressure of 100 – 5000 kPa. The gas stream pressure is also significantly high and goes up to 8000 kPa (in the case of natural gas processing).

- **Effect of lower partial pressure of CO_2 in the flue gas:**

1. Lower partial pressure requires larger equipment for better capture efficiency.

2. Larger equipment size and lower CO_2 concentration results in higher heating and cooling load. Energy will be consumed in heating and cooling the gases and components that are not supposed to be captured. This increases capture plant energy requirements.

3. Lower partial pressure would also mean that applicable capture technologies are different and thus the material used, processes used, etc. would change and result in a higher CO_2 footprint.

4. In contrast, higher CO_2 partial pressure results in greater and faster ab/adsorption in the solvent compared to when the partial pressure is low. This results in a smaller setup, lower energy penalty, and simpler processes, all leading to cost savings. One such solution could be easily seen

in natural gas production which routinely uses CO_2 capture processes by employing physical solvents resulting in lower regeneration cost and thus lower CO_2 capture cost overall.

5. Economy of scale would most likely reduce the cost for most of the commercially available CCS technology. However, control over CO_2 partial pressure or the scale of the stream, from which capture will occur, is typically non-negotiable. One may choose to collect many of the CO_2 sources available nearby and achieve a larger CO_2 stream or higher partial pressure of CO_2 to reduce the cost of capture.

- **Additional ways to reduce the cost of CO_2 capture for specific source gas streams include:**

1. Utilizing low-cost renewable energy and integrating the same into the CO_2 capture process.

2. Innovative financing support and implementing CO_2 credits to measure the actual cost of CO_2 capture.

3. Pooling together the learnings of different technologies scale-up and commercialization of CO_2 capture processes. This would help save close to 20% of Capex and an equal amount of Opex.

4. Technological innovation as discussed in an earlier section.

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CHAPTER 3

CARBON DIOXIDE UTILIZATION

CARBON DIOXIDE UTILIZATION

Introduction

The urgency to address climate change has reached a critical point, and India, as a rapidly growing economy having a strong science and technology base in chemical and materials sciences, as well as a burgeoning innovation ecosystem, is in a prime position to lead the way in carbon management through CO_2 utilization and sustainable energy. CO_2 utilization technologies offer an opportunity not only to mitigate emissions but also to transform CO_2 from a harmful waste product into valuable resources such as fuels, chemicals, and materials. These technologies can help India meet its climate commitments while simultaneously fostering economic growth and creating new industries.

This chapter outlines a strategic approach to advancing CO_2 utilization in India, focusing on both fundamental research and the commercialization of these innovations, supported by strong engineering innovations or adaptations and inputs. The primary goal is to accelerate the development of efficient, scalable processes for converting CO_2 into valuable products, ultimately contributing to a circular carbon economy. This chapter touches upon the following key issues that are central to CO_2 utilization.

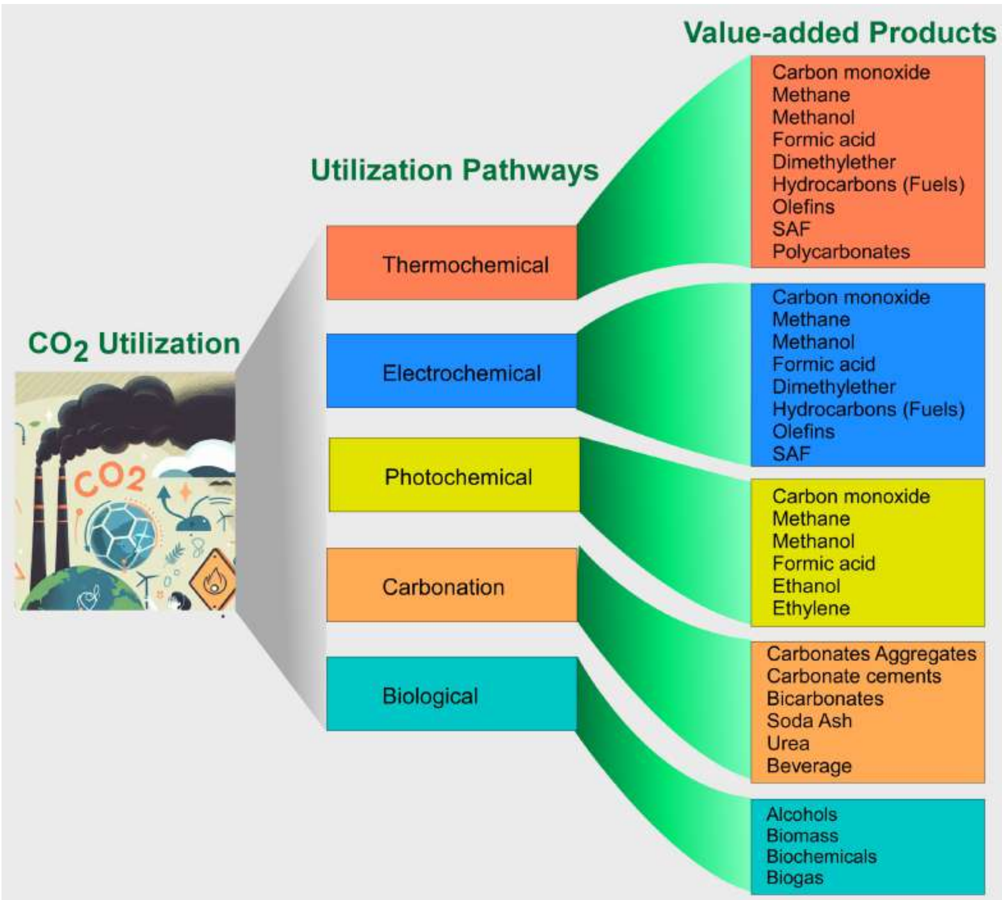

Figure 3.1: Typical CO_2 Utilization Pathways to high value-added products.

We acknowledge the inputs received from Prof. Vivek Polshettiwar, TIFR, Mumbai in preparation of Chapter 3.

Fundamental Research as a Pillar of Progress: At the heart of this roadmap is a strong emphasis on breakthrough scientific research. Overcoming the intrinsic challenges of CO_2 conversion, including high energy demands and slow reaction kinetics, requires a deep understanding of materials science and catalytic processes. Researchers in India are exploring new paradigms in catalyst design to enhance the efficiency of CO_2 reduction reactions. Coupling these advances with renewable energy sources offers a sustainable path forward for CO_2 conversion technologies. India's scientific community has the potential to lead the world in developing innovative catalysts that work under ambient conditions, are highly selective, and have long-term stability. Achieving this will require open-minded, curiosity-driven research that goes beyond incremental improvements and embraces novel approaches to material discovery and process integration.

Target, Results, and Potential Outcome Integrated Multipronged Approach: Broadly, CO_2 can be utilized through any of these pathways: thermochemical, electrochemical, photochemical, carbonation, and biological. The fundamental understanding of these processes and their scale-up has been achieved to varying degree of success. Each route has its own inherent advantages and challenges in terms of activity, selectivity, stability, economic viability, geography, and ease of implementation. However, each pathway exhibits different potential for containing CO_2 emissions. To this end, there is still a need for a multipronged approach at the fundamental level. However, careful considerations should be taken in decision-making based on desired targets, quality of outcomes, and future potential. Nascent and newer ideas with high potential should be encouraged. Only a multifaceted approach can help us guide to a path leading to the holy grail.

The Need for Translational Research: While fundamental research is essential, the roadmap also highlights the importance of creating pathways to translate these discoveries into real-world applications. This involves scaling up lab-based innovations to pilot plants and, eventually, to commercial technologies that can be deployed at an industrial scale. It should be noted that the translational research upscaling is required for both novel material synthesis (such as large-scale catalyst manufacturing) and process engineering (including reactor development and pre-processing and post-processing of reactants and products). At the same time, End-of-Pipe (EOP) or Conversion-in-One-Pot (COP) approaches need to be engineered during the integration of pilot-scale and demo-scale CO_2 conversion processes with existing CO_2 emitting plants. To facilitate this, long-term funding mechanisms, milestone-based investment models, and public-private partnerships are crucial. These frameworks will provide the financial support needed to advance CO_2 utilization technologies from the research phase to industrial implementation. Developing shared infrastructure, such as pilot plants and testing facilities, will be key to reducing scaling costs. By providing access to advanced equipment and collaborative spaces, India can support the rapid testing and commercialization of CO_2 conversion innovations, enabling startups and research institutions to bring new technologies to market more efficiently.

Interdisciplinary Collaboration and Innovation: The roadmap highlights the crucial role of interdisciplinary collaboration in advancing CO_2 utilization. Chemists, engineers, material scientists, and environmental experts must work together to develop integrated systems that can address the technical and economic challenges of CO_2 conversion.

The integration of artificial intelligence in catalyst discovery and the use of advanced photoreactor designs will further accelerate the development of efficient and scalable solutions. Moreover, Intellectual Property (IP) development and commercialization can be incentivized to ensure that India's innovations in CO_2 utilization can compete on a global stage. By fostering an entrepreneurial culture and providing support for IP protection, India can encourage its researchers and entrepreneurs to bring their ideas from the lab to the marketplace.

A Sustainable Path Forward: This roadmap aligns with India's broader goals of sustainable development and carbon reduction. By transforming CO_2 into valuable resources, India can reduce its carbon footprint while simultaneously creating new economic opportunities in clean technology and sustainable industry. The integration of techno-economic assessments (TEA) and life-cycle analysis (LCA) will ensure that the technologies developed are not only cost-effective but also environmentally sound, contributing to a net reduction in carbon emissions.

Thus, India's CO_2 Utilization Roadmap offers a strategic vision for how the country can leverage its strengths in scientific research and industrial innovation to become a global leader in carbon utilization. By combining breakthrough research, strong translational mechanisms, and interdisciplinary collaboration, this roadmap sets India on a path toward a sustainable, low-carbon future.

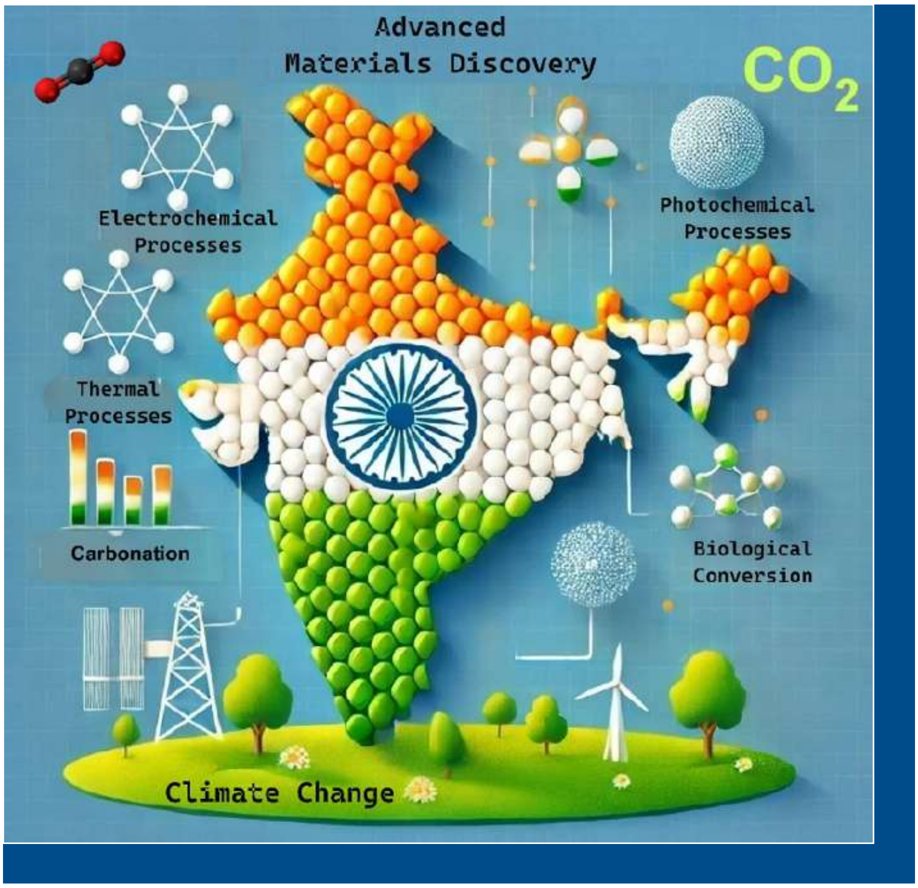

Figure 3.2: Potential landscape for CO_2 Utilization for India.

3.1 Fundamental Challenges

Before CO_2 conversion technologies can achieve industrial scale, several fundamental scientific barriers must be addressed. CO_2 is a remarkably stable molecule, and activating it efficiently under mild, sustainable conditions remains a major challenge. This section outlines the key thermodynamic, kinetic, and catalytic hurdles that currently limit progress.

3.1.1 Thermodynamic Challenges

- **Intrinsic Stability of CO_2:** CO_2 is characterized by a high degree of thermodynamic stability due to its linear molecular structure, sp-hybridized carbon, and strong double bonds. The Gibbs free energy of formation of CO_2 is significantly negative ($\Delta G° = -394.36$ kJ/mol), indicating that its conversion into other value-added products is inherently an endergonic process. Overcoming this requires considerable energy input to shift the equilibrium towards the formation of desired products such as syngas, hydrocarbons, or alcohols.

- **High Activation Energy Requirements:** The activation energy barriers associated with CO_2 reduction reactions are substantial. For instance, the hydrogenation of CO_2 to CO, or methane or methanol involves breaking the strong C=O bonds. This process demands elevated temperatures and pressures to achieve practical reaction rates. Such extreme reaction conditions pose significant challenges in terms of reactor design, material selection, operational safety as well as energy demands.

3.1.2 Kinetic Challenges

- **Low Reactivity of CO_2:** CO_2 is an inert molecule with limited reactivity under standard conditions. Its linear configuration and the strength of the C=O bonds contribute to sluggish reaction kinetics. Catalysts are essential to facilitate CO_2 activation by providing alternative reaction pathways with lower activation energies. However, designing catalysts that can operate effectively under mild conditions while maintaining high turnover frequencies remains a complex task and open challenge.

- **Catalyst Deactivation:** A major challenge in CO_2 conversion processes is the deactivation of catalysts. Precious metal catalysts (e.g., Pt, Rh, Ru) exhibit high activity but are prohibitively expensive and prone to deactivation due to sintering and poisoning. Non-precious metal catalysts (e.g., Ni, Co) offer a cost-effective alternative but often suffer from rapid deactivation caused by carbon deposition (coking) and oxidation. Enhancing the durability and resistance of these catalysts through alloying, doping, and support modifications is critical.

- **Mass and Heat Transfer Limitations:** Effective CO_2 conversion necessitates efficient mass and heat transfer to ensure uniform temperature distribution and reactant availability at the catalyst surface. Poor heat transfer can lead to hot spots, causing thermal degradation of the catalyst, while inadequate mass transfer can result in lower reaction rates and incomplete conversion. Optimizing reactor design and employing advanced materials with high thermal conductivity and controlled porosity can mitigate these issues.

3.1.3 Catalyst Design Challenges

- **Active Site Optimization for High Activity and Selectivity:** Efficient CO_2 conversion demands catalysts with precisely engineered active sites that can strongly adsorb and effectively activate CO_2. The nature, distribution, and electronic structure of these sites determine both the reaction rate and product selectivity. However, many catalytic surfaces promote multiple competing pathways, as the energy barriers for side reactions, are often similar. To overcome this, future catalyst development must focus on rational design of highly selective centres with molecular-level recognition, capable of guiding CO_2 along desired pathways while suppressing undesired reactions and impurities. Such selective and well-defined active sites are essential for achieving high efficiency, high selectivity, and long-term stability in CO_2 conversion technologies.

- **Catalyst Stability and Durability:** A major barrier to practical CO_2 conversion is catalyst deactivation over time due to sintering, coking, poisoning, or surface restructuring. These processes reduce active site availability and lower overall performance. To enable long-term industrial operation, catalysts must be engineered for high thermal, chemical, and structural stability, maintaining activity and selectivity over extended cycles. Designing robust materials that resist deactivation and can be easily regenerated is critical for reliable and scalable CO_2 conversion technologies.

- **Point Source Utilization of CO_2** involves directly converting industrial flue gases, containing CO_2, CO, CH_4, and nitrogen- or sulfur-based impurities, into valuable chemicals such as methanol, syngas, hydrocarbons, urea, carbamates, and thiols. This approach eliminates the need for energy-intensive CO_2 separation and purification, enabling in situ conversion at the emission source. The presence of CO, CH_4 and reactive N- and S-species further enhances product diversity and improves carbon utilization efficiency, making point-source conversion a highly attractive strategy for sustainable emission management. Direct flue gas utilization is attractive, but may not always be viable. Industrial emissions contain impurities like SO_x and NO_x that are often more reactive than CO_2 and can poison or deactivate catalysts. In such cases, flue gas cleaning or pre-treatment may be better approach before catalytic conversion.

3.1.4 Carrier, Medium and Component Design

- **Electrolyte Design:** While there is greater focus on catalytic material which is the most critical component, final CO_2 utilization is dependent on efficient working at system level. In this context, electrolyte design for electrochemical cells become critical. The solubility and mobility of desired reactive species (ions/atoms/molecules) need careful electrolyte design. Additionally, the stability of these electrolytes over a long period of time poses another challenge.

- **Membrane design:** Membranes play a critical role in separation and ion transport. However, they are often limited by chemical instability, mechanical degradation, and poor molecular transport efficiency. Designing membranes with high selectivity, durability, and compatibility remains a major challenge.

- **Multi-component Design and Integration:** CO_2 conversion technologies require the coordinated function of multiple components-catalysts, reactors, separation units, supports, and operating fluids. Even if individual components perform well, incompatibility between materials, degradation under reaction conditions, or mass-transfer limitations can drastically reduce overall efficiency. Achieving stable and synergistic performance at the system level is therefore critical.

3.1.5 Source of Hydrogen

One critical challenge in CO_2 conversion is the supply of green hydrogen, which must have a low carbon footprint. Green hydrogen is typically produced via electrolysis using renewable energy, but this process is energy-intensive and costly.

- **Direct Use of Water in Catalytic CO_2 Conversion:** A promising solution is to directly use water as the hydrogen source in the catalytic CO_2 conversion process, eliminating the need for separate hydrogen production and storage. This integrated approach requires the development of advanced catalysts capable of efficiently facilitating both water splitting and CO_2 reduction under mild conditions. Using water directly eliminates the need for hydrogen storage, thereby simplifying the required infrastructure. Addressing these challenges through innovation in catalyst design and reaction integration is essential for the sustainable and efficient development of CO_2 conversion technologies.

- **Alternative Sustainable Hydrogen Sources:** Hydrogen can also be derived from other renewable and waste-based sources such as compressed biogas, municipal solid waste, agricultural residues, and organic industrial waste through reforming or gasification routes. Integrating these hydrogen sources with CCU systems can establish a circular and sustainable model, ensuring efficient waste management while reducing the overall cost of hydrogen production. This approach not only contributes to cleaner hydrogen generation but also enhances the economic and environmental sustainability of CCU operations.

3.2 Development of Advanced Catalyst for CO_2 Conversion

Catalysis is the key to success for all CO_2 conversion technologies. Researchers across the globe are investigating a variety of innovative catalyst design concepts to improve the efficiency and effectiveness of CO2 conversion technologies.

3.2.1 Single-Atom Catalysts (SACs)

SACs, which consist of isolated metal atoms dispersed on support, have attracted significant attention due to their exceptional activity and selectivity. The uniform distribution of active sites and unique electronic properties of single atoms enhance catalytic performance in CO_2 reduction reactions. These catalysts are highly efficient in facilitating conversion processes by providing distinct pathways for reaction intermediates. But catalyst scaling up is a challenging part.

3.2.2 Bimetallic and Multimetallic Catalysts

The combination of two or more metals in bimetallic and multimetallic catalysts can produce synergistic effects, enhancing catalytic performance. These catalysts can introduce new active sites and improve stability, offering a versatile and effective platform for CO_2 conversion. Such combinations allow for fine-tuning of electronic and structural properties to optimize catalytic activity.

3.2.3 Perovskites Materials

This class of material has opened wide gamut of avenues for potential application in catalytic, electrocatalytic and photocatalytic space. The possibility of build-your-own-structure provide huge opportunity for tuning the desired physicochemical attributes of these novel materials.

3.2.4 Metal-Organic Frameworks (MOFs)/Covalent-Organic Frameworks (COFs)

These materials, known for their highly porous structures, extensive surface areas, and tunable pore sizes, are being extensively studied for their potential in CO_2 capture and conversion. By incorporating active metal sites within their frameworks, they can be engineered to exhibit high catalytic activity and selectivity, making them promising candidates for efficient CO_2 conversion processes. But the scaling up and cost are the challenging parts.

3.2.5 Defect Engineering

Introducing and manipulating specific defects within the catalyst structure is a strategic approach to enhancing catalytic properties. Defect engineering can create additional active sites and alter electronic properties, thereby improving the reactivity and selectivity of the catalysts. This method is crucial for developing catalysts that perform efficiently under mild conditions.

3.2.6 Morphology Control

Controlling the morphology of catalysts at the nanoscale can optimize their surface area, pore distribution, and the accessibility of active sites. Nanostructured catalysts, such as those with nanorod or nanowire morphologies, demonstrate superior performance compared to their bulk counterparts due to enhanced surface interactions and improved mass transfer properties.

3.2.7 Hybrid Catalytic Systems

The integration of different catalytic components, such as combining heterogeneous catalysts with enzymatic or homogeneous catalysts, is an emerging approach. Hybrid systems harness the strengths of each type to achieve higher overall efficiency and selectivity, providing novel pathways for CO_2 conversion. This approach enables the development of multi-functional catalysts capable of performing complex reactions with high efficiency.

3.3 Breakthrough Fundamental Research in CO_2 Conversion

Despite significant advancements in catalyst design for CO_2 conversion, achieving a true breakthrough remains a formidable challenge. The ideal catalyst - one that functions efficiently at ambient conditions, requires minimal external energy, exhibits high selectivity and productivity, and maintains long-term stability - has yet to be realized. This challenge calls for a fundamentally different approach to catalyst design. Simply modifying chemical compositions and textural properties may not be sufficient.

To achieve this breakthrough, novel concepts must be explored. Ideally, entirely new concepts for catalyst design that have not been previously considered need to be discovered.

Achieving these advancements requires a shift towards open-minded, curiosity-driven fundamental research. Researchers must be willing to venture beyond established paradigms and explore new theoretical and experimental approaches. Embracing unconventional ideas and conducting experiments free from the constraints of existing literature can lead to unexpected and potentially ground-breaking discoveries. The dream of an ideal CO_2 conversion catalyst can be realized only through such innovative research.

3.3.1 AI-Driven High-Throughput Catalyst Discovery

The convergence of Artificial intelligence (AI), high-throughput hardware, sophisticated analytical tools and materials science is revolutionizing catalyst discovery for CO_2 conversion. AI models can rapidly analyze vast datasets to predict the most effective catalyst structures, which if coupled with high-throughput robotic systems and analytical tools can significantly speed up the discovery process. This approach will help the identification of new catalyst materials that enhance the efficiency of CO_2 reduction reactions.

3.3.2 Integration with Renewable Energy Sources

Coupling CO_2 conversion processes with renewable energy sources, such as solar power, provides a sustainable solution to the high energy demands of these reactions. Photocatalytic and photoelectrochemical methods utilize solar energy to drive the reduction of CO_2, thus addressing both thermodynamic and kinetic challenges. These processes involve the use of semiconductor or plasmonic materials that can absorb sunlight and generate electron-hole pairs to facilitate CO_2 reduction reactions. Researchers are employing several innovative methods to integrate CO_2 conversion with solar energy, aiming for sustainable and efficient solutions in the CCUS-in-one-pot (COP) strategy.

- **Photocatalysis:** Light-activated catalysts such as titanium dioxide (TiO_2), graphitic carbon nitride (g-C_3N_4), and many more, are used to drive CO_2 reduction. These materials absorb sunlight, generating electron-hole pairs that facilitate the conversion of CO_2 into value-added chemicals and fuels. Enhancements such as metal doping and creating heterojunctions improve efficiency.

- **Photothermal Catalysis:** This method combines photochemical and thermal effects using photothermal materials to convert solar energy into heat, driving thermal catalytic reactions. This dual mechanism fully utilizes sunlight, increasing CO_2 conversion efficiency.

- **Photoelectrochemical Cells (PEC):** PEC cells integrate semiconductor photoelectrodes with electrocatalysts to directly convert solar energy into chemical energy. Sunlight generates electron-hole pairs in the semiconductor, driving electrochemical reactions that reduce CO_2 to carbon monoxide and hydrocarbons.

- **Hybrid Systems:** Combining different catalytic mechanisms, such as photocatalysis and electrocatalysis, enhances charge carrier separation and utilization. Integrating photothermal and photoelectrochemical processes leverages both thermal and light-driven reactions, resulting in more efficient CO_2 reduction.

- **Carbon-Based Materials:** Graphene, carbon nanotubes (CNTs), and activated carbon support photocatalysts, improving performance by providing high conductivity and large surface areas. Combining these with metal and non-metal nanocomposites further boosts photocatalytic activity.

- **Covalent Organic Frameworks (COFs):** COFs are highly porous materials ideal for photocatalytic CO_2 reduction. Their structural versatility and stability make them promising candidates for efficiently harvesting light energy and converting CO_2. Despite these advancements, a breakthrough photocatalytic system has yet to be discovered. Achieving this will require curiosity-driven, bold research that challenges established concepts in the literature and seeks to discover entirely new materials or approaches for CO_2 conversion. This innovative and fearless exploration is essential for making significant strides in the field.

- **Photoreactor Design Challenges:** Another significant challenge lies in the design of photoreactors. What is feasible in a laboratory setting on a small scale often proves impractical on an industrial scale. Ensuring effective light penetration and uniform exposure of the catalyst to light can be substantial obstacles. This issue requires parallel research efforts in photoreactor engineering, involving close collaboration between catalysis researchers and chemical engineers. Such interdisciplinary collaboration is crucial in developing scalable photoreactor designs that maintain efficiency and performance at industrial levels. Effective photoreactor design must account for factors such as light distribution, reactor geometry, and catalyst arrangement to ensure that the catalytic materials are optimally exposed to light, thus maximizing the efficiency of CO_2 conversion processes.

- **Photobioreactors:** Photobioreactors are used for controlled cultivation of microalgae by supplying light, nutrients, and carbon dioxide, thereby enabling CO_2 capture and sustainable biomass production. Unlike open pond systems, photobioreactors offer better control over environmental conditions, leading to higher productivity and reduced contamination risks. The produced biomass can be converted into biofuels using emerging technologies such as High Temperature Liquefaction (HTL), or converted into animal feed, and other bioproducts through advanced systems biology and biomanufacturing routes. Key challenges in these technologies include high capital and operational costs, energy demands for lighting, mixing and HTL, and scaling up to industrial levels.

3.4 Problem Statements for Scientific and Technological Advancement in CO_2 Conversion

The following are proposed problem statements. However, what the field truly needs now is a leap beyond conventional thinking, catalyst concepts that are fundamentally new rather than incremental variations of existing systems.

3.4.1 Problem Statement 1: Fundamental Understanding of Catalyst-CO_2 Interactions

Objective: Investigate the fundamental interactions between catalysts and CO_2 to enhance activity and selectivity.

Quantitative success criteria:

i) Achieve a detailed atomic-level understanding of catalyst surfaces using various techniques.

ii) Quantify and reduce the activation energy of CO_2 conversion reactions.

iii) Elucidate the complete reaction mechanisms of CO_2 reduction pathways using in-situ spectroscopy and computational modeling.

3.4.2 Problem Statement 2: Advanced Theoretical and Computational Models

Objective: Develop advanced theoretical models and simulations to predict and optimize catalyst performance.

Success criteria:

i) Utilize DFT to predict catalyst behavior and reaction energetics with an accuracy of ≥ 95% compared to experimental data,

ii) Implement machine learning algorithms to predict catalyst properties and performance, achieving prediction accuracy improvements of ≥ 50% over traditional methods.

iii) Integrate multi-scale modeling approaches to link atomic-level phenomena with macroscopic catalytic behavior, ensuring consistency across scales.

3.4.3 Problem Statement 3: Novel Catalyst Synthesis Techniques

Objective: Explore innovative synthesis techniques for creating catalysts with controlled morphologies and defect structures.

Success criteria:

i) Develop methods to introduce and control defects in catalyst materials.

ii) Synthesize catalysts with precise morphological features.

iii) Establish high-throughput synthesis techniques to rapidly generate and screen large libraries of catalyst materials.

3.4.4 Problem Statement 4: Interface Science in CO_2 Conversion

Objective: Investigate the role of interfaces in multi-component catalytic systems to enhance CO_2 conversion efficiency.

Success criteria:

i) Achieve nanoscale characterization of catalyst-support interfaces using various techniques.

ii) Study and optimize charge transfer dynamics at the catalyst-support interface using ultrafast spectroscopy, aiming to reduce charge recombination rates.

iii) Quantify synergistic effects in multi-component systems, demonstrating performance enhancements (activity and selectivity) as compared to single-component catalysts.

3.4.5 Problem Statement 5: Photocatalytic Mechanisms and Light-Matter Interactions

Objective: Deepen the understanding of photocatalytic mechanisms and optimize light-matter interactions for CO_2 reduction.

Success criteria:

i) Achieve photon absorption efficiencies of ≥ 90% across the visible spectrum in photocatalytic materials.

ii) Enhance electron-hole separation efficiencies to ≥ 90%, reducing recombination losses.

iii) Investigate and optimize the kinetics of photocatalytic reactions, achieving high turnover frequencies under solar irradiation.

3.4.6 Problem Statement 6: Advanced Material Characterization Techniques

Objective: Develop and apply advanced material characterization techniques to gain insights into catalyst structure and performance.

Success criteria:

I) Employ in-situ characterization techniques, such as in-situ TEM, XPS, XAS, DRIFTS, Raman spectroscopy, to monitor catalyst changes during CO_2 conversion in real-time.

ii) Use atomic resolution imaging techniques, such as aberration-corrected TEM, to visualize atomic-scale changes in catalysts during operation.

iii) Develop quantitative analysis methods to correlate structural features with catalytic performance.

3.4.7 Problem Statement 7: Development of Ultra-High Efficiency CO_2 Conversion Catalysts

Objective: Design and develop new CO_2 conversion catalysts that achieve 10 times greater productivity than current benchmarks, with 100% product selectivity and one-year catalyst stability.

Success criteria:

i) Increase catalyst productivity to achieve a turnover frequency (TOF) that is 10 times higher than the highest reported values.

ii) Ensure absolute product selectivity of 100% for a single desired product, such as CO, methanol, hydrocarbons, or another targeted value-added chemical.

iii) Demonstrate catalyst stability with no more than 10% performance degradation over one year of continuous operation.

3.4.8 Problem Statement 8: Integration of CO_2 Conversion with Renewable Energy

Objective: Integrate CO_2 conversion processes with renewable energy sources-including photo-, electro-, and thermochemical methods- to achieve sustainable and efficient CO_2 utilization.

Success criteria:

I) Achieve a photon conversion efficiency (PCE) of ≥ 50% in converting solar energy to chemical energy.

ii) Attain a CO_2 conversion rate of ≥ 10,000 mmol/g.cat.h using photo or/and electrocatalysts.

iii) Maintain over 90% of initial photo or/and electrocatalytic activity after 1,000 hours of continuous solar irradiation.

iv) Ensure that 100% of the energy required for CO_2 conversion is supplied by renewable sources, such as solar, wind etc.

3.4.9 Problem Statement 9: Reactor Design for Efficient CO_2 Conversion

Objective: Design reactors that optimize light distribution, mass transfer, and catalyst exposure to enhance CO_2 conversion efficiency.

Success criteria:

i) Design reactors to utilize the maximum photons within the penetration depth.

ii) Ensure an excellent mass transfer of CO_2 and reactants within the reactor.

iii) Demonstrate scalable reactor designs capable of processing ≥ 1,000 liters of reactant volume without efficiency loss.

3.4.10 Problem Statement 10: Electrochemical CO_2 Reduction in Acidic Medium

Objective: To overcome the CO_2 utilization limitation in neutral and alkaline medium in electrochemical CO_2 reduction processes, acidic electrolysis should be done. If developed successfully, it can give a huge leap to the field of electrochemical CO_2 reduction.

Success criteria:

I) Suppress hydrogen evolution reaction in acidic medium.

ii) High selectivity and activity of a particular product.

iii) Overcoming salt precipitation problem.

iv) Long-term stability.

3.4.11 Problem Statement 11: Enhancing the Energy Efficiency in Electrochemical CO_2 Reduction

Objective: The energy efficiency of the process is very low, because 90% of the electrical energy is consumed by the anode for oxygen evolution reaction, which has a very high overpotential of 1.23 V. So, focused studies must be undertaken to decrease the electrical energy consumption in the anodic compartment.

Success criteria:

i) Reduction in total cell potential.

ii) Value-added product formation at the anodic compartment.

iii) Long-term operation and stability.

3.4.12 Problem Statement 12:

Objective: Reduction of catalytic activity at pilot or commercial scale is an often encountered problem due to various reasons. These include for example, simpler issues such as insufficient mechanical strength of the catalyst leading to disintegration inside a reactor, or more complex issues such as inadequate understanding of the influence of reactor-level heat and mass transfer issues on catalysis. Further, engineering design of EOP and COP strategies into pilot or commercial plants need to be done carefully.

Success criteria:

I) Thermal and mechanical stability of the catalyst beyond few years.

ii) Activity of the catalyst.

iii) Develop low-cost catalysts that do not suffer supply chain constraints.

iv) Reactor engineering for thermo-catalytic CO_2 conversion.

v) Recycling unreacted CO_2 and H_2 to efficiently utilize and to reach carbon neutrality or carbon negative process

vi) Efficient utilization of thermal energy and water during designing of the EOP or COP approaches.

3.5 Parameters to Evaluate the Success of CO_2 Conversions Projects

- **Activity of Catalyst:** The catalyst should have a high rate of formation of the desired product.
- **Product Selectivity:** Ensure that the catalyst produces the target product exclusively, minimizing unwanted by-products. This simplifies downstream processing and increases overall efficiency. Verify that the produced chemicals meet industrial purity standards, typically 99.5% or higher.
- **Catalyst Stability and Longevity:** Demonstrate that the catalyst can maintain its performance for at least one year of continuous use, with less than a 10% drop-in activity. If not, assess whether the catalyst can be regenerated effectively without significant loss of activity, allowing for multiple use cycles.
- **Scalability:** Show that the catalyst and reaction system can be scaled from laboratory settings (mg scale) to industrial volumes (1,000 kg or more) without losing efficiency. Ensure that the developed technology can be integrated with existing industrial processes and infrastructure.
- **Sustainability and Environmental Impact:** Achieve an energy conversion efficiency of at least 50% from renewable energy sources to chemical fuel outputs. Conduct life-cycle assessments to confirm that the technology results in a carbon-negative method.
- **Economic Viability:** Techno-economic analysis is required to determine the cost of converting CO_2 into valuable products. The goal is to reduce this cost as much as possible.
- **Material Synthesizability:** Develop methods for catalyst synthesis that can be scaled up to industrial levels, ensuring consistent quality and performance. Use raw materials that are abundant and cost-effective to ensure the sustainability and economic feasibility of large-scale production.
- **Regulatory and Safety Compliance:** Confirm that the technology complies with all relevant environmental and safety regulations. Conduct comprehensive safety assessments to ensure the process and materials are safe for large-scale industrial use.

3.6 Expected Outputs and Outcomes of DST-Funded CO_2 Conversion Projects

The outputs include securing intellectual property through patents and contributing to scientific knowledge through high-impact publications. The outcomes, in turn, involve demonstrating practical applications via prototypes and pilot plants, and establishing industrial feasibility through scalable synthesis methods.

3.6.1 Patents

- **Innovative Catalyst Designs:** Securing patents for new catalysts that show significant improvements in efficiency, selectivity, and stability for CO_2 conversion. These patents would cover unique synthesis methods, specific catalyst compositions, and their application in CO_2 reduction processes.

- **Advanced Reactor Technologies:** Patents for novel reactor designs that optimize light penetration and mass transfer, making large-scale CO_2 conversion feasible. This includes innovations in photoreactors and photoelectrochemical cells that integrate seamlessly with renewable energy systems.

3.6.2 Publications

Publishing high-quality research articles in reputable scientific journals that detail breakthroughs in catalyst development, understanding of reaction mechanisms, and advancements in reactor design for CO_2 conversion.

3.6.3 Prototypes

- **Pilot-Scale Reactors:** Developing and showcasing pilot-scale reactors that employ the newly designed catalysts and optimized reactor configurations. These prototypes will demonstrate the scalability and practical implementation of the research findings.

- **Integrated Systems:** Creating prototypes of systems that integrate CO_2 capture and conversion with renewable energy inputs, showing the potential for continuous and sustainable operation.

3.6.4 Material Synthesizability

- **Scalable Synthesis Methods:** Establishing and documenting scalable synthesis methods for the new catalysts and materials, ensuring that these processes can be reproduced and scaled up for industrial applications.

- **Characterization Data:** Providing comprehensive datasets on the structural, chemical, and performance properties of the synthesized materials, which will be published or made available in public repositories.

CHAPTER 4

CARBON DIOXIDE TRANSPORT & STORAGE

CARBON DIOXIDE TRANSPORT & STORAGE

Introduction

While CO_2 capture has received significant attention, the transportation and storage aspects are equally critical components of the CCUS value chain. Transporting captured CO_2 to suitable storage sites, whether through pipelines, shipping, or other methods, requires robust infrastructure and careful planning. Once transported, the CO_2 must be stored securely in geological formations, such as depleted oil and gas fields, deep saline aquifers, or unmineable coal seams. In addition, storage in marine gas hydrate systems, gas-bearing shales and other potential unconventional hydrocarbon systems can be explored for commercial and technical feasibility. As shown in Figure 4.1, India's CO_2 storage potential in sedimentary formations is estimated at 300 Gt (3 Gt in oil fields, 3.7 Gt in underground coal seams, and 291 Gt in saline Aquifers). In addition, the basalt formations are estimated to have the potential of sequestering and storing upto 314 Gt of CO_2.

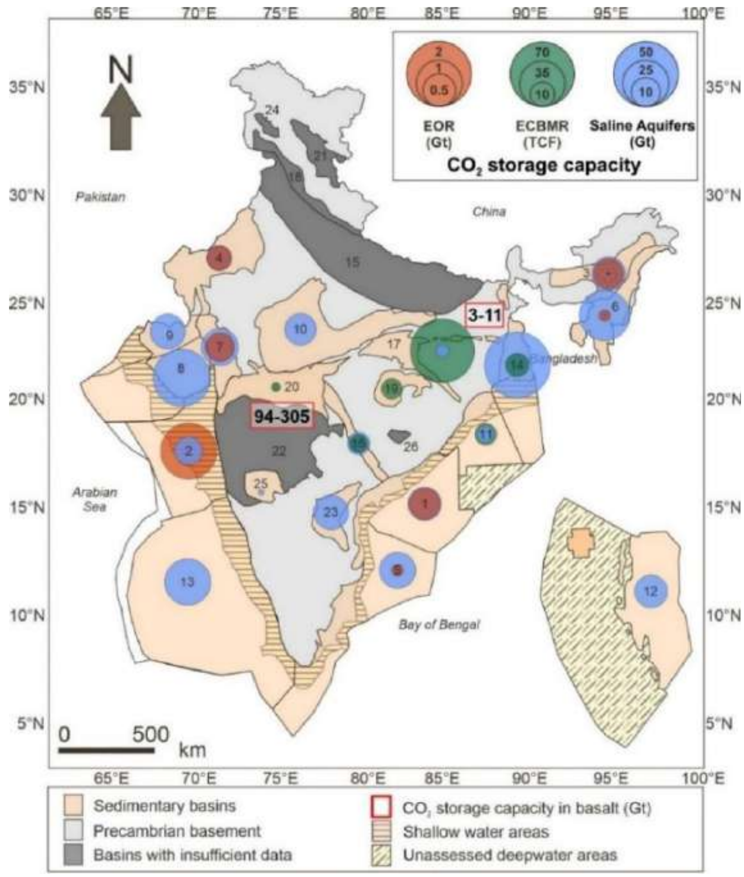

Figure 4.1: Geologic CO_2 storage potential in India through different storage pathways (Vishal et al., 2021).

These storage sites must be carefully selected and monitored to ensure long-term containment and avoid any adverse environmental impacts. In India, the diverse geography and geology present unique challenges and opportunities for CO_2 transport and storage, making it essential to develop tailored solutions.

4.1 Current state of technological advancements

CO_2 storage refers to the long-term sequestration of carbon dioxide, typically in geological formations such as deep saline aquifers, depleted oil and gas fields, or unmineable coal seams (shown in Figure 4.2). The primary objective is to prevent CO_2 from re-entering the atmosphere, thus mitigating the impacts of climate change. Geological storage involves injecting CO_2 into deep underground rock formations where it becomes trapped through physical and chemical processes. Secure storage depends on the geological characteristics of the site, including the presence of an impermeable cap rock that prevents CO_2 from migrating back to the surface. In addition to geological storage, emerging research is exploring mineral storage, where CO_2 reacts with specific minerals to form stable, solid carbonates. Effective monitoring and verification systems are critical to ensure the safety and long-term success of storage operations, as the injected CO_2 must remain isolated for centuries to have a meaningful impact on reducing atmospheric greenhouse gases.

In CO_2 storage, advances are being made in both geological and mineral sequestration techniques. Geologic storage in deep saline aquifers and depleted oil and gas fields has become more viable due to improved reservoir modeling and risk assessment tools. Enhanced monitoring technologies, including seismic imaging, and subsurface sensors, are enabling better tracking of CO_2 plume movements. Additionally, research into mineralization, where CO_2 reacts with minerals to form stable carbonates, is progressing, offering a permanent storage solution.

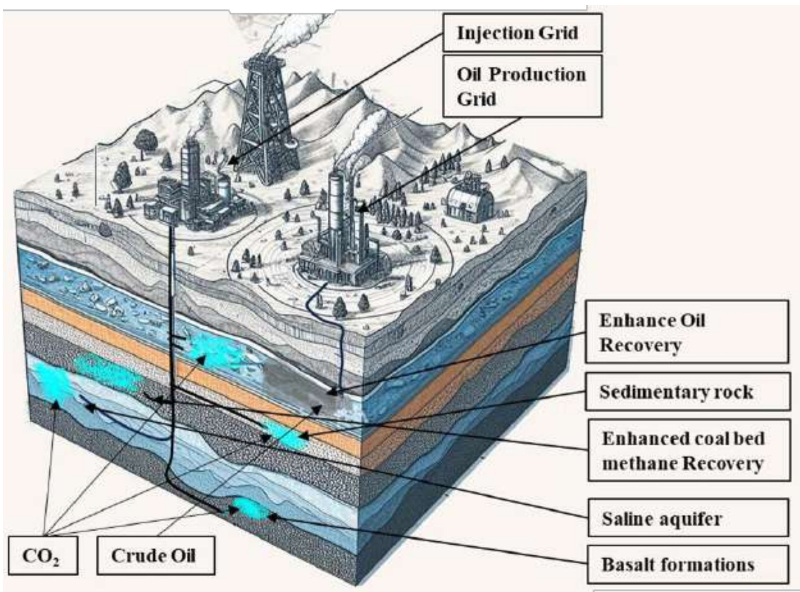

Figure 4.2: Geological storage options for CO_2 in the CCS.

CO_2 transport is another crucial element in the CCUS chain, enabling the movement of captured carbon dioxide from emission sources to storage sites. The main methods of CO_2 transport include pipelines, shipping, and, in some cases, rail or road tankers, see Figure 4.3. Pipelines are the most widely used due to their efficiency and scalability, particularly over land, and they are designed to handle the high pressures required to transport CO_2 in its supercritical state. Shipping is gaining importance, especially for offshore storage or international transport, and typically involves liquefying CO_2 at low temperatures to reduce volume. While CO_2 transport infrastructure has existed for decades, especially in enhanced oil recovery (EOR) projects, it now faces new challenges as part of large-scale CCS deployment. These challenges include the expansion of networks, ensuring the safety of transport, and maintaining the integrity of infrastructure under diverse environmental conditions.

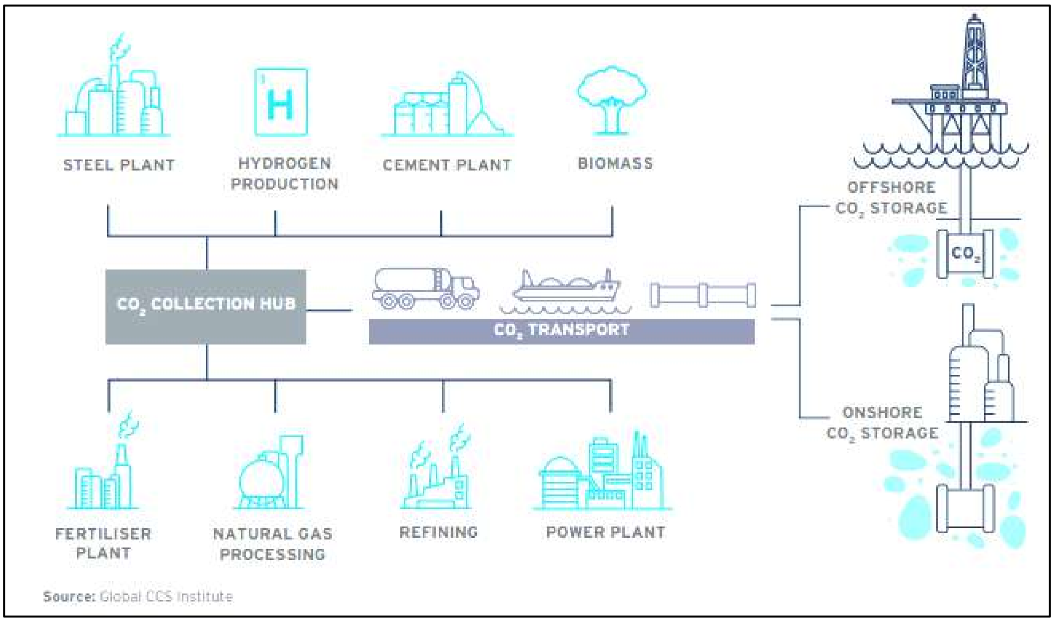

Figure 4.3: Role of CO_2 Transport in CCUS chain (Source: Global CCS Institute).

The technology for CO_2 transport has seen significant advancements, particularly in pipeline infrastructure, which is the most common method for large-scale CO_2 movement. Modern pipelines are designed with enhanced materials that offer higher corrosion resistance and integrity, improving safety and reducing the risk of leaks. Advanced sensors and monitoring systems utilizing IoT and AI are now integrated into pipelines, allowing real-time detection of any issues. For offshore and long-distance transport, developments in CO_2 shipping, including liquefied CO_2 carriers, are progressing. These ships offer a flexible alternative for moving CO_2 to storage sites, especially across regions where pipelines are impractical.

4.1.1 Geological Storage in Sedimentary Basins

Geological storage in sedimentary basins involves injecting CO_2 into underground rock formations, such as depleted oil and gas fields, deep saline aquifers, or unmineable coal seams. The CO_2 is trapped through several mechanisms: structural trapping (where CO_2 is physically trapped by impermeable rock layers), residual trapping (where CO_2 is immobilized in pore spaces), solubility trapping (where CO_2 dissolves in water), and mineral trapping (where CO_2 reacts with minerals to form stable carbonates).

- **Current Benchmarks:** The Sleipner Project in Norway was the first commercial-scale CO_2 storage project, injecting approximately 1 million tonnes of CO_2 annually into a deep saline aquifer. The Weyburn-Midale Project in Canada has been injecting CO_2 into depleted oil fields since 2000, storing over 30 million tonnes of CO_2. In Australia, the Gorgon Project aims to store 3-4 million tonnes of CO_2 annually in deep saline aquifers.

- **Suitability for Indian Conditions:** India possesses potential geological storage sites, such as deep saline aquifers and depleted oil and gas fields. However, challenges include the need for extensive site characterization, effective monitoring, and the development of regulatory frameworks to ensure safety and environmental protection.

4.1.2 Enhanced Oil Recovery (EOR)

Enhanced Oil Recovery (EOR) involves injecting CO_2 into mature oil fields to enhance oil recovery. The CO_2 injection increases the reservoir pressure and helps mobilize and extract additional oil. In this process, a significant portion of injected CO_2 remains stored in the reservoir, effectively combining oil recovery with CO_2 storage.

- **Current benchmarks:** The Permian Basin in the USA has extensively used CO_2 for EOR, with numerous projects storing millions of tonnes of CO_2 while enhancing oil production. The Petra Nova Project in the USA captures 1.4 million tonnes of CO_2 annually, which is used for EOR in the West Ranch Oil Field.

- **Suitability for Indian conditions:** Several mature oil fields in India could benefit from EOR, improving oil recovery while simultaneously storing CO_2. Implementing CO_2-EOR could store more than 50% of the injected CO_2 in mature oil fields like those in the Mumbai High or Cambay Basin. With the potential to inject millions of tonnes of CO_2 annually, CO_2-EOR could sequester significant amounts of CO_2, especially if 10-15 million metric tons of CO_2 per year are captured and injected for enhanced recovery and storage (IEA, 2023). Recent studies have estimated nearly 1.2 Gt of practical storage capacity through EOR in India. However, several challenges remain, including the need for reliable CO_2 sources and infrastructure for CO_2 capture and transport.

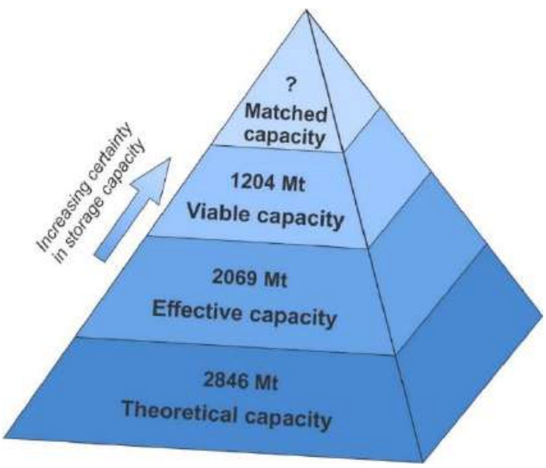

Figure 4.4: CO_2 storage resource pyramid for enhanced oil recovery in India (Vishal et al., 2021).

4.1.3 Enhanced Coal-Bed Methane Recovery (ECBM)

Enhanced Coal Bed Methane (ECBM) recovery technology involves injecting CO_2 into deep coal seams to increase methane production. The injected gas adsorbs onto the coal, displacing methane, which can then be extracted for use. This technique not only enhances methane recovery but also provides an opportunity for CO_2 storage, making it a dual-purpose technology in carbon capture and utilization.

- **Current benchmarks:** Globally, ECBM has seen significant advancements, with projects in countries like the United States, Canada, and China leading the way. The Allison Unit in the U.S. was one of the first ECBM projects, where CO_2 injection increased methane production by 50%. China has also made substantial progress, with pilot projects demonstrating CO_2 sequestration potential alongside methane recovery.

- **Suitability for Indian conditions:** In India, ECBM holds promise due to the country's extensive coal reserves, particularly in the eastern regions like Jharkhand and Odisha. However, challenges remain, including the need for extensive field trials, infrastructure development, and addressing environmental concerns. India's coal seams have different characteristics compared to those in other countries, requiring tailored approaches for successful implementation. With the right investments in technology and infrastructure, ECBM could become a viable option for enhancing methane recovery and supporting carbon capture efforts in India.

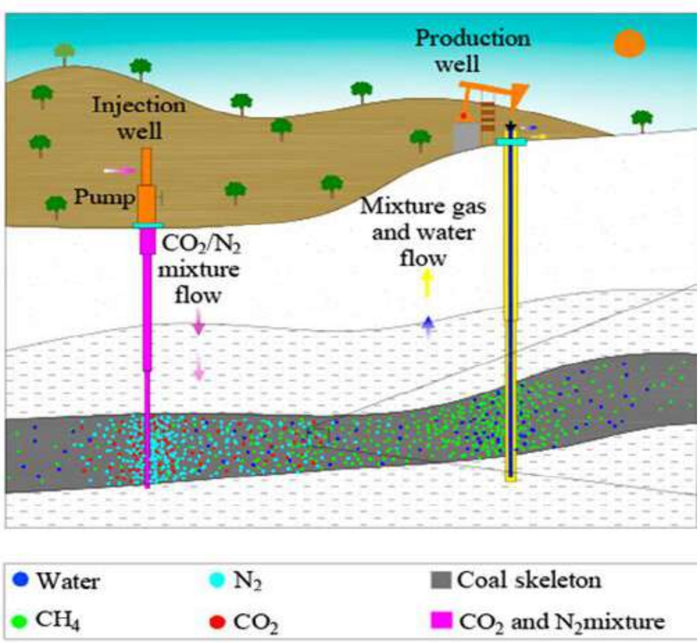

Figure 4.5: Enhanced coal bed methane recovery process (Fan et al., 2023).

4.1.4 Mineralization and Carbonate Formation

Mineralization involves reacting CO_2 with naturally occurring minerals to form stable carbonates, which can be stored permanently. This process can occur either in situ (underground) or ex-situ (on the surface), offering a potential long-term solution for CO_2 storage.

- **Current benchmarks:** The CarbFix Project in Iceland injects CO_2 into basalt formations, where it rapidly reacts to form stable carbonates, storing thousands of tonnes of CO_2. Similarly, the Wallula Basalt Pilot Project in the USA has demonstrated successful CO_2 mineralization in basalt formations.

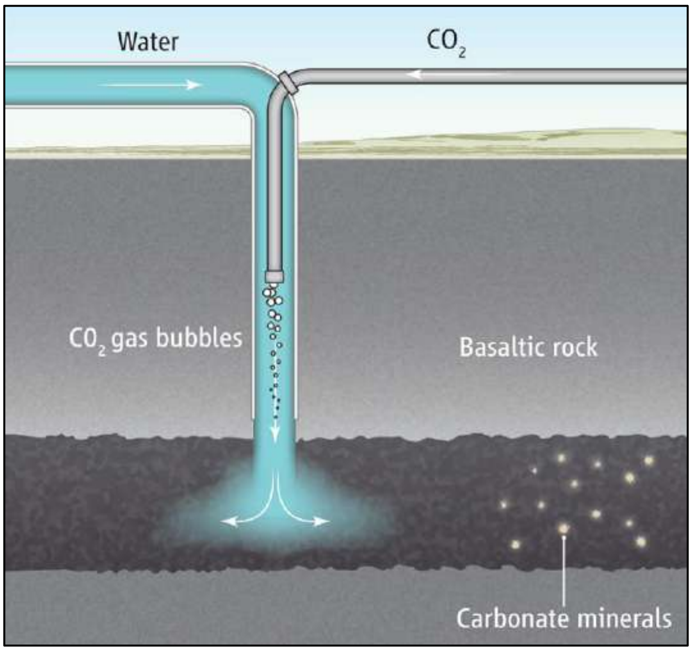

Figure 4.6: CO_2 storage through mineralization (Gislason and Oelkers, 2014).

- **Suitability for Indian conditions:** India has extensive basalt formations, particularly in the Deccan Traps region, making it suitable for CO_2 mineralization. However, challenges include optimizing injection techniques, reaction rates and ensuring effective monitoring of the mineralization process.

4.1.5 Pipeline Transport

CO_2 pipelines are a well-established method for transporting captured CO_2 from capture sites to storage sites or utilization points. Typically made of carbon steel, these pipelines are designed to handle high pressures and specific conditions to prevent corrosion and ensure safety.

- **Current benchmarks:** CO_2 pipelines in the United States, such as the Cortez Pipeline, transport millions of tonnes of CO_2 annually over long distances. These pipelines can reach pressures up to 2,200 psi (15 MPa) and can extend over 500 miles (800 km).

- **Suitability for Indian Conditions:** Pipelines offer efficient CO_2 transport for long-term projects, especially when established routes exist from industrial clusters to storage sites. However, challenges in India include high initial capital expenditure for infrastructure, potential land acquisition issues, and the need for robust regulatory frameworks.

Figure 4.7: CO_2 transport through pipeline.

4.1.6 Ship Transport

Ship transport involves compressing CO_2 into a liquid form and transporting it in specially designed vessels. This method is particularly suitable for countries with extensive coastlines and where storage sites are accessible by sea.

- **Current benchmarks:** CO_2 shipping projects in Norway and Japan demonstrate the viability of this transport method. Vessels can carry CO_2 at pressures around 7-8 bar and temperatures of -50°C to -60°C. The Northern Lights project in Norway aims to ship CO_2 from multiple European countries to offshore storage sites.

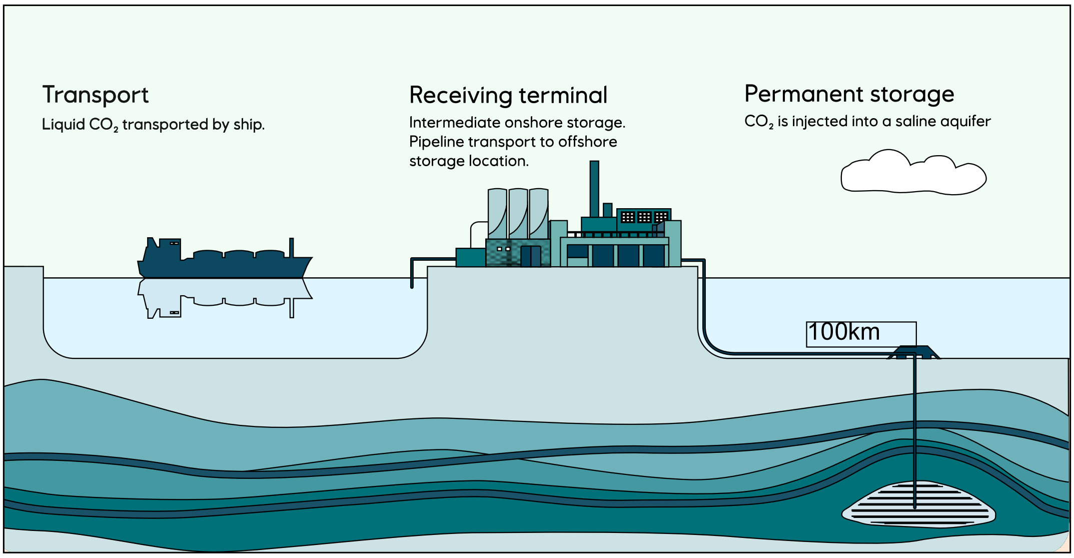

Figure 4.8: CO_2 transport through a ship for offshore storage (Northern Lights, Equinor).

- **Suitability for Indian conditions:** Ship transport offers flexible routing and scalability, making it suitable for regions where pipeline construction is challenging. However, challenges include the need for port infrastructure and CO_2 liquefaction facilities, as well as potential logistical and regulatory hurdles.

4.1.7 Road and Rail Transport

Road and rail transport involves using pressurized tankers or rail cars to transport CO_2. This method is typically used for shorter distances and smaller volumes of CO_2.

- **Current benchmarks:** Road and rail transport of CO_2 is commonly used in the food and beverage industries, where CO_2 is transported in tankers. Pressurized CO_2 tankers can transport CO_2 at pressures around 20 bar.

Figure 4.9: Road tankers for CO_2 transport.

- **Suitability for Indian conditions:** Road and rail transport is flexible and adaptable for small to medium-scale CO_2 transport, making it suitable for pilot projects and initial stages of CCUS deployment. However, challenges include limited capacity, higher operational costs compared to pipelines, and potential traffic and safety issues.

4.1.8 CO_2 Transport in Composite Cylinders

Composite cylinders are advanced storage containers made from materials like carbon fiber, designed to store CO_2 at high pressures while being lightweight and durable.

- **Current benchmarks:** Composite cylinders are used in various industries to store and transport gases under high pressure. These cylinders can withstand pressures up to 700 bar.

- **Suitability for Indian conditions:** High-pressure capacity and lightweight design make composite cylinders suitable for diverse transport methods, including innovative logistics solutions like drones. However, challenges include high manufacturing costs and the need for specialized handling and maintenance.

India's diverse geographical and infrastructural landscape presents unique challenges and opportunities for CO_2 transport in the CCUS value chain. While pipeline transport offers efficiency and capacity for large-scale projects, ship transport provides flexibility and scalability for coastal regions. Road and rail transport can support smaller-scale projects and pilot initiatives, and composite cylinders offer high-pressure storage solutions for innovative transport methods.

4.2 Challenges in CO_2 Transport and Storage

CO_2 transport and storage, while a promising method for mitigating climate change, faces numerous scientific and technical challenges. These challenges stem from the complexities of geological formations, the behaviour of CO_2 under various conditions, and the need for long-term containment and monitoring. Here are some of the fundamental difficulties in realizing effective CO_2 transport and storage:

4.2.1 Geological Site Selection and Characterization

Identifying and characterizing suitable geological formations for CO_2 storage is a significant challenge in CCUS projects. Geological formations vary significantly in their properties, such as porosity, permeability, and mineral composition. This heterogeneity affects how CO_2 will be stored and retained within a formation. Porosity can range from less than 10% in dense rock formations to over 30% in more porous media. Permeability can vary by order of magnitude, from less than 1 millidarcy (mD) in tight formations to several darcies in more permeable rocks.

Moreover, many potential storage sites have complex geological structures, including faults and fractures that can affect CO_2 migration and containment. Faults and fractures can significantly alter the migration pathways and storage efficiency of CO_2. For instance, a fault with a slip rate of just 1 mm/year can impact stability and containment over decades.

4.2.2 Injectivity and CO_2 Flow Dynamics

One of the key challenges in CO_2 storage is ensuring that the CO_2 can be efficiently injected into the reservoir without causing adverse effects. When CO_2 is injected, it increases the pressure in the formation, which can limit the amount of CO_2 that can be stored and may even induce seismic activity. To avoid inducing fractures or seismicity, safe injection pressures typically need to be maintained below 80-90% of the reservoir's fracture pressure.

Additionally, CO_2 often exists as a supercritical fluid under storage conditions, which leads to complex interactions with the formation fluids and rocks. Understanding these interactions is critical for predicting CO_2 migration and trapping. Supercritical CO_2 has a density of 600-800 kg/m^3 and a viscosity much lower than water, around 0.05-0.1 cP, which influences its flow and trapping mechanisms in porous media. These dynamics make it essential to carefully manage injectivity and flow behavior to ensure the success of CO_2 storage.

4.2.3 Long-term Containment and Monitoring

Long-term containment of CO_2 is crucial to ensure that the stored CO_2 remains securely trapped over extended periods. The integrity of the caprock, which acts as a barrier to prevent CO_2 from escaping, is essential to the effectiveness of a storage site. Understanding the mechanical and chemical stability of caprocks under CO_2 exposure is critical, as caprock permeability should typically be in the range of nano- to microdarcies (0.001-0.1 mD) to effectively trap CO_2 over geological timescales.

Existing wells, faults, and fractures pose risks for CO_2 leakage, and assessing and mitigating these risks is vital for safe storage. CO_2 leakage rates through improperly sealed wells can vary widely, from negligible amounts to several tons per year, depending on the well's condition and surrounding geology. Monitoring technologies are essential to detect and quantify CO_2 movement and ensure it remains contained. Effective monitoring systems need to detect CO_2 concentrations as low as 0.1-1% above baseline levels to identify leaks and migration pathways, making this an ongoing challenge in CO_2 storage.

4.2.4 Chemical Reactions and Mineralization

Managing the chemical interactions between CO_2, formation waters, and reservoir rocks is another significant challenge in CO_2 storage. CO_2 can react with formation water and minerals, leading to changes in reservoir properties and potentially causing the dissolution or precipitation of minerals. These reactions can take years to millennia to significantly alter porosity and permeability, with carbonate precipitation rates ranging from less than 1% to 10% per decade.

While mineralization can permanently lock CO_2 in solid form, the rates at which these reactions occur are often slow and dependent on the specific mineral composition of the storage site. For example, mineralization rates for CO_2 in basalt formations can be on the order of 1-10% of the injected CO_2 per year under optimal conditions. Understanding and managing these chemical processes are essential for ensuring the long-term stability of CO_2 storage sites.

4.2.5 High Energy Requirements for Compression and Liquefaction

Compressing CO_2 to a supercritical state or liquefying it for transport requires significant energy input, posing a considerable challenge for CO_2 capture and storage systems. The compression of CO_2 to supercritical conditions, typically above 70 bar, can consume about 15-25% of the total energy output of a power plant. This high energy demand necessitates the development of more efficient technologies to reduce the overall energy requirements of CO_2 compression and liquefaction.

4.2.6 Pipeline Transport Challenges

Transporting CO_2 through pipelines involves managing high pressures and potential phase changes, which can be challenging in maintaining pipeline integrity. The cost of building CO_2 pipelines can range from $1-3 million per mile, depending on terrain and population density. Ensuring the safe and efficient transport of CO_2 through pipelines requires careful planning and management of these pressures and phase transitions.

4.2.7 Corrosion and Material Integrity

CO_2 can form carbonic acid when combined with water, leading to corrosion of pipelines and transport vessels. This corrosion poses a significant challenge to maintaining the integrity of the transport infrastructure. The costs associated with pipeline maintenance and replacement due to corrosion can increase operational expenses by 10-20%, making it essential to develop materials and technologies that resist corrosion and extend the lifespan of the infrastructure.

4.2.8 Safety and Leak Prevention

Ensuring the safety of CO_2 transport is paramount, as leaks can be hazardous due to the asphyxiating nature of CO_2 at high concentrations. Preventing leaks requires constant monitoring and maintenance, which can add 5-10% to transport costs. Developing robust safety protocols and leak prevention technologies is critical to minimizing the risks associated with CO_2 transport.

4.2.9 Geological and Topographical Barriers

Transporting CO_2 across varied geographical and topographical conditions, such as mountains and urban areas, presents additional challenges for pipeline design and construction. Costs can escalate by 30-50% in challenging terrains compared to flat, rural areas. Overcoming these barriers requires innovative engineering solutions and careful planning to minimize costs and ensure the successful deployment of CO_2 transport infrastructure.

4.2.10 Public Acceptance and Regulatory Hurdles

Gaining public and regulatory approval for CO_2 transport infrastructure can be time-consuming and costly. Delays and additional requirements can increase project timelines by 1-3 years and add 10-15% to overall project costs. Addressing public concerns and navigating regulatory processes is essential to the successful implementation of CO_2 transport and storage projects.

4.2.11 Storage Compatibility and Integration

Ensuring compatibility between CO_2 transport systems and storage sites is critical to the success of CO_2 storage projects. This includes maintaining the integrity of storage formations and ensuring that the infrastructure is suitable for the specific characteristics of the storage site. Compatibility issues can lead to increased costs for additional infrastructure and integration measures, potentially adding 15-25% to overall project costs. Careful planning and coordination between transport and storage systems are essential to minimize these risks.

4.3 Breakthrough R&D in CO_2 Storage and Transport

Breakthrough R&D is the cornerstone of advancing CO_2 storage and transport technologies. It involves exploring new scientific principles, developing novel materials, and creating innovative processes that can significantly enhance the efficiency, safety, and scalability of CO_2 storage and transport. In India, breakthrough R&D must consider the unique geological, environmental, and socio-economic conditions that affect the feasibility and effectiveness of these technologies. By focusing on areas such as geological characterization, monitoring technologies, and transport infrastructure, India can develop cutting-edge solutions that address both local and global challenges in CO_2 management.

Current state-of-the-art in research

There have been some globally disruptive technologies that have shown promise in solving some of the problems associated with CO_2 transport and storage. The major ones are listed below.

4.3.1 Seismic and Electromagnetic Imaging

Advanced seismic imaging and electromagnetic techniques have significantly improved the precision and reliability of geological site characterization. These methods allow for detailed mapping of subsurface structures and fluid distribution, which is crucial for identifying suitable CO_2 storage sites and monitoring CO_2 behaviour after injection. For example, the Sleipner Project in the North Sea utilizes 4D seismic monitoring to track the movement of injected CO_2. This technique has successfully provided detailed images of CO_2 plumes over time, helping to ensure safe and efficient storage.

4.3.2 Machine Learning for Geological Data Analysis

Machine learning and AI algorithms have been developed to process and interpret vast amounts of geological data more efficiently. These tools can predict subsurface properties and identify optimal storage sites with higher accuracy than traditional methods. For example, the CarbFix project in Iceland uses machine learning models to predict CO_2 injection impacts and optimize site selection based on geological data.

4.3.3 Real-Time Seismic Monitoring Systems

Real-time seismic monitoring systems can detect and analyze microseismic events induced by CO_2 injection. This helps assess and mitigate risks related to induced seismicity. For example, the Decatur Project in Illinois uses a network of seismic sensors to monitor induced seismicity during CO_2 injection continuously. This approach has been crucial in managing and minimizing seismic risks associated with storage operations.

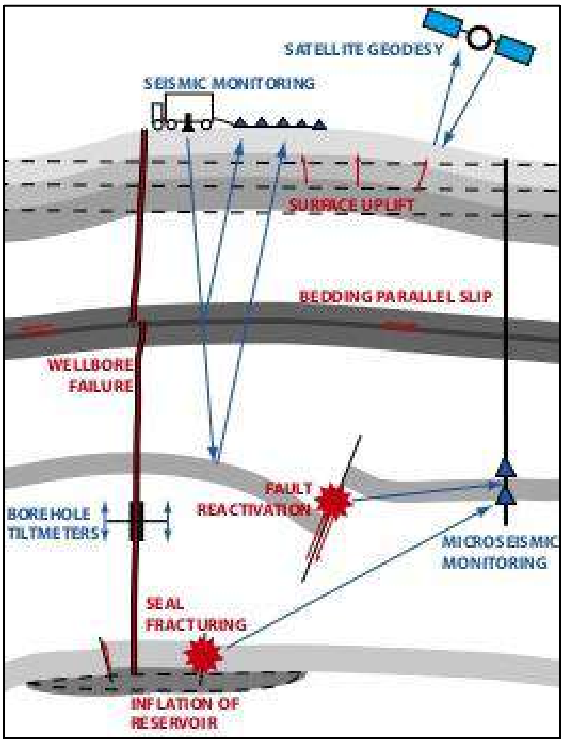

Figure 4.10: Seismic monitoring technologies (Verdon et al., 2013).

4.3.4 Fiber-Optic Sensing Technologies

Fiber-optic sensing technologies provide continuous, real-time monitoring of CO_2 injection and storage sites. These sensors can detect temperature, pressure, and acoustic changes within the storage formation, offering a comprehensive view of CO_2 behavior. For example, the Otway Project in Australia employs Distributed Acoustic Sensing (DAS) with fiber-optic cables to monitor CO_2 injection and detect any potential leakage paths, providing high-resolution data on subsurface conditions.

Possible directions for breakthrough fundamental research

To promote breakthrough research in CO_2 storage, it's crucial to define problem statements that address the current challenges in the field and provide clear, quantitative success criteria.

4.3.5 Advanced Geological Site Screening, Ranking, and Characterization

Enhancing the understanding and identification of optimal geological formations for CO_2 storage is critical to ensuring the long-term success of carbon capture and storage (CCS) initiatives. The directions for research and development (R&D) in this area include detailed geological mapping and modeling of potential storage sites. This involves assessing the characteristics of caprock integrity, which is crucial for ensuring long-term containment of CO_2.

Additionally, improved characterization of geological features such as faults and fractures, which influence CO_2 migration, is essential for predicting and managing the movement of CO_2 within the reservoir. Evaluating geothermal and hydrodynamic regimes is also necessary to optimize site selection, ensuring that the chosen sites provide favorable conditions for CO_2 storage over extended periods. It also includes the assessment of geomechanical risks, including integrity of caprocks, fault structures, and potential leakage pathways.

4.3.6 Advanced Multiphysics and Multiscale Fluid Flow Modeling

Developing sophisticated models that can accurately predict CO_2 behavior across different scales and conditions within storage reservoirs is another key focus for R&D. This includes multiscale modeling of CO_2 migration, ranging from pore-scale to reservoir-scale, to understand how CO_2 moves through the subsurface. Integrating multiphase flow dynamics is vital to understanding the interactions between CO_2, brine, and rock matrices, which are critical for predicting how CO_2 will behave once injected into a storage reservoir.

Reactive transport modeling, which simulates chemical reactions and mineralization processes, is also an important area of focus. These models are necessary for predicting long-term storage stability and the potential for CO_2 to mineralize into stable forms.

4.3.7 Risk Assessment, Mitigation, and Early Warning Systems for Induced Seismicity

CO_2 injection can induce seismicity, posing risks to storage integrity and public safety, and therefore, must be carefully managed. Research in this area focuses on identifying seismically sensitive areas and assessing the potential risks associated with CO_2 storage. The development of seismic monitoring technologies is critical for detecting and analyzing induced seismic events in real-time. Additionally, understanding dynamic pressure-limited capacities through a multi-pronged approach allows for better management of injection pressures and rates. Strategies for controlling injection pressures and rates are essential for minimizing seismic risks and ensuring the safe and effective operation of CO_2 storage projects.

Another approach is to develop predictive models that can assess the risk of induced seismicity based on geological data and injection parameters. These models can help identify high-risk areas and guide the selection of safe injection sites. They can also be used to optimize injection strategies, such as controlling the rate and pressure of CO_2 injection to minimize the risk of seismicity.

In India, where seismic activity is a concern in many regions, the development and implementation of early warning systems for induced seismicity are essential for the safe deployment of CO_2 storage projects. These systems must be tailored to the specific geological conditions of Indian storage sites and integrated into the overall monitoring and verification framework.

4.3.8 Improved Understanding of Caprock Integrity

Caprock integrity is a fundamental aspect of secure and long-term CO_2 storage in geological formations. Caprock, a low-permeability rock layer that sits above the storage reservoir, acts as a seal to prevent the upward migration of CO_2 and ensure its containment. The effectiveness of CO_2 storage relies heavily on the mechanical and chemical stability of this caprock, particularly under the conditions imposed by CO_2 injection, such as increased pressure and potential chemical interactions. A deeper understanding of these factors is essential to minimize risks associated with CO_2 leakage and to optimize the long-term performance of storage sites.

One key area of potential research in caprock integrity is the mechanical stability of the rock formation. Injecting CO_2 into a reservoir increases the pressure within the formation, which can place significant stress on the caprock. If the pressure exceeds the fracture pressure of the caprock, there is a risk of creating fractures that could allow CO_2 to escape. Therefore, it is crucial to identify the thresholds at which caprock remains intact under different geological conditions. Advanced geomechanical modeling, coupled with laboratory experiments, can help predict the caprock's behavior under various stress regimes, ensuring that injection pressures are kept within safe limits.

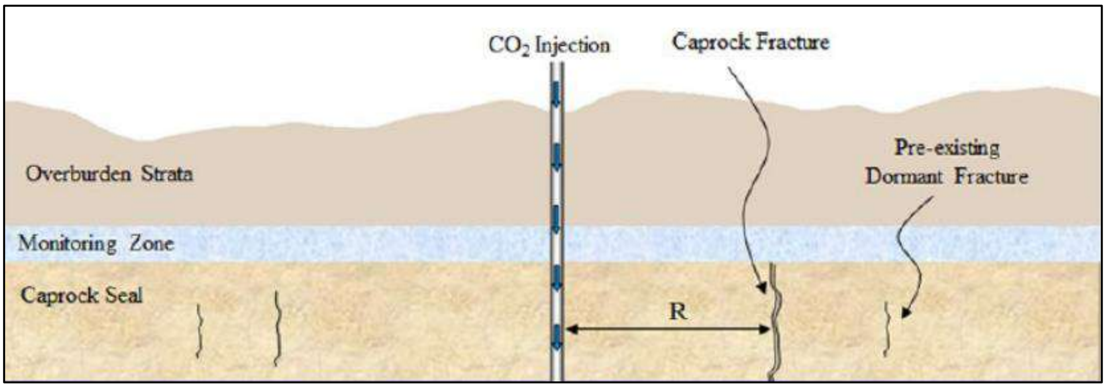

Figure 4.11: Caprock integrity issues (Siriwardane et al., 2013).

The chemical stability of caprock is another critical factor in ensuring CO_2 containment. When CO_2 is injected into a storage site, it can dissolve in the formation water, forming carbonic acid. This acid can react with the minerals in the caprock, potentially leading to changes in its structure and permeability. For example, the dissolution of carbonate minerals could increase the porosity of the caprock, compromising its ability to act as a seal. On the other hand, certain chemical reactions might precipitate new minerals that could reduce permeability. Understanding these reactions requires detailed studies of the mineralogical composition of caprocks, as well as experimental and modeling approaches to simulate long-term chemical interactions between CO_2, brine, and caprock minerals.

4.3.9 Advances in Reactive Transport and Mineralization Processes

Mineralization is a promising mechanism for the permanent storage of CO_2, as it involves the transformation of CO_2 into stable solid minerals, such as carbonates. This process can occur naturally in specific geological formations, particularly those rich in reactive minerals like basalt and ultramafic rocks. The advantage of mineralization is that once CO_2 is converted into a solid form, it is essentially locked away permanently, eliminating the risk of leakage that may be present in other storage methods. However, the rate of natural mineralization is often slow, making it necessary to explore ways to accelerate the process to be viable for large-scale CO_2 storage.

One approach to enhance CO_2 mineralization is through the injection of CO_2 into basalt formations, which are abundant in reactive minerals such as olivine and pyroxene. When CO_2 comes into contact with these minerals in the presence of water, chemical reactions occur, leading to the formation of stable carbonates. Pilot projects, such as the CarbFix project in Iceland, have demonstrated the potential of this method, with rapid mineralization observed within just a few years. However, further research is needed to optimize the conditions for mineralization, such as controlling the temperature, pressure, and water content to maximize reaction rates. Additionally, understanding the long-term stability of the formed carbonates and ensuring that the reactions do not negatively impact the integrity of the surrounding rock formations is crucial for scaling up this approach.

Understanding and optimizing the processes by which CO_2 reacts with reservoir rocks and fluids to form stable mineral compounds can enhance long-term storage security. Research into accelerating mineralization is a frontier area in CO_2 storage and is needed to demonstrate large-scale storage capacity.

Possible pathways can be to develop a reactive transport model that predicts CO_2 mineralization rates with an accuracy within 10% of experimental data. Furthermore, CO_2 mineralization efficiency should be increased through the use of catalysts or other enhancements. Finally, the process should be validated in laboratory and field studies, showing stable mineral formation in different geological settings.

4.3.10 Bio-geochemical Interactions

Bio-geochemical interactions add another layer of complexity and potential to CO_2 storage. These interactions involve the role of microorganisms in influencing the chemical environment within the storage site. Certain microbes can catalyze reactions that either promote or inhibit mineralization, depending on the conditions. For example, some bacteria can induce the precipitation of carbonate minerals by altering the local pH or by providing nucleation sites for mineral growth. Understanding the role of these microorganisms and harnessing their capabilities could lead to more efficient CO_2 storage solutions.

In addition to enhancing mineralization, bio-geochemical processes can impact the overall geochemical stability of the storage site. Microbial activity can influence the solubility of minerals, the mobility of CO_2, and even the integrity of the caprock. For instance, sulfate-reducing bacteria can produce hydrogen sulfide, which could react with metal components of the storage infrastructure or alter the geochemistry of the site. On the other hand, microbial-induced calcite precipitation has shown promise in sealing fractures and enhancing the sealing capacity of caprocks. Understanding these interactions and how they change over time is vital for predicting the long-term behavior of CO_2 in storage sites and ensuring that the storage remains secure.

Bio-geochemical interactions in the reservoir represent a critical area of research for the advancement of CO_2 storage technologies. By understanding and harnessing the role of microorganisms in the natural processes that convert CO_2 into stable minerals, we can enhance the security and permanence of CO_2 storage. Laboratory experiments, field trials, and advanced modeling techniques are necessary to explore the full potential of these processes. One of the challenges is scaling up these processes from laboratory to field conditions, where the complexity and variability of geological formations can significantly influence outcomes. Additionally, integrating these bio-geochemical processes with existing CO_2 capture and storage technologies will require interdisciplinary collaboration across fields such as geochemistry, microbiology, and environmental engineering.

4.3.11 Machine Learning Approaches for CO_2 Storage

The complexity of CO_2 storage operations generates vast amounts of data, which can be leveraged to improve storage management through advanced big data analytics and machine learning approaches. Developing machine learning models capable of predicting CO_2 storage performance metrics, such as pressure and leakage risk, with at least 90% accuracy is a key focus.

Identifying big data analytic approaches capable of processing and analyzing large datasets from multiple sources, including digital well information in real-time, is also essential. These advancements in data analytics will provide actionable insights that can improve the efficiency and safety of CO_2 storage operations.

4.3.12 Development of Advanced Materials for CO_2 Transport

Developing advanced materials for CO_2 transport is a promising breakthrough R&D direction within the CCUS framework. The focus should be on creating novel materials with high CO_2 adsorption capacity, superior selectivity, and exceptional stability. These materials could revolutionize CO_2 capture and transport systems by significantly reducing energy consumption and operational costs.

The key research goal should be to achieve a CO_2 adsorption capacity of at least 5 mmol/g at 25°C and 1 atm pressure. Such a breakthrough would enable more efficient CO_2 capture, potentially reducing the energy required for transport. Moreover, the materials must demonstrate stability over 1,000 adsorption/desorption cycles, with performance degradation of less than 5%, ensuring long-term viability.

Reducing energy consumption by at least 30% compared to current best practices is another critical criterion. This could be achieved by exploring materials with enhanced thermodynamic properties, enabling easier CO_2 release during desorption with minimal energy input.

In the Indian context, the development of such advanced materials could address both energy and infrastructure challenges, making CO_2 transport more sustainable and economically viable. By pushing the boundaries of material science, India could lead the way in developing next-generation solutions for CO_2 transport in the global CCUS landscape.

4.3.13 Corrosion-Resistant Pipeline Materials

Corrosion is a major challenge in the transport of CO_2, particularly in pipelines. CO_2 can react with water to form carbonic acid, which can corrode steel pipelines and other infrastructure. Developing corrosion-resistant materials and coatings is a critical area of breakthrough R&D that can enhance the safety and longevity of CO_2 transport systems.

One area of research is the development of new alloys that are more resistant to CO_2-induced corrosion. These materials must be able to withstand the harsh conditions of CO_2 transport, including high pressures, temperatures, and the presence of impurities. Laboratory testing and field trials are essential to validate the performance of these materials in real-world conditions.

Another area of innovation is in the development of advanced coatings that can be applied to existing pipelines to protect them from corrosion. These coatings must be durable, easy to apply, and cost-effective. Nanotechnology offers promising solutions, with the development of nanoscale coatings that provide superior protection against corrosion.

In India, where the CO_2 transport infrastructure is still in the early stages of development, the use of corrosion-resistant materials can help reduce maintenance costs and extend the lifespan of pipelines. These materials are particularly important in regions with high humidity or saline environments, where the risk of corrosion is higher.

4.3.14 Hydrate-based CO_2 Transport

The transportation of CO_2 in the CCUS value chain currently relies on liquid or supercritical CO_2, which presents energy inefficiencies and safety risks. An innovative alternative is CO_2 hydrates, where CO_2 is encapsulated in a solid-state crystalline structure formed with water molecules. This method offers potential advantages, such as reduced energy consumption and enhanced safety during transport.

Research should focus on achieving stable CO_2 hydrate formation within industrially relevant conditions, targeting formation times under one hour. Additionally, studies should demonstrate that transporting CO_2 hydrates is at least 20% more energy-efficient than supercritical CO_2 transport. The safety and stability of CO_2 hydrates over a transport distance of 100 kilometers must be validated through pilot studies, ensuring their viability as an alternative.

In the Indian context, this technology could address infrastructure challenges by reducing the need for high-pressure pipelines and aligning with energy efficiency goals. Key adaptations would include maintaining low temperatures in warmer regions and developing localized infrastructure. By advancing CO_2 hydrate transport, India could significantly contribute to global CCUS efforts, offering a safer, more sustainable solution for CO_2 transport.

4.3.15 Bio-inspired and Biomimetic Solutions for CO_2 Transport

Bio-inspired and biomimetic solutions offer a novel approach to addressing the challenges of CO_2 transport and storage. These solutions are inspired by natural processes and systems, which have evolved to operate efficiently in a wide range of environments. By mimicking these processes, it is possible to develop more sustainable and effective technologies for CCUS.

One example of a bio-inspired solution is the development of CO_2 transport systems that mimic the circulatory systems of living organisms. Just as blood vessels efficiently transport nutrients and gases throughout the body, a bio-inspired pipeline network could optimize the flow of CO_2, reducing energy requirements and improving transport efficiency.

Another example is the development of materials that mimic the properties of natural minerals, such as those that naturally trap and store CO_2 in the Earth's crust. By replicating these properties in synthetic materials, it may be possible to create more effective and durable storage solutions.

In the Indian context, bio-inspired and biomimetic solutions could offer innovative and sustainable approaches to CCUS. Research in this area should focus on identifying natural systems and processes that are well-suited to India's diverse environments and applying these principles to the development of new technologies.

Key recommendations

Several key research areas require attention to advance research in CO_2 storage and transport. For CO_2 storage, geological site screening and characterization are critical. Enhanced geological mapping and modeling will help identify optimal sites by assessing factors such as caprock integrity, fault systems, and geothermal conditions, which influence CO_2 containment. Additionally, multiphysics and multiscale fluid flow modeling are essential to predict CO_2 behavior across different scales, incorporating the effects of geomechanics and fluid dynamics to ensure storage safety. Improved models will allow better predictions of CO_2 plume migration and pressure buildup, which is essential for long-term integrity.

Risk management through induced seismicity monitoring is another area of importance. Research should focus on developing seismic monitoring systems and predictive models to manage risks posed by CO_2 injection. These tools will help optimize injection strategies and reduce seismic risks, particularly relevant for regions like India.

For CO_2 transport, breakthroughs in advanced materials and methods to improve efficiency are key. One priority is creating materials with high CO_2 adsorption capacity and corrosion resistance to enhance pipeline safety and durability. Tenhancing CO_2 adsorption and corrosion resistance is necessary. Developing materials with high adsorption capacity and durable coatings for pipelines will reduce energy consumption and improve transport efficiency. Reducing energy consumption during CO_2 transport, such as through hydrate-based transport systems, is also a significant area of innovation. Additionally, exploring bio-inspired solutions could revolutionize CO_2 transport by offering safer, more energy-efficient alternatives. Machine learning approaches could also optimize CO_2 transport and storage operations by predicting performance metrics and managing risks more effectively.

In summary, innovations in storage modeling, risk management, and material science will be key to advancing CO_2 storage and transport technologies. These advancements in materials science and data analytics will improve the sustainability of CO_2 storage and transport, lower operational costs, and ensure safer, more efficient carbon capture and storage (CCS) systems.

1.4 Applied and Translational Activities

Translational research plays a crucial role in bridging the gap between fundamental scientific discoveries and their practical application in the real world. In the context of CCUS, translational research involves taking breakthrough R&D findings and developing them into scalable, commercially viable technologies that can be deployed in industrial settings. This process requires close collaboration between researchers, industry, and policymakers to ensure that new technologies meet the needs of the market and comply with regulatory requirements.

In India, translational research is essential for adapting CCUS technologies to the country's unique challenges and opportunities. This includes tailoring technologies to specific geological and environmental conditions, as well as addressing the socio-economic factors that influence the adoption of new technologies. By focusing on applied research and development, India can accelerate the deployment of CCUS technologies and achieve its climate and energy goals.

4.4.1 Monitoring and Verification Technologies

Monitoring and verification (MRV) technologies are essential for ensuring the safe and effective storage of CO_2. These technologies allow for real-time tracking of CO_2 plume movement, detection of any potential leaks, and assessment of the long-term integrity of storage sites. The development of advanced MRV systems is a critical area of breakthrough R&D, particularly in the context of India's unique geological and environmental conditions.

One area of innovation is the development of fiber-optic sensors that can be deployed in CO_2 storage wells to provide continuous monitoring of temperature, pressure, and chemical composition. These sensors can detect even small changes in the subsurface environment, providing early warning of potential issues. Another promising technology is seismic monitoring, which uses passive seismic sensors to detect microseismic events that could indicate CO_2 movement or leakage.

Satellite-based remote sensing is another area of interest for MRV. Satellites equipped with hyperspectral imaging and other advanced sensors can monitor large areas for changes in surface conditions that might indicate CO_2 leakage. This technology is particularly useful in remote or offshore storage sites, where ground-based monitoring is challenging.

In the Indian context, MRV technologies must be tailored to the specific challenges of the region, such as high seismicity and diverse geological formations. Developing cost-effective and scalable MRV systems that can be deployed across multiple storage sites is crucial for the success of CCUS in India.

4.4.2 Legacy and Storage Well Integrity and Long-Term Performance Monitoring

Ensuring the long-term integrity and performance of both CO_2 storage wells and legacy wells from surrounding formations is vital for preventing leakage and ensuring the sustainability of storage sites. Research in this area includes the assessment and monitoring of well conditions, such as casing, cement, and near-well formations. The development of sensor technologies that provide real-time performance monitoring of wells is also critical. Novel remediation technologies are being explored to address integrity issues and prevent leakage. Furthermore, enabling remote sensing for field-wide assessment of the location and leakage state of wells offers an additional layer of security for long-term CO_2 storage.

4.4.3 Optimization of Injection and Near-Well Environment

Improving the efficiency and safety of CO_2 injection processes, as well as maintaining the stability of the near-well environment, are critical areas of research. Controlling injection parameters to optimize CO_2 distribution while minimizing risks is a key focus. This includes managing near-wellbore pressures and flow dynamics to prevent leakage and ensure effective storage. Additionally, the development of novel well materials and sealing techniques is necessary to maintain well integrity over the long term. These advancements will help to reduce the risks associated with CO_2 injection and enhance the overall effectiveness of CO_2 storage operations.

4.4.4 Monitoring and Sensing Technologies

Cutting-edge technologies for real-time monitoring are essential for ensuring the integrity of CO_2 storage sites. R&D in this area focuses on developing advanced geophysical sensors that can continuously monitor CO_2 injection and migration within the subsurface. Remote sensing technologies offer the capability for large-scale assessment of CO_2 storage performance, allowing operators to monitor extensive areas with greater efficiency. Smart convergence monitoring systems are designed to ensure containment by predicting site behavior and alerting operators to any potential issues. These advancements in monitoring technologies are crucial for maintaining the safety and reliability of CO_2 storage operations.

4.4.5 CO_2 Transport infrastructure

CO_2 transport infrastructure is a critical component of the CCUS value chain. The safe and efficient transport of captured CO_2 from industrial sources to storage sites requires robust pipelines, compression facilities, and, in some cases, shipping or other alternative transport methods.

Breakthrough R&D in this area focuses on developing new materials, improving transport efficiency, and exploring alternative transport solutions.

One of the key challenges in CO_2 transport is the risk of corrosion in pipelines. CO_2, especially when combined with water, can form carbonic acid, which can corrode pipeline materials over time. Developing corrosion-resistant materials and coatings is a critical area of R&D. These materials must not only resist corrosion but also withstand the high pressures required for CO_2 transport over long distances.

Another area of innovation is in CO_2 compression technology. Compressing CO_2 to a supercritical state is essential for efficient transport, but this process is energy-intensive. Advances in compression technologies, such as the development of energy-efficient compressors and heat exchangers, can significantly reduce the costs and energy requirements of CO_2 transport.

In addition to pipelines, alternative transport methods are being explored, such as utilizing existing natural gas pipelines for CO_2 transport or developing CO_2 shipping solutions for offshore storage sites. These alternatives can provide more flexibility and cost-effectiveness, particularly in regions where building new pipelines is challenging.

In the Indian context, CO_2 transport infrastructure must be designed to accommodate the country's diverse geography and climate conditions. For example, pipelines must be able to withstand extreme temperatures, high humidity, and seismic activity. Additionally, the development of transport infrastructure must consider the proximity of industrial sources to potential storage sites, as well as the availability of existing infrastructure that can be repurposed for CO_2 transport.

4.4.6 Integrating Renewable Energy in CO_2 Transport

The integration of renewable energy sources into CO_2 transport infrastructure is a promising area of research that could reduce the carbon footprint of CCUS operations. By using renewable energy for CO_2 compression and transport, the overall environmental impact of CCUS can be minimized.

One approach is to power CO_2 compression facilities with solar or wind energy. This can be particularly effective in regions with abundant renewable energy resources, such as solar-rich areas in India. Developing energy storage solutions, such as batteries or thermal storage, can help manage the intermittency of renewable energy sources and ensure a reliable supply of power for CO_2 transport operations.

Another area of innovation is in the development of hybrid systems that combine renewable energy with traditional power sources. For example, a hybrid solar-gas power plant could provide the flexibility and reliability needed for continuous CO_2 transport, while also reducing the overall carbon footprint.

In the Indian context, integrating renewable energy into CO_2 transport infrastructure could be a game-changer, given the country's ambitious renewable energy targets and growing renewable energy capacity. Pilot projects that demonstrate the feasibility and cost-effectiveness of such integration could pave the way for wider adoption in the future.

4.4.7 Economic, Policy, and Regulatory Frameworks for CO_2 Storage and Transport

Developing economic models and policy frameworks to support the deployment and scalability of CO_2 storage and transport technologies is crucial for the widespread adoption of CCS. Techno-economic analysis of CO_2 storage projects is necessary to identify cost-reduction strategies and ensure that projects are financially viable. Life-cycle analysis of the CCUS value chain can aid in policy development, providing the necessary regulatory support and financial incentives for CO_2 storage. Additionally, public acceptance and stakeholder engagement are critical for promoting the adoption of CO_2 storage technologies. Developing frameworks that address these economic, policy, and regulatory challenges will be essential for the success of CCS in India.

4.4.8 Translational Projects and Demonstrations

Translational projects and demonstration plants are critical components of applied research in CCUS. These projects provide an opportunity to test new technologies under real-world conditions, gather data on their performance, and identify any challenges or areas for improvement. In India, translational projects can also help build confidence in CCUS technologies among stakeholders, including industry, government, and the public.

One example of a successful project is the demonstration of CO_2 capture and storage at a coal-fired power plant. This project could involve capturing CO_2 emissions from the power plant, transporting the CO_2 to a nearby storage site, and injecting it into a deep saline aquifer for long-term storage. The project would provide valuable data on the efficiency and cost-effectiveness of the capture and storage process, as well as insights into the regulatory and permitting challenges involved.

In addition to large-scale demonstrations, smaller translational projects can also play a crucial role in advancing CCUS technologies. For example, a project could focus on testing a new corrosion-resistant material for CO_2 pipelines or a novel monitoring technology for detecting CO_2 leakage. These projects can help de-risk new technologies and pave the way for their wider adoption.

In the Indian context, projects should be designed to address the country's specific challenges and opportunities. This includes selecting sites with suitable geology for CO_2 storage, leveraging existing infrastructure where possible, and involving local communities and stakeholders in the planning and implementation of the projects.

Key recommendations

Applied and translational activities in CCUS are pivotal in converting scientific breakthroughs into practical and scalable technologies for industrial application. In India, this involves adapting solutions to the country's geological and environmental conditions while addressing socio-economic factors. Monitoring and verification (MRV) technologies are critical for safe CO_2 storage, with innovations such as fiber-optic sensors and satellite-based remote sensing enabling real-time tracking of CO_2 plume movement and early detection of leaks. Tailoring MRV systems to India's seismicity and geological diversity is essential for successful deployment.

Ensuring well integrity is another area requiring attention, focusing on long-term monitoring of both CO_2 storage and legacy wells to prevent leakage. Developing sensor technologies for real-time monitoring and novel remediation techniques is vital for maintaining well stability. Optimizing CO_2 injection processes through advanced well materials and pressure management is key to improving storage efficiency and minimizing risks.

In terms of CO_2 transport infrastructure, developing energy-efficient compression technologies and exploring alternative transport methods, like repurposing natural gas pipelines, are crucial. Integrating renewable energy into transport operations, such as using solar or wind power for CO_2 compression, could significantly reduce the carbon footprint of CCUS projects, aligning with India's emission targets.

Finally, demonstration projects are vital for testing new technologies in real-world conditions, addressing site-specific challenges, and building confidence in CCUS technologies among stakeholders in India. These projects, both large-scale and smaller, will provide critical data on performance, cost-effectiveness, and regulatory challenges and will subsequently pave the way for widespread adoption of CCUS. It is estimated that the R&D needs of geological storage, including basic R&D and pilots, would be approximately Rs. 3000 Cr.

4.5 Immersive Enablers for CO_2 Storage and Transport

The successful deployment of CCUS technologies in India will require a range of enablers, including risk assessment, capacity building and skill development, public awareness and acceptance, policy and financial incentives, and the development of infrastructure and resources. These enablers are essential for overcoming the barriers to CCUS deployment and ensuring that the technology is adopted at scale.

4.5.1 Risk Assessment

Risk assessment for CO_2 storage and transport requires a structured methodology capable of capturing both the technical complexity of subsurface systems and the operational uncertainties inherent in CCUS projects. Although general-purpose frameworks such as ISO 31000:2018 outline the broad workflow for risk governance, CCUS applications necessitate tools that can explicitly address geological behavior, injection dynamics, and environmental exposure pathways. One such specialized instrument is the Integrated Carbon Risk Assessment System (IACRAS), developed jointly by IFPEN, SINTEF, and TNO. IACRAS organizes the assessment into four analytical stages: scenario formulation, scenario-level analysis, impact quantification, and uncertainty evaluation; thereby enabling a coherent mapping of potential failure modes across the life cycle of a storage project.

Other regulatory bodies have adopted different methodologies to suit their own oversight requirements. The UK Environment Agency, for example, frames environmental risks through a source–pathway–receptor logic model, combined with a qualitative classification of exposure likelihood and consequence severity into graded categories (High, Medium, Low, Very Low). Such approaches can be integrated with decision-analytic tools that incorporate sustainability indicators or fuzzy/linguistic evaluation schemes, particularly when the available data are incomplete or where multiple competing social, economic, and ecological objectives must be balanced.

In the Indian context, adapting these established frameworks offers a pathway to develop a national risk architecture that reflects local geological heterogeneity, seismic conditions, legacy well densities, and regulatory priorities. Tailoring these tools to Indian basins would support earlier identification of CO_2 migration hazards, better quantification of reservoir stability issues, and clearer prioritization of monitoring demands. In effect, a robust, locally adapted risk assessment workflow becomes a core enabler for building confidence in large-scale CCUS deployment.

4.5.2 Public Outreach and Community Engagement

Public attitudes to CCS

Public responses to CCS typically reflect the novelty of the technology and the limited familiarity that most communities have with subsurface CO_2 management. Because CCS has not been historically associated with everyday energy systems, it is often scrutinised more intensely than conventional extractive industries. Community-level reactions, particularly in areas selected for pilot or demonstration projects, frequently emphasise concerns related to personal safety and local environmental impacts. These include apprehension about accidental CO_2 releases posing health risks, the possibility of contamination of potable aquifers, and the prospect of injection-induced seismicity near storage formations. Such concerns have been central in shaping the early resistance seen in several CCS initiatives.

At a broader societal level, public understanding of CCS tends to be substantially lower than that of renewable energy technologies or efficiency measures. Low baseline familiarity often leads individuals to form preliminary or unstable opinions that shift as they receive new information. For this reason, numerous studies exploring CCS perceptions aim to provide participants with background information before eliciting their views, ensuring that their responses are anchored in at least some factual context (Daamen et al., 2006; de Best-Waldhober, 2009).

The concerns expressed about CCS often fall into two overarching categories. The first relates to strategic or conceptual objections: for example, the argument that CCS allows continued reliance on fossil fuels, opportunities that investment in CCS may reduce investment in renewable alternatives, or the notion that any future leakage could effectively negate mitigation gains. The second category encompasses health and safety risks, including fears of acute CO_2 discharge events, concerns that injection pressures could induce seismic activity, and apprehension about water contamination due to brine displacement or geochemical mobilisation. These perceptions have been widely documented and remain influential in shaping attitudes towards CCS at both local and national scales.

Recommendations

International practice underscores that effective public participation is fundamental to the governance of environmental technologies. This principle is reflected prominently in Principle 10 of the United Nations Rio Declaration on Environment and Development, which affirms the importance of public involvement in environmental decision-making. Within CCS project planning, this implies that communication and engagement efforts must be woven into the development process from the outset, ensuring that public concerns guide early design choices and that project rationales are clearly explained.

Extensive experience from early CCS projects, particularly those that encountered public opposition, including in Netherlands and Germany, has informed a series of guidance documents produced by multiple international organisations. These include the NETL's *'Best Practices for Public Outreach and Education for CCS Projects'* (NETL, 2009), the World Resources Institute's *'CCS and Community Engagement'* (WRI, 2010), and a substantial set of studies and practical recommendations published by the Global CCS Institute (GCCSI) and CSIRO (Ashworth et al., 2010, 2011, 2013; Bradbury et al., 2011; Prangnell, 2013). Additional contributions by Hammond and Shackley (2010), the EU CCS Network (2011), and Hope (2012) further reinforce the need for carefully tailored engagement strategies.

A consistent lesson across these experiences is that public engagement cannot follow a uniform model. Each CCS project features distinct social contexts, political environments, land-use histories, and sets of stakeholders. As a result, engagement plans must be designed to reflect local conditions and must provide opportunities for iterative, transparent communication. For India, recognising the existing levels of public awareness, addressing prevalent misconceptions, and embedding meaningful public participation into both national CCS strategy and project-level planning will be essential. In doing so, communication moves from being a supplementary activity to becoming a central mechanism for ensuring project legitimacy, risk transparency, and long-term community trust.

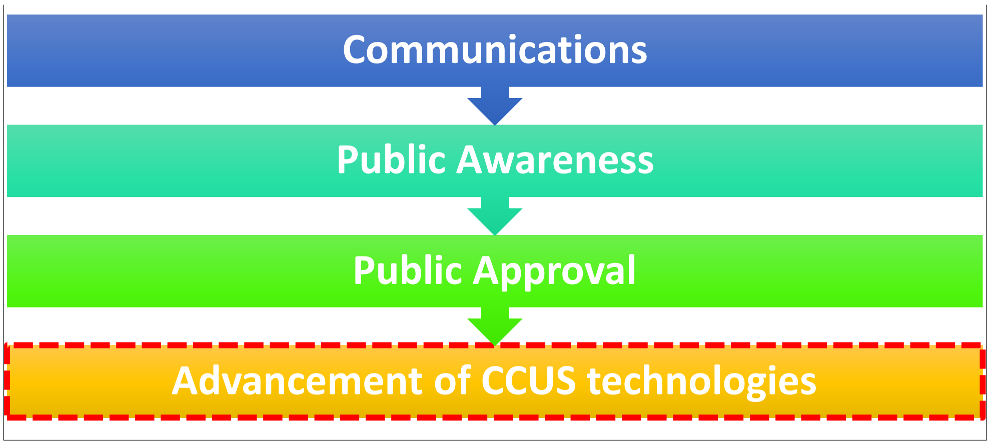

Figure 4.12: Importance of public outreach for the advancement of CCUS.

4.5.3 Capacity building and Skill development

Building a competent workforce is essential for supporting the rapid expansion of CCUS technologies in India. Although the national energy workforce is comparatively skilled, emerging clean-energy sectors, including CO_2 capture, transport, injection, and long-term geological storage, demand expertise that extends beyond traditional fossil-fuel operations. The transition therefore requires the establishment of new academic programmes, technical certifications, and dedicated vocational training focused on areas such as reservoir engineering, monitoring and verification (MRV), advanced materials for pipeline and CO_2, and data-driven subsurface modelling.

At the same time, India's conventional energy industries, including coal, oil and gas, steel, and transportation, are undergoing structural change due to automation and global decarbonization. The skills present in these sectors are invaluable for CCUS, and targeted reskilling and upskilling programmes will be necessary to redeploy existing expertise toward CO_2 management roles. Ensuring continuity of employment in these transitioning industries is also a strategic priority, given their economic significance and depth of operational experience.

To facilitate the green transition, insights from across the board will help steer what each group of vital stakeholders should consider when addressing sustainability education.

Policymakers:

- Embrace innovation by integrating emerging technologies like artificial intelligence (AI), which can forecast trends in the green sector.
- Build strategic partnerships to enhance the transition from education to employment, developing skilled professionals with practical, market-driven sustainability education.
- Actively engage youth to equip them with essential skills to address sustainability challenges and support the green transition.

The private sector:

- Embrace a comprehensive understanding of sustainability principles to drive economic growth and meet emerging market demands.
- Invest in talent development, promoting lifelong learning among students and employees and equipping them with green skills.

Educators:

- Leverage technological advancements and best practices to create personalized, gamified, and hands-on content, to instill sustainability concepts.
- Integrate sustainability across different education stages, encouraging critical thinking and lifelong learning to promote green habits, help youth analyze their sources, and avoid misinformation.

4.5.4 Consortium building

Consortium building and industry–academia collaboration are critical components for advancing CO_2 storage technologies and ensuring their successful deployment. In India, these collaborative efforts can significantly accelerate the development, scaling, and adoption of CO_2 storage solutions. Here's how they can act as enablers or accelerators:

Data sharing and standardization

Data sharing and standardization are crucial for advancing CO_2 storage technology. A data consortium facilitates the sharing of geological data, monitoring data, and modeling results across different projects and organizations. Larger, more comprehensive data sets improve the accuracy and reliability of CO_2 storage models and simulations. Standardizing data collection and reporting protocols ensures consistency, making it easier to compare results and share findings. This collaborative approach accelerates learning cycles, enabling faster identification of best practices and pitfalls.

Enhanced innovation and technology transfer

Industry collaboration ensures that research efforts are aligned with practical needs and market demands, fostering innovation that is both cutting-edge and commercially viable. Industry partners provide facilities for prototyping and piloting new technologies, speeding up the development process. Established industry players also help navigate pathways to commercialization, including regulatory approvals and market entry strategies, ensuring that research outputs are designed with real-world applications in mind.

International collaboration and knowledge exchange

International collaboration and knowledge exchange are also pivotal. Indian consortia can collaborate with international partners to exchange knowledge, technologies, and best practices. Learning from successful CO_2 storage projects around the world can inform and improve Indian projects. Access to international technologies and expertise can accelerate the development and deployment of CO_2 storage solutions. Joint research initiatives with international partners can expand the scope and impact of Indian CO_2 storage efforts.

In conclusion, consortium building is crucial for accelerating CO_2 storage in India. By pooling resources, sharing data, fostering innovation, aligning with regulatory frameworks, sharing risks, building capacity, and engaging in international collaborations, these collaborative efforts can overcome the challenges associated with CO_2 storage and drive the successful deployment of this critical climate technology.

4.5.5 Policy Support

Based on learnings from global projects, various policy measures and initiatives can be implemented to support CCUS as part of broader efforts to achieve sustainable development and reduce greenhouse gas emissions:

- **Regulatory frameworks** that encourage the development of commercial-scale CCUS projects.
- Implementation of an attractive carbon pricing mechanism and financial support from regulators to improve producers' willingness to pay for CCS.
- **Demand for tradeable carbon removal offset credits**, e.g., from bioenergy with CCS (BECCS) as a foundations of technology-based carbon removal.
- Examples include the Low Carbon Fuels Standard in California, trading schemes in China and Korea in Asia, and an incentive mechanism in Australia to reward CCUS projects.

4.5.6 Financial Incentives for CCUS

Incentives for CCUS in India can help drive the adoption and development of this technology, which is essential for mitigating climate change.

- **Tax penalties on CO_2 emissions:** Example from Norway (Sleipner).
- **Tax credits** from removed or avoided CO_2 emissions: Example from the United States.
- CO_2 credits and allowances (**carbon markets**): (i) Mandatory (such as EU ETS) and (ii) Voluntary (such as Verra, Gold Standard, etc.)
- Carbon Border Adjustment Mechanisms: Example from the European Union.
- Contract for difference (state aid): Example from the United Kingdom.

In addition to financial incentives, the government can also play a role in de-risking CCUS projects. This could include providing guarantees or insurance for CO_2 storage sites or funding research and development to reduce the costs of CCUS technologies. By reducing the risks associated with CCUS projects, the government can help attract private investment and accelerate the deployment of the technology.

In the Indian context, policy and financial incentives will need to be tailored to the country's specific challenges and opportunities. This could include targeted incentives for industries that are particularly well-suited to CCUS, such as the cement and steel industries, as well as support for the development of transport and storage infrastructure in regions with suitable geology for CO_2 storage.

4.5.7 CCUS Business Models

Developing viable business models for CCUS in India is essential for promoting investment and scaling up the technology. Below are some potential CCUS business models tailored to India's unique economic and industrial landscape:

- **The hub-based CCUS Model can help capture 65- 70% of the demand for CCUS in India**
- Driving **willingness to pay** for CCUS storage and transport through regulatory interventions can help increase commercialization opportunities in cement, chemicals & plastics, and EOR.
- CCUS-As-a-Service, Cluster Integrator and Transportation and Compression Pure Play could be **potential business models for CCUS in India**.

4.5.8 Infrastructure and Resource Development

The development of infrastructure and resources is a critical enabler for the deployment of CCUS technologies. This includes the development of transport and storage infrastructure, as well as the availability of resources such as water and energy.

In India, the development of CO_2 transport infrastructure, such as pipelines, will be essential for connecting industrial sources of CO_2 with suitable storage sites. This will require significant investment in new infrastructure, as well as the repurposing of existing infrastructure where possible.

The availability of suitable storage sites is another critical factor. This includes the identification and characterization of geological formations that are suitable for CO_2 storage, as well as the development of monitoring and verification systems to ensure the long-term safety and integrity of storage sites.

In addition to transport and storage infrastructure, the availability of resources such as water and energy is also important for the deployment of CCUS technologies. This includes ensuring that there is sufficient water for CO_2 capture and storage operations, as well as the availability of energy for CO_2 compression and transport.

In the Indian context, infrastructure and resource development will need to be tailored to the specific conditions of the country. This includes addressing the challenges of developing infrastructure in remote or rural areas, as well as ensuring that resources are used efficiently and sustainably.

Key recommendations

To successfully implement CO_2 storage and transport in India, several key enablers are essential. A robust risk assessment and management framework is necessary to anticipate and mitigate risks such as CO_2 leakage and reservoir integrity. Tools like the Integrated Carbon Risk Assessment Tool (IACRAS) can help India proactively address uncertainties in carbon storage.

Public outreach and engagement are critical for gaining community support, as public awareness of CCUS remains low. Transparent communication about risks and benefits, early stakeholder involvement, and addressing local concerns are vital for overcoming public resistance.

Building human capital through capacity building and skill development is another key enabler. New educational programs focused on sustainability and technical skills are needed to prepare the workforce for roles in the CCUS sector.

A consortium building between industry, academia, and government can enhance innovation and technology transfer by pooling resources and expertise. Collaboration can accelerate progress in developing scalable CO_2 storage solutions. It is estimated that the R&D needs of geological storage, including basic R&D and pilots, would be approximately Rs. 3000 Cr.

Finally, infrastructure development and policy support are critical for success. Investing in CO_2 transport networks, such as pipelines, and integrating renewable energy into operations will improve efficiency. Supportive policies, including carbon pricing and financial incentives, will encourage investment and foster the growth of CCUS technologies in India. By utilizing these enablers, India can significantly advance its CO_2 storage and transport capabilities.

4.6 An Overlap with Carbon Dioxide Removal (CDR) Technologies

Carbon dioxide removal (CDR) refers to a suite of approaches that seek to remove atmospheric CO_2 and store in geologic formations, soil/land, ocean beds or durable products. Since the flux of carbon in CDR approaches is from the atmosphere to the geosphere (i.e., reverse of fossil fuel combustion), these are also referred to as negative emissions technologies (Renforth et al, 2023). Removal of legacy carbon emissions from the atmosphere is a necessity to mitigate climate change and limit global temperatures to 1.5/2°C. Estimates in the IPCC Sixth Assessment Report show that global CDR deployment would have to reach 7-12 $GtCO_2$/year for economywide net-zero emissions (Clarke et al, 2022).

The key difference between CDR and CCUS is that, while CCUS focuses on the capture and conversion/storage of CO_2 emanating from point-sources such as flue gas from power plants and hard-to-abate industries (e.g., steel, cement, refineries, and fertilizer plants), CDR, on the other hand, seeks to counter legacy emissions that are already in the atmosphere. While this is a key difference between these two approaches, the similarity between CCUS and CDR technologies is the ultimate storage/sequestration of the captured carbon, irrespective of its origin, within geological sinks or in durable products. Keeping this in mind, India's stand has been to include CCUS under "removal activities" as reflected in the list of activities mentioned in Article 6.2 of MoEFCC that are eligible for trading of carbon credits under bilateral/ cooperative approaches (*OM No. CC-130081238/2022-CC (E-187765) dated 14.07.2025*).

This roadmap is limited to India's R&D strategy for CCUS technologies. However, given the importance of CO_2 removal and some overlap with CCUS, a short summary of CDR is included here.

A separate strategic document for R&D on CDR technologies is perhaps needed.

Some of the well-known CDR technologies with their current TRL status, regional potential and associated cost estimates are listed below:

Technology	Country-specific status	Key states/regions	Costs
Afforestation/ reforestation	High: TRL-9. Government of India intends to sequester 2.5–3.0 Gt-CO_2.	Rajasthan, Madhya Pradesh, Karnataka, Andhra Pradesh, Odisha, West Bengal	\$4–25/t-CO_2
Biochar sequestration	Medium: TRL 3–6. Detailed estimates and protocols published. Lab analyses carried out.	Uttar Pradesh, West Bengal, Bihar, Chhattisgarh, Andhra Pradesh, North Eastern States	\$20–50/t-CO_2
Enhanced rock weathering	Moderate: TRL 6. Lab characterization and field implementation carried out.	Maharashtra, West Bengal, Madhya Pradesh, Jharkhand	\$80–180/t-CO_2
BECCS	Low: TRL 3. Proof-of-concept analysis carried out.	Gujarat	\$200–250/t-CO_2 (without EOR), \$20–40/t-CO_2 (with EOR; but may undercut carbon removal)
DAC	Very Low: TRL 1	—	\$225–600/t-CO_2

Source: Modified after Chaturvedi et al, 2024, reproduced under the Creative Commons Attribution 4.0 license.

Among the above CDR strategies, India is already a global leader in afforestation/reforestation (AR), having created 1.97 billion tonnes of additional carbon sinks between 2005-2019 (MOEFCC, 2024) and a further goal of removing 2.5-3 $BTCO_2$ by 2030 through AR. While AR is central to mitigation pathways, it is limited in the amount of carbon that can be stored per unit land area as terrestrial biomass yield is usually limited to 20-40 t/ha (Posten and Schaub, 2009). The key research directions for AR are improved estimates of the carbon sinks by linking top-down and bottom-up inventory approaches, and monitoring the durability of said sinks.

Land CDR approaches with the largest potential (>10 $BTCO_2$/year at a global level each) are bioenergy with CCS (BECCS) and direct air carbon capture with storage (DACCS) (Smith et al, 2016). Like CCUS, these approaches are anticipated to directly benefit from growth in physical infrastructure - for CO_2 transport and geologic storage. However, the costs of BECCS (\$200-250/tCO_2) and DACCS (\$250-600/tCO_2) are well beyond CCUS. Therefore, we recommend the following research directions for these CDR approaches: (a) scale-up of CO_2 transport and storage technologies, (b) biomass co-firing in coal-fired power plants with CCS, (c) innovation in direct air capture with durable products (Vishal and Singh, 2023).

Another commonly discussed land-based CDR is in the form of biochar, which entails conversion of biomass via slow-pyrolysis. We suggest the following research directions for this class of CDR technologies: (a) use of farm residues and other waste biomass, (b) use of biochar in steel making coupled with CCS. As per the Green Steel roadmap produced by the Ministry of Steel, biochar can reduce the import dependence of coking coal by supplementing it in steel making (MOS, 2024).

In addition to land-based approaches, marine CDR is also considered as an important potential area to generate additional sinks. Several approaches have been discussed in the context of marine CDR. These include, but are not limited to (Doney et al, 2025):

- Ocean alkalinity enhancement (OAE): addition of alkalinity from enhanced weathering to alter ocean chemistry and remove CO_2 from the atmosphere.

- Seaweed cultivation and sinking: producing macroalgal biomass using photosynthesis and sinking into deep ocean sediments.

- Nutrient fertilization: addition of macro- or micro-nutrients to the ocean to increase photosynthesis by phytoplankton.

Some of the difficulties in marine CDR approaches are (a) nascent TRL (4-7), (b) uncertain costs, (c) lower durability of carbon storage compared to geologic storage, (d) uncertain quantification of the additional ocean sink created over and above natural sinks (Bach et al, 2025).

Like for CCUS, measurement, reporting, and verification (MRV) is a critical framework for ensuring transparency, accountability, and scientific integrity in CDR technologies, as well as provision of finance. It provides standardized methods/metrics to quantify CO_2 removed, track project performance, and independently verify outcomes. While India has developed robust capabilities through its national greenhouse gas inventories, forestry assessments by the Forest Survey of India, and compliance mechanisms under the Paris Agreement, scaling MRV for engineered CDR will require India-specific protocols. In particular, this would include baseline and additionality definitions for individual subsectors. Accelerated R&D efforts in MRV would include regionally calibrated monitoring approaches, expanded satellite and field-based observation systems, extensive data collection and analysis, and robust verification frameworks tailored to the country's diverse ecosystems, geological settings, and agricultural landscapes.

Given that CDR costs are well above $100/t-$CO_2$, financing such projects from international institutions such as the Green Climate Fund and multilateral development banks will be important, failing which the large cost would not justify investments (Garg et al, 2023).

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CHAPTER 5

FUNDING SCHEMES, FINANCING MODELS AND POLICY FRAMEWORKS

FINANCING MODELS, FUNDING SCHEMES & POLICY FRAMEWORKS FOR CCUS

5.1 Introduction

The impact of climate change is already evident, calling for immediate and urgent actions. The development and implementation of CCUS technologies require huge investments to achieve the Net Zero targets by 2070. CCUS comprises three key elements: capture, sequestration or conversion, and storage & transport. All of these are fraught with risks associated with either economic viability or safety. While capture technologies have reached reasonable Technology Readiness Level (TRLs), the hazard assessment of storage technologies and significant scale-up of conversion technologies are still not fully complete. To this end, it is critical to have committed funding schemes and financial models that can provide patient capital for CCUS technologies.

The readiness of CCUS technologies presents a wide spectrum, ranging from fundamental studies to commercial implementation. Many advanced technologies are still not economically viable and hence its implementation adversely impacts market competitiveness. A widespread implementation is still a long shot. To boost the entire value chain of CCUS technologies, there is a need for differentiated, targeted and synergistic approach. This will require long-term investments keeping following fundamentals in perspective: (a) Funding at every stage of value chain (as shown in Figure 5.1), (b) Time-bound incentives from government and industries, (c) Synergy of all stakeholders such as industries, governments, philanthropic organizations, national and international consortiums, and financial institutions, (d) Customizable approach based on target, need and context. Collectively, this will ensure a holistic technology growth and capacity building through breakthrough science, innovative translation, and large-scale deployment.

Figure 5.1: Funding mechanism to accelerate the efforts toward Net Zero.

5.1.1 Funding breakthrough science

Investment in fundamental research is the bedrock for the generation of deep intellectual rights and the development of self-reliant technology. To reduce the dependence on technology imports, we need national mission such as "Invent-in-India" to realise the dream of Atmanirbhar Bharat and to achieve the target of net zero. Unravelling the climatic situation and growing impetus to sustainable technologies with a special focus on CCUS technologies presents one such opportunity to establish ourselves as a world leader. This calls for strong funding support at the nucleating stage, and a commitment from the research community engaged in CCUS activities to use organically cured collaboration to develop unique technologies and products to support CO_2 capture, utilization, storage, and sequestration efforts. The silos need to be broken to accelerate high impact fundamental research through the following efforts:

- **Thematic Centres of Excellence (T-CoEs):** Establishing thematic CoEs will help in boosting research in the targeted domain of CCUS technologies (some CoEs are shown in Figure 5.2 for reference). These centres can have unique focuses on various processes, materials, products, and technologies dealing with thematics such as Direct Air Capture (DAC), or point source Carbon Capture, Carbon Storage, and Utilization. Special thematics have to be evolved around the value chain to ensure the development of each aspect of CCUS value chain through various T-CoEs. A few examples are presented below:

Figure 5.2: Thematic centres for catering the needs of various facets of CCUS technologies.

- **National Centre of Excellence (NCoE) on CCUS:** DST has established 3 National Centres of Excellence at Indian Institute of Technology (IIT) Bombay, Jawaharlal Nehru Centre for Advanced Scientific Research (JNCASR), Bengaluru and CSIR-National Environmental Engineering Research Institute (CSIR-NEERI) to accelerate the efforts towards net zero. A similar initiative can be seen by the Gulf Organization that established the Centre of Excellence research & development. It is the promoter of the Global Carbon Council and supports governments and the private sector with capacity building and development of its new methodologies on Carbon Capture and Storage (CCS) and Nature-Based Solutions (NBS).

- **Cluster of Excellence:** A Cluster of Excellence is a specialized, interdisciplinary research network that brings together academic institutions, research organizations, industry stakeholders, and policymakers within CCUS technologies. It will be a unique consortium that can synergize the efforts and initiatives of plenitude of Centre of Excellence having cross-disciplinary expertise. The focus is to provide impetus in enhancing the technology readiness level and system readiness level by providing a seamless platform to a gamut of researchers for technology deployment. UniSysCat is one such example of cluster of excellence as shown in Figure 5.3.

UniSysCat, Technische Universität Berlin, (Cluster of Excellence):
https://www.unisyscat.de/

- 300 researchers from 4 universities and 4 research institutes in the Berlin and Potsdam
- Unites biologists, chemists, engineers and physicists
- Partnership: Academia, Research Network, Knowledge Transfer
- Hosts ***Chemical Invention Factory*** (CIF) - a working space for young entrepreneurs.
- Joint lab of UniCat and BASF: BasCat as interface for industrial translation
- Financed by the ***Excellence Strategy*** funding programme of the Federal Government and the Länder in Germany

Figure 5.3: An example of center of excellence represented by UniSysCat.

- **Nurturing Mechanisms for Disruptive Science:** We need to build mechanisms to be able to harness Disruptive Science for creating indigenous CCUS solutions in India and for India as well as for the world. CCUS solutions that use AI tools and integrates AI-ML for searching innovative DAC sorbents, catalyst design, parallel reactors for synthesis, and catalytic evaluation, will enable creating a feedback loop to continuously improve and upgrade upon CCUS systems. These disruptive breakthroughs are an inspiring model for innovation, and while India may not have a dedicated centre yet to harness this Disruptive Science, with focus and collaboration, DST can work towards building similar capabilities in the near future with significant investments by relevant Industries following Public Private Partnership (PPP) mode.

Orbital Materials, founded in 2022 by chemists from a university in New Jersey, is a startup developing artificial intelligence tools to accelerate materials discovery. The company has built an AI model that predicts the characteristics of new materials using available datasets, computational simulations, and experiments conducted in its own. Orbital applies this model to search CleanTech materials, including catalysts for bio-based chemical manufacturing and a sorbent designed to capture carbon dioxide more affordably than existing methods. Its software evaluates how randomly arranged atoms interact, then use the information to restructure them to converge on promising material designs. From its advanced R&D facility in Princeton, Orbital uses its proprietary AI platform to design, synthesize, and deploy climate-focused materials far faster than traditional research approaches. The company has attracted substantial investment from companies such as NVentures, Toyota Ventures, and Radical Ventures etc.

5.1.2 Funding innovation through translational R&D

Achieving the target of net zero requires translation of breakthrough science in CCU or CCS from TRL 1-2 (conceptual ideation) to TRL 3-4 (proof of concept), and further to TRL 5-6 (prototyping and demonstration). Such an effort to cross the proverbial Valley of Death requires large investments and dedicated efforts of multiple stakeholders, such as government, networks (national and international), industry, and academia. A cross-functional team from research, economics, policy, legal, management, environmental, and social science is required for proper evaluation, execution and development of such a facility which can be easily understood by the schematic represented in Figure 5.4. Models for novel public-private partnerships in research and innovation, featuring industry-led and government-supported models, will have to be strengthened. Solution to complex CCUS problems will require breaking down of silos so that high-impact translational research can be accelerated to achieve technology validation and advancement to Market Readiness Level (MRL). The following model is proposed to support translational research of standalone CCU or CCS technologies:

Figure 5.4: Multifaceted partnership for synergizing the efforts of key stakeholders.

- **Funding National Test facilities:** Building national test facilities for CCUS will be an asset for the sustainable future of the country. It will be aimed at driving innovation and validating technologies at a near semi-commercial demonstration scale. These facilities will require significant investment to provide the necessary infrastructure and technical support for large-scale testing and validation. Examples of some research institution and their financing sources and management strategies can be seen in Figure 5.5.

  a) Barrier-less platform for validating and testing innovative CCUS technologies, by academia, researchers, research & technology organizations and industries.

  b) Designed for the evaluation of potential risks and challenges, and subsequently plan mitigation strategies prior to full-scale technological deployment.

  c) Openly accessible platform for knowledge sharing and showcasing available technology for advisory and licensing.

d) Joint consortia between various relevant Industries, Governmental agencies like DST and /or other line ministries, research networks/organizations and academia.

Key Drivers@ NCCC

- Advance innovative carbon management solutions toward deployment: Neutral Testing Site
- Bridge the gap between the labs and large scale demonstrations
- Serve as the U.S. Department of Energy's Primary Carbon Capture Research Facility
- Located at Alabama Power's Plant Gaston in Wilsonville, Alabama

Financing & Management

- Cost-shared collaborative venture
- Funding: DOE and its Office of Fossil Energy and Carbon Management and National Energy Technology Laboratory
- R&D investment through private-sector sponsorships, including energy industry leaders, industrial and technology participants and prominent policy advocates
- Managed and operated by Southern Company

Key Drivers @ TCM

- World's largest neutral facility for testing and improving CO_2 capture technologies
- Demonstration at large scale in a real industrial environment: TRL-7
- Reduce the cost of decarbonising and accelerating the transition to a low carbon future

https://www.projectaccsess.eu/partners/technology-centre-mongstad/

Financing & Management

- Joint venture between the Norwegian state (managed by Gassnova), Equinor, Shell and TotalEnergies
- Proprietary tests for the largest technology developers, as well as non-proprietary campaigns funded either by Technology Centre Mongstad (TCM) owners or governmental agencies
- Partner of larger ACCSESS consortium

ACCSESS

The ACCSESS consortium brings together 18 partners from eight countries, combining leading technology and research expertise across the entire CCUS value chain. It also includes specialists in key supporting areas such as financing, business model development, legal and environmental issues, and public perception and acceptance. The project focuses on applications in the pulp and paper industry, cement production, waste-to-energy facilities, and biorefineries.

Figure 5.5: Examples of international centres with key driving principles and financing models.

5.1.3 Funding up-scaling and Technology integration (upto TRL 6)

DST must identify 2 or 3 hard-to-abate sectors in which mature CCUS technologies can be scaled up and integrated. This can be done by bringing together a cohort of stakeholders, including academia, research institutes, and industry, to build an integrated industrial-scale CCUS hub/valley. The same will require consensus building with line ministries such as the Ministry of Power, Ministry of

Petroleum and Natural Gas, Ministry of Steel, Ministry of Heavy Industries, among others, along with DST to co-fund such projects through integration or new installations at large scale. To successfully implement such ambitious targets, two types of financial models and funding schemes are suggested:

(a) Firstly, funding is required for strengthening key enablers such as building the infrastructure of CO_2 pipelines connect the capture points to the vicinity storage wells in the envisaged CCUS valleys/hubs. Government can support such infrastructure investments in the valleys/hubs by means of viability gap funding over and above the earnings prorated based on facility usage. Funding could also be sought from CSR (Corporate Social Responsibility) initiatives of corporates/industries. In any case, there is a need for the development of appropriate business models for financing across the entire CCUS value chain, capturing potential risk factors.

(b) Secondly, the costs associated with capturing and concentrating CO_2 should be borne by the polluters aligned to "the polluter pays principle". However, implementing this principle is complex and may require international support through mechanisms such as CO_2 taxes and funding from global financial bodies.

Formulation and Structure of CCUS Hubs

A CCUS hub takes carbon dioxide from several emitting sources, and then transports and stores it using common infrastructure for utilization and/or sequestration.

Benefits and advantages

❑ Reduced cost per unit	I Maximise profits
❑ Enable consistent processes across operations	I Reduce investment risk through market diversification
❑ Enhance overall profitability	I Abrogate bilateral agreements (sources & sinks)
❑ Scale up quickly	I Lowers coordination complexities

Northern Lights Hub: This innovative public–private initiative in Norway relies on ships to collect CO_2 from various locations across Europe and store it in a shared storage site beneath the North Sea. During its initial phase, subsidized 80% by the Norwegian government, the project will handle 800,000 tonnes of CO_2 emission annually, sourced from the Brevik cement plant and the Hafslund Oslo Celsio waste-to-energy plant in eastern Norway.

https://ccushub.ogci.com/focus_hubs/northern-lights/

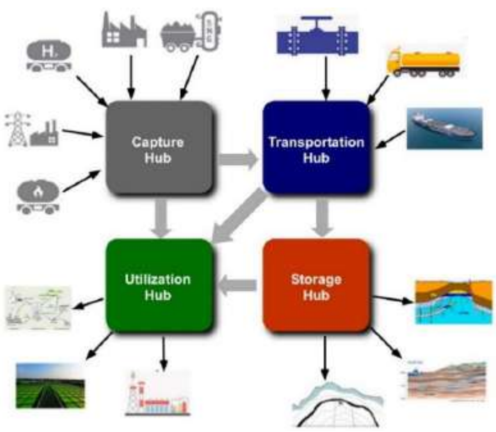

Figure 5.6: Schematic showing types of CCUS hub.

DST aims to establish CCU/CCS hubs in line with the European efforts like Longship-Northern lights and Scottish Cluster-Acorn based on the geographical hotspots identified in the country with industrial point sources from hard-to-abate sectors and potential storage sites in the vicinity.

The successful CCU/CCS hubs are envisioned to lead to the evolution of CCUS valleys that will be created by merging the individual hubs established at the identified hotspots, covering and showcasing the entire CCUS value chain seamlessly (Figure 5.6). Each valley is envisaged to have the value chain dovetailed with suitable business models with associated off-takers like relevant industries and customers. The financial viability of the life cycle will be incentivized through conversion of captured CO_2 into value-added products, further economic incentives like Carbon Trading, credits and Viable Gap Funding will also be incorporated in the value chain to make the CCUS lifecycle more economically feasible.

5.1.4 Funding Collaborative Capacity Building and Technology Acceleration

Broadly, the requirement and potential for capacity building in Research and Development in the Indian context spans over entire value chain of carbon capture, utilization, and storage. Capacity building would help accelerate and mature CCUS technologies. India should leverage several multilateral and bilateral programs focused on collaborative capacity-building efforts to facilitate the development of innovative technologies at higher TRLs in the CCUS domain. These programs would facilitate opportunities for Indian researchers to visit potential laboratories, pilot plants, and demonstration plants to learn about the implementation of novel CCUS technologies and methodologies, especially those that are amenable to Indian requirements with suitable engineering. These exchanges should promote knowledge sharing for enabling the participants to disseminate their learnings to researchers on either side. Specifically, the program objectives should be envisaged to: (a) Promote research, innovation, and capacity building in CCUS, (b) Develop potential long-term R&D linkages and collaborations, (c) Provide top Indian academics, scientists, and researchers the chance to access and gain exposure to leading global CCUS research and demonstration facilities.

5.2 International Funding/ Financing Models

International funding and financing models are crucial for advancing CCUS technologies and support their large-scale deployment. The World Bank (WB) has various funding mechanisms such as Climate Investment Funds (CIF) and Green Bonds to facilitate investment in CCUS technologies (Figure 5.7).

5.2.1 Climate Investment Funds (CIF)

The CIF is a large multilateral fund housed within the World Bank that supports climate action projects, including CCUS, particularly at higher TRLs. It manages two major funds relevant to CCUS: the Clean Technology Fund (CTF) and the Strategic Climate Fund (SCF).

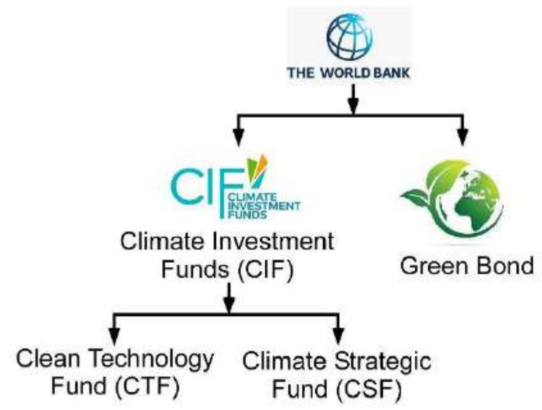

Figure 5.7: International funding through world bank.

- **Clean Technology Fund (CTF):** CTF offers substantial financial support for investing in clean technology in low- and middle-income countries. Its resources help demonstrate, deploy, and transfer low-carbon technologies that have strong potential to cut long-term greenhouse gas emissions. The facility can also back CCUS initiatives that aid in emission reduction or decarbonization efforts. To encourage public and private investment in low-carbon solutions, the fund employs a mix of financial tools, such as grants, contingent grants, concessional loans, equity, and guarantees, making these technologies more financially appealing.

- **Strategic Climate Fund (SCF):** The SCF funds the piloting of innovative methods and the scaling up of operations that target specific climate change problems or sector-based solutions. SCF provides financing for piloting innovative approaches or scaling up activities aimed at specific climate change challenges or sectoral responses.

5.2.2 Green Bonds and Climate Bonds

Green bonds and climate bonds are types of fixed-income instruments used to finance projects that deliver environmental benefits. The World Bank has been a leader in issuing Green Bonds, which support projects focused on cutting greenhouse gas emissions and advancing sustainable development. The World Bank's processes for issuing green bonds have become international best practices, known as the Green Bond Principles. For example, countries or companies could apply for green bond financing through the World Bank to support the construction or expansion of CCUS-related projects and or infrastructure.

5.2.3 International Finance Corporation (IFC)

IFC International Finance Corporation WORLD BANK GROUP

As a part of the World Bank Group, the International Finance Corporation (IFC) is instrumental in promoting private sector growth and can offer financing, loans, and equity investments for climate-focused initiatives, including CCUS projects. The IFC is particularly interested in financing projects that promote sustainability, innovation, and technology transfer in developing and emerging markets.

There are two types of Incentive Mechanisms devised by the World Bank:

5.2.4 Carbon Pricing Leadership Coalition (CPLC)

CARBON PRICING LEADERSHIP COALITION

The CPLC is an initiative led by the World Bank that brings together governments, private sector companies, and NGOs to advance carbon pricing policies and market-based instruments. CCUS could benefit indirectly from CPLC activities as these policies incentivize the deployment of CCUS by placing a price on carbon emissions.

5.2.5 Carbon Credits and Market Mechanisms

If nations adopt carbon pricing systems, such as carbon taxes or cap-and-trade programs, CCUS projects that lower emissions could earn carbon credits, helping improve their financial viability.

5.2.6 Partnership for Market Readiness (PMR)

pmr | PARTNERSHIP FOR MARKET READINESS

The Partnership for Market Readiness (PMR), another World Bank initiative, offers financial support and technical guidance to help countries design and implement market-based carbon pricing systems. Countries that adopt carbon markets or carbon taxes could integrate CCUS into their national strategies for reducing emissions.

Through the PMR, countries could also receive support to capacity building and pilot CCUS projects, particularly in hard-to-decarbonize sectors, as part of broader national climate change mitigation efforts.

5.3 DST's Action Point for CCUS Roadmap

5.3.1 Recommendations to Support CCUS Initiatives

Based on the discussion in this chapter, DST will strive to mobilize considerable amount of resources to fund fundamental science as well as direct initiatives for translation of successful technologies to higher technological readiness level. Such an effort will require the support of all relevant stakeholders from various ministries, start-ups, industries and philanthropic organizations at various stage of development adopting highly specific yet differentiated approach. At the same time, it is important to tap into various international agencies through multilateral or bilateral programs to seek funding and technical know-how in accelerating the efforts towards net zero targets. There are three levels of funding that are expected to nurture the CCUS ecosystem in India, as depicted in the below illustration (Figure 5.8). These could be available partially through DST and remaining through other sources. It is highly recommended that a new and ambitious National CCUS mission be launched with appropriate schemes and policy support for incentivizing and encouraging all stakeholders for greater engagement.

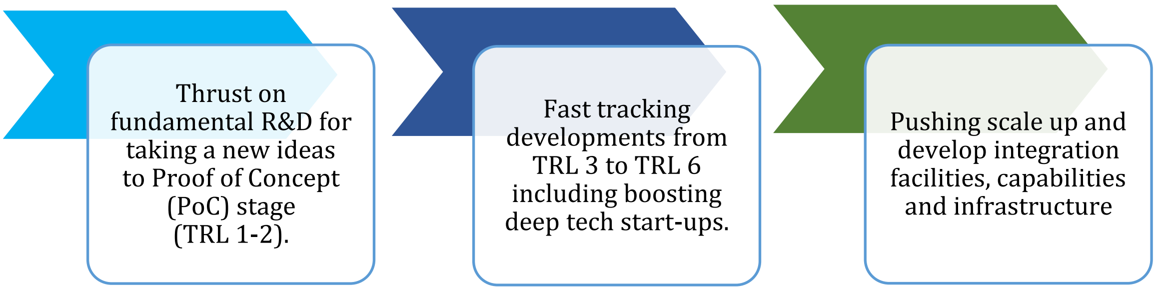

Figure 5.8: Different levels of funding by DST to nurture CCUS efforts.

5.3.2 Funding Mechanisms

Promoting the early adoption of CCUS can be achieved by supporting R&D, demonstration, and pilot projects. These programs can generate crucial knowledge and experience while reducing high capital costs and commercial and technical risks. An effective funding mechanism focused on supporting R&D and demonstration projects with clear targets and timelines will help generate essential knowledge and expertise, enabling the quick scale-up of CCUS. Additionally, this funding mechanism will facilitate the improvement of technology developed with academia and R&D labs from low TRL (≥5) to high TRL (≥8) for commercialization by the industry.

❑ **Foster Partnerships between Public and Private Sectors**

- **Sector-Specific Programs:** DST, with its Network of Experts, should identify sector-specific needs and promote participatory collaboration between academia, research, and industry, focusing on scalable projects/test beds for encouraging collaboration to pool resources, expertise, and funding for the successful implementation of CCUS technologies, ensuring a synergistic approach towards achieving Net Zero targets. Innovative funding models need to be devised for the sector specific interventions with relevant industries participating as technology providers and academia/research groups as knowledge partners . DST and relevant industries can co-fund these interventions in PPP mode. The involvement of both the public and private sectors can offer regulatory support, funding, innovation, technical expertise, sharing of risks and benefits and operational efficiency. Integrating the entire CCUS value chain in R&D valleys and hubs in partnership with relevant Industries is another approach DST should explore for accelerating the CCUS technologies.

- **Technology Acceleration:** DST can identify 2 or 3 hard-to-abate sectors and pursue CCUS technology acceleration and translation in those sectors, using a strong academia-research-industry collaboration. Line Ministry and DST can co-fund such projects that are at sufficiently large sizes which can be scaled and integrated with the industry. This will bring synergy in various CCUS initiatives and would require the development of a uniform model.

- **Facilitating Collaboration:** The Government can play a pivotal role in facilitating collaboration by creating platforms and initiatives that encourage joint efforts. This includes setting up forums for regular interaction between public and private entities, promoting transparency, and ensuring that all stakeholders are aligned towards common goals. Effective collaboration can accelerate the development and deployment of CCUS technologies.

- **Multi-Industry Collaboration:** Actively encourage collaboration among various industries to promote knowledge sharing and joint efforts in implementing CCUS solutions. The Government can establish forums or platforms where industries can share best practices, challenges, and innovations related to carbon capture, utilization, and storage. By sharing resources and expertise, industries can achieve greater efficiency and effectiveness in deploying CCUS solutions. Collaborative efforts can also lead to the development of standardized practices and technologies, enhancing overall industry performance. This precompetitive research through Multi Industry consortia approach will allow industries to share the risks and benefits associated with early-stage research, fostering innovation without compromising competitive advantages. By forming consortia, industries can increase their resources, expertise, and knowledge, leading to more robust and comprehensive research outcomes. This collective effort can accelerate the development of breakthrough technologies. Additionally, multi-industry consortia can address common technical and scientific challenges faced by all participants, ensuring that solutions are broadly applicable and beneficial to a wide range of industries. Leveraging public funding and government support for these consortia can further amplify the impact of their research efforts, attracting substantial investment and fostering the commitment to advancing CCUS technologies.

- **Funding CCUS Micro, Small, and Medium Enterprise (MSMEs) and Start-ups:** Enable them to bring their solutions to the market thereby accelerating CCUS technologies, making them more viable, and driving economic growth while meeting net zero targets. Engagement of MSMEs and start-ups with industry can be promoted through special PPP funding models and by leveraging CSR funding.

- **Business Model:** There is a need for the development of appropriate business models for financing across the entire CCUS value chain. Business models need to be developed for covering the risk factors around the lifecycle of CCUS chain. Viable gap funding models can be explored for de-risking and acceleration of the technology value chain.

- **Stage Gate Approach for CCUS:** At every stage, clear deliverables and criteria will be established, which will in turn guide funding decisions for the next stage. Using a staged approach will also support the development and refinement of the technology transfer framework, as the technical details and engineering interdependencies across the project life-cycle become more fully understood. It will be important to clearly define the technology interface points so that, once the project is underway, performance responsibilities are well allocated and upheld by all parties involved.

    a) **Cost Sharing and Project Contributions:** Project partners should contribute to the cost share at each stage, ensuring a vested interest in the project's success. This approach promotes accountability and ensures that all stakeholders are committed to achieving the project's goals. Cost sharing also helps leverage additional funding and resources, enhancing the overall project budget.

b) **Developing Technology Transfer Models:** A staged approach will support the development and refinement of potential technology transfer models. As the project advances, the technical details and engineering interdependencies throughout the project lifecycle become more transparent. It is essential to define the technology interface points precisely so that, once the project is executed, performance responsibilities are clearly assigned and upheld by all parties. This clarity ensures that each stakeholder understands their role and expectations, promoting seamless technology transfer and deployment.

DST should leverage funding through policies and missions implemented by other ministries such as a National CCUS Mission, CO_2 mitigation incentives, CO_2 credits, and CO_2 taxation as and when they become available.

Funding Recommendation

- DST needs to develop mechanisms of funding to focus on blue-sky research or disruptive science, inculcating pioneering new concepts and innovative solutions in CCUS, nurturing "research without a clear goal. Because of the inherently uncertain return on investments, blue-sky approach in CCUS will require a structured mechanism based on a well-defined research and techno-economic matrix. This will include developing novel materials for capturing CO_2, highly efficient catalysts and innovative processes for converting CO_2 into valuable products, new ways for CO_2 storage, and creating better economic models to support CCUS. The goal is to evolve disruptive approaches that could transform the field of carbon capture, utilization, and storage.

- Appropriate funding models need to be evolved for pushing the current state-of-art to the next level of deployment across entire value chain from pretreatment-capture-compression-conversion or storage to developing business models for incorporating CCUS within existing processes or for deploying direct capture processes using incentives, credits and taxation strategies. Viability Gap Funding (VGF) could be used for in the initial phase of large scale integration and deployment of CCUS.

- Besides funding CCUS technology development from TRL 1-8, funding is also needed to support the Indian manufacturing ecosystem for the development, prototyping, and advance manufacturing of many critical components which are otherwise imported. Examples include CO_2 compressors, compact heat exchangers, candle filters, and critical materials such as catalysts, sorbents, amine solvents, membranes etc. India's vibrant MSME sector and start-up ecosystem may be nurtured by DST through suitable incentives or funding mechanisms to enable them to make use of advanced manufacturing processes.

- A carbon credits-based policy is optimal for India, promoting CCUS adoption, lowering capture costs, fostering low-carbon product markets, and industrial de-carbonisation. The recommended framework emphasizes carbon credits or incentives, offering tax and cash credits, and early-stage financing for CCUS projects. Initially, the focus should be on incentives to jump start the sector, while transitioning towards carbon taxes for long-term sustainability, aligning with India's net zero objectives by 2070. Moreover, mechanisms for early-stage financing and funding are crucial components of the policy. DST should actively fund policy research in India that can help develop critical framework for decarbonization through CCUS.

- During the UN Climate Change Conference of Parties (COP29) that was held in Baku, Azerbaijan, in November 2024, as a breakthrough development Carbon Credit Trading has been officially recognized, marking a significant milestone for global Climate efforts. Supervisory body for the creation of carbon credits and standards under Article 6.4 has been recognized. These standards will ensure that the international carbon market has high integrity, and that emissions reductions and removals are real, incremental, verified and measurable. In this context, an innovative funding model Figure 5.9 maybe be explored, based on carbon market incentives to devise sustainable financing mechanisms for creating Hubs/Clusters dealing with Point Source CCUS & DAC - CDR initiatives. This maybe an OPEX based model (Figure 5.9) that will include a project developer who will fund the project and charge an industrial partner a fee per tonne of CO_2 captured/utilised/stored annually. Financing will primarily rely on carbon credits and non-dilutive funds such as DST support, providing a sustainable path for CCUS/CDR initiative. Need is to focus on economies of scale for wider adoption of CCUS in the industry large scale projects of 300 to 500 tonnes per day CO_2 capture, use or storage may be considered. It would enable the assessment of actual cost for industrial scale projects in hard-to-abate sectors. Lower capacity projects would not be able to provide this information regarding implementation and operation of large scale plants.

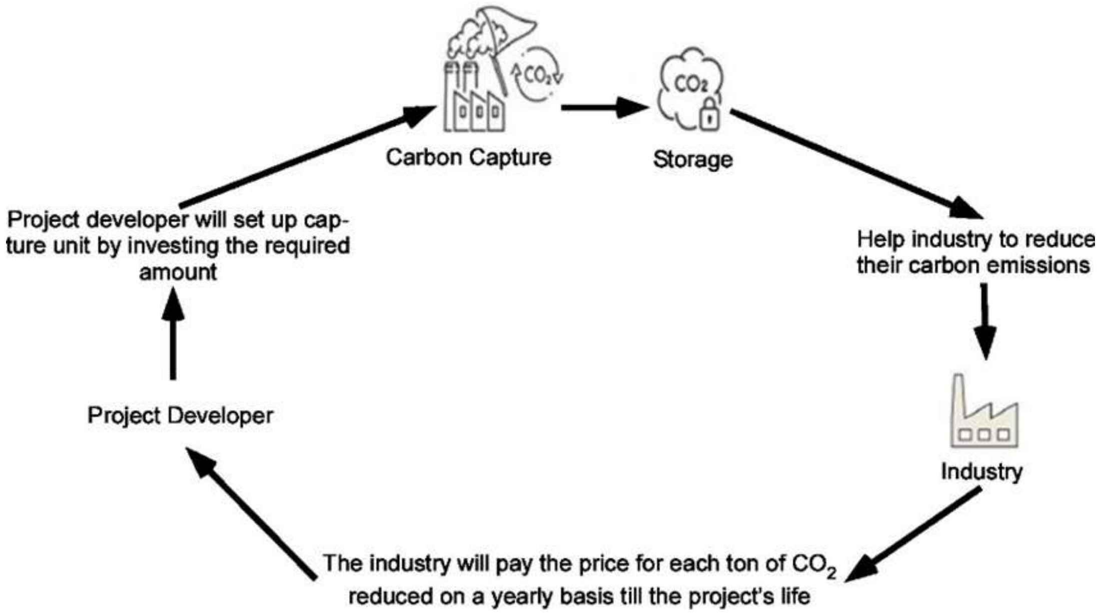

Figure 5.9: Opex based model to fund projects for CCUS technologies.

- **Opex subsidy, the most critical component:** Opex subsidy has been identified as the most critical component in the CCUS business models. It ensures a steady revenue flow for long-term operations. NITI Aayog has also recommended to provide an Opex subsidy of Rs. 2,300 per ton of CO_2 captured. The industry likewise considers this a crucial component of the financial model for CCU projects. Similarly, recommendations have been made for CCS and EOR projects by NITI Aayog, which is very much aligned to the successful global financial models. The Opex subsidy may be introduced as Generation Based Incentives (GBI) on monitoring of captured CO_2, utilised for CCU or CCS operation.

a) **Capital subsidy for Capture plant:** The capture part forms around 60% of the total cost of the overall CCUS chain. At the same time, the capture plant is primarily a cost and by itself, does not contribute to any revenue generation for large-scale CCUS operation (except beverages options at very small scale). Providing a capital subsidy for a capture plant is critical to create a successful business model.

b) **Accelerated Depreciation (AD) for downstream infrastructure, post CO_2 capture:** Post capture of CO_2, downstream activities in the value chain would be transport/direct conversion to products/storage/off-site utilisation. To encourage private sector participation, the post-capture infrastructure should be provided with 100% accelerated depreciation benefit. Apart from the revenue from the sale of the product, in the case of CCU, the AD benefit would help to bridge the viability gap.

c) **Tax holiday on CCUS business model:** Tax holiday models have been well established in India for the scaling of renewable energy projects. A 10–15-year tax holiday system may be introduced into the CCUS business model in the country to further bridge the viability gap funding of the projects.

d) **Availability of 24-hour renewable electricity through 100% RE power banking:** CCUS projects are only sustainable if driven by renewable electricity. In the absence of renewable electricity, the carbon footprint of the captured CO_2 further adds to the overall emissions profile and it becomes a less attractive proposition from an environment and sustainability perspective. To enable CCUS projects with round-the-clock (RTC) RE, 100% RE power banking is required. It would enable upstream partners (RE generators) to setup capacity and provide RTC - RE power to the CCUS operations.

e) **Waiver of RE interstate transmission charges for CCUS operations:** The RE transmission charges should be waivedoff if the same is utilised for CCUS projects. This has already been allowed in Green Hydrogen projects and a similar provision may also be introduced for CCUS projects.

- Grants and tax incentives are designed to encourage companies to explore cost-effective methods for deploying CCUS technologies and to shift the economics in favor of their adoption. Ultimately, the objective is to make CCUS not just viable but commercially profitable. This can be achieved by using captured CO_2 as an input for producing other goods, such as feed-stocks and fuels, thereby converting carbon emissions into a revenue-generating business model. The concept of CCUS valley, which provides a platform for promoting scaleup, integration, demonstration, and techno-economic validation of innovative indigenous technologies through a PPP-VGF funding model across the entire CCUS value chain, is an option that DST should actively explore, either independently or in collaboration with other ministries.

- The acceleration of CCUS activities in India can be significantly bolstered by establishing a functional Carbon Market Mechanism. By creating such a mechanism, India can provide incentives for industries to invest in CCUS technologies and infrastructure. This would involve implementing policies that allow companies to trade carbon credits, encouraging emission reductions and the adoption of cleaner technologies. Additionally, a well-designed Carbon Market Mechanism could also attract international investments and partnerships, facilitating technology transfer and knowledge sharing. Ultimately, the establishment of a working Carbon Market Mechanism in India would not only drive the growth of CCUS activities but also contribute to the country's efforts in mitigating climate change and achieving its sustainability goal.

5.4 Policy Frameworks for CCUS

To accelerate the adoption of CCUS technologies and incentivise the efforts from the academia, research community, and relevant industries, there is a strong need for policy support. The key to a successful CCUS policy for India can be a framework that will envisage to support the creation of sustainable and viable markets for CCUS projects. A comprehensive mix of government policies, incentives, and advanced low-cost technologies with high life-cycle efficiency and minimal environmental impact is crucial. The policy framework should focus on integrating CCUS into India's broader industrial landscape while promoting economic and environmental sustainability.

Coordinated support from both government and industry is essential for helping project developers manage the costs and risks tied to CCUS initiatives, spanning capture, utilization, transport, and storage and for advancing and scaling up CCUS technologies.

The Figure 5.10 below summarises these levers and their associated action points, which the government can facilitate to create a supportive environment for CCUS. This framework is designed to establish the necessary conditions for the effective implementation and scaling of CCUS technologies.

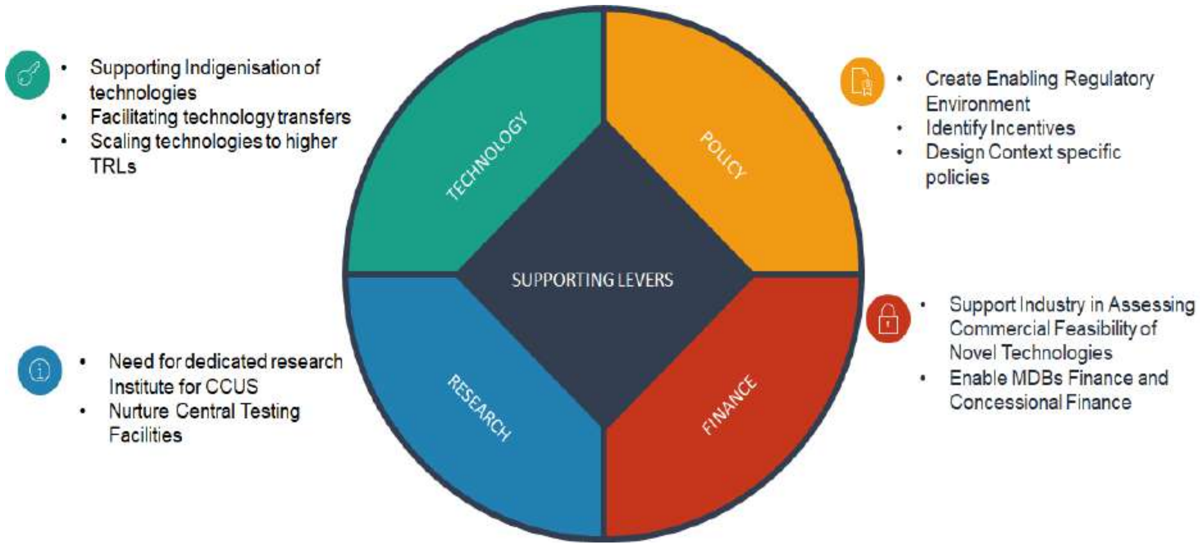

Figure 5.10: Policy levers for DST to accelerate CCUS technologies.

In the realm of CCUS, detailed enablers are necessary for the advancement of these technologies. The four fundamental levers that form the backbone of this framework -technology, policy, research, and finance - are essential for accelerating CCUS and addressing the challenge of CO_2 emissions in the atmosphere. Each of these levers triggers a cascade of positive outcomes, progressively bringing us closer to mitigating the adverse impacts of greenhouse gases. DST should fund interventions with academia and industries for applied research, technology development & assessment, technology derisking through translational R&D in PPP mode and policy research in the area of CCUS.

Proposed Policies and Regulatory Considerations for India's CCUS Initiative

CCUS is one of the most important tools to fulfil India's obligations under the Paris Agreement. India's total CO_2 emissions are expected to exceed 4 gigatons per annum (Gtpa) by the year 2030. Achieving a net zero world without CCUS is virtually impossible, as it will play a critical role in reducing Scope-1 (direct emissions owned or controlled by an organisation) and Scope-2 (indirect emissions resulting from the purchase of energy) emissions.

- Define and enforce standards for CCUS technologies to ensure safety, efficiency, and environmental sustainability.
- Establish a certification process to verify the compliance of CCUS projects with established standards.
- Implement a system for monitoring and reporting emissions to ensure accountability.
- Formulate policies promoting collaboration between the government, private sector, and research institutions.
- Establish agreements for international collaboration on CCUS related research and technology.
- Once the process of selection of next generation technologies is done by a body of experts comprising representatives from both public and private, the next step should be to fast-track the approvals and disbursement.
- The policy advocacy for CCUS has many facets where the industry needs to be actively involved, if not leading from the front. There will be challenges with handling IP issues as well. While it is a public good, but private sector investing in these initiatives must answer their shareholders and follow the company's interests. There is a need of alignment between public and private interests.
- There is a need for a policy framework that has an all-inclusive and consistent approach. The dual-track development and delivery model should be promoted, and this model needs to be refined and further adjusted for more uniform and inclusive outcomes.
- These proposed policies and regulatory considerations aim to create a conducive environment for the successful implementation of CCUS initiatives in India, fostering innovation, sustainability, and responsible industry practices.

- India's success in CCUS policy depends on establishing a framework that enables sustainable and economically viable markets for CCUS projects. This framework must recognize that private-sector investment will remain limited unless adequate incentives (or penalties for non-action) are in place, or unless companies can earn revenue from selling captured CO_2 or secure credits for avoided emissions through carbon pricing mechanisms.

- A mix of policy tools such as direct capital grants, tax incentives, carbon pricing mechanisms, operational subsidies, regulatory mandates, and preferential public procurement of low-carbon products will be essential for enabling the deployment of CCUS in India.

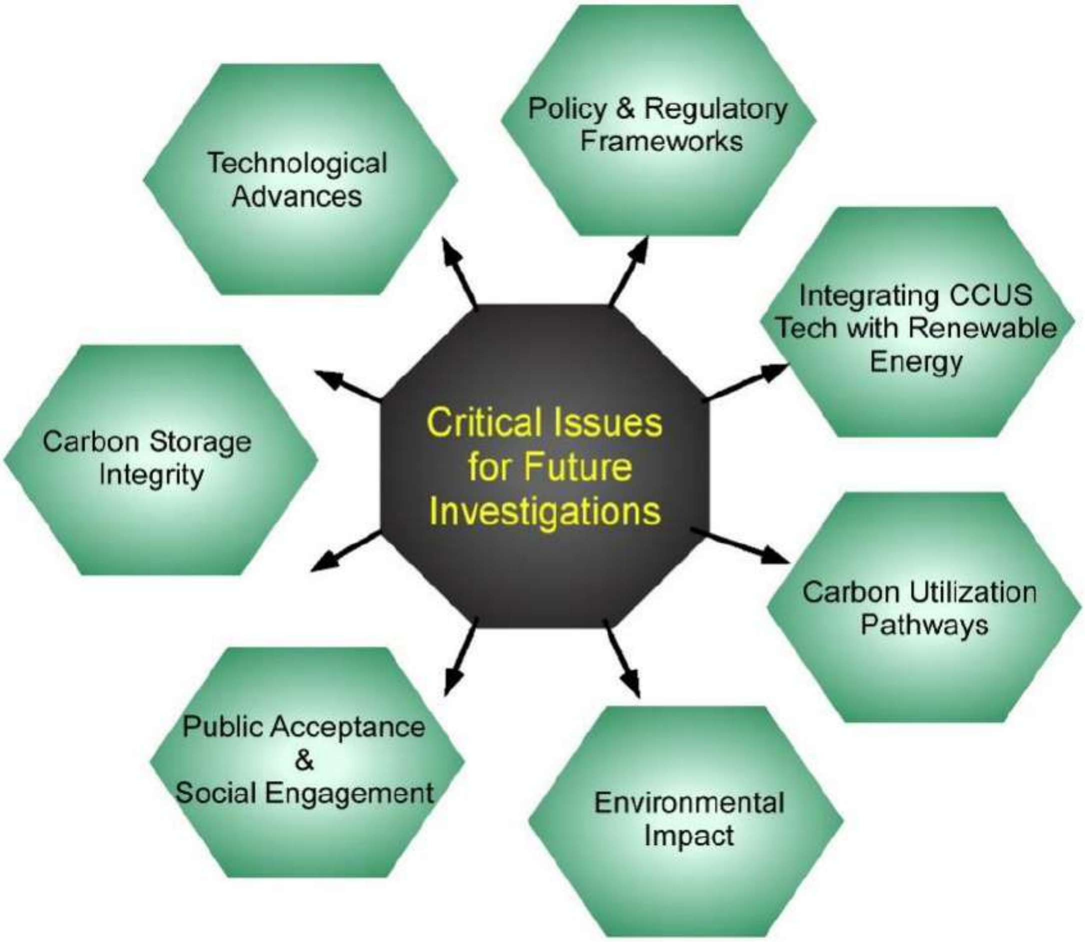

Figure 5.11: Critical issues for future investigations.

- Carbon credits as climate finance can be a great funding opportunity for CCUS to take off in India. Globally, there is a Voluntary Carbon mechanism available, such as VERRA (VM0043 Methodology) for CO_2 utilisation in concrete production. All CCUS carbon credits have maximum value compared to other credits globally.

- Carbon Credits and Tax mechanisms should be differently graded from developed nations to the least developed ones to enable uniform and consistent diffusion of technologies.

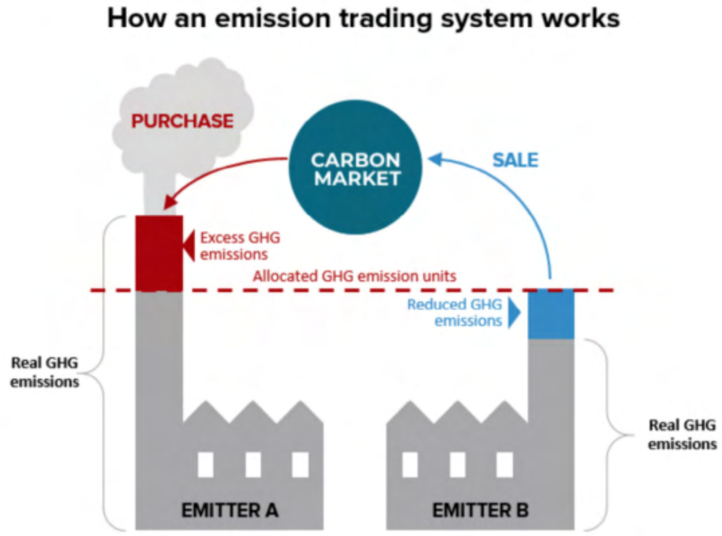

Figure 5.12: Working of emission trading .

- EU-ETS (Emissions Trading System) (Figure 5.12) or EU-CBAM (Carbon Border Adjustment Mechanism) kind of trading structures need to be in place and well thought through.

Sector-wise consultative discussions are proposed to strengthen the CCUS value chain, covering sectors like steel, cement, fertilisers, power, and refineries, along with their nodal agencies. These ministries and nodal agencies are already aware of the challenges that threaten India's export potential due to the restrictive CBAM, which acts as an entry barrier for non-green products. While they are attempting to respond through developing public policy and carbon taxation and funding, DST's intervention is imperative to address technological needs. India should avoid becoming dependent on vendor-driven technology pathways.

India has designated CCUS as a removal activity eligible for participation in international carbon markets under Article 6.2 mechanisms, allowing countries to trade carbon credits, or Internationally Traded Mitigation Outcomes, through mutual agreements. India's Emission Trading Scheme (ETS), dubbed the Carbon Credit and Trading Scheme (CCTS), was enacted in 2023. The CCTS will play a crucial role in the country's journey toward achieving net-zero emissions by 2070, as it provides financial incentives for industries to lower their emissions.

5.5 Role of DST on Policy Framework for CCUS

5.5.1 Strategic Role

- **Policy Formulation and Collaboration:** DST can play a key role in developing policies and regulatory frameworks that shape the research agenda for CCUS technologies. This includes aligning India's R&D goals on CCUS with global best practices. To develop the qualifying requirements which will bring the Life Cycle Assessment (LCA) into the selection process of pilot projects will be provided by DST through its pool of experts, and if needed, involve the international bodies.

- **Guidance and Oversight:** DST provides high-level guidance for integrating CCUS technologies into the national climate strategy. It collaborates with other ministries and agencies like the Ministry of Power, NITI Aayog, and the Principal Scientific Advisor's (PSA's) office to ensure a cohesive approach to implementing and scaling CCUS projects.

5.5.2 Operational Role

- **Research and Development (R&D):** DST oversees and funds disruptive R&D activities related to CCUS, translating new inventions into PoCs and prototypes, and adaptation of new technologies to suit Indian conditions. It coordinates efforts among national research institutions, universities, and private sector players to build the technical know-how needed for effective carbon capture, utilization, and storage.

- **Technical Support and Pilot Project Execution:** While the Ministry of Power may lead the overall implementation, DST supports the execution of pilot projects by providing technical expertise, managing R&D resources, and facilitating partnerships with international technology providers. It ensures that the technological interventions are viable and suitable for scaling up across various industries. DST with its network of experts, should identify sector-specific needs and promote participatory collaboration between academia, research, and industry, focusing on scalable projects/test beds for encouraging collaboration for the successful implementation of CCUS technologies, ensuring a synergistic approach towards achieving net zero targets. DST and relevant industries can co-fund these interventions in PPP mode. Integrating the entire CCUS value chain in R&D valleys and hubs in partnership with relevant industries is another approach DST should explore for accelerating the CCUS technologies.

5.5.3 Start-up and Incubator Development Role

- DST can also focus on developing an incubation ecosystem to synthesise critical materials for CCUS that can be scaled up to the industrial level. The success of CCUS depends on the availability of materials such as MOF, ZIF, amines, catalysts, and sorbents, which will play a key role in pilots and commercial-scale plants in future. In case CCUS, DST must also initiate a parallel effort focused on materials development.

In conclusion, DST's role is essential for laying the groundwork through research and creating the technological and regulatory infrastructure needed for successful CCUS deployment, while the Ministry of Power oversees the broader implementation and alignment with energy policies.

5.6 Funding/Financing CCUS Projects in India: Need and Quantum

The proposed R&D strategy, along with the corresponding funding strategy and policy framwork, is a direct outcome of the discussions in the earlier chapters on capture, storage and conversion processes. The EoP, CCD and COP remain the three pillars to India's CCUS strategy, coupled with CO_2 transport via pipelines or trucks, large-scale sequestration in the geological formations and to a smaller extent, CO_2 conversion into fuels and chemicals. India's CCUS R&D roadmap should align with this strategy and maintain a balance between breakthrough research and translational research as well as the necessary enabling mechanisms. While breakthrough research provides the basis for innovative and viable CCUS technologies, translational research involves navigating the innovation journey of taking foundational research through pilot-scale validation, followed by integrating all aspects of the CCUS value chain in hubs and clusters to increase investor confidence. Financing the CCUS R&D should be strategically positioned to meet these objectives. At the same time, the creation of enabling policy mechanisms and building favorable public opinion are critical for the deployment of commercial-scale CCUS technologies.

The funding mechanisms to support the proposed R&D roadmap is summarized below:

1. Sovereign funding from DST can be used to set up pilot-scale (< 100,000 TPA) "sand-box facilities" for enabling the demonstration, validation and certification of end-of-pipe CO_2 capture (EOP-CCU) or CO_2 conversion technologies developed by start-ups/ industries. Such facilities will provide common infrastructure such as access to CO_2 emissions, basic plant utilities, IT infrastructure, and engineering expertise, as well as provide support for regulatory approvals and certification as required. They can be set up as non-profit organizations run by professionals who can help technology developers on a project-mode basis by providing support for engineering design, Engineering, Procurement, and Construction (EPC) and operations of the pilot plants. DST can provide financial support for novel CO_2 capture projects that are selected through a call for proposal. Selected projects will get access to such facilities to enable scale-up, demonstration, validation, and certification of innovative CCU technologies. This will provide startups/sectoral industry clusters an opportunity to work collaboratively with R&D institutes/academia to de-risk technologies and test the techno-economics. Clarity of IP ownership is equally critical to success. It is suggested that such centres do not claim ownership of any foreground IP created during the projects.

2. It is highly recommended that DST should support part funding of pilot-scale (< 100,000 Tonnes Per Annum) geological CO_2 Storage (CS) projects in collaboration with industries/ industrial clusters and in partnership with academia/ R&D institutes as knowledge partners. Such projects should be planned and executed in phases that cover detailed geological mapping, risk analysis based on laboratory studies and detailed simulations, galvanizing public opinion, addressing CO_2 liability issues, pilot injection, and continuous monitoring of the plume. Coupling CCS with blue hydrogen initiatives would be beneficial in terms of sharing infrastructure costs. CS projects should prioritize industrial requirements over power because coal power CCS is too expensive, while sectors like cement/steel have no viable alternatives.

3. DST must also fund translational R&D projects on CCUS compliant designs (CCD), which involve new concepts like pre-combustion capture, oxy fuel combustion, pyrolysis, heat integrated design, low cost amines, process integrated amine capture and stripping, which can be scaled up easily.

4. Translational R&D for the development of advanced CO_2 conversion (CU) processes for cement, steel or fertilizer industries based on a tight integration between RE and clean fossil

fuel will need to be given an early impetus through focused funding schemes so that they can be developed to pilot scale and then to commercial scale.

5. Direct Air Capture (DAC) is perhaps the most difficult of CO_2 capture options, and yet it would be required to take out residual emissions to achieve a true net-zero target as well as to remove some of the large legacy emissions. Funding for translational projects in DAC based on a tight integration between RE and clean fossil fuel will need to be given an early impetus so that they can be developed to pilot scale and then to commercial scale.

6. The translational R&D projects on DAC, CU, CCD and COP will need inputs from breakthrough research in order to improve their viability. For instance, the discovery of novel catalysts for CCU that offer high conversion and selectivity with excellent durability, or the development of improved temperature and acidity-tolerant carbon capture materials having high durability, will be essential for such projects. Such discoveries can be catalyzed by DST-funded Advanced CCUS Materials Discovery Centres, which house AI-enabled High Throughput Experimentation Facilities.

7. Like the hydrogen valley innovation cluster scheme of DST-MNRE, which is attracting funding from many industries, it is suggested that DST funds the creation of CCUS hubs/clusters for showcasing the end-to-end CCUS value chain comprising CO_2 Capture coupled with Transportation, Utilization and Storage at pilot/demonstration scale. Individual technologies in the value chain that have already reached a certain TRL can be coupled in the hubs/clusters. This will essentially address several issues at the interfaces of the different parts of the CCUS value chain. Funding from DST would be in the form of Viability Gap Funding (VGF) to make the projects viable. Once again, this will provide startups/sectoral industry clusters an opportunity to work collaboratively with R&D institutes/academia so as to derisk technologies, test techno-economics, address regulatory barriers, galvanize public opnion, upskill technical workforce, showcase indigenous technologies and provide opportunities for multi-national collaborations. It is suggested that 3–4 priority industrial regions (Gujarat, Chhattisgarh, Odisha, Tamil Nadu etc.) may be identified to set up CCUS hubs/clusters where capture + transport + storage can be demonstrated.

8. Carbon credits could be used to fund these projects. Over the years, the carbon credit trading scheme, 2023 CCTS will mature and can become a source of funding for many such programs. GHG emission intensity (GEI) is based on the reduction of greenhouse gas emissions by obligated entities in energy-intensive sectors and industries. With GEI target, industries will know exactly what they need to achieve to earn carbon credits, which can then be traded in India's carbon market. This mode will allow funding to be made available, if tax incentives are also provided for these early, large-scale demonstration plants. Similarly, as international regulations such as Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) and Voluntary Carbon Markets (VCMs) evolve, the DST funded CCS projects in India should get access to carbon credits.

9. International funds (e.g., World Bank etc) also might be brought into this fold as per India's commitment to net zero and the global commitment to fund this transition. DST should

mobilize bilateral partnerships (such as CSIRO-Australia, Northern Lights project-Norway, Japan Organization for Metals and Energy Security (JOGMEC)-Japan) and foster strategic R&D drives within the overall framework.

Opportunity for India

India could explore both international and internal funding mechanisms using the resources from the World Bank (WB) and the International Monetary Fund (IMF). The following are potential financing mechanisms for CCUS in India:

- ❑ **World Bank Part Funding: Secure part funding from the World Bank for CCUS projects while pledging sovereign funds.**
- ❑ **Evaluate the feasibility of utilizing provisions like the U.S. 45Q tax credit or Canada's Investment Tax Credit (ITC) for carbon capture, along with other globally available models, to incentivize CCUS investments.**
- ❑ **Develop a Performance, Achieve, and Trade (PAT)-like scheme specific to CCUS, tailored for different sectors based on the complexity of managing CCUS in each sector. This could include a trading system that rewards sectors for achieving CCUS targets and allows trade of carbon credits.**
- ❑ **A scheme like PLI can be built where in 30% of the capital investment can be provided for the MCDS projects.**
- ❑ **Financing through Carbon Trading with minimum funding from government.**

CHAPTER 6

INTEGRATION OF CCUS TECHNOLOGIES IN INDUSTRIAL SECTORS

INTEGRATION OF CCUS TECHNOLOGIES IN HARD-TO-ABATE INDUSTRIAL SECTORS

Carbon Capture, Utilization, and Storage (CCUS) is one of the critical technologies for achieving decarbonization across several high-emitting industrial sectors, including Cement, Steel, Oil and Natural Gas, Thermal Power, Chemicals, etc. These sectors are responsible for a significant share of global CO_2 emissions and are considered "hard-to-abate" sectors. The integration of CCUS within these industries presents a promising opportunity to reduce emissions while maintaining industrial productivity, ensuring sustainable growth in line with global net zero targets.

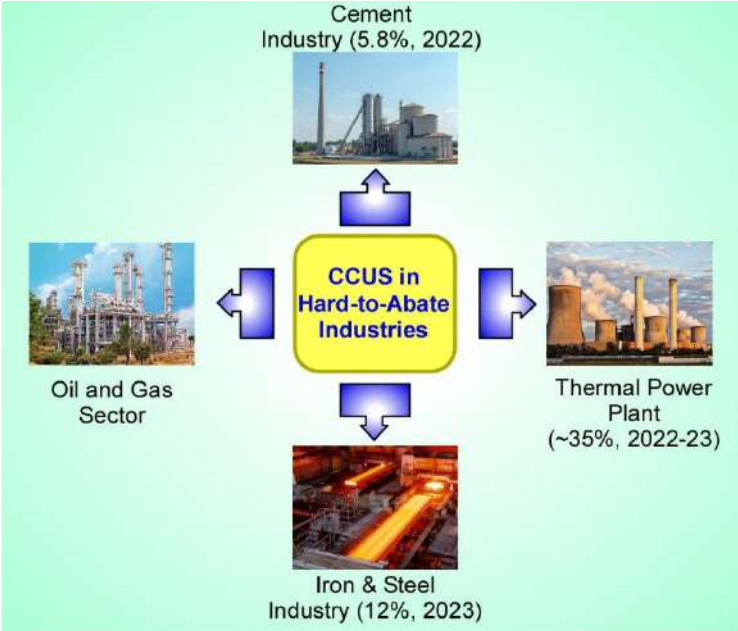

Figure 6.1: Sectorial contribution to CO_2 emissions.

CCUS technologies provide an effective solution for reducing emissions in these sectors by capturing CO_2 from industrial processes, utilizing it in various value-added applications, or storing it permanently in geological formations. The integration of CCUS can mitigate the environmental impact of these industries, allowing them to continue operating efficiently while contributing to global efforts to limit temperature rise to below 2°C, as outlined in the Paris Agreement.

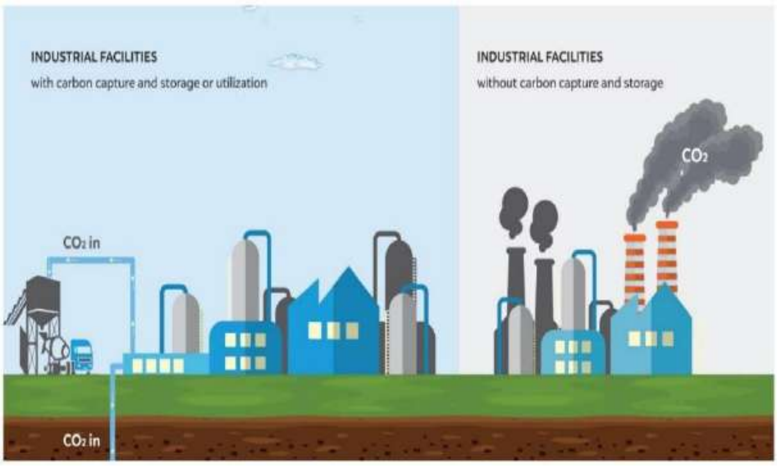

Figure 6.2: Difference between the industrial processes with and without carbon capture, utilization and sequestration (CCUS).

As Governments and industries work toward achieving net-zero emissions, the deployment of CCUS in these hard-to-abate sectors will be crucial. This chapter outlines the significance of integrating CCUS technologies to transform hard-to-abate industries from being significant carbon emitters to integral players in a low-carbon economy, supporting long-term sustainability.

6.1 CCUS in Cement Sector

The Indian Government's commitments to combat climate change have gained significant momentum, with a focus on reducing greenhouse gas emissions across various sectors. Recognising the urgency of the climate crisis, the Indian Cement Industry has embarked on a transformative journey, aligning its strategies with the Government's commitment to net zero by 2070.

India is the world's second-largest cement producer with an installed capacity of over 600 million tonnes and annual production of around 450 million tonnes in FY2025. Even at this scale, the Indian cement industry has achieved a lower emissions intensity than the global average. India's average emissions intensity is ~0.64 tCO_2 per tonne of cement compared with the global average of ~0.67–0.72 tCO_2 per tonne of cement. A key driver of this performance is India's lower clinker-to-cement ratio enabled by higher use of supplementary cementitious materials such as fly ash and granulated blast furnace slag, which reduce process emissions from clinker production. In addition, Indian plants have achieved high thermal and electrical efficiency through widespread adoption of modern dry-process kilns, waste heat recovery systems (WHRS), and increasing use of alternative fuels and raw materials (AFR), resulting in lower energy consumption and further emissions reduction relative to global benchmarks.

The Government of India has been proactively engaging with the Cement Manufacturers' Association (CMA), India, to accelerate decarbonisation efforts in the Indian Cement Industry and achieve sustainability targets. The Cement Industry has undertaken collaborative initiatives to promote cleaner production processes and reduce carbon emissions. Through strategic partnerships, joint endeavors, and policy dialogues, the cement sector is looking to work hand in hand with the Government of India to implement innovative technologies for decarbonisation.

India's progress in reducing clinker use has been driven largely by the use of established supplementary cementitious materials (SCMs), particularly fly ash and granulated blast furnace slag, which have enabled the production of blended cements (PPC/PSC) with significantly lower carbon intensity than Ordinary Portland Cement (OPC). As long as these industrial by-products remain available, they continue to provide a cost effective and technically proven route for reducing clinker content, and have been central to India's position as a global leader in carbon-efficient cement production. The availability of fly ash and slag, however, varies regionally and may not fully keep pace with future Cement demand, making it necessary to diversify the SCM base over the coming decades.

A range of next generation SCMs offers potential to support further clinker substitution. These include:

- Calcined clay, where India has an estimated ~2.9 billion tonnes of suitable reserves and which can be used in combination with limestone in limestone–calcined clay cements to enable higher substitution levels;
- Bio-ash derived from agricultural residues, projected to reach ~45 MMT annually by 2070, providing a circular economy opportunity; and

- Construction and demolition (C&D) waste, expected to increase to ~225 MMT per year by 2070, with scope for beneficiation and reuse as SCMs.

Among emerging options, calcined clay–limestone systems (LC3-type cements) have shown potential to replace up to ~50% of clinker, with associated CO_2 reductions of ~30–40% compared to OPC, along with favourable strength and durability characteristics. In the near and medium term, fly ash and slag will continue to play a key role, while next-generation SCMs, including LC3, bio-ash, and processed C&D materials, can progressively expand the portfolio of low carbon cement options.

Brimstone, a US based organization has developed a process to make cement from calcium silicate rocks, which do not release CO_2 during processing. Brimstone uses calcium-bearing silicate rocks, such as basalt and olivine, as its feedstock. Clinker formation is achieved through a two-step process step-1 is hydrometallurgy and step-2 is pyrometallurgy. On a similar line, Sublime Systems, an MIT start-up, has demonstrated cement production from an electrochemical process which uses basalt instead of calcium carbonate. Electrochemically, these rocks are refined using electrochemical treatment methods, ultimately using renewable energy source to produce CO_2 free cement. A 250 ton per year process was demonstrated in Somerville, and a 30000 ton/year process is being built in Holyoke, Massachusetts for commercialization.

As the next significant tool for decarbonisation, the time is now ripe for CCUS initiatives to pick up pace in India. CCUS holds immense importance for the cement industry as it offers a viable pathway to mitigate process emissions associated with cement production. While CCUS is not the sole solution for decarbonising the Cement sector in India, it is widely considered an indispensable tool for achieving optimal decarbonisation given the unique challenges and scale of emissions associated with cement production. Integrating CCUS with other decarbonisation strategies, such as renewable energy use and alternative cementitious materials, will contribute to the industry's long-term sustainability and global climate goals.

With the TRL of some CCUS technologies demonstrating significant potential, the high capital costs, technical complexities, and regulatory uncertainties associated with CCUS projects necessitate robust support and interventions by the Government. Through supportive policies, financial incentives, and regulatory frameworks, there can be measures to stimulate investment in CCUS infrastructure and research, fostering innovation and technology development. Government led initiatives can facilitate the establishment of the CCUS value chain, providing the linkages from Capture to Utilisation and Storage of carbon.

Given the current cost constraints for adopting novel decarbonisation technologies, it is imperative that the cement industry receives targeted incentives to accelerate the adoption of advanced technologies. Without such incentives, the pace of technological advancement and implementation of CCUS will likely remain sluggish. Considering the significant and growing volumes of CO_2 emissions produced by the cement industry, it is crucial to identify and implement the most cost-effective carbon capture technologies. The Government of India is providing leadership, coordination and strategic direction to enable the Indian Industry to harness the full potential of CCUS in achieving its emissions reduction targets and transitioning towards a low-carbon future.

The Indian economy is projected to grow rapidly in the coming years. The demand for infrastructure and housing will witness a significant spurt, invariably warranting a scale-up in cement production.

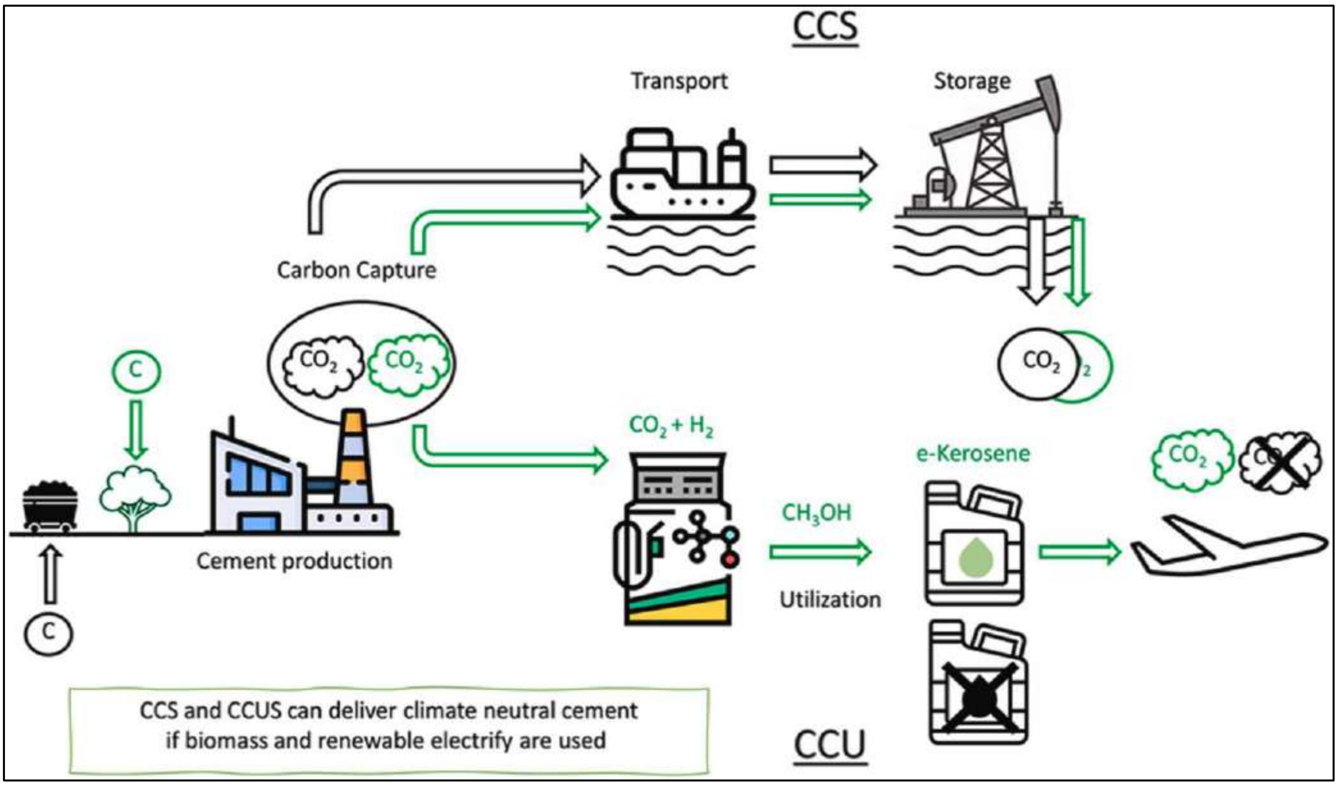

Figure 6.3: Preconditions for achieving carbon neutrality in cement production through CCUS. Journal of Cleaner Production, 425, 138935. (Source: Gallego Davila, J., Sacchi, R., & Pizzol, M., 2023, Journal of Cleaner Production, 425,138935).

With the cement industry committed to align with the decarbonisation commitments of the Government, new technologies to decarbonise the emission intensity of the sector would play a key role. As part of the discussion, technologies that are currently available globally need to be explored to help mitigate CO_2 in the Cement sector. There is a need to understand technologies, scalability, and implementation in the Indian context, related specifications, operational details, challenges and economics of the technologies.

6.1.1 CCUS in Cement Sector: Approach and Perspective

- **Carbon Capture**

Norway is a leader in implementing CCS technology. The Heidelberg Materials cement plant in Brevik, Norway, is a prime example, as it is the world's first large-scale cement plant to integrate CCS, capturing and storing CO_2 that would otherwise be released into the atmosphere. It's a conventional process which captures slightly richer CO_2 stream from the kiln using amine based process. A key innovation at Brevik is the use of a heat recovery system. This system captures waste heat from the cement production process and the CO_2 compression unit to power the capture and regeneration process. Further, the pure CO_2 is compressed to liquefy, stored at the site and later shipped with the help of Northern Light Consortium and sequestered off-shore under geological sites in the North Sea bed. The project is not a purely commercial endeavor. It is an initiative of the Norwegian government's "Longship" project, the government committed to funding over 80% of the project's construction and initial 10-year operation, thus covering both capex and opex. Further, to make such operations economically viable, Norway has a high carbon tax, which provides a strong incentive for companies to invest in this technology. It is estimated that the total cost of the Brevik project for construction and 10 years of operation is roughly €400 million. A significant portion of this is for the capture facility itself, as well as the additional energy required for the process. Thus almost the entire project is funded by the taxpayers money. An IEA study estimates that the cost of capturing CO_2 in Brevik could be around €40 per ton of CO_2. Given that the Brevik plant aims to capture 400,000 tons of CO_2 annually, this translates to a significant per-unit cost on the final product. The Brevik cement comes under “evoZero” brand, a premium product aimed at customers who are willing to pay a higher price for sustainability. The first volumes of evoZero cement were fully booked for 2025, signaling a market demand for such products.

Heidelberg Materials, the owner of the Brevik plant, is a major player in this space and has several other similar projects underway. To name a few, Slite, Sweden, which could be a CO_2 negative process due to CCS and use of bio-mass for generating thermal energy. Devnya, Bulgaria, aims to be the first full-chain CCUS project in Eastern Europe. CO_2 will be stored in the offshore storage sites under the Black Sea via a pipeline system. The GeZero project in Geseke, Germany, would be a model solution for inland industrial sites that are not close to the coast. It will include a transport solution to bridge the gap until the necessary pipeline infrastructure is available. Other proposed plants in Europe are in Antoing, Belgium and Airvault, France. All funded by taxpayers money. It is also worth noting that no Brevik like cement plants are operational in US, however, a few are under feasibility study stage, Mitchell, Indiana; Mitchell, Pennsylvania and Mitchell, Utah. China is the world’s largest cement producer, however, large scale demonstrations of CCUS are not in public knowledge.

The Indian cement industry faces considerable challenges in implementing effective Carbon Capture technologies. In particular, the integration of technologies such as absorption, adsorption, membrane, and cryogenic capture requires focused R&D to overcome the barriers mentioned below, and subsequently scale them for industrial use.

For absorption technologies, the main hurdles include the high energy demand for solvent regeneration, low solvent lifetime, and the significant capex required for system retrofitting. To address these issues, advanced research needs to focus on developing solvents that require less heat for regeneration, have longer operational lifespans, and are more cost-effective. Additionally, finding alternatives to amine-based solvents or solutions, which have high associated costs and safety concerns, is essential. There is also a need for innovations in process safety to ensure that Carbon Capture systems are secure and manageable at scale. Research aimed at reducing both capex and opex will be crucial for making these technologies viable for cement plants across India.

Adsorption based systems face similar challenges, such as the contamination of gases, low adsorption efficiency and the high energy requirements for regeneration. Research into new, low-cost, energy- efficient adsorbents, including indigenous materials, can help mitigate these issues. Additionally, efforts need to focus on improving the scalability of adsorbent-based systems, enhancing their lifespan, and reducing the environmental footprint by minimising space requirements and improving overall efficiency. The development of high-performance adsorbents that are safe to handle and capable of operating at higher CO_2 concentrations will be a key area for future research.

For membrane-based technologies, the challenges include high temperatures that reduce efficiency, impurity presence and high replacement costs. Research needs to focus on developing membranes that can withstand high temperatures, have high CO_2 separation efficiency and are cost-effective. Additionally, the development of biodegradable membranes and low-energy cooling systems for gas purification is vital. Increasing the durability of membranes to extend their useful life will also be an essential focus of R&D efforts.

Cryogenic capture, though promising, is hampered by high electricity consumption and significant capital and operational costs. Research into low-cost cryogenic systems, particularly those that can efficiently store CO_2 in liquid form, is a priority. Additionally, exploring natural carbon storage solutions and leveraging low-cost renewable energy sources will be critical enablers for this technology to become economically viable at scale.

In all these areas, supporting R&D, scaling up proof-of-concept technologies, and facilitating funding for translational R&D will be necessary to transition from early-stage developments to industrial scale applications.

DST in India can play a pivotal role in accelerating the adoption of Carbon Capture technologies in the cement industry by providing targeted funding for research and test beds, facilitating industry-academia collaborations, and supporting technology incubation programs. Additionally, supportive policy frameworks and regulations that incentivise the adoption of low-carbon technologies and help establish national standards for their implementation are important measures for the Government to consider. By promoting and offering training programmes for industry professionals and fostering international collaborations, DST can create an ecosystem conducive to the rapid scaling and commercialisation of Carbon Capture technologies. These efforts will not only drive innovation but also stand to support the Indian cement sector towards achieving its sustainability goals.

The success of CCS deployment in the European cement sector, as seen with projects like Brevik, relies heavily on a blend of public funding, private investment, and supportive policy frameworks. A purely commercial model has not proven viable, given the high upfront capital costs and operational expenses of CCS technology.

The key financing models observed are:

Direct Government Grants and Subsidies: Governments provide significant upfront capital grants to de-risk the projects and cover a large portion of the construction and operational costs. The European Union's Innovation Fund, which is financed by the EU Emissions Trading System (ETS), is another critical source of direct grants for industrial decarbonization projects, including several cement-related CCS projects.

Carbon Contracts for Difference (CCfDs), is another highly promising model gaining traction in Germany and other parts of Europe. A CCfD is a long-term contract between a government and a project developer that guarantees a stable price for carbon abatement. If the market price for carbon falls, the government pays the difference to the project developer. Conversely, if the market price exceeds, the developer pays the difference to the government. The basis for this scheme is a robust EU Emissions Trading System (ETS).

Table 6.1: Carbon Capture: Challenges and Suggested Enablers for Cement Industry.

S. No.	Technology	Challenges	Requirements	Enablers	Scale
I.	Absorption	Amine based 1. cleaning of flue gases 2. high heat requirement 3. high electricity consumption 4. low life of amine/solvent 5. high cost of technology for purification of CO_2 6. existing kiln system retrofitting issues. 7. Investment costs (Capex) 8. Opex costs 9. Safety concerns Regenerating the solvent to reuse it in the absorption process consumes significant energy and reduces overall efficiency	1. Alternative to solvents/solutions 2. Technology development with low heat and energy requirement 3. Longer life of solvent 4. Low Capex/ cost of adoption and minimum modification in the existing facility 5. Process safety	1. R&D support i. Solvent/ Solutions ii. Process development 2. Proof-of-concept 3. Scale up to industrial level 4. Funding i. R&D 5. Test bed Policy for low carbon producer and consumer incentives 6. Availability of low cost RE	Current TRL: 7-8 Desired TRL: 8-9
	Technology	**Challenge**	**Requirements**	**Enablers**	**Scale**
II	Adsorption	1. Contamination of gases 2. Availability of suitable adsorbents 3. Requirement of high concentration of CO_2 4. Low degree of adsorption/low efficiency 5. Handling of adsorbent materials, including end of life 6. Large space requirements 7. High energy (RE-thermal, electric) requirement 8. Investment costs (Capex) 9. Opex costs 10. Safety concerns	1. Alternative adsorbent, which are less energy intensive, high adsorption efficiency, and safe to handle 2. Low cost gas purification technology 3. Increased life of usage 4. Indigenous low cost technology 5. Safe to handle 6. Minimise the footprint/high efficiency of adsorption	1. R&D support for new adsorbent materials 2. Proof-of-concept 3. Scale up to industrial level 4. Funding ii. R&D 5. Test bed Policy for low carbon producer and consumer incentives 6. Availability of low cost RE	Current TRL: 4-5 Desired TRL: 8-9

	Technology	Challenge	Requirements	Enablers	Scale
III	Membrane	1. High temperature reduces efficiency 2. Presence of impurities (suspended particulate matter and moisture) 3. High material and replacement cost 4. High energy required for cooling the gases 8. Investment costs (Capex) 9. Opex costs	1. Availability of high temperature and high efficiency membranes at low cost 2. Low energy cooling system 3. Bio degradable membrane 4. Durability of membrane	1. R&D support for new membrane development 2. Proof-of - concept 3. Scale up to industrial level 4. Funding i. R&D ii. Pilot 5. Policy for low carbon producer and consumer incentives 6. Availability of low cost RE	Current TRL: 3-4 Desired TRL: 8-9
	Technology	**Challenge**	**Requirements**	**Enablers**	**Scale**
IV	Cryogenic	1. High electrical energy consumption 2. Investment costs (Capex) 3. Opex costs	1. Low cost cryogenic technology	1. Policy for off take of CO_2 in liquid form 2. Low cost RE availability 3. Natural carbon storage opportunities	Current TRL: 6-7 Desired TRL: 8-9

The EU ETS decides a price on carbon emissions, it creates a financial incentive for companies to reduce their CO_2 footprint. The revenue generated from the ETS is then used to fund initiatives like the Innovation Fund, creating a self-reinforcing loop. Further, major cement companies like Holcim and Heidelberg Materials are increasingly leveraging "green" financial instruments to fund their decarbonization efforts. This includes issuing green bonds and sustainable-linked bonds and securing sustainable loans. These financial products are made attractive to investors through ESG mandates which further lowers the cost of capital for CCS projects.

6.1.2 Suggested Enablers for Carbon Capture in the Indian Cement Industry

- **Urgent need for sustained technical evaluation:** Carbon capture deployment in the Indian cement industry depends on various factors such as quality and source of emissions, limitations/challenges of the technology selected, status of the plant (new plant or an old plant), layout constraints, local infrastructure (electricity, utilities), waste generation, conducive regulatory framework, local social conditions etc., among other factors. As such, a consistent technical evaluation of Carbon Capture technologies focusing on emission abatement and energy performance in the cement industry in India needs to be conducted. The Government should initiate feasibility studies involving all stakeholders, including globally renowned consulting organisations, which have successfully carried out such studies. Further, test beds can be listed before deciding on demonstration projects to understand the requirements of the Indian cement industry, considering variations such as location, climate, etc.

- **Finances, A Key Challenge:** Amongst the most formidable challenges for the Indian cement industry for incubating Carbon Capture Translational R&D projects is the finance component of technology deployment. The Indian cement industry sources estimate a capex cost of approximately INR 1,400-1,600 crore per million tonne of carbon abatement annually and an approximate opex of INR 3,000-4,000 per tonne of carbon abatement (CCUS Report, NITI Aayog, 2022). A pilot project will also help compute the final estimation on capex and opex involved for Carbon Capture in the Indian cement industry.

- **Government Support for Funding, Information and Resources:** As true for most innovations, an enabling environment needs to be fostered by the Government for constant technological evaluation through pilot projects. Government institutions are best placed to facilitate funding, information and resources to support the development of nascent carbon capture technologies, especially for leveraging support from international lending institutions.

- Other than the financial models like PPP, VGF, PLI scheme linked to emission trading and carbon pricing and creation of "carbon capture finance corporation", one important difference which India could bring is "utilization" aspect of captured CO_2 which potentially offsets the cost of CO_2 capture. However, for this to happen, the cost of green hydrogen has to drop significantly below the current price. Finding commercially viable pathways to use captured CO_2 to produce high-value products like e-methanol, synthetic fuels, or chemicals is not possible without surplus green hydrogen at cost.

Carbon Utilisation

To drive advancements in Carbon Capture in the Indian cement industry, focused research is required for both improving existing capture technologies and enabling the successful utilisation of CO_2. A key area of research is the development of cost effective and efficient technologies for capturing CO_2, which can then be used in various applications such as urea production, carbon black synthesis, and alternative cementitious materials (ACMs). Research must focus on optimising the techno-economics of CO_2 conversion processes, such as enhancing the efficiency of catalysts for urea and chemicals production while addressing the high costs associated with scaling up these technologies. Specifically, carbon black production could benefit from innovations that utilise captured CO_2 more efficiently, reducing reliance on conventional methods and creating new, sustainable solutions.

In the area of mineralization, which involves converting CO_2 into stable carbonates, research is needed to identify suitable minerals for CO_2 absorption and develop technologies to scale up these processes to industrial levels. This includes exploring ways to incorporate mineralized CO_2 into the cement production value chain, such as producing aggregates or Supplementary Cementitious Materials (SCMs) from waste materials. Advancing these technologies will also require overcoming challenges related to material availability, large-scale plant capacity, and process integration. Government support in the form of capex funding, performance-based standards and policies that incentivise the use of captured CO_2 in these processes could significantly accelerate their adoption in the cement industry in India.

Table 6.2: Carbon Utilisation: Challenges and Suggested Enablers for Cement Industry.

S. No.	Technology	Product	Challenges	Requirements	Enabler
I	Conversion	Urea	Techno - economic challenges, especially due to regulated markets	Cost-effective and efficient technology	1. Policy for use of captured CO_2 only 2. Cost incentive for producers and consumers
		Chemicals production	Techno economic challenges with respect to market requirements	Cost effective and efficient technology	Policy for use of captured CO_2 in product use
		Carbon Black	Conventional easy methods are available in the market – techno-economic challenges	Cost effective and efficient technology	Policy for use of captured CO_2 in carbon black synthesis
II	Mineralisation	Mineral Carbonate	1. Availability of suitable material for mineralisation by CO_2 absorption 2. Large plant capacity required	1. Suitable mineral 2. Large scale of operation 3. To be incorporated in the construction value chain	1. Funding & financing support for Capex needs 2. Performance based standardization
		SCMs for waste material	Large plant capacity required	1. Large scale of operation 2. To be incorporated in the construction value chain	1. Funding & financing support for Capex needs 2. Performance based standardisation
		Aggregate	1. Large plant capacity required	To be incorporated in the construction value chain	1. Funding & financing support

			2. Suitable material for mineralisation in required volumes		
		Raw Mix for clinker synthesis	1. Large plant capacity required 2. Separation from different other minerals	1. Suitable technology for other minerals separation 2. Large scale operation 3. To be incorporated in the construction value chain	Funding & financing support support
		Alternative Cementitious Material (ACM)	1. Large plant capacity required 2. Proof of characteristics of the ACM	1. Large scale operation 2. To be incorporated in construction value chain	Performance based standardisation
III	Hydrogenation	Ethanol	1. Scale- up challenge 2. High cost	Development of cost-efficient and suitable catalyst for low temp and low pressure reactions with high per pass conversion and yield	Policy to ensure compulsory offtake
		Methanol	1. Scale up challenge 2. High cost	Development of cost efficient and suitable catalyst for low temp and low pressure reactions with high per pass	Methanol Economy and Policy Support

				conversion and yield	
		Synthetic Aviation Fuel (SAF)	1.Scale up challenge 2.High cost	Development of cost efficient and suitable catalyst for low temp and low pressure reactions with high per pass conversion and yield	Policy Support
IV	Food Grade Application	Beverages	1. Scale up challenge 2. High cost 3. Low market requirements		Policy for utilisation
		Purification	Efficiency and cost	Integration with current available technology	Policy for integration
V	Microbiological Conversion	Photosynthesis	Purity of CO_2	Availability of technology for purity	1. Investment and Capex support 2. Land procurement of large sizes
		Bio ethanol	1. High cost 2. Large scale process	1. Low cost technology 2. Large area required 3. Development of cost-efficient and suitable catalyst	Policy support for raw material availability and support for Market readiness
		Growth of Algae	Large scale process	Large area required	Land procurement policy

**LCA for each utilisation technology should be individually assessed for value chain assessment*

Carbon Storage

To advance Carbon Storage technologies in the Indian cement industry, focused research and strategic planning are required to overcome significant challenges in both offshore and onshore storage. For offshore carbon storage, where cement plants are predominantly landlocked, the key requirement would be to create demand for CO_2 storage by collaborating with nearby oil and gas agencies. Research must focus on identifying and developing viable transportation mechanisms for capturing and transporting CO_2 from cement plants to offshore storage sites. Government policy and infrastructure development will be critical enablers, facilitating the creation of necessary storage facilities and ensuring robust logistical support for CO_2 transport.

For storage, where there is currently no policy for CO_2 sequestration, research must focus on conducting comprehensive geological studies to identify suitable areas for safe and long term CO_2 storage. Understanding the geological formations and their capacity to securely store CO_2 is essential for scaling up onshore storage options. The development of clear policy frameworks and the necessary infrastructure to support onshore Carbon Storage will be crucial to overcome the current gaps. Government support, including incentives and regulations, will be vital in facilitating both offshore and onshore Carbon Storage, ensuring the successful integration of these technologies into the Indian cement industry's sustainability efforts.

6.1.3 Recommendations for an enabling environment for CCUS in the Cement sector

- The cement industry is currently focusing on reducing the CO_2 footprint by utilising byproducts of other industries in the process of cement manufacturing or in utilising the same in concrete formulations; fly ash (from power plants) and steel slag (steel making) are a few such materials. Increasing these components in the process would ensure overall lesser CO_2 emissions. Due to the projected demand of cement in the next decade and a probable reduction in coal-fired electricity generation in future, the availability of byproducts that can significantly contribute to CO_2 reduction in cement, such as fly ash, would see constrained supplies. It is, therefore, essential that these levers and their potential for CO_2 reduction be fully assessed to ensure articulation of necessary policies with implementation for the sustainability of such resources towards facilitating low-carbon transition.

- There is a need to build an R&D ecosystem for the cement industry in India. For full decarbonisation, a CCUS ecosystem needs to be developed.

- As a first step in this direction, feasibility studies involving all stakeholders may be initiated. Further, test bed projects can be listed before deciding on demonstration projects to understand the requirements of the Indian cement industry, considering variations such as location, climate, etc.

- Given that the feasibility of CCUS deployment is shaped by multiple contextual factors-ncluding emission characteristics, technology-specific constraints, status of plant (age) and configuration, availability of supporting infrastructure such as power and utilities, and issues related to waste management, it is advisable to undertake a systematic and comparable techno-economic assessment of CCUS options for the Indian cement sector, with particular emphasis on emission mitigation potential and overall energy performance.

- A cluster level approach for CCUS implementation is required, where carbon capture of various cement plants and power plants in each cluster can be integrated. Pure CO_2 gas grid needs to be set up so that user industries like urea, ammonia, methanol, polymers, chemicals, soda ash, food-grade CO_2, liquid fuel can be linked to convert CO_2 into value added products and rest of the CO_2 can be stored in oil wells and gas wells in the respective clusters.
- Pipelines for transport and geologic storage need to be built in these CCUS Cement hubs.
- CCUS hubs, once in place, may also be largely funded through carbon credits without depending too long on Industry – Government funding.
- A coordinated approach is needed for Private-Public sector joint funding for CCUS.
- Creating demand for cleaner and Greener Cement.
- Ensure the ability to fund, create valuable business case or models around it.
- Carbon utilisation or conversion into value-added products may add to the business model and sustainability of the hubs or facilities.
- Create enabling measures by policymakers and funders, and create the much-needed awareness among the consumers.
- Transport and storage are the missing links in most of the capture projects in the cement sector.
- Policy frameworks and incentives need to be more conducive for CCUS in the cement sector.

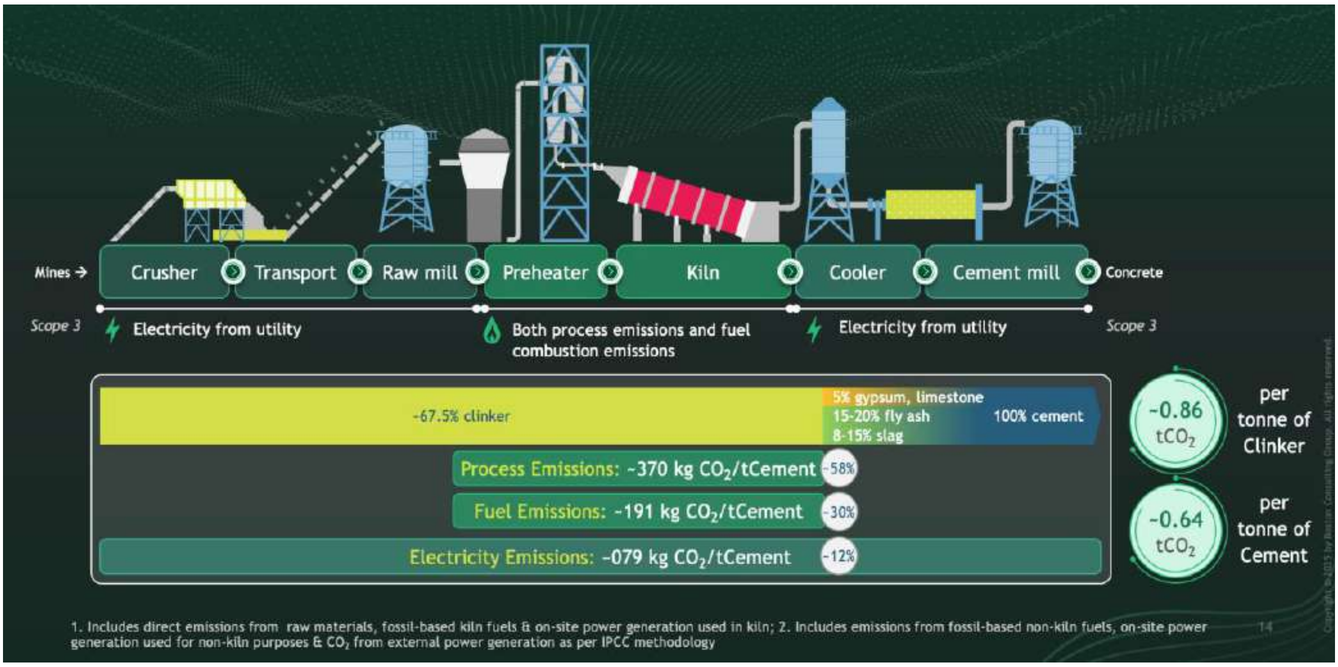

Figure 6.4: Stepwise cement manufacturing with CO_2 contribution (Source: CMA-BCG Decarbonisation Study on Cement and Concrete 2025 (forthcoming) (McKinsey Report).

6.2 CCUS in the Steel Sector

6.2.1 Sustainable steel making for the reduction of Greenhouse Gas Emissions

Unlike cement, where the CO_2 generation happens during calcination and use of fossil fuels to achieve the calcination temperature, in steel making, one needs to add coke as a reducing agent which results in the release of excess CO_2. The Iron and Steel-making industries are one of the largest industrial sources of CO_2. To decarbonise the steel sector, approximately 2.4-3.0 tons of CO_2 needs to be abated per ton of crude steel production based on the process adopted. Countries like the USA and Italy, which got industrialized quite early have a significantly large supply of high quality steel and most of their new steel requirements (up to 70%) are being fulfilled by recycling of these accumulated scrap which has 80% lower CO_2 emission compared to the steel production in blast furnace which is the major process in countries like India and China. According to the World Steel Association (WSA), there is no single solution to CO_2 free steelmaking, and a broad portfolio of technological options is required. These technologies can be deployed alone or in combination. The steel industry can adopt two approaches for the reduction of CO_2 emissions. Firstly, CO_2 emission can be minimised by reducing fossil carbon utilisation as a reductant using an alternative green reductant, which is termed Carbon Direct Avoidance (CDA). In CDA, hydrogen or hydrogen-bearing gas can be used as an alternative reductant in blast furnaces. These gases can be used for the production of Direct Reduced Iron (DRI). Scrap recycling and Electric Arc Furnace (EAF) are also part of CDA.

Furthermore, CCUS is widely regarded as a crucial pathway for mitigating emissions from the world's blast furnaces, which are expected to continue contributing substantially to steel production in the coming decades. According to IEA projections, achieving a Net Zero Emissions trajectory will require deploying CCUS across more than 53 per cent of primary steel output by 2050-representing roughly 700 Mt CO_2 per year.

The **Ministry of Steel, Government of India**, has developed a **taxonomy for green steel** in the country. This initiative aims to establish clear standards and guidelines for producing environmentally sustainable steel, promoting reduced carbon emissions, energy efficiency, and the adoption of cleaner technologies in the steel manufacturing sector.

Moreover, CO_2 can be captured from steel mill off-gases and subsequently it can be stored or converted into value added product.

- **Capture:** Advanced materials for CO_2 absorption and adsorption represent a key area for research. Detailed studies on synthesis and performance in real-gas scenarios are necessary to optimize these materials. Computational modeling and process simulation (e.g., ASPEN) can aid in identifying optimal absorbents or adsorbents from databases, ensuring they are fit for industrial use.

Sorbent development must align with reactor configuration and regeneration methods to enhance process efficiency and minimize footprint and costs. An effective gas-solid contacting system is critical, as it directly influences capture performance and economic viability.

The major source of CO_2 production in the steel-making process is the blast furnace (1.7–2.0 t CO_2/ton crude steel for the BF-BOF route). The emitted CO_2 can be captured using an amine-based absorption process, adsorption process using membrane, or cryogenic separation process. The amine-based CO_2 separation process is technologically mature, although the corrosion associated with amines and the CO_2 regeneration process needs further optimization.

Blast furnace gas (BFG) contains only 20–25% CO_2, mixed with nitrogen, carbon monoxide, and hydrogen. This low concentration makes post-combustion CO_2 capture more energy-intensive. Retrofitting CO_2 capture systems into existing blast furnaces is difficult due to space constraints and process disruptions. Dynamic load changes in steel plants can also affect the performance of capture systems. Heat integration between capture and other processes (e.g., power generation) is also complex but necessary for efficiency.

Post-combustion capture technologies (like amine scrubbing or membranes) are applied after the blast furnace gas (BFG) is produced. These systems do not interfere with the ironmaking process itself, they treat the exhaust gases to remove CO_2. It is not pure End of Pipe (EOP) solution, due to the following reasons:

1. BFG must be cleaned and cooled before CO_2 capture. This involves pre-treatment steps that are integrated with upstream operations.
2. CO_2 capture systems often require steam or heat, which must be sourced from the plant. This creates a need for process integration with the blast furnace's energy systems.
3. BFG is often used for power generation or heating. Capturing CO_2 can change the calorific value of the gas, affecting its usability.
4. Some advanced strategies aim to modify the blast furnace operation to produce gas streams more suitable for CO_2 capture (e.g., increasing CO_2 concentration). This blurs the line between end-of-pipe and process-integrated solutions.

There are possibilities for heat integration between an existing Blast Furnace (BF) and EOP CO_2 capture solutions - but it's complex and highly site-specific.

Apart from CO_2 capture, other gas separation processes are also integral for achieving carbon neutrality. For example, after separation of CO_2 from BF gas, the depleted gas consists of 25-30% CO and 55-60% N_2, 3-5% CO_2, and 4-5% H_2. In this regard, an adsorption-based cost-effective separation process can be developed for the separation of CO, which can be directly used in the iron-making process as an alternative reductant. However, one should do a proper analysis if this would be beneficial or not from a CO_2 footprint point of view, as currently the BFG is already being used quite effectively.

Advancement in sorbent materials must be aligned with the design of the gas–solid reactor and its regeneration strategy. Consequently, effective utilisation of any chosen sorbent also requires parallel research into appropriate gas–solid contacting systems, as these greatly influence process efficiency, carbon footprint, and overall capture costs.

In an integrated steel plant, the CO_2 capture process can easily be retrofitted in the existing system for BF- BOF route or DRI/EAF based route. The overall process is described in Figure 6.5.

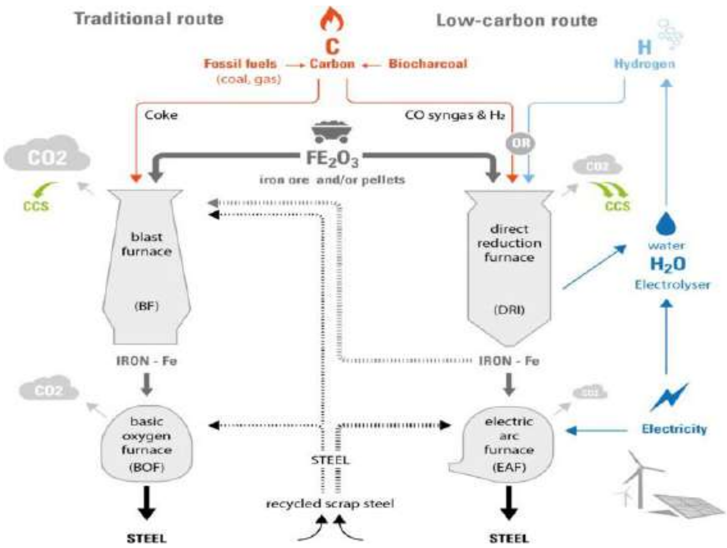

Figure 6.5. Schematic presentation of classical and low-carbon route steel production and CO_2 capture unit (Source: https://netzeroindustry.org/methodology/).

Apart from the adsorption process, a rotating packed bed (RPB)-based absorption process can also be considered. It became popular recently as RPB enhances mass transfer through rapid rotation and centrifugal acceleration, creating a gravitational field 100-1000 times stronger. JSW has recently come up with a joint agreement with Carbon Clean (https://www.carbonclean.com) to explore the RPB based cyclone CC technology. The following are the steel industries in India where the carbon capture process has been implemented:

a) **Tata Steel Ltd.:** Tata Steel, Jamshedpur, has commissioned a 5 tonne per day (TPD) CO_2 capture plant from the BF gas stream. The process is based on an amine-based absorption technology. The captured CO_2 is utilised for the treatment of wastewater from the gas cleaning plant. CO_2 is used in the treatment of wastewater from blast furnace gas cleaning plants. Wastewater from scrubbers is typically alkaline due to the presence of lime or other basic compounds used in gas cleaning. CO_2 micro-bubbling is introduced into the wastewater, where it reacts with hydroxide ions to form bicarbonates and carbonates, effectively lowering the pH.

b) **JSPL:** 2000 TPD plant which captures concentrated CO_2 from commercial-scale coal gasification at Angul, Odisha. In addition, the same plant has a 1500 TPD CO_2 capture unit connected with a DRI unit. In the gasification unit, CO_2 needs to be captured and removed to increase the gross calorific value (GCV) of syngas. Rectisol process (methanol) developed by Lurgi, Germany, as a part of the gasification process, is used for the removal of gas. In DRI, Midrex, USA, a technology supplier, has a tie-up with a CO_2 capture technology supplier that uses methyldiethanolamine (MDEA) as a solvent.

A 100-TPD CO_2 capture facility has been installed at a gas-based DRI plant in Salav, Maharashtra. The recovered CO_2 is converted into carbonates, and the liquefied CO_2 is subsequently supplied to the beverages sector.

CO_2 Utilisation: CO_2 is utilised using different processes in steel industry. Depending upon the available resources and market demand, different CO_2 utilization routes have been identified. CO_2 can be converted into value- added products using hydrogen or without it. CO_2 can be directly converted into mineral/ organic carbonates or polymers (polycarbonates) using metal oxides or epoxide as raw material. Further, CO_2 can also be transformed into CO/ syngas/ chemicals using electrochemical/ photochemical routes for recycling of the emitted CO_2 in the Steel making as CO. However, detailed technical understanding is still required to make the process viable and scalable. In hydrogen-based CCUS, CO_2 can be converted into syn-gas, methanol, ethanol and finally SAF. However, the requirement of capex, energy, and land are too large to make the translation to a higher scale rather unviable presently. The detailed area for prospective research is as defined below in Figure 6.6.

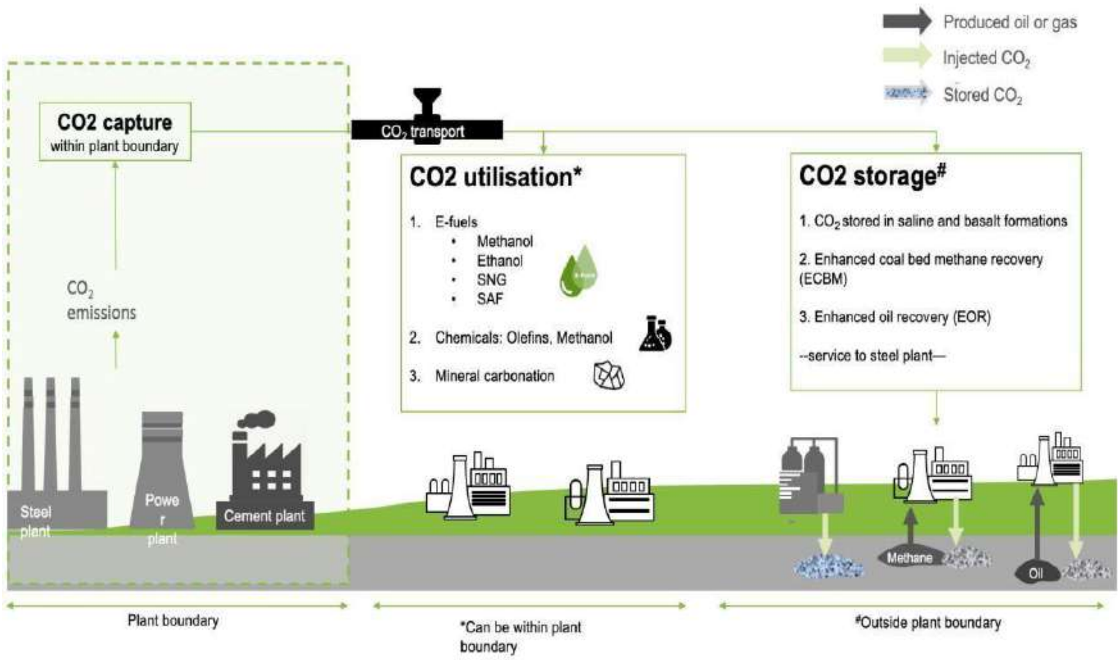

Figure 6.6: Schematic process flow of CCUS pathways in steel industries (Figure adapted from Greening the Steel Sector in India Roadmap and Action Plan: Ministry of Steel, September 2024).

6.2.2 Summary of CCUS processes and requirements for upscaling

Table 6.3: Carbon utilization pathways for generating value-added products with/without H_2.

CCUS process		Category	Capacity (TPD)	Remarks
CO_2 capture		Scale-up	1800	Amine absorption-and rectisol physical absorption based processes demonstrated • Other processes need to be evaluated
CO_2 Utilization without H_2	Organic carbonates	R&D & Pilot	1	• Targeted product: dimethyl carbonate (DMC)/ ethylene or propylene carbonate
	Mineral Carbonates	R&D & Pilot	1	• Usage of Linz-Donawitz (LD) slag
	Electrochemical	R&D & Pilot	1	• Targeted product: Syn-gas/ ethylene/ ethanol
	Photochemical	R&D & Pilot	1	• Targeted product: Syn-gas/ methanol/ ethanol
	Plasma	R&D & Pilot	1	• Targeted product: Syn gas using high temperature and low temperature DBD plasma
	Biological	R&D & Pilot	1	• Targeted product: ethanol/ butanol/ enzyme
CO_2 utilization with H_2	Thermochemical	Pilot & Scaleup	1-5	• Targeted product: Syn-gas/ methanol/ SAF
CCUS enablers: H_2	WGS	Pilot & Scaleup	1-5	• Usage of BF gas
	Methane Pyrolysis	R&D & Pilot	1	• Usage of Coke oven/ BF gas
	Methane reforming	Pilot & Scaleup	1-5	• Usage of Coke oven gas (<1.00kWh/ kg CO_2 for syn-gas
	Biomass gasification	Pilot & Scaleup	1-5	• Usage of MSW/ food waste
CO_2 sequestration		R&D & Pilot	1	• Geographic location to be identified

Overall energy requirement, cost, CO_2 and area footprint are of importance for all the above processes

6.2.3 CCU Enablers

Hydrogen is a key requirement for CCU. Till now, water electrolysis is the only mature technology for hydrogen production. However, the cost of electrolysis hydrogen is high, making CCU unviable. In a steel plant, hydrogen can also be generated through chemical looping process, water-gas shift reaction, methane reforming, etc. Biomass presents an alternative feedstock for hydrogen production through the gasification process, provided consistent availability is ensured. For generating the economically viable H_2, there is a strong need for catalyst development and reactor optimization that can be easily integrated into the process in the steel plant. To this end, various enablers such as specialized facilities for AI- and robotics driven high throughput catalyst discovery research centres, scale-up facilities and industrial-scale testing facilities could be the key enablers for developing viable and robust CCU technologies. At the same time, clear policy guidelines and regulatory frameworks are needed in India for a successful CCUS implementation. Various countries have already developed a policy framework on CCUS, while India is at nascent stage.

6.2.4 Action plans for CCUS

Dedicated policy for CCUS: The policy may envision the deployment of CCU and CCS to achieve the maximum scale of decarbonization in India. A careful consideration is required, ensuring socio-economic fairness, protection of the environments and inclusive participation by all stakeholders involved. Further, the policy framework shall allow for transitions through stage-wise deployment of technology contingent on the maturity of the technology and the capability of all stakeholders involved.

Policy guidelines should also include provision for preferential procurement of CCU products manufactured in steel plants to scale up the technology development and deployment in India. Different ministries should provide necessary support for the deployment of pilot projects in the area of CCUS in the steel sector. Adequate coordination is needed among various ministries to extend benefits provided to green hydrogen projects in the refinery and fertilizer sector to the steel industry for not only development of experimental blast furnaces, DRIs and shaft furnaces in India for trials with hydrogen injection, but also for the implementation of CCUS at pilot plant and demonstration scale. For successful integration of CCUS technologies in steel industries, the following considerations need to be paid:

a. **Aggregation of demand and negotiation of long-term offtake contracts**

b. **Coordination with MoPNG to provide access to natural gas for the steel industry**

c. **Assessment of the feasibility of a common gas- based shaft in DRI clusters**

d. **Scaling up technologies for high-ash-coal gasification**

Techno-economic feasibility study: Considering the high energy demand for CCUS projects, detailed techno-economic feasibility study, including CO_2 footprint for each pathway need to be undertaken. For evaluation of the same, support for pilot projects in the area of CO_2 capture and utilisation in steel industries should be expedited. This may include a dedicated site for CCUS technology demonstration near steel industries.

Joint project proposals may be sought at different TRL levels in the area of breakthrough & translational R&D and integration and upscaling in the area of CCUS pertaining to steel industries from academics, research institutions and industrial R&Ds. While the basic level research may be done at either academic institutions or industrial R&D, integration and upscaling may be done at the industries. A dedicated infrastructure may be set up for the demonstration of CCUS technologies, where various institutions and organisations can work in a consortium mode.

6.2.5 Collaboration with international partners

Table 6.4: Steel plants across the world are also working on different CCUS projects. Few of them are listed below.

Steel Plant	CCUS Projects
Arcelor Mittal	Ethanol (collaborating with Lanzatech)
	Syngas (collaborating with Haffner Energy on biomass gasification)
	Syngas (dry reforming of methane using plasma)
	CO (collaborating with D-CRBN & Mitsubishi Heavy Industries using plasma based technology)
Emirates steel	CO_2 capture followed by EOR
Posco	CCS
Nippon Steel	CO_2 capture followed by EOR
Shougang steel	Bioethanol
US steel	CO_2 carbonation

6.2.6 Conclusion

The availability of green electricity and hydrogen are the major challenges for both CDA and CCUS. To ensure the economic feasibility of CCUS technologies and integration with existing industries and deployment in newer industries, a strong thrust has been put on the resourcing of green hydrogen from renewable sources of energy such as solar energy, geo-thermal energy, wind energy etc. Considering the challenges associated with each process, both CDA and CCUS will play a crucial role in decarbonizing e the steel sector in India. Besides scientific/technical evolution, a new socio-economic policy must be adopted to achieve net- zero targets in the steel sector.

6.3 CCUS in Oil and Natural Gas sector

6.3.1 CCUS Strategy for Oil and Natural Gas

- **Upstream Sector: Oil and Gas Extraction**

The upstream oil and gas sector contributes approximately 10% of India's total energy-related CO_2 emissions, mainly from: Flaring of Associated Gas, Methane Emissions and Energy Consumption (IEA, 2023).

a) Flaring of Associated Gas

During oil extraction, associated natural gas often cannot be transported or utilized economically, resulting in its flaring. This process directly generates significant CO_2 emissions.

In 2022, India flared approximately 3.6 bcm of natural gas, releasing around 10.5 Mt CO_2 into the atmosphere (IEA, 2023). Flaring remains a significant source of CO_2 emissions in the upstream sector.

CCUS Application: Technologies like amine scrubbing, membrane separation, and cryogenic separation can capture CO_2 from flare gases. Post-combustion capture can recover up to 50% of flare gas emissions, which can either be utilized for energy production or sequestered (IEA, 2023).

b) Methane Emissions (Venting and Leaks)

Methane is a highly potent greenhouse gas emitted from oil and gas fields during production operations. Leaks from equipment such as pipelines, compressors, and storage tanks, along with venting during well tests, contribute to significant emissions. Methane has a global warming potential 84 times greater than CO_2 over 20 years.

Methane emissions are estimated to account for 6-10% of total emissions from the upstream sector in India. This translates to roughly 25 Mt CO_2 equivalent annually from leaks and venting (IEA, 2023).

CCUS Application: Advanced technologies like hydraulic separation, membrane filtration, and adsorption can capture up to 90% of methane emissions from oil and gas facilities, mitigating a significant portion of India's methane-related CO_2 equivalent emissions (IEA, 2023).

c) Energy-Related CO_2 Emissions

Extraction and processing of oil and gas require large amounts of energy, often sourced from fossil fuels. This energy consumption results in direct CO_2 emissions from the combustion of fuels such as natural gas, diesel, and coal.

The upstream sector's fuel combustion contributes approximately 30-40 Mt CO_2 annually (IEA, 2023). Most of these emissions come from energy-intensive extraction processes, including drilling, pumping, and crude oil processing.

CCUS Application: Post-combustion CO_2 capture from flue gases generated during power generation in upstream operations can reduce CO_2 emissions. Enhanced oil recovery (EOR) techniques could also be used to sequester CO_2 and enhance oil production by injecting captured CO_2 into oil reservoirs.

Downstream Sector: Refining Operations

The downstream sector, which includes the refining of crude oil into various petroleum products, is another major emitter of CO_2 in India. Refining operations in India contribute a significant share of CO_2 emissions, primarily from energy-intensive processes like steam and power generation, as well as hydrogen production via natural gas reforming. Key sources include fossil fuel combustion and process emissions.

CCUS in Downstream: Technical Approaches and Potential

a) Fuel Combustion in Refining

Refineries require substantial amounts of heat and power, primarily generated by burning fossil fuels such as natural gas and fuel oil. This results in high levels of CO_2 emissions.

The refining sector in India emits approximately 50-60 MtCO_2 annually due to fuel combustion in boilers and furnaces.

CCUS Application: Post-combustion CO_2 capture technologies, such as amine scrubbing and membrane separation, can capture up to 85-90% of CO_2 emissions from refinery stacks. These technologies, if widely deployed, could capture around 45-55 $MtCO_2$ annually **Hydrogen Production (Natural Gas Reforming)**.

Hydrogen is essential in refining processes like hydrocracking and desulfurization, but its current production method-steam methane reforming (SMR)-is highly CO_2 intensive.

Hydrogen production for refining contributes about 10-15% of total refinery emissions. The SMR process typically releases 9-12 tons of CO_2 per ton of hydrogen produced.

CCUS Application: Blue hydrogen, produced via SMR with integrated CCUS, can reduce emissions from hydrogen production by up to 70%. The CO_2 captured in this process can be either sequestered underground or used for enhanced oil recovery (EOR) transitioning to green hydrogen, produced via electrolysis powered by renewable energy, could further eliminate emissions from refining operations.

b) Process Emissions during Refining

Refining processes such as cracking, distillation, and hydrotreating result in process emissions, including CO_2 released during chemical reactions. Process emissions can account for around 15-25% of total emissions in a refinery (IEA, 2023).

CCUS Application: Post-combustion capture technologies can also address process emissions. Furthermore, CO_2-to-chemicals technologies, which convert captured CO_2 into valuable chemicals like methanol or urea, offer additional ways to utilize captured CO_2 while contributing to a circular carbon economy.

The CO_2 emission intensity in the oil and gas sector refers to the amount of CO_2 emissions produced per unit of energy or product produced. This metric is important for understanding the carbon footprint of different activities in both the upstream (oil and gas extraction) and downstream (refining) sectors. The breakdown of current CO_2 emission intensity for both sectors is as follows:

■ Upstream Oil and Gas Sector: Emission Intensity

In the upstream oil and gas sector, emissions are primarily linked to extraction activities, which include drilling, well testing, extraction, flaring of associated gas, and methane leaks. The emission intensity in upstream operations can vary based on several factors such as the extraction method, the type of oil field, the amount of flaring, and the energy efficiency of operations.

Emission Intensity Estimates for Upstream

General Estimate: The CO_2 emissions intensity in the upstream sector is often measured in terms of tonnes of CO_2 per barrel of oil equivalent (BOE) produced.

CO_2 Intensity Range: Emissions intensity in the upstream sector can range from 0.1 to 0.6 tonnes of CO_2 per barrel of oil equivalent (tonnes/BOE), depending on the field's location and operational practices. For offshore fields or more energy-intensive extraction methods, the intensity could be higher, while conventional onshore fields may have lower emission intensities.

India's Upstream Sector

In India, emissions from upstream oil and gas activities (exploration and extraction) are estimated at 100-150 MtCO_2 annually, accounting for approximately 10-15% of India's total energy-related CO_2 emissions.

Intensity in India: Considering India's total oil production of approximately 800,000-900,000 barrels per day, this translates to an average CO_2 emission intensity of roughly 0.3-0.5 tonnes CO_2 per barrel of oil equivalent (India Energy Outlook, 2025).

- ## Downstream Oil and Gas Sector: Emission Intensity

The downstream sector, which includes refining, is highly energy-intensive due to the need for large amounts of heat and power for crude oil processing, hydrogen production, and the energy requirements of various refining units.

Emission Intensity Estimates for Downstream

Refining CO_2 Intensity: In the refining sector, emissions are typically measured as tonnes of CO_2 per tonne of product (e.g., per tonne of refined product like gasoline, diesel, or jet fuel).

General Refining Intensity: The emission intensity in refineries varies based on the technology used, the energy efficiency of the plant, and the type of crude processed. A typical refining process produces 1.5 to 3.0 tonnes of CO_2 per tonne of refined product.

India's Downstream Sector

Refining Emissions Data: India has a refining capacity of over 250 million metric tons per year, and the refining sector is responsible for about 4-6% of India's total CO_2 emissions (IEA, 2023).

Intensity in India: Given India's refining capacity and the CO_2 emissions from this sector, the emission intensity in Indian refineries is generally in the range of 1.5 to 2.5 tonnes CO_2 per tonne of refined product (based on industry reports and emissions factors).

For instance, refineries such as those operated by Indian Oil Corporation (IOCL) and Reliance Industries have CO_2 intensities close to the 2.0 tonnes per tonne of refined product range (IOCL, 2023).

Table 6.5: Summary of CO_2 Emission Intensities in India's Oil and Gas Sector.

Sector	Emission Intensity	Unit	Reference
Upstream	0.3 to 0.5	Tonnes CO_2 per barrel of oil equivalent (BOE)	IEA India Energy Outlook, 2023
Downstream	1.5 to 2.5	Tonnes CO_2 per tonne of refined product	IEA World Energy Investment, 2023

CCUS has emerged as a crucial technology in India's strategy to reduce CO_2 emissions in its oil and gas sector. India is committed to achieving net-zero emissions by 2070, with an intermediate goal of reducing its carbon intensity by 45% by 2030, relative to 2005 levels CCUS technologies offer a pathway for significant emissions reductions in both the upstream (oil and gas extraction) and downstream (refining) sectors.

Upstream Sector: Potential for CO_2 Reduction through CCUS

The upstream oil and gas sector in India primarily generates emissions through fossil fuel combustion, gas flaring, methane leaks, and energy use for extraction processes. Given the significant emissions footprint of upstream activities, CCUS offers an important mitigation option.

Target Reduction via CCUS

Flaring Gas Capture: In India, approximately 3.6 bcm of natural gas was flared in 2022, emitting about 10.5 $MtCO_2$ (IEA, 2023). Capturing 50% of flare gas using post-combustion technologies such as amine scrubbing or cryogenic separation could reduce 5-7 Mt CO_2 annually. Alternatively, on-site natural gas can be reformed and subsequently converted into easier-to-transport liquid fuels such as methanol and dimethyl ether (LPG substitute), which would also reduce methanol and LPG imports.

Methane Recovery: Methane is a potent greenhouse gas and capturing up to 90% of methane leaks from upstream operations could mitigate up to 25 Mt CO_2-equivalent.

CO_2 Enhanced Oil Recovery (CO_2-EOR): Implementing CO_2-EOR could store 20-30% of the injected CO_2 in mature oil fields like those in the Mumbai High or Cambay Basin with the potential to inject millions of tonnes of CO_2 annually, CO_2-EOR could sequester significant amounts of CO_2, especially if 10-15 million metric tons of CO_2 per year are captured and injected for enhanced recovery and storage (IEA, 2023).

Projected Emission Reduction Target for Upstream by 2030

By implementing flare gas capture, methane recovery technologies, and CO_2-EOR, the upstream sector could reduce its total CO_2 emissions by 20-30% by 2030, targeting reductions of approximately 25-45 million metric tons of CO_2 annually, based on current emissions levels (IEA, 2023).

Downstream Sector: Potential for CO_2 Reduction through CCUS

The downstream refining sector is responsible for a significant portion of industrial emissions in India, primarily from energy consumption during refining processes, including hydrogen production, combustion of fuels, and process emissions during refining operations.

Current Emissions in Downstream Sector

The downstream refining sector contributes around 4-6% of India's total CO_2 emissions, roughly translating to 50-100 million metric tons of CO_2 annually. The energy-intensive nature of refining, particularly through hydrogen production and energy generation, contributes substantially to this emission footprint.

Target Reduction via CCUS

Post-Combustion CO_2 Capture: Refineries can achieve 85-90% CO_2 capture from flue gas using technologies such as amine-based absorption and membrane separation. If fully implemented, this could capture 45-55 $MtCO_2$ annually from India's refineries

Hydrogen Production with CCUS: As refineries are major consumers of hydrogen for processes like hydrocracking and desulfurization, transitioning to blue hydrogen (produced via steam methane reforming with CCUS) could reduce emissions from hydrogen production by up to 70% (IEA, 2023). If refineries switch to blue hydrogen, this could reduce CO_2 emissions by 15-20 $MtCO_2$ annually by 2030.

CO_2 Utilization: Captured CO_2 can be used in processes such as CO_2-EOR or converted into value-added products like methanol or synthetic fuels. The integration of CO_2-to-chemicals technology could reduce emissions by another 5-10 $MtCO_2$ annually, contributing to a circular carbon economy

Projected Emission Reduction Target for Downstream by 2030

By adopting CCUS technologies in refining operations, including post-combustion CO_2 capture, hydrogen production with CCUS, and CO_2 utilization technologies, the downstream sector could reduce CO_2 emissions by 30-40% by 2030, targeting reductions of 45-60 million metric tons of CO_2 annually (IEA, 2023; IOCL, 2023).

Core CCUS Technologies in Oil and Natural Gas sector

CCUS technologies are crucial for reducing CO_2 emissions in both the upstream (oil and gas extraction) and downstream (refining) sectors of the oil and gas industry. The choice of capture method depends on factors such as the type of emission source, the concentration of CO_2, and operational conditions. Below is a brief overview of the most effective carbon capture methods for the upstream and downstream oil and gas sectors:

a) Amine-Based Capture (Post-Combustion)

Application: Both Upstream and Downstream Sectors

Amine-based capture is one of the most widely used and mature technologies for capturing CO_2 from flue gases and process streams. It works by absorbing CO_2 in a liquid solvent (amine solution), which selectively reacts with CO_2 to form a stable compound. The solvent is then regenerated, releasing the captured CO_2 for transport, utilization, or storage.

Upstream: This method is especially effective in capturing CO_2 from flare gases during oil and gas extraction, where the CO_2 concentration is relatively high. Amine scrubbing can be applied to reduce CO_2 emissions from flared gases by up to 90%.

Downstream: In refineries, amine-based absorption is often used to capture CO_2 from the combustion gases generated during hydrogen production, steam generation, and other energy-intensive refinery processes. This method can capture around 85-90% of CO_2 from flue gases.

Efficiency: Can achieve up to 90% CO_2 capture (IEA, 2023).

Challenges: High energy requirements for solvent regeneration and solvent degradation over time.

b) Membrane Separation

Application: Both Upstream and Downstream Sectors

Membrane separation involves the use of semi-permeable membranes to selectively allow gases to pass through, separating CO_2 from other gases in the stream. This method is typically used for pre-combustion capture and can be an efficient solution for natural gas processing and refinery gas streams.

Upstream: In gas processing plants, membrane technology can be used for separating CO_2 from natural gas during purification, preventing its release into the atmosphere. It can also be used in flare gas capture to separate CO_2 before it is either utilized or stored.

Downstream: In refineries, membranes are used to capture CO_2 from the flue gases produced during combustion processes. Membranes are often more compact and energy-efficient than amine-based solutions, particularly in facilities with lower CO_2 concentrations.

Efficiency: Membranes can achieve 70-85% CO_2 capture.

Challenges: Membrane degradation, sensitivity to feed composition, and the need for frequent maintenance.

c) Cryogenic Separation

Application: Upstream and Pre-Combustion in Downstream

Cryogenic separation involves cooling gas streams to very low temperatures, causing CO_2 to condense and separate from other gases. This method is particularly effective when dealing with high CO_2 concentrations in natural gas or in processes where CO_2 is present in significant volumes.

Upstream: Cryogenic separation can be used in natural gas processing to separate CO_2 from methane in offshore and onshore fields. This method is highly effective for CO_2-rich natural gas and flare gas streams.

Downstream: While less common in refineries, cryogenic separation can be used in refineries to capture CO_2 from hydrogen production processes or during process gas cleanup before the gas is sent to combustion.

Efficiency: Cryogenic separation can achieve 95-98% CO_2 capture, making it one of the most efficient methods for high CO_2 concentration streams.

Challenges: High energy consumption due to the cooling process, and it is more suited to larger facilities with high CO_2 content.

d) Pre-Combustion Capture (Integrated Gasification Combined Cycle - IGCC)

Application: Primarily Downstream, but also Upstream for Synthetic Fuels.

Pre-combustion capture involves the removal of CO_2 before combustion by converting the fossil fuel into a mixture of hydrogen and CO_2 (via gasification or reforming). The CO_2 is then separated and captured.

Downstream: In refineries, pre-combustion capture is applied to hydrogen production via steam methane reforming (SMR), which is a significant source of CO_2 emissions. The captured CO_2 can either be stored or utilized in processes like CO_2-EOR (enhanced oil recovery).

Upstream: Pre-combustion technologies can also be applied in gas-to-liquids (GTL) or syngas conversion plants, where CO_2 can be separated from the syngas before combustion.

Efficiency: Pre-combustion capture can remove up to 90% of CO_2 before the fuel is burned, but it requires significant infrastructure investment.

Challenges: High capital cost, complex integration with existing infrastructure, and the need for advanced syngas cleaning systems.

e) Direct Air Capture (DAC)

Application: Future Potential for Both Upstream and Downstream

Direct Air Capture (DAC) is an emerging technology that captures CO_2 directly from the ambient air using chemical processes or physical sorbents. Although still in the experimental phase, DAC holds promise for offsetting emissions from industries where direct capture is difficult.

Upstream and Downstream: While not yet widely used, DAC could play a role in capturing CO_2 from the atmosphere that is indirectly associated with upstream and downstream emissions (e.g., methane leaks, and flaring). It could be used as a complementary technology to offset hard-to-abate emissions.

Efficiency: DAC technologies are still under development but have the potential to capture CO_2 at rates comparable to other industrial methods (up to 90%), but at a high cost.

Challenges: High operational costs and energy consumption.

■ Carbon Utilization Conversion Pathways in the Upstream and Downstream Oil and Gas Industry

Carbon utilization technologies are essential for converting captured CO_2 into valuable products, thereby reducing emissions while creating economic opportunities. In the oil and gas industry, both upstream (oil and gas extraction) and downstream (refining) sectors have significant potential for CO_2 utilization, transforming waste CO_2 into useful chemicals, fuels, or materials. The key conversion pathways include syngas production, carbonates, and other advanced technologies that facilitate a circular carbon economy.

a) Syngas Production (Fischer-Tropsch Synthesis)

Application: Primarily Upstream, but also in Downstream

Syngas (synthesis gas), a mixture of carbon monoxide (CO) and hydrogen (H_2), is a foundational building block for the production of synthetic fuels, chemicals, and other valuable products. CO_2 captured from flared gas or natural gas processing can be converted into syngas through processes such as reverse water-gas shift reaction (RWGS) or dry reforming of methane (DRM). This syngas can then be further processed using Fischer-Tropsch synthesis (FTS) to produce synthetic fuels like diesel, jet fuel, or even chemicals like methanol.

Upstream: CO_2 captured from flare gas during oil and gas extraction, or associated gas from offshore fields, can be converted into syngas using CO_2 reforming or reverse water-gas shift

(RWGS) reactions. This syngas is used in gas-to-liquid (GTL) or CO_2-to-syngas technologies to produce synthetic fuels, which can offset the need for crude oil.

Downstream: Refineries can use captured CO_2 for syngas production, particularly in processes where hydrogen production is required for hydroprocessing and desulfurization of crude oil. The syngas produced can be further processed to generate synthetic fuels or chemicals.

Syngas can be converted into a range of liquid fuels or chemicals, which creates a market for captured CO_2 and helps offset emissions.

Challenges: The process requires significant energy input and infrastructure investment, however, it offers long-term potential for the production of high-value products. Moreover, an industrially viable catalyst for RWGS process is still a long shot, as current catalysts suffers from challenge of low space-time yield and poor stability owing to high temperature and water release.

b) Carbonates and Carbonated Minerals (Mineral Carbonation)

Application: Upstream and Downstream Applications for Long-Term Storage and Material Production

Carbonate formation involves reacting CO_2 with minerals (such as magnesium silicates) to form stable carbonates, which can be utilized as building materials. This process is a form of mineral carbonation and is gaining traction as a long-term CO_2 storage solution while providing economic benefits.

Upstream: Captured CO_2 can be injected into basalt formations or other suitable minerals found in oil fields, forming carbonates as a permanent storage option. This approach, known as carbon mineralization, can be a useful way to sequester large amounts of CO_2 while maintaining or enhancing the oil field's economic value.

Downstream: In refineries, CO_2 can be captured and used for carbonated building materials such as concrete, aggregates, or bricks. The process converts captured CO_2 into useful construction materials, contributing to a circular carbon economy.

Carbonation processes can sequester CO_2 for hundreds to thousands of years, providing a long-term storage solution while producing materials that are in high demand.

Challenges: The scalability of mineral carbonation for large-scale CO_2 capture is still under development. Also, it requires suitable mineral deposits and infrastructure for large-scale CO_2 injection.

c) Methanol Production

Application: Downstream – Refining and Chemicals Production

Methanol is one of the most common and commercially viable products derived from captured CO_2. It can be produced through CO_2 hydrogenation (reacting CO_2 with hydrogen) to form methanol, which is an essential feedstock for the chemical industry, including the production of plastics, solvents, and synthetic fuels.

Downstream: Refineries can use captured CO_2 from flue gas or hydrogen production streams to produce methanol. The process typically involves CO_2 hydrogenation over a catalyst, where blue hydrogen (hydrogen produced using natural gas with CCUS) provides the necessary hydrogen.

Upstream: CO_2 captured from associated gas or flare gas in oil fields can be used to produce methanol or methanol-based fuels, further contributing to the reduction of flaring and creating an additional revenue stream for oil operators.

Methanol is a key building block chemical in the production of many industrial products, including plastics, fertilizers, and synthetic fuels.

Challenges: The hydrogen production process for methanol is still energy-intensive, and while it can utilize CO_2, it also requires a reliable source of blue hydrogen or renewable energy for full decarbonization.

d) Urea Production

Application: Downstream – Fertilizer Production

Urea is another valuable product that can be synthesized from captured CO_2. The Haber-Bosch process, which traditionally uses ammonia, can be modified to incorporate CO_2 into the process to produce urea for the fertilizer industry. This process reduces CO_2 emissions while simultaneously providing a key feedstock for agriculture.

Downstream: Refineries and chemical plants can integrate CO_2 capture systems to supply urea production, which is then used in fertilizers or other agricultural products.

Upstream: CO_2 captured from flared gas or natural gas processing can be used in urea synthesis, contributing to the circular carbon economy while reducing environmental impact.

Urea is a critical material in agriculture, and using captured CO_2 for its production can reduce emissions from both the oil and gas industry and the fertilizer sector.

Challenges: The integration of CO_2 capture into urea production requires syngas as a precursor, and achieving large-scale deployment may face challenges with infrastructure and cost.

e) CO_2-EOR (Enhanced Oil Recovery)

Application: Upstream

CO_2-EOR is a well-established method for improving oil recovery from mature oil fields. Captured CO_2 is injected into mature reservoirs to increase pressure and enhance the flow of oil, allowing more crude oil to be extracted. At the same time, CO_2 is permanently sequestered in the geological formation.

Upstream: CO_2 captured from flare gas or natural gas processing can be injected into oil reservoirs to increase recovery and simultaneously sequester CO_2. This method is particularly useful for mature oil fields, as it can increase recovery by up to 15-30% of the original oil in place.

CO_2-EOR has the potential to increase oil recovery while simultaneously providing CO_2 sequestration. It is a mature, commercially viable process used globally in oil fields.

Challenges: The CO_2 sequestration potential depends on the geological conditions of the field, and the process requires significant infrastructure.

CCUS Research & Development Needs in Upstream Oil and Natural Gas Refineries

The implementation of CCUS technologies in the upstream oil and gas industry, as well as in refineries, is an essential step in reducing CO_2 emissions from one of the world's most carbon-intensive sectors. However, significant challenges remain in developing and scaling CCUS technologies to meet global climate targets. The key R&D needs for improving CCUS across the upstream oil and gas extraction operations and the downstream refining industry are as follows:

a) Advanced Carbon Capture Technologies

i) Post-Combustion CO_2 Capture

Scientific Challenge: Post-combustion capture, typically involving amine-based absorption systems, is the most established carbon capture method in industrial applications. This process absorbs CO_2 from exhaust gases using a chemical solvent (typically amines like monoethanolamine or diethanolamine). However, there are significant scientific and technical barriers, primarily energy consumption for solvent regeneration and solvent degradation over time, leading to both high operational costs and reduced capture efficiency (Zhang et al., 2023).

Next-Generation solvents are needed. Traditional amine solvents suffer from issues such as high vapor pressure, toxicity, and reactivity with acidic gases (e.g., SO_2, NO_x). Research into ionic liquids, amine-functionalized adsorbents, and deep eutectic solvents is vital. These solvents would ideally exhibit low energy consumption for regeneration, enhanced CO_2 absorption capacity, and resistance to degradation.

For instance, recent advancements in ionic liquids offer the potential to reduce energy penalties for solvent regeneration, as these compounds have a higher selectivity for CO_2 and are chemically stable under harsh operating conditions (Yao et al., 2023).

Hybrid Capture Systems: Hybrid systems that combine amine-based capture with membrane separation or adsorption could enhance both CO_2 selectivity and capacity. Membrane-assisted absorption, for instance, shows promise by reducing energy costs and improving capture efficiency through a combination of CO_2-permeable membranes and chemical solvents (Barakat et al., 2022).

Advanced Solvent Regeneration: Improving thermal regeneration methods, such as pressure swing adsorption (PSA), can reduce the energy requirements of CO_2 capture systems, addressing one of the main barriers to large-scale implementation in industrial plants, including refineries and extraction facilities.

ii) Membrane Technologies

Scientific Challenge: Membrane separation technologies are an emerging area of interest in CCUS because they offer compact, modular, and energy-efficient solutions for CO_2 capture. However, the selectivity and permeability of membranes must be improved for high-volume applications in industrial settings, particularly in refineries, where flue gas contains low concentrations of CO_2 (usually less than 10%).

High Selectivity Membranes: Membrane technologies must be designed to maximize CO_2 selectivity over other gases such as nitrogen, oxygen, and methane. For instance, polymer-based membranes like polysulfone have been explored for CO_2 separation, but their low permeability limits scalability (Molina et al., 2023).

Mixed-Matrix Membranes: A promising approach to overcoming these limitations is the development of mixed-matrix membranes, which combine polymer and inorganic fillers (e.g., zeolites, silica, or metal-organic frameworks, MOFs). These materials can improve both CO_2 permeability and selectivity (Khan et al., 2021).

Durability and Fouling Resistance: A major scientific challenge for membrane technology in upstream oil extraction and refining is fouling from compounds like sulfur, nitrogen, and volatile organic compounds (VOCs). Research is needed to develop fouling-resistant membranes and improve membrane longevity in the presence of contaminants (Pereira et al., 2021).

iii) Cryogenic CO_2 Capture

Scientific Challenge: Cryogenic CO_2 capture involves the cooling of gas streams to very low temperatures (typically below -50°C) to separate CO_2 from other gases by condensation. This technology is effective but suffers from high energy demands for cooling and cost limitations associated with large-scale application in refineries and upstream oil and gas operations.

Energy-Efficient Cryogenic Systems: Improvements in the thermal efficiency of cryogenic systems, such as through the development of multi-stage refrigeration cycles or integrating waste heat recovery, could significantly reduce energy consumption. Research into magnetic refrigeration, an energy-efficient cooling technology, could also be a potential breakthrough.

Direct CO_2 Capture from Low-Pressure Streams: Cryogenic systems need to be optimized for use with low-concentration CO_2 found in many upstream extraction processes and refinery flue gas streams, where CO_2 concentrations are typically between 5-10%. Developing low-temperature absorption processes that can operate efficiently at low CO_2 concentrations will increase the viability of cryogenic separation in real-world industrial environments (Smith et al., 2022).

b) CO_2 Utilization in Upstream Oil and Gas

i) CO_2 Conversion to Synthetic Fuels

Scientific Challenge: CO_2 conversion technologies, such as the Fischer-Tropsch synthesis and methanol production, allow for the conversion of CO_2 into valuable chemicals or fuels. However, these processes are energy-intensive, and the efficiency of CO_2-to-fuel pathways remains low, particularly when hydrogen is sourced from natural gas reforming, negating the benefits of CO_2 reduction.

Electrochemical Reduction of CO_2: Research into the direct electrochemical reduction of CO_2 to produce methanol, ethanol, or formic acid is crucial for enabling more energy-efficient conversion pathways. Developing catalysts for CO_2 electroreduction such as copper-based catalysts, that are highly selective and stable under industrial conditions is a priority.

Integration with Renewable Energy: Utilizing renewable electricity (from wind, solar, or nuclear energy) to produce green hydrogen through electrolysis and combining it with CO_2 to produce synthetic fuels like methanol or syngas will provide a pathway for creating low-carbon fuels that can offset emissions from the upstream sector.

c) Process Integration and Efficiency

i) CCUS Integration into Existing Infrastructure

Scientific Challenge: Upstream oil and gas operations and refineries often operate with high energy demands and infrastructure limitations, making the integration of CCUS technologies challenging. There is a need for innovative solutions that enable seamless integration of capture, transport, and storage systems into existing facilities with minimal operational disruption.

Process Integration: Developing integrated carbon management solutions that combine capture, utilization, and storage within existing oil and gas operations can optimize energy consumption and reduce costs. For example, heat integration strategies could be employed to utilize excess heat from the refinery or extraction processes for solvent regeneration in capture systems (Wang et al., 2023).

Cost-Effective Retrofitting: Research on modular CCUS systems that can be easily retrofitted into existing infrastructure without significant capital expenditure would significantly accelerate deployment. These modular units could handle various capacities depending on the emissions from different types of oil and gas facilities.

d) Cost Reduction and Economic Viability

i) Reduction in Capital and Operational Costs

Scientific Challenge: The high capex and opex associated with CCUS technologies, particularly in large-scale industrial applications, remain a critical barrier to adoption in upstream oil and gas operations and refineries.

Material Innovation: Developing lower-cost materials for CO_2 capture (e.g., ammonia-based systems, high-performance adsorbents) is essential for reducing the financial burden of CCUS.

Economies of Scale: Research into centralized CO_2 transport networks, such as pipeline corridors or marine shipping, can reduce the transport costs associated with CCUS, which are currently prohibitive for smaller-scale operations.

e) Funding Needs /Void

High Costs and Infrastructure: The capital costs of CCUS technologies, along with the lack of transport and storage infrastructure, pose significant barriers to large-scale implementation in India.

Technological Maturity: While some CCUS technologies, such as amine scrubbing and CO_2-EOR, are mature, others like membrane separation and DAC remain in the research phase. Continued technological development is necessary to improve efficiency and reduce cost.

f) Dedicated Policy and Regulatory

Regulatory and Policy Support: India's regulatory framework for CCUS is still developing. Policy measures, such as carbon pricing or tax credits for CCUS adoption, will be essential to encourage industry uptake (IEA, 2023).

6.4 CCUS in Power Sector

CCUS technologies are poised to play a critical role in decarbonising power systems worldwide, most of which still rely heavily on fossil fuels, and in facilitating the broader transition toward net-zero emissions. CCUS has been identified as one of the most effective tools to achieve India's Net Zero targets, along with a thrust to renewable sources of energy. CCUS can abate the unavoidable CO_2 emissions in the country.

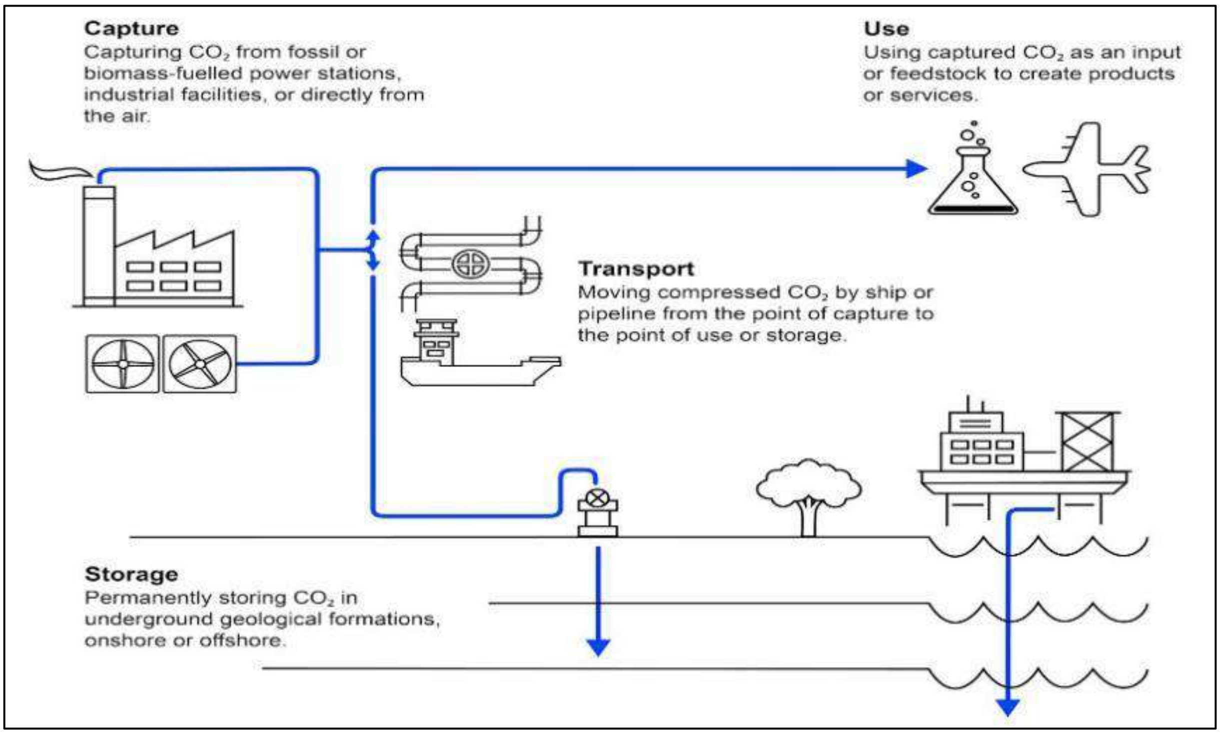

Figure 6.7: Schematic of CCUS (Source: https://www.iea.org/reports/ccus-in-clean-energy-transitions/a-new-era-for-ccus).

6.4.1 Industry Emissions and CCUS Potential Overview

- **Power Sector CO_2 Emissions:** ~1000 MTPA CO_2 from ~213 GW Coal Power Plant in FY in 2022-23.

- **CO_2 Utilization Potential:**

  (I) Liquid Fuel: Methanol, Ethanol, Sustainable Aviation Fuel (SAF), Di-methyl Ether; (ii) Gaseous Fuel: Synthetic Methane, (iii) Fertilizer: Urea, (iv) Building Material: Carbonated bricks, Carbonated aggregates etc.

  CO_2 Storage Potential: Potential storage sites include: (i) Enhanced Oil Recovery, (ii) Basalt Rock Formation, (iii) Saline Aquifer, (iv) Unusable Coal Seam.

6.4.2 CCUS Goals and Key Technologies

- **Current CO_2 Emission Intensity:** 0.85 kg CO_2/kW

- **Target Reduction via CCUS:** The power sector in India is at an emerging stage in adopting CCUS. Multiple R&D and technology demonstrations have been initiated; however, specific CO_2 abatement targets through CCUS are yet to be established.

6.4.3 Core CCUS Technologies

- **Carbon Capture:**

  The purity of CO_2 (>99%) is important for its effective utilization in the synthesis of any chemical. However, for storage purposes, purity is not a governing factor, therefore, PSA membrane-based capture technology can be deployed.

  While the capture part is most explored area within CCUS, more technology demonstration projects, based on different carbon capture technologies need to be set up to assess the technical feasibility and ascertain and optimise capex and opex in the Indian scenario. The suitability of various capture technologies with respect to low partial pressure of CO_2 and impurities present in flue gas can be established based on data from these demonstration pilots.

  The high energy cost of CO_2 capture and its conversion into a saleable product prevent power plants from opting for this technology adaptation. The large-scale utilisation of CO_2 also requires access to the cheapest hydrogen. Adaptation of CO_2 capture in thermal power plants will reduce its power production by 15-20%.

- **Carbon Utilization:**

  Various conversion pathways include syngas production, methanol, ethanol, SAF, carbonates through different conversion routes like thermocatalytic, electrochemical, biochemical, carbonation etc.

Apart from mineralisation, other CO_2 utilisation routes invariably involve reduction of CO_2 to other useful chemicals (like CO, Methanol, DME etc.) using hydrogen. Cost of the products generated from CO_2 through these routes, hence depends on the availability and cost of hydrogen available at the location of thermal plants. The technology /demonstration projects establishing and optimising the entire chain of converting the technology captured CO_2 to useful products along with hydrogen production (using various routes) can be set-up/funded to ascertain technology suitability and viability of CO_2 utilisation in power sector. Utilisation of products, such as CO produced, can done within the power plants (e.g. CO based gas turbines) or in the industrial clusters (e.g. methanol, DME) near the plant to keep transportation and handling costs at minimal. Here, we are highlighting one such effort by NTPC Vindhyachal where the CO_2 to methanol plant was set up that encompasses 20 TPD CO_2 capture plant, 2 TPD Proton Exchange Membrane (PEM) based H_2 generation unit and 10 TPD methanol Synthesis Plant.

Figure 6.8: Both images show efforts taken up by NTPC. First image showcase the 10 TPD CO_2 to Methanol plant at NTPC Vindhyachal and second image demonstrate drilling and CO_2 injection borewell infrastructure at Pakri Barwadh coal mine.

- **Carbon Storage:**

CO_2 can be stored at various geological sites such as oil fields, coal seams, saline water aquifers, basalt formation. Storage of CO_2 from any source (including Power plants) depends on the availability of suitable geological formations in the vicinity of the source along with factors such as population density, forest cover, and ecological sensitivity of the area. Power plants in suitable areas can be identified in whose vicinity sequestration/ storage projects can be taken up. Pilot/demonstration studies can be taken up at these plants to deploy suitable sequestration / storage technologies (depending on the geological formations available near the given plants) and ascertain economic viability as well as long term environmental and ecological aspects of these projects. **CO_2 injection borewell at Pakri Barwadih Coal Mine by NTPC is one such**

unique assessment study which revealved the estimated potential of 4.3–15.5 million tons of CO_2 Storage. This ambitious effort is aimed at drilling upto 1200 meter which can be used for sampling core, methane and water; followed by CO_2 injection.

6.4.4 CCUS Research & Development Needs / Void pertaining to Power sector

- Innovations to lower specific energy consumption in CO_2 capture technological to improve the viability towards the synthesis of fuels and chemicals.
- Technological support to mapping potential sinks, transportation of CO_2 and its monitoring.
- Technological gaps meeting poor compressive strength in various carbonation cured products.
- Development of critical and technology-based equipment like reactors, catalyst, solvent, & electrode.

6.4.5 Action Plan, Partnerships, and Funding Strategy

- **Dedicated Policy and Regulatory:**
  - Establish a financial body "Carbon Capture Finance Corporation (CCFC)," to promote and fund CCUS projects in India.
  - CCUS Mission: Establish a regulatory body to monitor lab-scale, pilot, and scalable projects, providing technological support and facilitating future technology transfers.
  - Industry-specific guidelines for CCUS implementation with financial support.
  - Mandated Purchases: Policies requiring mandatory purchases of products derived from CCUS processes to boost demand.
- **Techno-Economic Feasibility Studies:**
  - Detailed feasibility assessments for capture, utilization, and storage, costs, CO_2 impact, funding allocation for feasibility studies and pilot projects in Power sector.
- **International Collaboration and Funding Sources in Power sector:**
  - Existing or potential partnerships with global CCUS leaders (e.g., partnerships with European or Asian CCUS projects)
  - Joining hands with potential sources of debt like IFC, World Bank, ADB, EIB etc.

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Abbreviations

LIST OF ABBREVIATIONS

AAS	Amino Acid Salts
ACM	Alternative Cementitious Material
ADB	Asian Development Bank
AD	Accelerated Depreciation
AF	Alternative Fuels
AFR	Alternative Fuels and Raw Materials
AI	Artificial Intelligence
BECCS	Bioenergy with Carbon Capture and Storage
BF	Blast Furnace
BFB	Bubbling Fluidized Bed
BFG	Blast Furnace Gas
BOF	Basic Oxygen Furnace
BUR	Biennial Update Report
CaL	Calcium Looping
CBAM	Carbon Border Adjustment Mechanism
CCD	CCUS Compliant Design
CCfD / CCFD	Carbon Contracts for Difference
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture, Utilisation and Storage
CEA	Central Electricity Authority
CIF	Climate Investment Funds
CLC	Chemical Looping Combustion
CMA	Cement Manufacturers' Association
CO_2-EOR	Carbon Dioxide Enhanced Oil Recovery
CO_2-ECBM	Carbon Dioxide Enhanced Coal Bed Methane Recovery
COP	Conference of the Parties
CPLC	Carbon Pricing Leadership Coalition
CSR	Corporate Social Responsibility
CTF	Clean Technology Fund
C_xH_Y	Hydrocarbon Compounds

DAC	Direct Air Capture
DAS	Distributed Acoustic Sensing
DMF	Dimethylformamide
DMX	DMX™ Low-Energy Solvent Process
DRI	Direct Reduced Iron
DRI–EAF	Direct Reduced Iron–Electric Arc Furnace
ECBM	Enhanced Coal Bed Methane Recovery
EAF	Electric Arc Furnace
EC	Electrochemical
EIA	Environmental Impact Assessment
EOP	End of Pipe
EOR	Enhanced Oil Recovery
ETS	Emissions Trading System
EU-ETS	European Union Emissions Trading System
EV	Electric Vehicle
FDI	Foreign Direct Investment
FGD	Flue Gas Desulphurisation
FGR	Flue Gas Recycling
FT	Fischer–Tropsch
FY	Financial Year
GBI	Generation-Based Incentives
GCV	Gross Calorific Value
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GWh	Gigawatt-hour
Gt	Gigatonne
GT	Gas Turbine
H_2-DRI	Hydrogen-Based Direct Reduced Iron
HFC-23	Hydrofluorocarbon-23
HMI	Hydration Mechanism Indicator
HTF	High-Level Task Force
IEA	International Energy Agency
IFC	International Finance Corporation
IGCC	Integrated Gasification Combined Cycle

IP	Intellectual Property
IPCC	Intergovernmental Panel on Climate Change
IPPU	Industrial Processes and Product Use
IS	Indian Standard
LCA	Life Cycle Assessment
LC3	Limestone Calcined Clay Cement
LNG	Liquefied Natural Gas
LoS	Line of Sight
LULUCF	Land Use, Land Use Change and Forestry
MEA	Monoethanolamine
MDEA	Methyldiethanolamine
ML	Machine Learning
MMT	Million Metric Tonnes
MOFs	Metal–Organic Frameworks
MoEFCC	Ministry of Environment, Forest and Climate Change
MoP	Ministry of Power
MSMEs	Micro, Small and Medium Enterprises
NBS	Nature-Based Solutions
NGCC	Natural Gas Combined Cycle
NGO	Non-Governmental Organisation
NO_x	Nitrogen Oxides
OPC	Ordinary Portland Cement
PCR	Process Carbon Reduction
PEC	Photoelectrochemical
PF	Pulverized Fuel
PM	Particulate Matter
PMR	Partnership for Market Readiness
PPU	Product Process Use
PPP	Public–Private Partnership
PVT	Pressure–Volume–Temperature
R&D / R&D&I	Research, Development and Innovation
RE	Renewable Energy
RET	Renewable Energy Technologies
ROV	Remotely Operated Vehicle

RR	Reduction Requirement
SAF	Sustainable Aviation Fuel
SC	Supercritical
SCADA	Supervisory Control and Data Acquisition
SCF	Strategic Climate Fund
SCM / SCMs	Supplementary Cementitious Materials
SCR	Selective Catalytic Reduction
SDGs	Sustainable Development Goals
SO_x	Sulfur Oxides
STF	Solar-to-Fuel Efficiency
TCM	Technology Centre Mongstad
TCeEs	Thematic Centres of Excellence
TPD	Tonnes Per Day
TRL	Technology Readiness Level
TWh	Terawatt-hour
UNFCCC	United Nations Framework Convention on Climate Change
UREA	Urea (CO_2 utilisation product)
WB	World Bank
WRI	World Resources Institute
WSA	Waste Slag Analysis

सत्यमेव जयते

विज्ञान एवं प्रौद्योगिकी विभाग
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