ACBCCU 2025

Workshop on Awareness and Capacity Building

Carbon Capture, Utilization and Storage

June 11-13, 2025, New Delhi

Objectives of ACBCCUS-2025

I) To create awareness about Carbon, Capture, Utilization and Storage (CCUS) Technology

ii)To discuss recent advances in scaling-up carbon dioxide removal Technology

ii) To learn about case studies and success stories in Energy Intensive industry and identify Policy and Regulatory issues and submit recommendations

Workshop Highlights

Carbon Capture, Utilization and Storage: Overview and Status

Recent Advances in Scaling-up CCUS Technologies

Case Studies and Success Stories in Steel, Cement, Oil and Fertilizers

Policy and Regulatory Aspects – Bridging the gap with International examples

Convener / Organizing Secretary:

Dr. (Mrs.) Malti Goel
Chief Executive, CCRI and Former Adviser & Emeritus Scientist, MST
Contact: info.acbccs@gmail.com

Pre-Workshop Bulletin of Lecture Notes

Workshop Theme

Recent Advances in CCUS Technology, Policy and Regulations: towards Net-Zero strategy

Supported by

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Ministry of Earth Sciences
Government of India

Awareness and Capacity Building in Carbon Capture, Utilization and Storage (CCUS) Technology, Policy and Regulations: towards a Net Zero strategy

(ACBCCUS-2025)

India International Centre, New Delhi, June 11th – 13th, 2025

Workshop Highlights

- Recent Developments in Carbon Capture, Utilization and Storage: Overview
- Case Studies and Success Stories in Steel, Cement, Oil and Fertilizers etc.
- Scaling-up CCUS Technologies and Techno-economies of CO_2 Utilization
- Policy and Regulatory Aspects – Learning from the National and International Experience

Convener

Dr. (Mrs.) Malti Goel

Chief Executive, Climate Change Research Institute and Former Adviser & Emeritus Scientist, Ministry of Science & Technology, New Delhi

Awareness and Capacity Building in Carbon Capture, Utilization and Storage (CCUS) Technology, Policy and Regulations: towards a Net Zero strategy (ACBCCUS-2025)

June 11th – 13th, 2025 at IIC, New Delhi

Preface

This Pre-Workshop Bulletin contains the lecture notes for the program on Carbon Capture, Utilization, and Storage (CCUS) ACBCCUS-2025, organized by the Climate Change Research Institute. The workshop will take place from June 11th to 13th, 2025, at the Indian International Centre (IIC) in New Delhi.

CCUS involves capturing carbon dioxide (CO_2) from industrial processes and power plants, utilizing it in various applications, and/or permanently storing it underground. In many advanced countries, storage has been the preferred method for CO_2 sequestration. However, a recent study by the Global Carbon Initiative (GCI) at Michigan University suggests that CO_2 capture and utilization (CCU) could be more advantageous than carbon capture and storage (CCS) and may play a crucial role in promoting a circular carbon economy.

The Climate Change Research Institute (CCRI) has been conducting capacity-building workshops to address critical challenges in climate change mitigation, particularly aimed at empowering youth in the country. CCUS is the core area of focus for our climate change research and outreach activities. The current workshop aims to raise awareness about the latest developments in CCUS technology, as well as the relevant policies and regulations for applying CCUS in energy industries, including steel, coal, cement, and power.

I would like to express my sincere gratitude to Prof. D. P. Agrawal, Chairman of the Governing Council of CCRI, for his encouragement. On behalf of CCRI, I also thank Shri Alok Kumar, Chairman of the National Advisory Board, for his advice and support, and Shri V. S. Verma, Chairman of the National Organizing Committee. We are deeply grateful to the eminent experts and delegates from leading institutions and industries across the country for their valuable contributions. The support from the Ministry of Earth Sciences, Government of India, for this capacity-building workshop is acknowledged with thanks.

Dr. (Mrs.) Malti Goel
Convener, ACBCCUS-2025
Chief Executive, Climate Change Research Institute

Climate Change Research Institute

Science & technology solutions for sustainable energy future

C-85, Shivalik, New Delhi – 110017, (INDIA)

Tel: +91-11-41034450, Email: contactus@ccri.in

Message

India's commitment to achieving net-zero emissions by 2070 calls for a multifaceted approach that integrates technological innovation, policy support, and capacity building. I am happy that the **Awareness and Capacity Building workshop on Recent Advances in CCUS Technology, Policy and Regulations: Towards a Net-Zero Strategy ACBCCUS -2025** is being organised by the Climate Change Research Institute. It is a very timely and an important step in that direction. By fostering awareness and enhancing technical competencies in Carbon Capture Utilization and Storage, we are investing in the future of climate leadership and environmental stewardship.

I commend the organizers of ACBCCUS-2025 for bringing together experts, scholars, industry professionals, and policymakers under one platform. Such interdisciplinary engagement is essential for building a robust ecosystem that ropes research, deployment, and scaling-up of climate technologies.

I urge all participants to make the most of this opportunity—ask questions, share insights, challenge assumptions, and most importantly, envision practical solutions. Your active involvement today could shape the strategies and frameworks that guide our nation and the world toward a resilient and sustainable future.

My greetings to all distinguished speakers and delegates.

I convey my best wishes for a fruitful and impactful workshop.

Prof. D.P. Agrawal
Chairman, Governing Council
Former Chairman, Union Public Service Commission (UPSC)
Founder Director, Atal Bihari Vajpayee Indian Institute of Information Technology and Management, Gwalior

सत्यमेव जयते

डॉ. एम. रविचंद्रन
Dr. M. Ravichandran

सचिव
भारत सरकार
पृथ्वी विज्ञान मंत्रालय
पृथ्वी भवन, लोदी रोड़, नई दिल्ली–110003

SECRETARY
GOVERNMENT OF INDIA
MINISTRY OF EARTH SCIENCES
PRITHVI BHAWAN, LODHI ROAD, NEW DELHI-110003

Message

It is with great pleasure I extend my warm greetings to the participants of 'Awareness and Capacity Building on CCUS Technology, Policy, and Regulations: Towards a Net Zero Strategy (ACBCCUS-2025)' workshop being held on June 11-13, 2025 at IIC, New Delhi.

As the global community faces the threats of climate change, the need for a transition to low-carbon economy has never been more urgent. In this context, Carbon Capture, Utilization, and Storage (CCUS) is a complex set of technology, emerging as an important option for sustainable growth. The CCSU methodologies are getting acceptance as environment friendly approach towards net-zero strategy, both in power and industry sectors as a vital solution for promoting the sustainable use of natural and industrial resources.

I am happy that ACBCCUS-2025 workshop being organized by the Climate Change Research Institute is a capacity building programme for students and researchers to provide them exposure to recent advancements in CCUS technology, relevant policies, and regulatory frameworks. It is an opportunity to interact with the experts, and explore the potential to support the transition towards a low-carbon economy.

The Pre-workshop Bulletin comprises outlines of lectures notes that provide glimpses of proposed deliberations. I compliment Dr. (Mrs.) Malti Goel, President Climate Change Research Institute, for her leadership and dedication. Her outreach efforts and contributions to advancing climate science and policy are commendable.

I wish the workshop a great success and look forward to the deliberations.

(M. Ravichandran)

Tel. : +91-11-24629771, 24629772 ❑ Fax : +91-11-24629777 ❑ E-mail : secretary@moes.gov.in

ACBCCUS-2025

Pre-Workshop Lecture Notes

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CCUS Technology: Challenges in Scaling-up

Dr. (Mrs) Malti Goel
Chief Executive and President, Climate Change Research Institute, New Delhi
Former Adviser and Emeritus Scientist, Ministry of Science & Technology, Govt. of India

Extended Summary

Carbon Capture, Utilization and Storage (CCUS) is a crucial technology for reducing greenhouse gas emissions from various sectors of economy including power, cement, steel, chemicals and others. India, being a signatory to the Paris Agreement, has committed to reducing its carbon intensity by 40-45% below 2005 levels by 2030. The CCUS can play a significant role in achieving this target by reducing the emissions.

The Global Stocktake (GST), the first review under the Paris Agreement that assesses collective progress towards meeting the Agreement's goals, including limiting global warming to well below 2 degrees Celsius, preferably to 1.5 degrees Celsius, took place in the meeting of United Nations Conference of Parties (COP 28) held in UAE in early December 2023. Global Stocktake document was endorsed, also known as *The UAE Consensus* for Parties to act and accelerate. World leaders agreed to put forward new NDCs to accelerate climate action plan in a move towards net-zero emission targets. Energy transition away from fossil fuels and including CCS in the list of zero and low emission technology for countries to act upon was agreed. India as a nation is striving for Green Growth and Climate Justice. The country would become carbon neutral and achieve net-zero emissions by the year 2070.

The CCUS being vital technology for a clean energy transition towards a net-zero strategy, scaling-up CCUS is crucial for achieving the goal. '*If we were in a global war against climate change, we would be carrying out CCUS on large scale*', said Prof. B. Smit in 2014 [1]. Significant challenges remain in scaling up from the million ton level where it is today to the gigaton level where it needs to be to help mitigate global climate change. According to McKinsey analysis, CCUS uptake needs to grow 120 times by 2050 from the present level, reaching 4.2 gigatons per annum or more**.** Main hurdles in scaling-up of CCUS have been identified as

(i) High CO2 capture cost
(ii) Sub-system technologies are yet to mature fully
(iii) As climate change mitigation option competition with renewal energy
(iv) Absence of regulatory frameworks

1. ACBCCUS 2025

The ACBCCUS 2025, the Awareness and Capacity Building workshop on **Recent Advances inCarbon Capture, Utilization and Storage (CCUS) Technology, Policy and Regulations: towards a Net-Zero strategy,** is a national level workshop aiming at knowledge sharing for understanding of issues and challenges in CCUS technologies, policy and regulations towards a net-zero strategy and to address the knowledge & skill gaps. Capacity building is very important for the advancement of technology. The CCUS value chain demands diverse range of expertise. The workshop has following Technical Sessions on

- Recent Developments in Carbon Capture, Utilization and Storage
- Case Studies and Success Stories in Steel, Cement, Oil and Fertilizers etc.
- Scaling-up CCUS Technologies and Techno-economics of CO_2 Utilization

and a Panel Discussion on Policy and Regulatory Aspects – Learning from the National and International Experience

Current global status of CCUS technology, scaling-up challenges and India position are discussed below.

2. CCUS Technology- Current Status

The main components of CCUS are; separation of CO_2 from point sources, utilization and secure storage.

Carbon Capture

The CO_2 capture is a mature technology and it adaption in a coal fired plant for different modes viz. pre combustion, during combustion and post combustion have been extensively researched. These carbon capture technologies can capture up to 85-99% of plant CO_2 although increasing energy needs by 10-40%. The overall plant efficiency is reduced 20-30%. Among the technologies; Pre combustion carbon capture has an advantage that CO_2 concentrations are higher, but it requires coal gasification and use of advance technologies such as Integrated Gasification Combined Cycle (IGCC). Whereas, Post combustion capture from tail pipe gases is more flexible in terms of fuel, but has to deal with low CO_2 concentrations. Additional energy is consumed thereby increasing the carbon footprints.

Innovations such as oxy fuel combustion, chemical looping combustion and co-firing biomass are currently being aggressively researched. These can help in reducing the energy requirements. In Membrane based CO_2 capture and cryogenic separation technologies development of advanced materials and high investment in infrastructure development continue to be challenging.

Carbon Utilization

CO_2 utilization using chemical, catalysis, physical, biological and mineral carbonization methods are intense research topics. For cost-effective utilization of captured carbon dioxide main strategies can be; lowering energy requirement in the process of conversion of CO_2 captured into chemicals & fuels, frontier research in materials science & engineering, and use of renewable energy in place of conventional energy in the conversion process. These strategies contribute to a circular economy model. Innovative approaches like; metal organic frameworks (MOFs), electrochemical reduction, photocatalysis and biocatalysis technologies can prove economically and environmentally beneficial once developed. In industry value chain, waste CO_2 has been suggested as a fifth feedstock as a source of chemicals. Several commercial proven CO_2-based polymers, particularly polyurethane foams and polycarbonates are in view for making Green products from captured CO_2. Utilization of waste CO2 in producing value added chemicals need to be scaled-up on industrial scale.

Use of natural CO2 for enhanced oil recovery (EOR) from depleted oil fields is commercially proven, yet the anthropogenic CO_2 for extraction of oil is in demonstration stage. There is a possibility that some of the injected CO_2 may come out along with the oil. Nevertheless, it does help extraction of residual oil, providing economic benefits.

Carbon Storage

For long-term storage in geological formations the options are saline aquifers, depleted oil & gas fields, unmineable coal seams and gas hydrates. Saline aquifers at a depth of more than 800m are safe as a long-term storage option due to good cap rock present. In depleted oil fields, the rocks are more porous making it less sustainable. Underground storage of CO_2 has many challenges in scaling-up due to risks associated with leakage of CO_2. Monitoring, reporting and verification (MRV) techniques are expensive. Besides the operational cost of MRV, the environmental concerns exit. They provide for some risks, which include CO_2 leaks, induced seismicity and mixing with ground water (in case of saline aquifers). Long-term stability of stored CO_2 and compliance with safety and legal requirements continue to be challenges in carbon storage. Further, carbon sinks including forests, oceans, mangroves and wetlands are required to be pursued vigorously. Location specific studies can help scaling up to overcome these challenges.

3. Challenges in Scaling-up of CCUS

Scaling up carbon capture and storage (CCS) is crucial for achieving net-zero emissions and mitigating climate change, As a climate change strategy integration of carbon capture, its utilization and/or storage as an economically viable system remains a greatest challenge. Scalability of CCUS projects to have a meaningful influence on GHG emissions reduction targets is facing many obstacles. It requires infrastructure for CO_2 capture, CO_2 transport, and appropriate geological formations to store CO_2 on permanent basis. Furthermore, all components of CCUS technology/system viz., CO_2 separation from the flue gas, CO_2 conversion into chemicals, transportation of CO_2 and storage on ground or underground are individually commercially viable. However, their integration in the actual field conditions on an industrial scale plant does not prove economical.

Research & Development

The minimum conditions for CCUS deployment are; balancing economic viability, minimising energy consumption, ensuring effective monitoring & reporting, and continuous innovations to reduce costs and environment impacts across all subsystems. There many gaps in current research and how to address them to make the system scalable is the main issue. Some of the Key research gaps areas for scaling-up CCUS on industry scale can be identified as

i) Techno-economic modelling of studies of components
ii) Materials Science and engineering research for improving the capture efficiency
iii) Conventional energy integration with Renewables
iv) CO_2 conversion efficiency improvement and development of cost-effective adsorbers
v) Digital and AI Integration in capture, storage and MRV systems

Techno Economic Analysis of CCUS

The techno-economic analysis of CCUS projects involves evaluating the technical feasibility and economic viability of capturing, transporting, and storing carbon dioxide (CO_2) emissions. Technical feasibility considers environment impact assessment throughout its life cycle. The TE Regulatory frameworks and incentives like tax credits at a place can significantly influence the economic viability of a project. Techno-economic aspects of each CCUS sub-systems are analyzed for various technological pathways and economic considerations to assess their current progress for achieving a net-zero CO_2 emissions future analysis helps decision making by determining the cost-effectiveness of scalability of CCUS technologies in achieving net-zero emissions.

In a techno-economics study conducted of using CCS to decarbonize China's coal-fired power plants, four proposed roadmap scenarios to achieve carbon neutrality of Chinese power sector by 2060 were developed [2]. It compared the economic competitiveness of coal-fired power plants with CCS with those of nuclear (NP), hydro (HP), wind (WP) and solar photovoltaic (PV) power plants and developed a model of the levelized cost of electricity (LCOE). This novel approach can offer combined technical benefits from the processes, which can possibly improve the overall system performance, particularly in terms of energy efficiency and cost [4]. Electricity generation can have a lower total cost than when coal-fired power plants are aggressively replaced by wind and solar PV power plants.

In a cement industry the feasibility of integrating three alternative CO_2 capture methods were evaluated from the techno–economic and environmental standpoint [3]. The evaluation demonstrated that CO_2 capture with amine scrubbing is favorable for new investments, presenting the lowest CO_2 capture cost (~56$/tonne), followed closely by the carbonate looping technology.

Development of industrial hubs with shared CO_2 transport and storage infrastructure (such as pipelines, shipping, port facilities and storage wells), a transition from large, stand-alone CCS and CCUS facilities could further reduce unit costs through economies of scale, reduced commercial risk and financing costs by separating out the capture, transport and storage components, and create new investment opportunities. In the absence of techno-economic modeling of CCUS subsystems, business modeling remains less effective. Global CO_2 Initiative (GCI) at University of Michigan has developed the guidelines for analyzing techno-economic feasibility of CO_2 utilization at industrial scale[5]. The report provides decision tool for policy makers involved in planning for scaling-up CCU. In India while renewable energy has made substantial progress and the growth is on track but reliance on fossil fuel is to continue, there is a greater responsibility to develop CCUS techno-economic models for scaling-up.

Policy and Regulations

Legal and regulatory frameworks to implement national policy commitments are critical for deployment of CCUS technology. Absence of policy guidelines or incentives for carbon capture discourages investment from industry. To achieve the net-zero commitments pledged by 64 governments at COP26 of reaching net-zero by 2050, approximately 715 MT per anum are required by 2030 and 4.2 GT per anum are by 2050. According to Farsaqui et al [6] there are many socio-technical challenges that must be addressed for scaling up (Fig.1). It is pointed out that besides the technological challenges, socio-technical challenges, CCUS Readiness, CCUS Acceptance and CUS Investment are the key barriers.

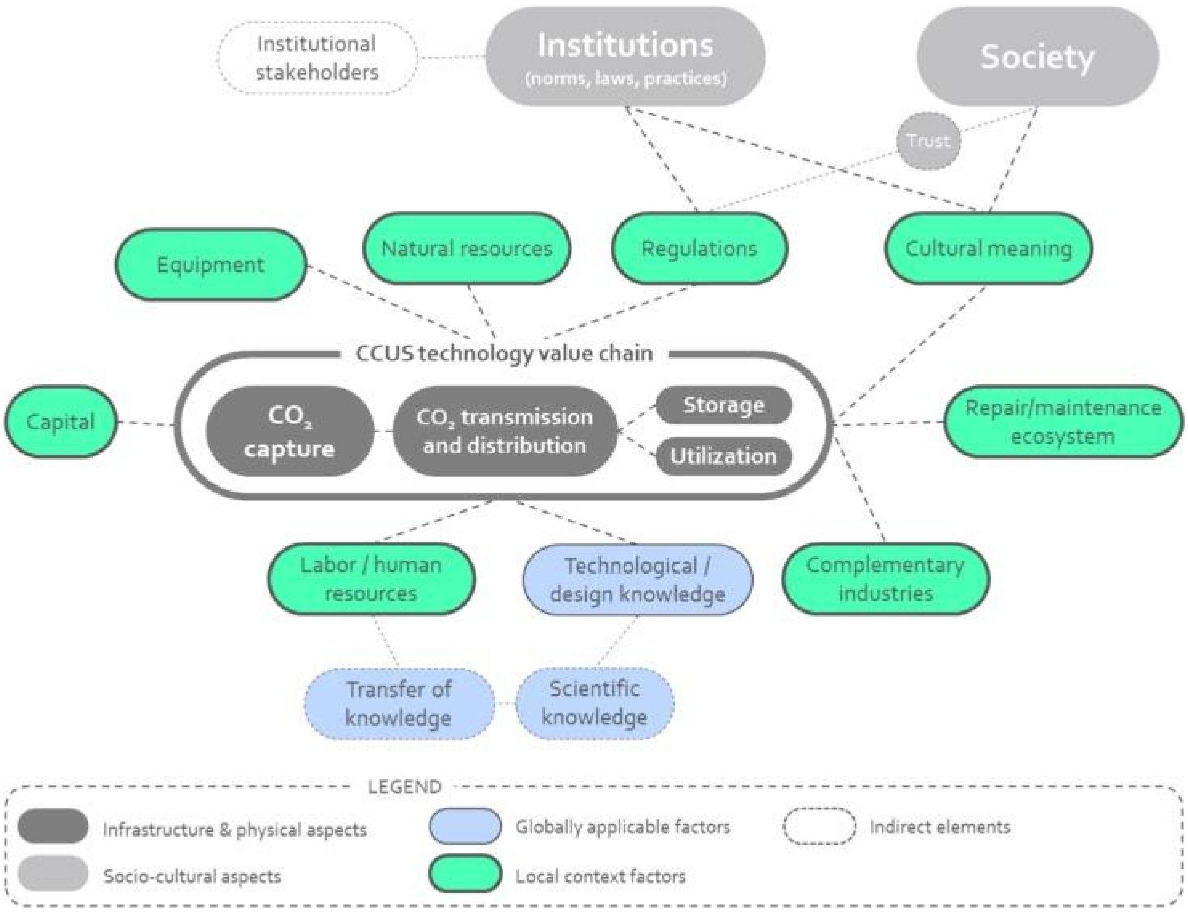

Fig.1 Main technology value Chain and socio-technical elements in policy framework [6]

The policy of incentives and tax credits for adopting CCUS in USA, EU and China are cited below.

USA

The 45Q tax credit scheme in USA is providing substantial financial benefits for capture, CO_2 storage and utilization. California's LCFS standards, State Primacy for CO_2 injection and the SCALE Act are other policy instruments for support of sub-systems of CCUS.

European Union

The EU has introduced many funding programmes for CCUS R&D and incentives from time to time. EU Innovation Fund, Horizon Europe and European Green Deal offer promising support for innovations to take place in CCUS technology and a move towards net-zero targets.

China

China introduced 'Ecological and Environment Protection Initiative' in the Plan projections in 2016, and incorporates CCUS into overall energy framework with low-carbon technology Plan. It outlines scaling-up CCUS as a goal of achieving carbon neutrality by 2060.

India

Niti Aayog in India came out with a CCUS Policy framework for India [7] defining key elements and suggesting the policies, financing and funding mechanisms striving for CCUS acceleration in Industry. The Key to successful CCUS policy for India lies in creation of on enabling environment for advancement of CCUS projects. It proposes;

(i) *Hub & Clusters Model* for scaling-up CO_2 Capture and disposal by integrating carbon emission across emitters and providing infrastructure for transportation, storage across geographical regions.
(ii) *Carbon Capture Finance Corporation (CCFC)* creation in India as a financial institution for funding CCUS projects through debt and equity.
(iii) *Introduction of Production linked incentives* for low-carbon green products.
(iv) *Subsidizing* CO_2 abatement project cost through cash credits and tax credits.
(v) *Funding* of demonstration projects to identify the most appropriate CCUS technologies for different sectors and application in the Indian Context.

India began its CCS journey in 2004, by joining as founder member of 'Carbon Sequestration Leadership Forum' for accelerating joint R&D projects. 'Indian CO_2 Sequestration Applied Research Network' came into being in 2007 under Inter-sectoral Science & Technology programme of Department of Science & Technology initiated for funding with the participation of stakeholders Ministry, leading to some pilot projects (FACE at JNU, Micro-algae CO_2 capture at NTPC) and feasibility studies for CO_2 storage (Saline Aquifers, Basalt rocks). It led to creation of NTPC Energy Technology Research Alliance (NETRA). In the early stage deliberations differed on the policy track of Deployment. The industry role was therefore mainly to invest in R&D (MoP O.M. dt 21.04.2009).

India is founder member of Mission Innovation and has launched a model CCUS program by involving CSIR laboratories and. MOES, DST, DBT and Industry viz. NTPC, ONGC, and Reliance among others. However, the development and deployment of CCUS technology continues to face several challenges, including high costs, lack of infrastructure, and regulatory hurdles.

The G20 group of countries under the leadership of India has recognized the circular carbon economy and CCUS as key to reaching a net-zero future. In order to provide a roadmap for scaling up CCUS to the giga-tonne (GT) scale, Dastur Energy conducted a study on the technology gaps across the CCUS value chain and provide a pathway to international collaboration and roadmap for the development of technologies, projects, and enablers across the CCUS value chain [8]. This study draws upon the expertise and experience of CCUS technology development & projects across the world and seeks to provide project proponents, policymakers, institutions, investors, and industries a holistic understanding of key actions required for the accelerated deployment of CCUS and meaningfully contribute to the future net-zero world.

DST has established Centers of Excellence at IIT Bombay, Mumbai and JNCASR at Bangalore. Technology readiness level of sub-systems for carbon capture, CO_2 transport, carbon utilization and carbon storage has been studied and technology gaps identified. A National Mission to provide financial incentives to promote carbon capture, utilization and storage (CCUS) technologies aiming to achieve the net-zero goals is in consideration by the Union Government. NITI Aayog has established task forces under stakeholders Ministries to develop the roadmap.

On technology front NETRA in collaboration with Carbon Clean Solutions and Green Power International Pvt. Ltd is setting up the carbon capture plant at Vindhyachal plant.The captured CO_2 will eventually be combined with hydrogen and produce 10 tonnes per day of methanol through a catalytic hydrogenation process**.**India'sfirst commercial-scale plant to capture CO_2 emissions from a coal-powered boiler to converts into soda ash was built in 2017 at Tuticorin Alkali Chemicals and Fertilizers Limited (TFL), Tamilnadu. The plant captures approximately 60,000 tonnes of CO2 annually. Carbon Clean is a global leader in carbon capture solutions and has demonstrated CDRMax™ carbon capture technology that can be used for low CO_2 concentrations between 3% and 25% by volume and produce CO_2 with purityy greater than 99%. The company's leading innovation in the CCUS market is development of a fully modular technology – CycloneCC. for implementation at scale in steel industry. Feasibility of Carbon Clean's CycloneCC modular technology to capture up to 100,000 tonnes per year of CO2 emissions is being carried out at JSW Steel's Vijayanagar site in Karnataka.

4. Conclusions

Increasing CO_2 emissions from industrial activities are giving rise to global warming and climate change. Management of CO_2 emissions through capture and utilization is becoming critical research topic. Being a multi-disciplinary scientific & engineering topic it requires inputs from diversified fields. Increasing R&D investment in cross-cutting issues can lead to certain benefits from CCUS technology development, besides climate change mitigation. The science & technology breakthroughs that can be expected from application of CCUS in coal based plants are;

a) Development of new materials
b) Understanding of mineralization of rocks
c) Development of Innovative Chemistry tools
d) Improved understanding of geological formations

e) Learning to mimick Nature (Trees are nature's best carbon capture technology)

Advancements in CO_2 capture, development of new adsorbents, membranes can lower the capture costs. Success achieved so far suggests that strategies are working, but challenges lie ahead. As India gears to achieve global presence in Green industry, the policy, regulatory frameworks and government incentives can advance scaling up of CCUS.

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What Needs to be Done to Promote Development of CCUS Technologies in India

Shri Alok Kumar
Ministry of Power, New Delhi-110001

Extended Summary

To achieve its goal of Net Zero by 2070, India needs to not only accelerate the deployment of commercially viable technologies but also take timely steps to support R&D and development of emerging technologies with high relevance for it. In view of the abundant coal reserves and high dependence on coal for its domestically produced energy supply, CCUS technologies present high potential for its journey to 2070 goal. In FY 2024, coal supplied 79% of domestically produced energy.

Even after 50 years since the first CCUS project started in the world, the progress and contribution of CCUS to reduction of global emissions has been negligible and far less than the expectations. However, IEA says that achieving Net Zero at global level would not be possible without CCUS technologies. Capture technologies have matured and pipeline transport of captured CO2 has been proven commercially. Progress on utilisation of captured gas will be critical. However, the sequestration will be the mainstay as the world expands deployment of CCUS. A number of countries have put in place policy framework and incentives to support its growth.

In India, a few pilot scale projects have been taken up by CPSEs and some private companies. NITI Aayog has come out in 2022 with a comprehensive study recommending the policy framework and deployment mechanism of CCUS. Further action is required without any delay. First step would be to nominate a lead Ministry. Though applications of CCUS will fall in the jurisdiction of several Ministries, It is recommended that the Ministry of Coal should lead it for obvious reasons. A national mission is needed with participation of all concerned Ministries and institutions.

Recommended national policy framework should come out with specific national targets with priority amongst the sectors for development. Applications in hard-to-abate industrial sectors should be given the highest priority as emissions from the same are projected to grow rapidly in our journey to *Vikshit Bharat* by 2047. Cost of capture in Rs per tonne is also lower in these sectors than the coal based power plants. CCUS technologies will have definite relevance for the power sector. However, there are more cost effective technologies available for its decarbonisation in the next two decades. CCUS technologies may emerge important for the power sector in the decade of 2060s if grid operations require support of base load generation and inertia from coal power plants in the scenario of less than projected expansion of nuclear power plants. The policy should also address the concerns associated with any new technology,

with due attention to the liability against the project proponents arising from uncertainties in transport and storage.

As India has limited availability of concessional finance to support its energy transition, it will be appropriate to take up three to four Hub and Cluster mode projects to achieve the objectives of shared cost of transport and storage infrastructure and regulatory sandboxes in various types of geographies. The grant support should be in part capex support upfront and balance per tonne of captured gas to ensure actual outcomes and successful demonstration. CCUS projects can also be supported through carbon credits by expediting the development of methodology under the offset mechanism of the Carbon Credit Trading Scheme.

It will also be necessary to set up a dedicated national institute, like we have for solar and wind, which can act as a repository of all the knowledge and updated information on identified geological formations for sequestration.

3

Derisking geological CO_2 storage in India

Dr. Vikram Vishal
Convener, DST-National Centre of Excellence in CCUS
Professor, Department of Earth Sciences, Indian Institute of Technology Bombay
Mumbai-400076

Extended Summary

India's ambitious commitment to achieving net-zero greenhouse gas emissions has intensified the focus on carbon capture and storage (CCS) as a critical strategy to mitigate industrial CO_2 emissions that are otherwise difficult to abate. While high-level assessments have indicated substantial potential for CO_2 storage across various sedimentary basins in India, detailed, site-specific technical evaluations remain limited, leaving a large portion of this resource underexplored. Addressing this knowledge gap is essential for identifying representative CO_2 storage complexes and unlocking the country's capacity to meet its emission reduction targets.

This work presents a comprehensive assessment of CO_2 storage opportunities in India by identifying key geological formations suited for carbon sequestration. These include hydrocarbon-bearing sandstones with proven reservoir characteristics and marine shales which serve as effective caprocks or seals, crucial for the containment of injected CO_2. By integrating novel experimental methodologies and extensive geomechanical modeling, we quantify the CO_2 storage capacity of these formations, assess the mechanical integrity of seals, and evaluate well integrity, especially in regions affected by legacy wells from prior hydrocarbon extraction activities.

A significant focus of the study is on the geomechanical behavior of reservoir and seal rocks during CO_2 injection, with particular attention to rock deformation characteristics under varying stress conditions and fluid pressures. These deformation properties are critical inputs for developing robust large-scale numerical models that simulate CO_2 plume migration and containment over the long term. By coupling experimental data with advanced geomechanical simulations, this work improves the accuracy of storage capacity estimates and risk assessments, thereby providing a more reliable foundation for future CCS project design.

Currently, CCS initiatives in India are predominantly at a pre-feasibility stage, with early readiness of the storage processes. This study highlights pathways to accelerate CCS deployment by leveraging India's diverse geological settings. Translational research and pilot projects can harness advances in subsurface monitoring technologies, optimized CO_2 injection strategies, and comprehensive risk management frameworks to maximize storage efficiency, indicative of readiness for commercial-scale implementation.

Moreover, the research underscores the importance of multi-sector collaboration involving academia, industry stakeholders, and government agencies. Such partnerships are essential to develop scalable CCS technologies tailored to India's unique industrial emissions profiles and geological conditions. The study also emphasizes the necessity of derisking CCS projects through detailed, site-specific investigations and advocates for supportive policy frameworks that incentivize pilot deployment and subsequent scaling.

Beyond geological assessments, the study discusses early opportunities for implementation of CCS in India, including the integration of enhanced oil recovery (EOR) techniques. By coupling CO_2 storage with EOR, the study identifies a dual benefit strategy that can improve oil recovery rates while simultaneously sequestering significant volumes of CO_2, providing an economic impetus for CCS adoption.

In summary, this study provides a holistic evaluation of India's CO_2 storage potential, combining experimental insights, geomechanical modeling, and practical considerations surrounding legacy well integrity and seal performance. It delivers actionable data to guide the identification and development of representative storage complexes, thereby supporting India's net-zero ambitions. The findings demonstrate that, with strategic investment and collaboration, CCS can become a viable and scalable component of India's climate mitigation portfolio, contributing meaningfully to emission reductions across hard-to-abate industrial sectors.

4

Conversion of Carbon Dioxide into Chemicals and Fuels: A Strategic Technology for the Future

Prof. Michele Aresta
Innovative Catalysis for Carbon Recycling-IC2R, Tecnopolis, Valenzano (BA)
Italy

Extended Summary

The UN Conferences of Parties (COP26-29) have strongly recommended the implementation of a Cyclic Econom[1] for reducing the impact on climate change of fossil-C (coal, oil, natural gas), that is today the source of >81% of the total energy (620 EJ: it was 607 EJ in 2022) used worldwide (2023 data).[2] Oil contributes 31.6% (196 EJ) of the total amount of energy used, Coal 26.5% (164 EJ) and Natural Gas 23.1 % (144 EJ). The remaining energy is sourced from Nuclear (25 EJ, 4.0%) and Hydro (40 EJ, 6.5%), with other perennial energies such as solar, wind and geothermal summing at 8.22% or 51 EJ, having surpassed hydro and showing a continuous growth. Such increase may possibly compensate the increase of energy-demand by our Society, but really does not substitute fossil-C: indeed, the emission of CO_2 reached a new high in 2023[3], equal to 37.4 Gtc02 (1.1% higher than in 2022). This questions whether the political claim of *"defossilization by 2050"* is an achievable target.

Noticeably, the Chemical Industry will need carbon as feedstock forever and the Transport sector will require carbon-based fuels for a while in the Avio and Maritime subsectors. Today, the Chemical Industry emit 932 Mt_{CO2} (from the use of fossil-C as both fuel and feed) and uses ca. 365 Mtc/y for chemicals and ca. 360 Mtc/y for plastics.[4] Such an amount of carbon, should the extraction of fossil carbon be stopped, must be available anyway. Moreover, the avio (380 Mtc as per 2023) and maritime (330 Mtc as per 2023) transport, will demand an additional 710 Mtc/y. Therefore, the Chemical Industry raw material-feedstock and the avio- maritime transport sectors will need together some 1.5 Gtc per year (or 10% of the total amount of used fossil-C today) that must be provided by either fossil or alternative (Biomass, Waste plastics, CO_2) sources, for guaranteeing that scarcity of carbon will not negatively affect the progress of our Society in general and of developing economies in particular.

1. **Biomass**

The global amount of biomass produced worldwide is estimated at 146 Gt/y (or 4500 EJ), 50 Gt/y of which are land-grown, the balance is aquatic biomass. 16.7 Gt/y of terrestrial biomass are harvested: 14 Gt/y as food for humans or feed for animals and 2.7 Gt/y of wood, with 1.3 Gt/y used for energy production and 1.4 for other industrial uses. The "sustainable biomass harvesting" principle limits (from prudential 8 to maximum 32 Gt/y[5]) the use of biomass.

Therefore, considering that fertile soil is necessary for growing biomass for food-feed, if the use of biomass for energy purposes should be extended without further implementing deforestation, three are the key action-points: i. use of marginal land; ii. proficient use of aquatic biomass; iii. implementing the Integrated Biorefinery Strategy-JBS at all levels, incrementing forest management and waste valorization.[6] IBS allows to make a wiser use of the complexity of the biomass, relegating energy-intensive processes based on large entropy-changes, such as gasification or even pyrolysis, to the energetic valorization of inert/recalcitrant residues.[7] Waste wet-biomass (MSWs, agricultural residues, industrial waste, farm sewage, water treatment slags, *etc.)* should be valorized on a much larger scale than today: Biomethane potential is estimated at 730 Mtoe with a large margin of improvement with respect to actual *ca.* 4 Mtoe (1 Mtoe is equal to 11 630 GWh or 1.21 Gm^3 of gas). The installed power of electricity made from biogas was 18 GW in 2018 (or 47 300 GWh compared to 1 469 133 GWh of total electric energy produced from natural gas in the same year).[8] Accordingly, aquatic biomass should be better exploited for producing proteins, fine chemicals and energy-products, implementing economically viable technologies for its growing, harvesting and processing, possibly making use of all fractions: proteins, carbohydrates, lipids and specialty chemicals, so to maximize its value.[9]

2. Waste plastics

Even if the whole amount of waste plastics were recycled as source of recycled-carbon, it would not satisfy the request of the sector itself. In fact, as for 2024, *ca.* 360 Mtc/y were used in the sector (Table 1) for the production of some 460 Mt of plastics.[10] Up to 220 Mt of plastics entered the compartments of our planet (soil, water, air), with more than 75% produced by only twenty countries, while the recycling of plastics was as low as 9%.[11] The production of polymeric materials and plastics is expected to grow in future years and by 2050 it is foreseen to double or triple with respect to today, as refers E. Amsen, mentioning a 2024 report by the Lawrence Berkeley National Laboratory.[12] Therefore, an extended recycling of plastics can only partially cover the request of carbon by the same sector.

3. Carbon dioxide

Carbon dioxide is by far the most abundant and at hand source of renewable carbon from: a. Bio-processes (fermentation to produce ethanol, and anaerobic wet-biomass digestion to afford biogas, 120 Mtc02/y, 30 Mt_{CO2} coming from biogas and the balance from ethanol production); b. The atmosphere (880 Gt_{CO2} that could be captured using the Direct Air Capture-DAC advanced technology at any point of our planet making atmospheric CO_2 ubiquitary, freely-accessible source of carbon.[13] Even if DAC is today much more expensive (roughly 5 times) than capture of CO_2 from power plants (that ranges around 80-100 US$/$t_{CO2}$), the continuous progress in technology development makes that a forecast of less than 80-100 US$/$t_{CO2}$ appears as a putative target in the medium-long term. The cost of recovery of CO_2 plays a key role in the implementation of the DAC technology, as it dictates the cost of carbon and of goods derived from it. As for today, with a cost of *ca.* 550 US$/t of recovered CO_2 using DAC the cost of carbon would be around *ca.* 2000 US$/tc that makes it too high for making any kind of product that might be competitive with the same product derived from fossil-C and, thus, would result out of market. Noteworthy, the cost of carbon sourced from oil is around 400-450 US$/tc (at the price of oil of 61-65 US$/barrel as per May 2O25)._Therefore, if DAC has to be cost-effective, a recovery cost lower than 100 US$/$T_{CO2}$ must be reached. Under such conditions, the atmosphere would represent a perennial source of carbon for future generations, supposed that efficient processes for converting CO_2 into chemicals, materials and fuels will be available on the market. It is worth to emphasize that the conversion of CO_2 requires a quite different input of energy and materials according to the end product.

The classic production of chemicals from CO_2 has been studied since the middle 197Os, when the first transition metal bearing CO_2 as a ligand was discovere[14] and a few processes have been developed at demo scale. Conversely, the use of CO_2 as source of carbon for fuels, even if studied since the 199Os, has found application only more recently,[15] after cheap PY-energy has become available for either running the process or producing H2 from water through electrolysis. Noteworthy, if fossil-C were used for CO_2 conversion into fuels more CO_2 would be released than fixed. Using non-fossil renewable energy for producing hydrogen, it is possible to hydrogenate CO_2 to energy products avoiding CO_2 emissions. Either methanol (INOVYN Process targeting 8 kt/y of CH30H from CO_2 and green-H2)[16] or methane (Falkenhagen Demonstration Plant, EU Project 691797)[17] can be produced at demo- or even full-scale, while thermocatalytic processes to C_n hydrocarbons, olefins or alcohols are still under development.[18]

The use of hydrogen for the hydrogenation of CO_2 to fuels is often questioned as the direct use of H2 as energy vector would save some 20% energy lost in the chemical process of hydrogenation of CO_2. Co-processing CO_2 and water under solar energy using either photochemical or photo (electro) chemical processes is a very attractive option, which is under deep study these days.[19]Issues to solve for a large scale exploitation of such innovative options are: i. the availability of materials for building photoelectrodes, ii. the stability of photomaterials over a long term application (months to year), iii. the upscale of the entire apparatus. A must is to avoid the use of rare, expensive and critical materials. Interestingly, solar CO2Reduction processes could be integrated with solar water treatment so to use waste water as source of protons and electrons. A serious and continued program of investment in research and technology transfer is necessary in order to deploy such Nature-inspired approach to carbon-cycling.

Figure 1 shows the potential of use of captured CO_2.

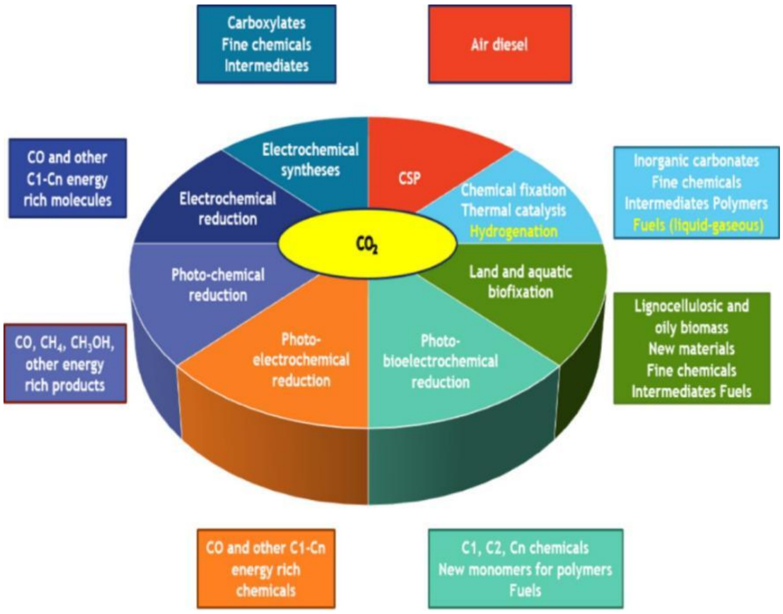

Figure 1: Technologies for the conversion of captured CO_2.

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5

Design Optimization and Scaling up of Solar Integrated Carbon Capture and Sequestration (CCS) Plant on a Mega Size Thermal Power Plant

Dr. Vinod Krishna Sethi*

DG (Research) RKDF University & Member MC, CCUS Mission CSIR

Dr. Rashmi Dwivedi

Professor (Mech.), RKDF University, Bhopal-462033

Extended Summary

Carbon Capture, Utilization, and Storage/Sequestration (CCUS) technologies are gaining critical importance in addressing both global and local climate change challenges. These technologies focus on capturing carbon dioxide (CO_2) emissions from industrial and energy production sources, utilizing the captured CO_2 for value-added applications, and safely storing or sequestering the remainder. CCUS plays a vital role in reducing greenhouse gas emissions and achieving the targets set in the Nationally Determined Contributions (NDCs) under the Conference of Parties (COP) agreements. Despite their potential, CCUS technologies face challenges related to innovation, cost-effectiveness, and public acceptance. To overcome these hurdles, governments, industries, and research organizations are investing heavily in CCUS research and development.

In alignment with India's commitment to achieve net-zero emissions by 2070, CSIR has initiated a CCUS mission. Under this mission, CSIR scientists have proposed projects categorized under three verticals—Capture, Utilization, and Storage. One such initiative is the Carbon Capture Pilot Plant set up at RKDF University, Bhopalbeing used for testing by various CSIR labs under the Umbrella MoU, initially involving five CSIR labs—NML, CECRI, CBRI, IIP, and NEERI. This pilot plant, sponsored by CPRI, aims to demonstrate the feasibility of sustainable clean coal thermal power integrated with CCUS technologies. The facility captures 45 kg/hr. of CO_2 from a coal-fired boiler and integrates with a solar thermal plant for steam generation.

A key focus has been the feasibility study for retrofitting CCUS Plant on a 500 MW unit at ANPARA B TPS, in Singrauli coal field region. The plant demonstrated during pilot study on RKDF Pilot Plant the capture efficiency to the tune of 87–90% CO_2 and significant reduction in energy penalties from 4.6 MJ/kg to 2.18 MJ/kg CO_2 using solar-generated steam for solvent regeneration. Additional studies include CO_2-based algal biofuel and hydrogen production, where algal species grew successfully in ash decantation water, capable of producing 55 tons/hr. of biomass in a scaled-up plant. The study also explores CO production from CO_2 using gasifiers and hydrogen production via the water-gas shift (WGS) reaction. Incorporating a 70 tons/hr solar thermal plant, the retrofit would increase auxiliary power usage by 0.8% and water consumption by 3 tons/hr. The pilot project demonstrates optimized energy balance and a range of utilization and sequestration pathways for a scalable CCS solution.

This paper focuses on results of a solar Integrated CCUS Pilot Plant sponsored by CPRI and installed at RKDF University, Bhopal and evaluates broad parameters through ASPEN Plus Simulation for the proposed CCUS Plant on a 500 MW Thermal Unit in Singrauli Coal belt of the country. It also addresses several challenges in scaling up process of Carbon capture plat both green field and retrofitted CCS on Coal fired existing mega Unit.

Key Words: Conference of Parties (COPs), Carbon Capture Utilization & Sequestration /Storage (CCUS), Nationally Determined Contribution (NDC) Million Tons per Annum (MTPA), Post Combustion Carbon Capture (PCCC), Central Power Research Institute (CPRI), Concentrated Solar Plant (CSP), Thermal Energy Storage (TES)

2. Introduction – Climate Change Abatement and CCUS

India's commitment to achieving net-zero carbon emissions by 2070 represents a bold and ambitious target, one that necessitates the use of high-quality raw materials and significant innovation in existing industrial processes. Carbon dioxide (CO_2), a key component in Earth's carbon cycle, has increasingly become a critical factor influencing global climate change. Scientific studies indicate that the global average concentration of atmospheric CO_2 reached a record 409.8 ppm in 2019, with the rate of increase now approximately 100 times faster than historical trends over the past 60 years.

The Paris Agreement marked a turning point in global climate action, with countries committing to limit global temperature rise to well below 2°C, and ideally to 1.5°C. At the 26th Conference of Parties (COP26), India pledged to achieve net-zero carbon emissions by 2070. In addition, India announced five major climate goals, also referred to as the *Panchamrit* commitments:

1. *Achieve 500 GW of non-fossil fuel-based energy capacity by 2030.*
2. *Fulfils 50% of total energy requirements through renewable sources by 2030.*
3. *Reduce projected carbon emissions by 1 billion tonnes between 2021 and 2030.*
4. *Lower the carbon intensity of the economy by less than 45% by 2030.*
5. *Achieve net-zero emissions by 2070.*

Advances in solar PV and thermal energy and Thermal Energy Storage (TES) systems are also gaining momentum through focused R&D, contributing to the broader net-zero framework. Net-zero essentially refers to balancing carbon emissions with carbon removal efforts, ensuring that any greenhouse gases released into the atmosphere are offset by equivalent absorption or mitigation.

Coal remains India's primary energy source, fulfilling over 58% of its commercial energy demand. However, coal-fired thermal power plants are also major contributors to pollution, accounting for over 50% of total emissions. These plants emit approximately 2030million tonnes of CO_2 annually from a total installed capacity exceeding 221GW—nearly half of India's total emissions of about 2700 MTPA.

To meet its carbon intensity reduction targets set during COP-21 in Paris—specifically, reducing emissions from 0.9 kg CO_2/kWh to about 0.58 kg CO_2/kWh in coal fired mega projects—India must adopt Carbon Capture and Storage (CCS) technologies. Post-Combustion Carbon Capture (PCCC) systems, when retrofitted to existing coal-fired plants, offer a practical and scalable solution to help India meet these climate objectives.

3. Methodology:

3.1 Carbon Capture and Sequestration (CCS) Pilot Plant

The R&D Pilot Project established at RKDF University, Bhopal, under the aegis of CPRI (Ministry of Power), serves as a testbed for demonstrating the feasibility of sustainable clean coal thermal power plants integrated with Carbon Capture and Sequestration (CCS) technologies. The project also explores strategies to minimize the energy penalty associated with CCS through the integration of solar thermal energy, process optimization, and innovative system design.

A pilot-scale Carbon Capture Plant with a CO_2 capture capacity of 45 kg/hr has been successfully commissioned using a dedicated coal-fired boiler. This plant is integrated with a solar thermal system to produce steam for solvent regeneration. The pilot setup has achieved a high CO_2 capture efficiency of 87–90%. The incorporation of solar-generated steam for solvent regeneration has reduced the energy penalty from approximately 4.6 MJ/kg CO_2 to 2.18 MJ/kg CO_2.

This facility, developed at Sir J C Bose Integrated, is currently being offered to five CSIR laboratories—NML, CECRI, CBRI, IIP, and NEERI—for advanced collaborative research under an 'Umbrella MoU' with CSIR. The amine-based CO_2 absorption system implemented in the pilot plant has revalidated through studies involving the conversion of captured CO_2 into fuel molecules, including algal bio-diesel and hydrogen via the water-gas shift (WGS) reaction route.

3.2 Feasibility Study for Scaling Up

A feasibility study was conducted to evaluate the retrofit of a Post-Combustion Carbon Capture (PCCC) system on the 500 MW ANPARA B TPS (2×500 MW) located in the Singrauli region, Madhya Pradesh. The study revealed that a scaled-up CCS facility would require integration with a solar thermal plant of 70 tons/hr steam capacity for MEA solvent regeneration and WGS reactions. The estimated additional water make-up requirement is 3 tons/hr. with an expected increase in auxiliary power consumption by 0.8%.

In parallel, a pilot tabletop study on the production of multi-purpose fuels like hydrogen and biodiesel via algal routes was conducted. The feasibility of cultivating microalgae in ash pond environments of thermal plants was investigated, showing the potential for algal biomass production at ~55 tons/hr using selected species that thrive even in ash decantation water and absorb heavy metals.

Several critical challenges must be addressed before CCS can be deployed at scale in India, including:

- **R&D and Site Assessment**: Identification of potential CO_2 conversion pathways and geo-sequestration sites remains a key area of ongoing research. A national-level geological assessment of CO_2 storage capacity is still pending.

- **Financing and FDI**: Implementation of CCS technology requires substantial investment. The lack of government funding and foreign direct investment (FDI) policies currently hinders large-scale deployment.
- **Environmental and Legal Concerns**: Issues related to land acquisition, CO_2 leakage, and groundwater contamination require comprehensive legal and regulatory frameworks.
- **Energy Penalty**: Given India's high energy demand and limited economic margins, CCS is not yet a mandatory requirement. However, pilot results show that integration with solar thermal systems can reduce the energy penalty by up to 50%.
- **Thermal Energy Storage (TES)**: A significant innovation involves operating the CCS plant using thermal energy storage in off sun-shine hours too. In the pilot study, steam is supplied from a solar thermal TES system between 6 PM and 11 PM. It was made possible through a novel Solid Halide TES device developed in collaboration with Rensselaer Polytechnic Institute (RPI), NY, and manufactured by ENLYSIS Energy, USA.
- **Scale-Up Tools and Process Simulation**: Tailor-made adaptations of ASPEN Plus software are being employed to address scale-up challenges, supporting the design of a PCCC plant focused on producing hydrogen and bio-diesel from captured CO_2, highlighting the novelty in CO_2 utilization.

This initiative at RKDF University, in partnership with CPRI (MOP), represents a foundational step toward mainstream CCS deployment in India. The work on solar-integrated CCS is complemented by concurrent solar thermal TES research at the university, funded by the Ministry of New and Renewable Energy (MNRE) since 2015, under technology transfer collaboration with RPI, NY.

4. Results & Discussions

4.1 The CCS Pilot Project at RKDF University – Some Results

At the Solar Integrated CCS Pilot Plant (45 kg/hr. CO_2 capacity) at RKDF University, flue gas is tapped at a rate of 250 kg/hr (equivalent to 6 tons/day) from a coal-fired boiler, containing approximately 18% CO_2. This corresponds to 45 kg/hr. of CO_2, captured during an 8-hour operational shift, with solvent regeneration carried out in additional shifts using steam from a solar thermal system. The solar system comprises 10 Scheffler reflectors, each producing 5 kg/hr of steam, achieving a total steam output of 50 kg/hr. The system also includes high energy density halide salt-based thermal storage (in excess of 300 kWh/m^3), enabling 6-10 hours of extended steam supply.

The pilot plant has achieved a CO_2 capture efficiency of 87–90%, with CO_2 release from the reactor maintained at 18–23%. The integration of solar-generated steam has significantly reduced the solvent regeneration energy penalty from 4.6 GJ/ton (conventional turbine extraction) to just 2.187 GJ/ton of CO_2. ASPEN Plus software was used to estimate the reduction in energy penalty in regeneration of MEA solvent. Additionally; algal biomass production was optimized in Ash water using selected species such as Scenedesmus obliquus, Monoraphidium minutum, and Chlorella vulgaris in custom-designed bioreactors. The study confirms the effectiveness of the amine-based CO_2 absorption system for further applications in algal biofuel and hydrogen production.

Figure 1: A View of Pilot Plant Integrated with Solar Thermal Steam Generator & A Coal Fired Boiler for Production of CO_2

4.2 The Scaling-Up study of CCUS Plant on a 500 MW UNIT:

In this project, the scale-up of Carbon Capture and Sequestration (CCS) has been proposed for a 500 MW coal-fired thermal power unit at Anpara B Thermal Power Station, located in the Singrauli coalfields region on the Uttar Pradesh–Madhya Pradesh border. The scale-up targets 30% CO_2 capture—equivalent to 100 tons per hour—from a single 500 MW unit, which typically emits about 8000 tons of CO_2 per day (or 330 tons/hour). Collaboration efforts are underway with the Government of Uttar Pradesh and Toshiba Corporation, the EPC contractor and technology provider of the Anpara B (2x500 MW) plant, for deploying the CCS system on Unit 4.

The scale-up strategy includes (Figure-2):

- *Optimizing the CCS system capacity between 30% to 100% CO_2 capture,*
- *Implementing algae cultivation using selected microalgae species,*
- *Modifying the power plant for producing multi-purpose fuels such as hydrogen and methane,*
- *Utilizing hydrogen in fuel cells for lighting,*
- *Recycling carbon monoxide back to the boiler using short flame burners,*
- *Integrating solar thermal energy for solvent regeneration and WGS reaction to minimize energy penalty,*
- *Exploring sequestration in depleted coal mines.*

Salient outcomes of the feasibility study include the incorporation of a 70 tons/hour solar thermal plant to generate steam, with only 3 tons/hour of makeup water needed. Algal biomass production is estimated at 55 tons/hour, with bio-diesel derived through the transesterification process. Species as stated above have been successfully tested in ash pond water, making the process both sustainable and site-compatible.

Importantly, this renewable-integrated approach reduces the typical energy penalty of 15–17% to just 4–5%, making CCS more viable. For long-term CO_2 sequestration, initial use of the depleted coal mine in vicinity, the Kakri coal field has been proposed, followed by expansion to the larger Bina coal field within the Singrauli region. This multi-faceted utilization of captured CO_2 represents a novel, scalable, and sustainable path forward.

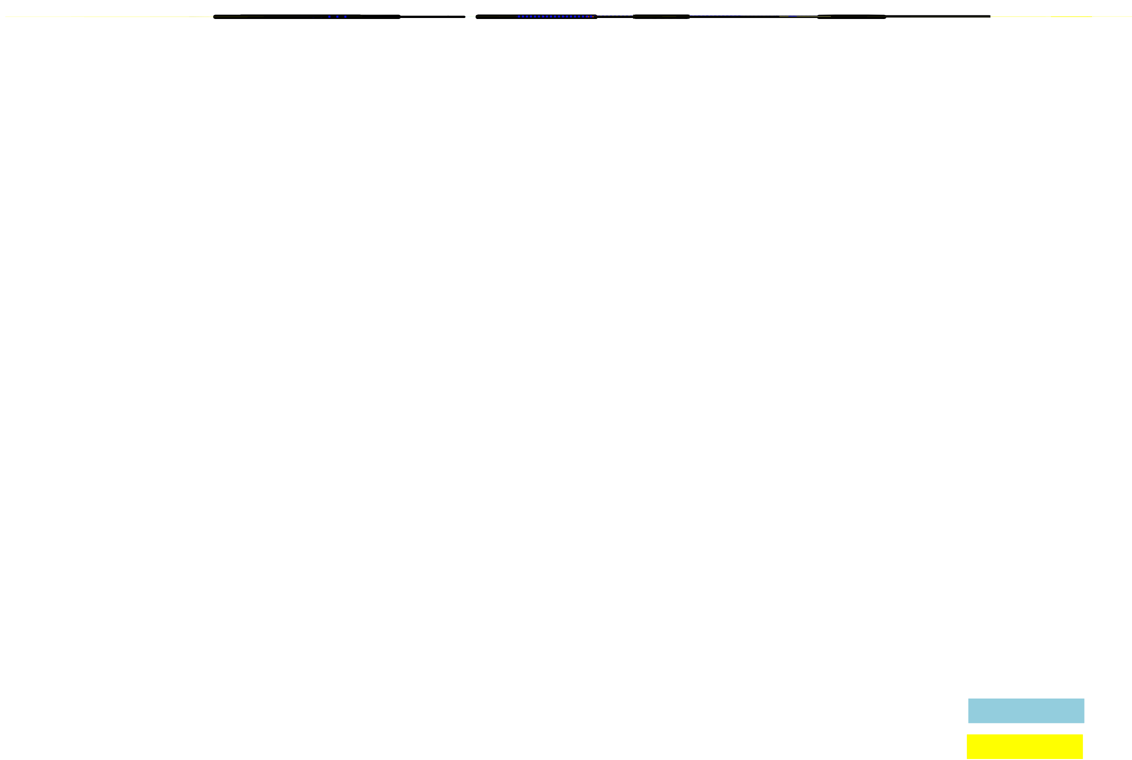

Figure 2: Strategies in Scaling – Up of CCS Plant on A 500 Mw Unit

Mega-scale Carbon Capture, Utilization, and Storage (CCUS) plants face significant challenges that hinder their widespread deployment, despite their potential to mitigate climate change by reducing CO_2 emissions. These challenges span technical, economic, infrastructural, and regulatory domains and must be strategically addressed to accelerate CCUS adoption.

One of the foremost challenges is the **high capital and operational cost** of CCUS plants, especially when integrated with coal-fired power stations. Additionally, the **energy penalty**—the extra energy required to capture and compress CO_2—can significantly reduce the overall efficiency of the power plant. Although solar thermal integration offers a promising solution to offset this penalty, its deployment on a large scale remains limited.

Geological challenges present another major hurdle. Effective site selection and characterization are crucial for safe and long-term CO_2 storage. This includes delineating subsurface geological structures, understanding CO_2-fluid-rock interactions, quantifying storage capacity, and evaluating the economic and technical feasibility of storage sites [11]

Transportation of CO_2 from capture sites to storage locations is also a critical issue. The absence of an integrated carbon management infrastructure, such as a dedicated **pipeline network**, hampers efficient CO_2 transport. Developing such infrastructure is essential for enabling source-to-sink matching and ensuring safe, continuous CO_2 flow.[12]

Moreover, **policy and regulatory frameworks** must evolve to support CCUS at scale. Governments need to implement clear regulations, carbon pricing mechanisms, financial incentives, fast-track approvals, and cross-border collaboration agreements to create a favourable environment for CCUS development.[13]

Addressing these interconnected challenges is vital for realizing the full potential of CCUS technologies in global climate mitigation efforts.

5. Conclusion

Over the next few decades, renewable energy and other low-carbon technologies will play an increasingly important role in the power generation mix, but coal remains our primary source of energy. 'Low Carbon Technology Vision for India' and strategies, difficulties and possibilities in Renewable Power for energy stability and ecological sustainability are presented in this study, which includes Carbon Capture and Sequestration as a crucial aspect.

Capturing, using, and storing carbon will be an essential part of a portfolio of low-carbon energy technologies that will help us to meet our commitment to combating Climate change as we increase our use of fossil fuels. The deployment of CCUS is critical given the current trends of rising global carbon dioxide emissions from the energy sector and coal's continued dominance in primary energy consumption.

Solar Thermal Plant with Thermal Energy Storage for Steam Generation in Off-Solar Hours and Strategies for Scaling-up CCUS Plant on a 500 MW Unit are also covered in this paper and feasibility study of deployment of PCCC Plant on a 500 MW Unit has been presented based on results of CCS pilot plant installed at RKDF University with CPRI, MOP, Government of India funding.

MEA was used as the solvent in the process since it is highly reactive with CO_2. MEA is a primary amine and highly alkaline in nature. It gives high separation rate of CO_2. Since it's highly reactive it is also difficult to regenerate the solvent after absorption and hence high amount of steam is required in stripping tower. Unless a RE source of steam like solar thermal is integrated the energy penalty cannot be reduced to a moderate level of below 15%. ASPEN Plus software was used to estimate the reduction in energy penalty in regeneration of MEA solvent from a level from 4.6 GJ/ ton CO_2 to 2.187 GJ/ ton CO_2. The ASPEN Plus has also been used to provide layout plan and overall design of a scaled up CCS Plant integrated with solar thermal plant on a 500 MW Unit in Singrauli coal pit head region on the border of UP and MP states of India.

This paper basically focuses on results of a solar Integrated CCUS Pilot Plant and highlights broad parameters of a CCUS Plant on a 500 MW Thermal Unit and addresses several challenges in scaling up process of Carbon capture plat both green field and retrofitted CCS on Coal fired mega Unit

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6

Single-Step Absorption and Isolation of CO_2 as Carbamates

Dr. K. Palanivelu
Centre for Climate Change and Environment
VIT Chennai Campus, Chennai-600127

Extended Abstract

The emission of carbon dioxide continues to rise due to increasing industrial activities, leading to global warming. Therefore, it is critical to develop technologies that can mitigate CO_2 emissions and capture it effectively from major emission sources. CO_2 capture and storage (CCS) technologies—such as geological or ocean storage—have been proposed to reduce these emissions. Meanwhile, CO_2 capture and utilization (CCU) technologies aim to convert CO_2 into high-value products through chemical processes. CCU not only contributes to emission reduction but also enables the utilization of waste CO_2 as a resource. CO_2 can be utilized through physical or chemical methods. Physical methods involve direct application, while chemical methods involve either breaking down CO_2 into basic molecules or using it as a precursor for valuable compounds.

Single-step absorption and isolation of CO_2 as carbamates refers to a simplified process in which CO_2 is simultaneously absorbed (captured) and converted into an isolable compound—carbamate—using amines, all within a single step. This avoids multi-stage treatments, regeneration, or the use of intermediate solvents. Carbamates, which contain the functional group –$NHCOO^-$ (or their neutral counterparts), are typically formed through the reaction between CO_2 and primary or secondary amines:

$$2\ RNH_2 + CO_2 \rightarrow RNHCOO^- + RNH_3^+$$

This reaction forms a carbamate salt in the presence of counterions such as NH_4^+, quaternary ammonium ions, or alkali metals (e.g., K^+, Na^+). Reactions usually occur in solvents such as water, alcohols, or ionic liquids. The desired features of these reactions include: fast CO_2 absorption kinetics, high absorption capacity (mol CO_2/mol amine), easy solid/liquid separation and regenerability or potential for stable storage.

We explored the use of ammonia and alkylamines in non-aqueous media, where CO_2 bubbling leads directly to carbamate formation. In particular, carbon dioxide can be used as a feedstock to produce ammonium carbamate, a precursor to urea. For instance, waste cooking oil has been employed as a non-aqueous medium for the continuous generation of ammonium carbamate achieving a CO_2 conversion rate of 88.86%.

$$2\ NH_3 + CO_2 \rightarrow NH_4COONH_2$$

The choice of phase-changing solvent significantly affects both the absorption capacity and carbamate yield. For example, 2-amino-2-methyl-1-propanol (AMP) in coconut oil exhibited high CO_2 absorption capacity, with a maximum yield of 52% AMP-carbamate under optimized conditions. Green solvents like vegetable oils and deep eutectic solvents (DES) have been explored in combination with various amines (e.g., triethylenetetramine or TETA) to produce solid carbamates. Among the various alkyl amine and vegetable oil combinations, triethylenetetramine in coconut oil medium showed the maximum CO_2 capture capacity of 72%. AMP in a choline chloride: urea (2:1) DES system demonstrated high CO_2 absorption capacity.

Other systems, such as N-methyl-1,3-diaminopropane/N,N-dimethylformamide (DMF), have also been reported for carbamate formation by other group of researchers. Recent studies have also investigated polyamines, ionic liquids, and metal-organic frameworks (MOFs) functionalized with amine groups for CO_2 capture. These materials enable solid carbamate formation, enhancing adsorption capacity and selectivity. For example, amine-functionalized Mg-MOFs have demonstrated improved CO_2 uptake. However, isolating the final product in such systems can be challenging, especially when the medium is solid and must be heated to regenerate CO_2. Amino acids and their salts are promising alternatives to conventional alkanolamines due to their similar functional groups but superior environmental and operational properties.

Carbamates serve as intermediates in urea and other chemical feedstock production. Key challenges in this process include: solvent stability, carbamate solubility and crystallization control, moisture removal and scale-up and solid handling. Overcoming these challenges will enable further development of this single-step absorption and isolation process—a promising pathway for efficient CO_2 capture and utilization. With enhanced energy efficiency and product value, this approach supports the vision of a circular carbon economy.

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7

Recent Advances in Geologic Carbon Storage – Need of Implementation in India

Dr. Vinod Atmaram Mendhe*, Sameeksha Mishra
CSIR-Central Institute of Mining and Fuel Research
Dhanbad-826015, Jharkhand

Extended Summary

The need of implementation of CO_2 geologic storage in India is not just an environmental necessity but also an opportunity for sustainable industrial development, energy resilience and international climate leadership. Accelerating its deployment through policy support, R&D and public-private partnerships are critical to achieve India's climate and development goals. The country has a large and growing industrial sector, including cement, steel, oil refining and power generation contributes significantly to national CO_2 emissions. Geologic storage of CO_2 provides a long-term and viable solution to permanently sequester emissions from these industries, supporting deep decarbonization efforts. While renewable energy is expanding, fossil fuels are likely to remain part of India's energy mix for the foreseeable future. In this context, implementation of CO_2 storage can enable the continued use of fossil resources in a more environmentally responsible manner, supporting a just energy transition without compromising energy security. India has significant potential for CO_2 storage in deep saline aquifers, basalt formations, depleted oil and gas fields and unmineable coal seams. Regions like the Gondwana sedimentary Basins (Damodar, Mahanadi, Son-Koel, Ib Valley, Wardha Valley, etc.), as well as Cambay, Krishna-Godavari, Cauvery and Vindhyan Basins offer promising sites for long-term CO_2 sequestration, these sites must be precisely assessed and strategically utilized. The estimated geologic storage capacity in India is around 291 gigatonnes of CO_2 ($GtCO_2$). Within this, saline aquifer CO_2 storage potential is estimated to be more than 200 $GtCO_2$, unminable coal seams can store between 3.5 and 6.3 $GtCO_2$ with additional benefits of enhanced methane recovery (ECBM), while Enhanced Oil and Gas Recovery (EOR or EGR) techniques could enable the storage of an additional 1.2 $GtCO_2$, simultaneously boosting the productivity of mature oil fields. In present scenario, to align with the Paris Agreement, India would require an investment of approximately $1–8 billion annually for the development of CCUS infrastructure. Given this financial requirement, the identification of optimal storage sites near major CO_2 point sources becomes essential to enhance the cost-effectiveness and impact of CCUS projects. To stay on a sustainable pathway, India must implement a diverse set of climate mitigation strategies. Among these, CO_2 geologic storage stands out as a key technology for achieving deep emissions cuts, especially in sectors with few viable alternatives. Investment in CCUS infrastructure can stimulate technological innovation, create high-skilled green jobs and build domestic capabilities in advanced carbon management. Despite the substantial potential, India faces challenges related to technological readiness, economic viability and regulatory frameworks. Addressing these barriers is crucial to unlocking the full potential of CO_2 geologic storage as a reliable solution to reduce greenhouse gas emissions an essential step on the road to net-zero emissions.

Keywords: Geologic carbon storage (GCS), Carbon Capture, Utilization and Storage (CCUS), CO_2 sequestration, Need of Implementation, Challenges and Issues.

8

Indigenized Technology of Adsorbent Based Carbon Capture from Point Sources and Direct Air

Dr. Ravi Babu V

Senior Scientist, ECPS – Division, CSIR-Central Electrochemical Research Institute

Karaikudi-630006

Extended Summary

At present, there prevails huge demand for energy consumption worldwide due the escalation in population growth and industrial development. Due to which it is estimated that 50 GT of CO_2 will be liberated into environment by 2050.The United Nations Climate Change Conference (COP 21) was held in 2015 at France. The key result was an agreement to set a goal of limiting global warming to less than 2 °C as compared to pre-industrial levels. Since the concentration of CO_2 in flue gas emitted from coal-fired thermal power stations is about 500 times higher than that in the atmosphere, CO_2 capture from power plants has become a major focus of the environmental agenda.

Among different technologies practiced for CO_2 capture, liquid amine absorption (LEA) is the dominant technology used worldwide in industries. In several industries, LEA processes such as UCARSOL and Flour Econamine have been used for several decades to remove CO_2 from various gas streams. The commercial implementation of the LEA process suffers from severe shortcomings like requirement of energy intensive and expensive stripping processes, low absorption−desorption rates, absorption tower corrosion issues, enormous solvent loss and amine degradation. Hence, the need to explore an indigenous energy-efficient approach for CO_2 capture remains to be a challenging task for scientists all over the world. Adsorption is regarded as the effective technology to capture CO_2 from gas streams. Till now, several adsorbents such as zeolites, activated carbon, metal organic frameworks have been tested for their CO_2 capture efficiency under flue gas conditions. All these adsorbents demonstrate high adsorption capacity only at lower temperature conditions and found to be inefficient for high temperature conditions that prevail with flue gas. Therefore, the current work aims to develop a novel nanomaterial adsorbent which exhibit CO_2 capture potential in accordance with DOE target under flue gas conditions.

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Greening the Coal through CCUS
NTPC Experience of First CO2 to Methanol Plant and Way Forward

Mr. Sujay Karmakar
GM (NETRA & Green Chemicals) NTPC Limited
Greater Noida-201310, UP

Extended Summary

1. Outline of presentation

India shared its vision on Energy Transition when Honourable Prime Minister of India declared Nation's intent to progressively decarbonize Indian economy to achieve Net-Zero by 2070 in 2021 at COP 26 in Glasgow. Through Nationally Determined Contribution (NDC), India submitted a graded action plan wherein it is targeted to reduce carbon intensity of our GDP by 45% wrt 2005 level and to achieve 50% of installed electricity capacity from non-fossil fuel sources. Since then, the growth of Renewable Energy has shown a significant uptrend, but it still will take some time for RE power to be available Round-The-Clock (RTC).As on Dec-2024, India's total Installed capacity stands at 462 GW, with 217.6 GW of RE. Fossil fuels contribute to almost 52.89 % of total generation capacity, with coal-based thermal power capacity alone accounting for around 45.96% (212.35 GW). As per present estimate, 80 GW of coal-based plant need to be additionally commissioned to meet Nation's growing power demand till 2032 wherein coal-based plant shall co-exists along with RE for at least 20-30 years. Thus, it becomes important to reduce CO2 emission from thermal power plants to achieve the "JUST TRANSITION" ensuring Energy Security as India transition towards Net Zero. In this scenario Carbon Capture Utilization and Storage (CCUS) technologies shall become important for the "Just Transition"

This paper discusses NTPC's initiatives and experiences of technology development and design carried out by NETRA and execution by Green Energy Department at NTPC Vindhyachal. Work carried out in CO2 Capture using various technologies is discussed along with advantage and disadvantage of each, integration of Green Hydrogen with Captured CO2 for producing product which meets the scale required for successful commercialization, experience and lesson learnt from design, erection and commissioning of the World's unique CO2 to Methanol Project (CTM) at NTPC Vindhyachal and the way forward.

*[**Keywords:** Energy Transition, CCUS, CO2 Capture Plant, CO2 to Methanol, NETRA, Green Chemicals Department, CTM]*

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Decarbonisation as a Journey, Not a Destination: Reflections from the Indian Cement Industry

Ms. Aparna Dutt Sharma
Secretary General, Cement Manufacturers' Association (CMA)
New Delhi-110070

Extended Summary

The Indian cement industry has come a long way- *from being considered a hard-to-abate sector* to becoming a credible and committed stakeholder in India's low carbon transition. Over the past two decades, this journey has shifted from fragmented efficiency gains to a more deliberate, sectoral transformation. Today, the Industry is not just reacting to global climate calls, it is co-authoring India's decarbonisation playbook in active collaboration and engagement with the Government. This session examines the evolving policy and regulatory ecosystem responding to the needs and the challenges for carbon mitigation in the Cement sector in India.

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Scaling CCUS in India: Business Models, Hydrogen Integration, and Policy Enablers for Industrial Decarbonisation

Dr. Balawant Joshi
Managing Director, IDAM Infrastructure Advisory
Mumbai-400093

Extended Summary

Introduction

Carbon Capture, Utilisation, and Storage (CCUS) is a pivotal technology for achieving India's net-zero target by 2070. With hard-to-abate sectors such as steel, cement, thermal power, oil and gas, and chemicals contributing to over 60% of the country's CO_2 emissions, CCUS is essential not only to reduce emissions but also to retain the viability of existing infrastructure and support economic competitiveness. Electrification and renewable energy alone cannot sufficiently decarbonise these sectors, particularly due to process-related emissions and reliance on fossil feedstocks.

India's CCUS opportunity is significant, with a theoretical CO_2 storage capacity of over 395 gigatonnes and growing demand for low-carbon products. Yet, the deployment remains at a nascent stage, hindered by high capture costs, lack of transport and storage infrastructure, and the absence of a formal policy framework. This session will explore the technologies, market models, and institutional mechanisms needed to mainstream CCUS in India's industrial strategy.

Objectives of the Session

- Showcase business models and financing mechanisms that make CCUS viable in industrial applications.
- Highlight CCU pathways that integrate with the hydrogen economy and contribute to circularity.
- Discuss sectoral and regional CCUS implementation priorities based on emission intensity and storage feasibility.
- Present a roadmap for policy, regulatory, and institutional enablers to unlock CCUS at scale.
- Generate actionable recommendations for national deployment through multi-stakeholder collaboration.

Sectoral Prioritisation and Industrial Relevance

- Steel and Cement: These sectors together account for more than half of industrial CO_2 emissions. Over 56% of their emissions can only be abated through CCUS due to inherent process-related CO_2 generation. Notably, for the steel sector, CCUS offers a pathway to reduce CO_2 intensity per tonne of steel — critical for avoiding penalties under mechanisms like the European Union's **Carbon Border Adjustment Mechanism (CBAM)**, which will impact Indian steel exports from 2026.

- Thermal Power: Despite renewable energy expansion, coal-based power will remain essential for baseload requirements. CCUS allows sustainable operation of existing 200+ GW coal capacity.
- Chemicals, Refining, Fertilisers: These sectors offer integration-ready CCUS opportunities through inbuilt CO_2 generation points and established processing streams.

CO_2 Utilisation and Product Diversification

- Production of green urea, methanol, ethanol, and synthetic fuels enables significant import substitution and carbon circularity.
- CO_2 conversion into construction materials, aggregates, and polymers presents scalable, low-energy utilisation options.
- Integration of CCUS with hydrogen production (especially blue hydrogen) enhances energy security and drives competitiveness in the emerging hydrogen economy.

Business Models and Regional Deployment Strategies

- Hub-and-Cluster Model: Large industrial emitters linked to shared transport and storage infrastructure improve cost-effectiveness and enable phased scale-up.
- Low-Carbon Product Markets: Government-led preferential procurement and carbon certification create market pull for green steel, green cement, and CO_2-derived fuels.
- Carbon Procurement and Financing Institutions: Establishment of a Carbon Procurement Corporation and a Carbon Capture Finance Corporation will provide revenue certainty and capital access, respectively.
- Priority Geographies: Eastern and western regions of India are identified as high-potential zones for initial CCUS hubs based on emission intensity and geological storage availability.

Policy and Regulatory Enablers

- Credit-Based Incentives: Carbon credit trading, production-linked incentives, and tax rebates are essential to reduce upfront and lifecycle costs of CCUS projects.
- Lifecycle Carbon Accounting: Integrating Scope 1–3 emissions assessments and low-carbon product certification standards.
- Risk De-Risking Mechanisms: Clear frameworks for long-term liability, public-private partnerships, and regulated CO_2 transport and storage access.
- Innovation and Indigenisation: Support for R&D in capture and utilisation technologies, manufacturing of CCUS components, and technology transfer from global leaders.

Way forward

- Roadmap for national CCUS scale-up in key sectors with pilot project priorities.
- Recommendations for inclusion in national carbon market mechanisms and climate finance instruments.

- Strategic blueprint for aligning CCUS with India’s industrial policy, energy transition, and hydrogen economy.
- Identification of institutional structures to manage aggregation, financing, and infrastructure development.

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Decarbonizing India's Power Sector through CO_2 Storage in Deep Unmineable Coal Seams: Potential and Pathways

Dr. Ajay Kumar Singh
Chief Research Coordinator, PMRC Private Limited
Dhanbad – 826 004, Jharkhand

Extended Summary

India's energy landscape continues to be fundamentally shaped by coal, which remains a cornerstone of the country's electricity generation and industrial activity. As of 30 April 2025, coal—including lignite—accounts for approximately 46% of India's total installed power generation capacity. However, its role is even more pronounced in actual electricity generation, contributing to over 60% of the country's total output. This heavy reliance underscores coal's critical position in sustaining India's energy security and supporting its economic development. Nevertheless, this dependence also brings significant environmental and climate-related concerns, particularly in the context of global efforts to reduce carbon emissions. Although the renewable energy sector has expanded rapidly, the transition to a low-carbon energy system remains constrained by coal's entrenched dominance and infrastructural legacy within India's power sector.

India is actively working to diversify its energy mix by investing heavily in renewable energy sources such as solar, wind and hydroelectric power. The country's National Electricity Plan aims to increase the share of non-fossil fuel-based capacity to 50% by 2030, reflecting a strong commitment to sustainable development and climate goals. However, considering the present energy demands, economic constraints and existing infrastructure, coal is expected to continue playing a substantial role in meeting India's electricity generation needs for the foreseeable future.

As the country grapples with the twin challenges of ensuring energy security and driving economic development, it is simultaneously confronted with the imperative to decarbonize its energy systems. Carbon capture, utilization and storage (CCUS) technologies present a viable pathway to reconcile these competing demands. In particular, the geological storage of carbon dioxide (CO_2) in deep, unmineable coal seams offers significant potential—not only for reducing emissions but also for enhancing coalbed methane (CBM) recovery and utilization.

In 2024, global coal demand reached 8.77 billion tonnes, marking a 1% year-on-year increase, with China and India continuing to drive demand. India, in particular, experienced a 5% growth, bringing its annual coal consumption to approximately 1.3 billion tonnes. Despite the increasing push toward renewable energy and a national target of 500 GW of non-fossil fuel energy by 2030, coal remains India's primary energy source due to its affordability, domestic resource availability,

established infrastructure, and the critical role it plays in meeting rising industrial and residential power demands.

India's journey toward achieving a low-carbon economy is fraught with multifaceted challenges, both technical and socio-economic. One of the most critical hurdles is the integration of renewable energy sources into the nation's existing electricity grid, which is predominantly coal-based. Despite significant advancements in solar and wind power generation, issues related to grid stability, intermittency\ and energy storage continue to hamper seamless integration. Transitioning away from coal requires not only infrastructural revamps but also comprehensive policy reforms.

Carbon Capture, Utilisation and Storage (CCUS) technologies represent a vital pathway to achieving emission reductions from large point sources such as thermal power plants and industrial facilities. However, their deployment in India is constrained by high implementation costs, lack of mature commercial-scale projects and complex retrofitting requirements for existing power infrastructure. Many of India's coal-fired power plants are relatively old, making them less suitable for economically viable retrofitting. The absence of a robust carbon pricing mechanism further weakens the business case for CCUS investments.

Equally important are the socioeconomic dimensions of this transition. India's coal mining industry supports millions of livelihoods directly and indirectly, particularly in states like Jharkhand, Odisha, Chhattisgarh, Madhya Pradesh, Telangana and West Bengal. The regional economies of these coal-bearing states are heavily dependent on mining-related revenues and employment. Therefore, any decarbonization initiative must incorporate a just transition framework that safeguards the interests of workers and communities dependent on the coal economy. A carefully calibrated policy approach is essential—one that aligns climate action with inclusive development.

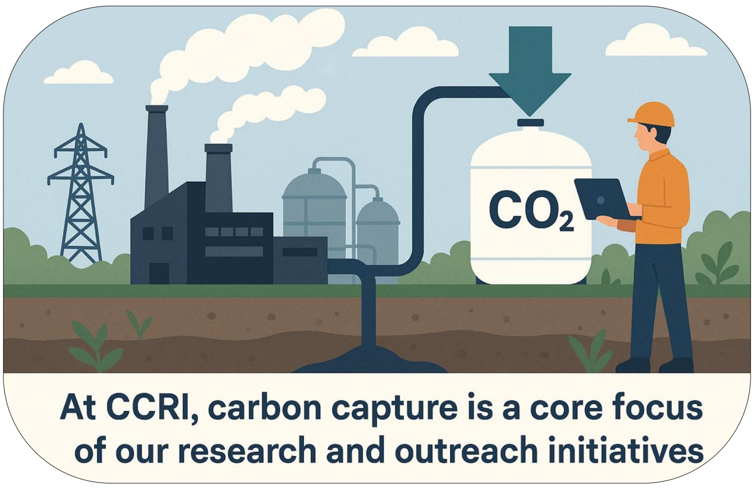
Amid these complexities, India possesses a significant, yet underutilized, opportunity in the form of deep coal seams suitable for CO_2 sequestration, particularly through CO_2-Enhanced Coalbed Methane (CO_2-ECBM) recovery. The Damodar Valley Basin, located in eastern India, holds several coalfields with substantial geological promise for such applications. Key among these are the Jharia, Raniganj, East and West Bokaro and North and South Karanpura coalfields. These regions exhibit favorable geological and geochemical parameters, including seam thickness, gas content, and total organic carbon (TOC) levels.

For instance, the Jharia Coalfield—especially the Mohuda Sub-basin—comprises coal-bearing formations such as Raniganj, Barren Measures and Barakar. Coal seam thicknesses here reach up to 33 meters. Vertical borehole investigations have revealed *in-situ* gas content ranging from 10 to 35 m^3/tonne in coal and 0.15 to 3.69 m^3/tonne in associated shales. High TOC values, between 9% and 17%, underscore the source rock's excellent capacity for gas adsorption and potential CO_2 sequestration.

Similarly, the East Bokaro Coalfield hosts the thick Barakar Formation, where coal seams can be as much as 63.9 meters thick, offering ample capacity for both CO_2 storage and methane recovery. In the North Karanpura coalfield, seam thicknesses reach up to 35.2 meters across multiple formations, with favorable adsorption characteristics. The South Karanpura coalfield is even more extensive containing 42 identified coal seams with thicknesses up to 54.2 meters.

Scientific studies have confirmed that Indian coals have a strong preferential adsorption for CO_2 over methane, often in a 2:1 molar ratio. This sorption behavior is critical to the success of CO_2-ECBM, as it enables effective methane displacement while locking CO_2 into the coal matrix. Understanding variables such as coal rank, porosity, depth and temperature-pressure conditions is essential for accurate modeling and optimization of both methane recovery and carbon sequestration.

Estimates suggest that India's deep, unmineable and concealed coalbeds could store up to 4,459 million tonnes of CO_2. While this capacity may not completely neutralize the country's emissions, it nonetheless offers a substantial mitigation pathway. The co-benefit of enhanced CBM production further strengthens the economic viability of CCUS deployment. As India pursues its National Hydrogen Mission and ramps up its renewable energy ambitions, incorporating CCUS strategies—particularly in coal-rich regions—will be vital to balancing energy security, economic resilience and achieving its net zero target by 2070.



Climate Change Research Institute

Contact:

C- 85 Shivalik
New Delhi 110017, India
Email: maltigoel2008@gmail.com,
Contactus@ccri.in