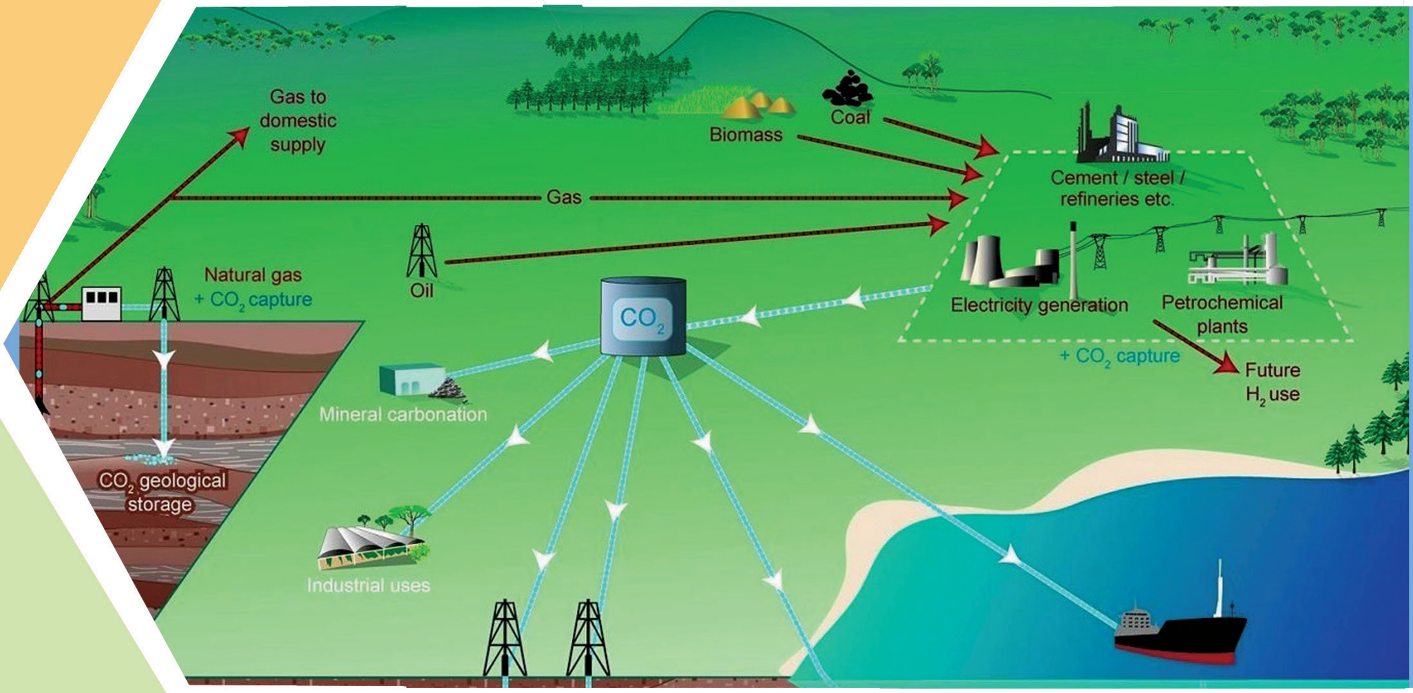
ISSN NO. 0254 - 8003

MGMI News Journal

Vol 50, No.2
July - September 2024



COVER ART SOURCE : IPCC SRCCS (2005)

Established 1906

THE MINING, GEOLOGICAL AND METALLURGICAL INSTITUTE OF INDIA

MGMI COUNCIL FOR 2023 - 24

Established 1906

President
Dr B Veera Reddy
Director (Technical), Coal India Limited

Immediate Past Presidents
P M Prasad, Chairman, Coal India Limited
Anil Kumar Jha, Former Chairman, Coal India Limited

Vice-Presidents
J V Dattatreyulu, Former, Director (Operations), SCCL
Thomas Cherian, Managing Director, Essel Mining & Industries Limited
Bhola Singh, Former CMD, Northern Coalfields Limited
Jagdish Prasad Goenka, Managing Partner, Nanda Millar Company

Honorary Secretary
Ranajit Talapatra
Former GM (WS), CIL

Immediate Past Secretaries
Rajiw Lochan
Former GM (CED/CBM), CMPDI
Prasanta Roy
HOD (Geology), CIL

Hony Jt Secretary
Dr Chandra Shekhar Singh
GM, PMD, CIL

Hony Editor
Dr Ajay Kumar Singh
Former Scientist
CSIR-CIMFR

Hony Treasurer
Dr Prabhat Kumar Mandal
Chief Scientist,
CSIR-CIMFR

Members

Virendra Kumar Arora
Chief Mentor (Coal), KCT & Bros

Dr Jai Prakash Barnwal
Former Chief Scientist, RRL

Bhaskar Chakraborty
Former, Dy. DG, GSI

Prof (Dr) Ashis Bhattacharjee
Former Prof., IIT, Kharagpur

Anup Biswas
Former Deputy Director General, Mines Safety

Pravat Ranjan Mandal
Former Advisor (Projects), Ministry of Coal

Awadh Kishore Pandey
GM, MCL

Nityanand Gautam
Former Advisor, UNDP

Dr Netai Chandra Dey
Professor, IIEST, Shibpur

Prof (Dr) Ganga Prasad Karmakar
Former Prof. IIT, Kharagpur

Tapas Kumar Nag.
Former CMD, NCL

Dr Peeyush Kumar
GM & MD, BCGCL

Prof (Dr) Bhabesh Chandra Sarkar
Former Professor, IIT (ISM), Dhanbad

Dr Kalyan Sen
Former Director, CIMFR

Dr Amalendu Sinha
Former Director, CSIR-CIMFR
Dr Rajib Dey
Professor, Jadavpur University

MGMI NEWS JOURNAL

Vol. 50, No. 2 ● July - September ● 2024

THEME

"Carbon Capture, Utilization and Storage."

ISSN 0254-8003

The Mining, Geological and Metallurgical Institute of India

ATTENTION MEMBERS

Are you up to date in paying your subscription? Please do pay it for getting the News Journal and other correspondences on regular basis and for exercising your voting right. Why not opt for LIFE MEMBERSHIP by paying a one-time subscription! This is both convenient and economical.

Members are requested to kindly let us have their Current Address with Pin Code no., Contact Telephone no. (Land & Mobile), Email ID, Date of Birth and also Membership no. etc. to update in our records for onwards sending communications.

The members are requested to send contributions for the columns of the MGMI News Journal, like "Technical Articles" related to the mineral industry on topics dear to the members, Articles as Case History on various mine practices in the field, interesting write ups for "Down Memory Lane", "Opinion" on burning issues of the Mining Industry. "Safety & Health" issues, research finding for "Technology Updates", etc.

ATTENTION BRANCHES

Branches are requested to send the list of members of the Executive Committee with Addresses, Telephone Numbers and Email IDs for maintaining records at MGMI Headquarters. They may also activate their Branches and send Reports for inclusion in the News Journal.

A Quarterly Publication
MGMI NEWS JOURNAL
Vol. 50, No. 2, July - September, 2024
ISSN 0254-8003

CONTENTS

EDITORIAL BOARD

CCUS: BOOM OR DOOM?

Carbon capture, utilization and storage (CCUS) refers to a suite of approaches seeking to capture CO_2 from point sources and either transform it to value-added products or store it deep beneath the earth's surface. It would be fair to state that these approaches came into scientific discourse around the 1990s. If we look at the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) published in 1995, carbon capture was mentioned, both for coal-fired power plants and natural gas processing. Interestingly, the cost of carbon avoidance at that point of time was \$578/tCO_2. The Third Assessment Report brought in more detailed estimates at a global level, while quoting comparable – albeit somewhat lower – costs. It is only in 2006 that the IPCC came out with the its special report on carbon capture and storage (CCS). This report synthesized the capture, transport, storage and other aspects associated with CCS. Interestingly, it is also in 2006 that the first study estimating geologic storage potential of CO_2 in India was carried out in an exercise led by our current Honorary Editor, Dr. Ajay Kumar Singh.

Now that nearly two decades have passed since this watershed moment in the scientific literature, what lessons have we learned about CCUS? Practitioners and the general public who are averse to large-scale CCUS deployment often point to the failures of this approach. For instance, they point out the high overruns and shutting down of Plant Ratcliffe in the United States. They may also point to the suspension of operations of the Petra Nova plant due to low oil prices (the plant captured CO_2 for enhanced oil recovery) during the peak of the COVID-19 pandemic. There was an excellent paper published in 2021 estimating that the projects, which did not materialize likely led to emissions of 475 MtCO_2 (Martin-Roberts et al, 2021, One Earth, 4, 1569-1584).

Should we then write off CCUS? Are the several billions of dollars being invested for these approaches globally not justified? I would caution against this level of pessimism. From an economist's perspective, CCUS is near-essential if the Paris Agreement targets are to be met at a global level. Indeed, an analysis by the Indian Institute of Management Ahmedabad indicates that scenarios aligning with India's net-zero by 2070 target would require anywhere between 12 and 140 GW of coal capacity with CCUS.

As an engineer, I see this target as attainable. My mind goes back to a keynote lecture delivered by Padma Shri, Dr. R.B. Grover at an MGMI seminar in September 2023. Using the example of the digital economy, Dr. Grover made the observation that new technologies that have rapidly transformed the market are new technologies per se. Quite the contrary, these technologies have been around for the last several decades. It is the 'combinatorial evolution' of these approaches that can drive innovation. This phrase was coined by famed economist Dr. W. Brian Arthur who noted that technologies are created not afresh but via a combination of existing technologies. We can very well see this in the energy business. The defining story of the energy business in this century has been the shale gas revolution. The two key technologies that drove this revolution, hydraulic fracturing and horizontal drilling, were studied in isolation by researchers. It was only when these were applied in tandem, that gas extraction could be lucrative enough.

If we use this framework for CCUS, we can highlight several developments across the value chain. CO_2 capture, for example, is not a new technology. As back as 1987, the Jagdishpur fertilizer plant has been capturing CO_2 internally for urea production. India has an extensive gas transport network, which is not very different from CO_2 transport. One could actually argue that it is safer to transport CO_2 given the flammability of natural gas. Similarly, CO_2 storage is also not new. Though not extensively practiced in India, CO_2 storage for enhanced oil recovery has been underway since the oil crises of the early 1970s. Thus, we have most tools and techniques already in place.

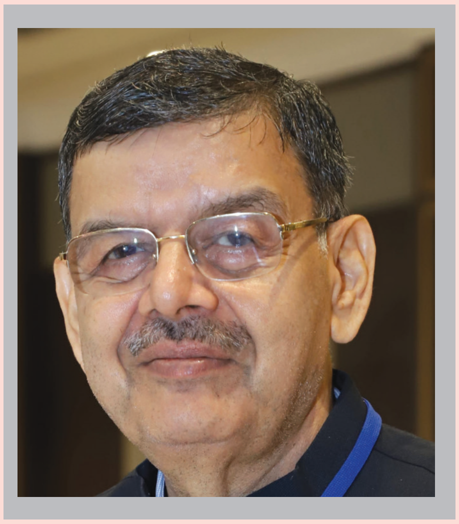
The other aspect of the theory of combinatorial evolution is that technologies develop due to pressing human need. My sense is that this need will have to be geared at local, and not global, levels. What does this mean in the Indian context?

First, CCUS approaches will have to target niches that are necessary for Indian consumers. Agrarian purposes cannot be ignored even as industrialization speeds up. It is therefore imperative to develop approaches to convert captured CO_2 into urea and formic acid that can improve farm economies. Second, CCUS approaches have been thus far framed as a way to keep coal in the energy mix, and therefore, as a way for India to maintain energy security. At the same time, we need CCUS to accelerate a path to energy security, particularly for liquid fuels. Whether in the form of oil production enhanced with CO_2 injection or e-fuels produced via combining CO_2 and green hydrogen, there is a big business opportunity that could also serve our national purpose. Third, CCUS needs to align with societal development targets. Say coal-fired power plants are equipped with amine-based capture. In that case, they would also require extensive polishing of SO_2. This, in turn, could address the alarming air quality in many of our cities.

Of course, all the above targets can be achieved with the availability of large-scale finance, either from international funds like GEF, or multilateral development banks. The Government of India has rightly noted in the Long-Term Emission Reduction Strategy that CCUS deployment in India is conditional on international finance provision. Existing programmes, such as the National Programme on Carbon Sequestration Research of the Department of Science and Technology, have played an important role in building of an ecosystem of CCUS researchers in India. Scaling up would inevitably require sustainable finance from specialized institutions. The international community would need to step up in improving access and quantum of the financing available for CCUS to ensure an economically robust future for our young generations.

Dr. B. Veera Reddy
President, MGMI

CCUS : PAVING THE PATH TO A LOW-CARBON FUTURE



Carbon Capture, Utilisation, and Storage (CCUS) is critical in addressing global climate change by reducing greenhouse gas emissions. As the world transitions to cleaner energy, CCUS provides a viable solution for industries that remain reliant on fossil fuels, such as coal, oil and natural gas. By capturing carbon dioxide from industrial processes and power plants, it prevents harmful emissions from entering the atmosphere. The captured CO_2 can be stored underground or repurposed for use in products like concrete or fuels. CCUS helps meet global climate targets, supports energy security, and fosters economic growth while mitigating the environmental impacts of industrialization.

Carbon capture technologies, such as post-combustion, pre-combustion, and oxy-fuel combustion capture, are used globally to mitigate CO_2 emissions. Post-combustion systems are widely adopted due to their compatibility with existing power plants, while pre-combustion is often used in gasification. Emerging techniques like Direct Air Capture (DAC) remove CO_2 directly from the atmosphere. Despite their potential, these technologies face challenges such as high costs, energy intensity, and infrastructure needs, limiting their current large-scale viability. Advancements are essential for widespread adoption.

Captured CO_2 utilization technologies are gaining traction globally as part of efforts to mitigate climate change. These technologies involve capturing carbon dioxide emissions from industrial sources and repurposing them into useful products, such as fuels, chemicals, and construction materials. One prominent method is transforming CO_2 into synthetic fuels, methanol, or plastics. Enhanced oil recovery (EOR) is another method, where CO_2 is injected into depleted oil reservoirs to boost production. However, the viability of these technologies depends on scalability, cost-effectiveness, and the carbon footprint of the overall process. Current challenges include high operational costs and limited infrastructure. Long-term success depends on policy support and carbon pricing to incentivize adoption. While promising, captured CO_2 technologies still require significant investment and development to become mainstream solutions in the global fight against climate change.

Captured CO_2 storage technologies, such as geological sequestration and mineralization, are also gaining attention globally. Geological sequestration involves injecting CO_2 into deep underground formations, like deep saline aquifers, depleted oil and gas reservoirs, and unmineable coal seams, where it is stored long-term. Mineralization converts CO_2 into stable minerals. Both methods show promise, but challenges include high costs, scalability, and the need for long-term monitoring.

CCUS technologies are vital in helping coal and oil and gas sectors achieve net-zero emissions. These sectors are traditionally high in carbon emissions, but CCUS allows for the capture of CO_2. By reducing the carbon footprint of coal and fossil fuel operations, CCUS provides a pathway to decarbonization without completely eliminating the use of these energy sources. This technology is essential in bridging the gap towards sustainable energy, while maintaining energy security and economic stability during the transition to a low-carbon future.

India's commitment to achieving net-zero emissions by 2070 is a monumental step toward global climate goals, especially given the nation's reliance on coal, oil, and natural gas for energy production. With coal contributing to nearly 70% of India's electricity generation, decarbonizing this sector is critical. Carbon Capture, Utilization, and Storage (CCUS) technologies will play a pivotal role in balancing India's energy security needs with environmental goals. CCUS can capture up to 90% of CO_2 emissions from fossil fuel-based power plants and industrial processes, preventing it from entering the atmosphere. This is crucial for India, which cannot immediately transition away from coal and oil due to its growing energy demands and economic considerations at least for next three decades.

By incorporating CCUS, India can continue to use its abundant coal resources, while minimizing the carbon footprint. Captured CO_2 can be utilized in enhanced oil recovery, chemical production, or stored underground, reducing atmospheric emissions. Coupling CCUS with renewable energy adoption can accelerate India's journey toward net-zero, allowing for a phased transition to cleaner technologies. Moreover, advancing CCUS aligns with global efforts and helps India meet its climate targets without jeopardizing economic growth. It also offers an opportunity for innovation, opening doors for investment in clean energy technologies and infrastructure development.

NTPC Limited, India's largest power producer, is exploring CCUS technologies at its Vindhyachal power plant to reduce its carbon footprint. The plant is part of NTPC's broader initiative to decarbonize coal-based operations by capturing CO_2 emissions and converting them into useful products like methanol or other chemicals. This aligns with India's national goals for achieving net-zero emissions by 2070. Other companies like Tata Steel and Reliance Industries are also actively pursuing CCUS technologies. Tata Steel is capturing CO_2 from blast furnace gas and converting it into biofuels, while Reliance is focusing on using captured CO_2 for enhanced oil recovery and chemical production. These initiatives collectively mark a significant step towards integrating CCUS into India's industrial framework, fostering sustainability in heavy industries like coal and steel. ONGC is actively planning to incorporate CCUS technologies as part of its broader strategy to achieve net-zero emissions by 2050. The company aims to enhance its research and development in CCUS, which includes initiatives to mitigate emissions from existing processes while transitioning towards renewable energy sources like green hydrogen and ammonia. This approach aligns with India's commitment to significantly reduce carbon emissions and foster sustainable practices in the energy sector.

During India's G20 Presidency, Indian Institute of Management Ahmedabad in a report emphasized the crucial role of CCUS technologies in achieving sustainable development and net-zero emissions. It is reported that these technologies are essential for mitigating greenhouse gas emissions from industries such as coal and cement, which are significant contributors to climate change. By capturing carbon dioxide and converting it into valuable products or safely storing it underground, India can enhance energy security, foster innovation, and promote environmentally responsible economic growth.

The implementation of CCUS technologies, however, faces several risks that require careful consideration. One significant concern is the uncertainty surrounding the economic value of CO_2 storage, which can deter substantial investments. Projects like enhanced oil recovery often rely on market-driven incentives, leading to fluctuations in viability, as evidenced by the suspension of the Petra Nova project due to falling crude prices. Acceptability of the technology also remains a challenge, with public and government perception often skewed negatively compared to other low-carbon solutions. Effective communication and engagement strategies are essential to build trust and support. Furthermore, the complexity of the CO_2 value chain necessitates the establishment of hubs and clusters to ensure consistent supply and reduce dependency on individual sources, thereby enhancing project resilience.

CCUS technologies, therefore, offer India a crucial pathway to mitigate carbon emissions, while maintaining reliance on coal, oil, and gas. This is also vital for sectors like steel and cement, where emissions are substantial. India can ensure energy security and economic growth while fostering innovation. These efforts will not only align with global climate commitments but also position India as a leader in sustainable industrial practices.

This edition of the News Journal, focusing on CCUS, marks my final contribution as Editor. I would like to take this opportunity to convey my heartfelt gratitude to Dr. B. Veera Reddy, former Director (Technical), Coal India Limited and President, MGMI, for his steadfast support throughout my tenure. My sincere appreciation also goes to Shri Ranajit Talapatra, Hony. Secretary, for his unwavering assistance. I extend special thanks to the esteemed Council Members and the Editorial Board for their timely suggestions and thorough reviews of the articles. I am particularly grateful to Prof. Epling for the enlightening interview, which significantly enriched our understanding of catalysts and also CCUS. Finally, I wish to acknowledge the invaluable contributions of all the distinguished authors.

Ajay Kumar Singh

Hony. Editor

INTRODUCING OUR NEW PRESIDENT

SHRI JAI PRAKASH DWIVEDI

At the 118th Annual General Meeting of the Mining, Geological & Metallurgical Institute of India (MGMI), held on 21st September 2024, Shri Jai Prakash Dwivedi, Chairman and Managing Director (CMD) of Western Coalfields Limited (WCL), was unanimously appointed as the Institute's new President.

Shri Dwivedi took on the role of CMD at WCL on 1st February 2024, having previously served as the company's Director (Technical). His extensive experience of over 37 years in both opencast and underground coal mining began in 1986 when he joined Coal India Limited (CIL) as a mining engineer after graduating in mining engineering from IIT(BHU), Varanasi. Over the years, he contributed significantly to CIL, working across its subsidiaries SECL, ECL, and NCL before moving to WCL.

Known for his achievements in labour-force management within the coal mining industry, Shri Dwivedi has held numerous roles throughout his career, including General Manager (Coordination) at WCL's Headquarters. He has participated in various professional training programmes both in India and abroad. Recognized for his contributions to the field, he received the prestigious 'Best Engineer Award' from the Institution of Engineers.

SCCL Gold Medal

SCCL Gold Medal for the Best Student in Mining Engineering to **Miss Challa Gayathri** of Kakatiya University

Oil India Medal

Oil India Medal for the Best Student in B.Tech. Petroleum Engineering to **Shri Raj Prasar** IIT (ISM) Dhanbad

Hadfield Medal for Metallurgical Engg.

Hadfield Medal for Metallurgical Engineering to **Ms Anushka Bhardwaj** of BHU.

Hayden Medal for the year 2022-23

Hayden Medal for the Best Student in M.Sc/M. Tech. in Applied Geology to **Shri Suryasish Mozumder** of IIT (ISM) Dhanbad.

Pickering Medal for the year 2022-23

Pickering Medal for the Best Student in B.Tech Final of Mining Engineering to **Shri Suyash Ranjan** of IIT (ISM), Dhanbad.

Smt. Nirja Sahay Medal for the year 2022-23

Smt. Nirja Sahay Medal for M.Sc in Applied Geology to **Shri S. Gowtham** of IIT(KGP).

Indranil Award - IIT, BESU

Indranil Award for B.Tech. in Metallurgy to **Ms Ananya Das** of IIEST, Shibpur

Roberton Medal for the year 2022-23

Roberton Medal for Mining Engineering to **Ms. Harshita Kumari** of IIT(BHU).

Kalyan Mukherjee "61 Geology" Medal for the year 2022-23

Kalyan Mukherjee "61 Geology" Medal for M.Sc (Geology) 2022-23 to **Shri Aplab Chatterjee** of University of Calcutta.

S. Lal Medal for the year 2022-23

S Lal Award for Mining Engineering to **Shri Samik Ghosh** of IIEST, Shibpur.

La Touch Medal for Geology for 2022-23

La Touch Medal for Geology to **Ms Anchal Arora** of IIT (BHU).

Dr. Hari Narain Medal for the year 2022-23

Dr. Hari Narain Medal for the Best Student in M.Sc (Tech.) Applied Geophysics to **Ms Atanima Mondal** of IIT (ISM) Dhanbad

MGMI AWARD OF EXCELLENCE FOR THE YEAR - 2023 -24

MGMI Award for Non Coal Mining for the year 2023-24

K. Madhusudhana
CEO, MSPL Limited

MGMI Award for Coal Mining for the year 2023-24

Dr. Anindya Sinha

Professor of Practice, IIT(ISM), Dhanbad, Consultant to MoC, Govt. of India

Former Director (Tech/Oprn), NCL, CIL, Former Project Adviser, Ministry of Coal, GoI

Former Regional Director, CMPDI, CIL

MGMI Award for Excellence of Earth Sciences / Mineral Engineering for the year 2023-24

Dr.Atul K.Varma

Professor (HAG) & Ex-HOD / Applied Geology, Coal Geology and Organic Petrology Lab.,

Dept. of Applied Geology,Indian Institute of Technology, (Indian School of Mines), Dhanbad-826004, India

R. B. Bansal (12th October 1932 - 19th August 2024)

It is with deep sorrow that we announce the passing of Shri R. B. Bansal (LM-3720), Founder and Chairman of Mining Associates Pvt. Ltd (MAPL), on 19th August 2024, at the age of 92. A visionary leader in India's mining and drilling industry, Shri Bansal's life was marked by innovation, dedication, and a profound commitment to the advancement of the field.

Shri Bansal was a distinguished graduate from the 1956 batch of ISM Dhanbad, where he excelled academically. Subsequently he acquired the 1st class mining certificate. His early career began with a British company, followed by a significant role at the Western Bengal Coalfields under the Birla Group's Coal Mining Division at Samla-Mandarbani Colliery in Pandaveshwar area. Few years before the nationalisation of coal mines, he briefly served as an Inspector in the Coal Board. His stint at the Birla Group was marked by notable contributions, including ramping up the coal production using innovative ideas in solving the pressing issue of sand stowing.

After nationalisation of coal mines, he served for a very brief period in ECL. Thereafter he rejoined the Birla Group in their Drilling Division (Diamond Drill Syndicate). After sometime Shri Bansal founded MAPL and transformed it from a modest venture into one of India's leading names in drilling, geological report preparation, and geophysical logging. His leadership resulted in the development of one of the largest and most technologically advanced fleets of drilling rigs in India.

Shri Bansal's expertise was crucial following the tragic Chasnala mine disaster of 1975. He played a key role in preventing further accidents by drilling 8-inch upward holes to drain water from underground to the overhead Open Cast Pit (OCP), showcasing his technical prowess and dedication to safety in mining operations.

He made significant contributions in the diamond core drilling industry in India by designing and developing the first Hydrostatic Diamond drill rigs through M/s KLR Industries of Hyderabad. By engaging in discussions on design innovations with international companies that supplied rigs to Indian users, he gained valuable insights. He then used this knowledge to guide and support Indian manufacturers, viz, Dynatech Industries Pvt Ltd, Hyderabad, in redesigning their rigs and enhancing their functionalities. Today's crop of drilling rigs being used in India by various drilling companies and being manufactured by various companies owe their design and success to the early experiments and developments by Shri Bansal.

Drawing from his previous experience in sand stowing in Birla mines, he offered his expertise as a master Drilling Engineer and solved many mining problems by facilitating sand stowing through large dia boreholes in ECL, BCCL, TISCO and IISCO mines and by paste filling process in HZL through large diadrillholes and very effective dewatering solutions in UG coal mines by installation of dewatering pipe ranges in deep boreholes.

Based on capability and technical prowess of

Mining Associates Project Meghdoot was launched by BCCL that involved drilling large dia borehole was drilled from surface through multiple seams and stagewise casings were lowered for dewatering of waterlogged underground working. On similar note Singareni Collieries Company Ltd invited Shri Bansal for complete installation of large diameter dewatering boreholes so that their underground mines which were being excavated by open cast method could be closed and dewatering could take place from surface. Very high capacity 500 to 1000 gpm pumps were installed at these large dia holes in SCCL so that water level could be controlled as per requirement from the surface itself and all underground operations could be totally avoided.

In 1989, Shri Bansal's bravery and technical skills were on full display during the historic rescue operation at ECL's Mahabir Colliery, Raniganj, where 65 out of 71 trapped miners were rescued. This operation was done in phases where a 8″ hole was first drilled through which communication was established and food and water could be supplied. Subsequently a large 24-inch diameter hole was drilled to rescue the trapped miners within just 60 hours. Throughout this arduous operation, Shri Bansal led his team, despite the fact that he suffering from fever until the last miner had come out of the mine.

In January 1994 a fire broke out in the workings of Dobrana seam at New Kenda Colliery. The fire occurred in the main intake airway close to the downcast shaft. Shri Bansal again helped out the mining industry by drilling holes overnight and then these holes were used to pump in liquid nitrogen gas and foam for extinguishing the fire.

MAPL's achievements under Shri Bansal's guidance include the 2013 acquisition of the Indian arm of Mitchell Drilling International Pty. Ltd., a leader in Coal Bed Methane (CBM) exploration. The company also expanded internationally through a joint venture with Oman's National Drilling and Services Company LLC (NDSCO), forming Transnational Drilling & Mining Associates Pvt. Ltd (TDMAPL) which is a major drilling service provider to HZL and also provides specialised directional drilling services in India for core drilling. This technology has considerably saved drilling costs in the exploration domain by drilling two or three lateral holes from one mother hole.

Shri Bansal will be remembered not only for his technical brilliance and leadership but also for his humanity, humility, and care for his colleagues. He was directly accessible and looked at his employees as his own children. He often extended financial help in times of urgent need. He was a mentor to many, leaving a legacy of excellence, innovation, and safety in India's mining and drilling sectors.

He is survived by his family, who remain dedicated to continuing his vision for MAPL. His visionary prudence is evident in the fact that currently the third generation (his grandson Shri Pratik Bansal, a Mining Engineer from IIT, Kharagpur) is at the helm of the company affairs under the able guidance of his father Bansal Sahab's son Shri Sanjay Bansal and his uncle Shri Rajesh Bansal.

Our deepest condolences are with them during this time of loss.

Rest in peace, Shri R. B. Bansal. Your legacy will endure, and your contributions will forever shape the industry you served so passionately.

118th Annual General Meeting

The 118th Annual General Meeting of MGMI was held on 21st September 2024 at 03.30 P.M. at Williamson Magor Hall, Bengal Chamber of Commerce & Industry, Royal Exchange Building, 6, Netaji Subhas Road, Kolkata. The meeting was chaired by Dr B Veera Reddy, President, MGMI. The office bearers and members, who joined the meeting are S/Shri Subrata Panigrahi, U S P Yadav, Tapas Kr Nag, Amalendu Sinha, Rajiw Lochan, Bhabesh Ch Sarakar, Subroto Choudhury, Debdas Roy, D K Mitra, Anindya Sinha, N C Jha, R P Ritolia, S P Banerjee, Suchandra Sinha, Pradip Kumar Thakur, Murari Prasad Roy, Bijon Kumar Saha, Asit Baran Bhol, Sumit Kumar Rai, A K Karmakar, Ranjit Datta, Prabir Kumar Mukhopadhyay, Hemant Agarwal, R K Dash, Prasanta Roy, Subrata Biswas, Debasish Chattopadhyay, MD Basiruddin SK, Shiba Kant Jha, Rajib Dey, Ligampally Sai Vinay, Samik Ghosh, Amit Sarkar, Ajit Singh Choudhary, Asheesh Kumar, P K Mandal, J P Goenka and Ranajit Talapatra.

The compere invited the dignitaries Dr B V Reddy, President, MGMI, Shri J P Goenka, Vice President, Ranajit Talapatra, Honorary Secretary and Dr P K Mandol, Honorary Treasurer, MGMI on the dais.

Shri Talapatra read out the names of the members who left for their heavenly abode during the last one year and 1 minute silence was observed for the departed souls of the following members:

Sudhir Bandopadhyay	Life Member - 6071
S.N. Ghosh	Life Member - 2609
(Dr.) Sunit Kumar Sarkar	Life Member - 3272
Er. Surendra Singh, FIE	Life Member – 2414
Ajit Das	Life Member – 3541
Aparesh Chandra Bagchi	Life Member – 8994
Tapodhir Bhattacharjee	Life Member - 6467
Sujoy Kumar Gupta	Life Member - 1734
Ardhendu Banerjee	Life Member - 6192
Asit Kumar Ghosal	Life Member – 8143
Biswanath Khan	Life Member - 7976

Welcoming the members present, he mentioned that the year was very good for MGMI in membership drive with increase of around 180 life members, in organization of a huge number of successful events in different parts of the country by MGMI and its chapters. In future there are plans to hold Foundation Day lecture, Holland Memorial lecture, which could not be held this year, and other seminars.

Next the Secretary proceeded with the agenda of the meeting as follows.

1. He read the Notice convening the 118th Annual General Meeting, which he said was already circulated by email earlier and in hard copy there in the hall.
2. The minutes of the 117th AGM held in Kolkata on 23/09/2023 was passed by voice vote.
3. The Council's report, Audited balance sheet and Statement of accounts for the year ending on 31/03/2024, circulated by email earlier and in hard copy there in the hall, were adopted by voice vote. Dr P K Mandol read out a short account of the income and expenditure incurred by MGMI during the last year.
4. M/s Jha & Co was reappointed the Institute's Auditor for the year 2023-24 with a remuneration of Rs of 15,000/-. The Secretary pointed out during registration, MGMI was originally documented as 'Mining, Geological & Metallurgical Institute of India'. But somehow in Income Tax documents and PAN card, the word 'The' has been prefixed to its name. This dual name has posed problems for the agencies handling online payments of MGMI. To avoid conflict, it was decided in Council Meeting to henceforth use the original name (without 'The') and the

Income Tax affair would be handled by the auditor. The proposal was approved by the members present.

5. Shri Dr B Veera Reddy, President, MGMI delivered the presidential address. Hard copies of the address were circulated to the members present in the hall. This was also his farewell address. He welcomed the members, award winners and their families and thanked the office bearers, especially Ranajit Talapatra and Prasanta Roy for their help during his tenure as President.

   Minerals, especially the energy minerals, form the backbone of key industries such as steel, cement, and electricity generation. The mining sector also generates employment, attracts foreign investment, and boosts export earnings. Overall, the exploitation of minerals and energy resources is essential for India's economic progress and self-reliance.

   He discussed the challenges and opportunities faced by mineral sector in India. Environmental concerns and pressure to meet global climate targets, energy security, and the moderate pace of renewable energy adoption are the challenges. Grid integration, storage solutions, and infrastructure upgrades are needed to fully harness the potential of renewable energy sources. Opportunities for growth are through the adoption of cleaner technologies and practices, such as renewable energy integration, carbon capture, and sustainable mining techniques. Coal India Limited is focusing on underground coal mining to optimize resource extraction, while ensuring safety and sustainable practices to fulfil India's increasing energy demands. Government policies encouraging green initiatives offer a path way to reducing emissions while supporting economic growth in the sector.

   MGMI has a solid foundation in technical expertise and extensive experience, which can play a pivotal role in ensuring the sustainability of the mineral energy sectors in India. For the foreseeable future, fossil fuels, particularly coal, will remain indispensable to the nation's energy needs. Mineral and coal sectors are evolving with in a set of limitations, and it is crucial for MGMI to emphasize the ongoing efforts of stake holders in overcoming challenges.

   Having dedicated forty years to the coal industry Dr Reddy firmly believed that the sustainability of our country's energy sector hinges significantly on the coal sector's contributions. It is imperative to appreciate this reality. MGMI should develop comprehensive recommendations to bolster the growth of the mining sector, addressing critical areas such as environmental clearances, land acquisition, resettlement and rehabilitation, ecological restoration, social impact, and a just transition for affected communities.

   He appreciated the membership growth, revitalization and activities of some chapters of MGMI, while some are relatively inactive. He suggested to reactivate the dormant branches / chapters. He acknowledged the successful execution of the 10th Asian Mining Congress and Exhibition organized by the Institute. The landmark event brought together mining professionals, entrepreneurs, researchers, and academics from across the region. The News Journal continues to receive commendation from its readership for its improved quality and informative content. He extended heartfelt congratulations to the Honorary Editor and the Editorial Board for their dedication. Dr Reddy offered his wholehearted support to the new team promising full cooperation, both as an active member and in his role as Past President to ensure collective success.

6. The secretary announced that Shri Jai Prakash Dwivedi would be the incoming President

of MGMI. Shri Dwivedi, in a virtual speech, thanked MGMI for selecting him and promised to work for advancement of the institute.

7. Next the report of the Board of Scrutineers on the Election of the Council Members for the years 2024-27 was presented by Shri J P Goenka, Chairman. He read out the names of 9 successful candidates, which are – Prof. Bhabesh Chandra Sarkar, Dr Murari Prasad Roy, Dr Hemant Agarwal, Dr Chandra Sekhar Singh, Prof. Khanindra Pathak, Prof Netai Chandra Dey, Shri Ajit Singh Choudhary, Shri Deb Kumar Kundu, and Dr Rabi Narayan Patra. He told that only 433 votes were cast in the online election out of 2213 voters. The Secretary pointed out that now the members' list is available in the website and MGMI repeatedly requested the members through mails, social media to update their particulars including mobile number and personal email, so that MGMI notices reach them.

8. The Secretary informed before the audience that in the last AGM held on 23rd September 2023 at Crystal Banquet of Taj City Centre, New Town, Kolkata (117th AGM) it was decided and approved that as the M&AoA of MGMI requires some modification / amendment considering changed scenario since last modifications, like e-voting and increased membership drive, a committee is to be formed to amend the M&AoA to include provisions of e-voting and to consider reviewing the membership qualification criteria hindering induction of new members from industry, among others. Accordingly a Committee was formed in the 904th Council Meeting held on 01st of September 2024. The Committee met on 4 occasions and deliberated on the issues. The 905th Council accepted the recommendations of the Committee related to e-voting and membership qualification and agreed to place it in the AGM. The proposal was presented in detail by Honorary Secretary on screen. There was a suggestion from one member that there should be a provision of paper voting for members who were not having e-mail id and not technologically savvy because of advance age and there should be a provision where paper ballots are also simultaneously considered. This idea was intensely contested with justifications. It was suggested that this issue may be noted and discussed in detail in the Council. The recommendations of the Committee set up to review the MoA for suggesting -- (i) modification in voting clauses like timeframe needed in e-voting process, (ii) qualification clauses for enlisting interested members working and associated with mining industry for long, but lacking requisite qualifications like engineering degree etc. was agreed to in the AGM.

9. Regarding the MGMI Awards of Excellence, Honorary Secretary also mentioned that as a few members of the Council felt that Geology and Metallurgy (being the founding streams of MGMI) should have Awards specifically given in those fields, a committee was formed in the 902nd Council Meeting to look into this and suggest changes if needed.

   The Committee met once and after discussion recommended to the Council that from next year, there will be 4 categories of MGMI Awards of Excellence in consonance with the name of the Institute, as follows:

   MGMI Award of Excellence for outstanding contribution in the Coal Mining Industry; MGMI Award of Excellence for outstanding contribution in Mining Industry other than Coal; MGMI Award of Excellence for outstanding contribution in any Branch of Earth Science. MGMI Award of Excellence-for outstanding contribution in the Metallurgical Industry;

   The Committee also recommended that the fifth award, which is the "The Best Technical Paper Award" to be selected from the papers published in MGMI Transactions for every Calendar Year may be suspended till the MGMI Transactions are published regularly every year.

Accordingly, the 904th Council had agreed and recommended that the changes may be put forward to the AGM for final approval. The recommendations were unanimously accepted in the AGM for being applied from next year onwards.

10. The recommendations of the Judging Committees for 3 MGMI awards and medals for 2023-24 were announced and presented to the recipients by the President. The Students' Awards for 2022-23 were announced and the awards were presented by the President
    a. MGMI Award of Excellence for Coal Mining for outstanding contribution in Coal awarded to Dr. Anindya Sinha, Professor of Practice, IIT(ISM), Dhanbad
    b. MGMI Award of Excellence for Non-Coal Mining for outstanding contribution in Mining other than Coal is awarded to Mr. K. Madhusudhana, Chief Executive Officer, MSPL Limited
    c. MGMI Award of Excellence for Earth Science/Mineral Engineering for outstanding contribution in Earth Science awarded to Dr Atul Kumar Varma, Professor (HAG) & Ex-HOD / Applied Geology, Coal Geology and Organic Petrology Lab., Dept. of Applied Geology, Indian Institute of Technology (Indian School of Mines), Dhanbad Student Awards for 2022-23
    d. Pickering Medal for the Best Student in B.Tech Final of Mining Engineering to Shri Suyash Ranjan of IIT (ISM), Dhanbad.
    e. Hayden Medal for the Best Student in M.Sc/M.Tech. in Applied Geology to Shri Suryasish Mozumder of IIT (ISM) Dhanbad.
    f. Yule Medal for the Best Student in B.Tech. Mining Machinery to Shri Vadranam Sai Krishna of IIT (ISM) Dhanbad.
    g. McNally Bharat Medal for the Best Student in B.Tech. Mineral Engineering to Ms Aditi Raj of IIT (ISM) Dhanbad.
    h. Dr. Hari Narain Medal for the Best Student in M.Sc (Tech.) Applied Geophysics to MsAnonya Das of IIT (ISM) Dhanbad andDr. Hari Narain Medal for the Best Student in M.Sc (Tech.) Applied Geophysics to MsAtanima Mondal of IIT (ISM) Dhanbad
    i. Oil India Medal for the Best Student in B.Tech. Petroleum Engineering to Shri Raj Prasar IIT (ISM) Dhanbad.
    j. Kalyan Mukherjee "61 Geology" Medal for M.Sc (Geology) 2022-23 to Shri Aplab Chatterjee of University of Calcutta.
    k. S Lal Award for Mining Engineering to Shri Samik Ghosh of IIEST, Shibpur
    l. Indranil Award for B.Tech. in Metallurgy to Ms Ananya Das of IIEST, Shibpur.
    m. SCCL Gold Medal for the Best Student in Mining Engineering to Miss Challa Gayathri of Kakatiya University.
    n. Nava Bharat Ferro Alloys Medal for Mining Machinery to Mr Kotoje Rakesh of Kakatiya University.
    o. Roberton Medal for Mining Engineering to Ms. Harshita Kumari of IIT(BHU).
    p. Hadfield Medal for Metallurgical Engineering to Ms Anushka Bhardwaj of BHU.
    q. La Touch Medal for Geology to Ms Anchal Arora of IIT (BHU).
    r. Smt. Nirja Sahay Medal for M.Sc in Applied Geology to Shri S. Gowtham of IIT(KGP).

11. The meeting concluded with presentation of a farewell bouquet to the outgoing President and Vote of Thanks by Ranajit Talapatra. He thanked the President, Jt. Secretary, Treasurer, Council Members, all the members who helped in MGMI activities and also the staff members of the Institute.


118th
ANNUAL GENERAL MEETING
OF
THE MINING, GEOLOGICAL AND METALLURGICAL INSTITUTE OF INDI
21st SEPTEMBER 2024
WILLIAMSON MAGOR HALL
BCC&I, ROYAL EXCHANGE BUILDING
KOLKATA
DR. B VEERA REDDY
PRESIDENT - MGMI
SHRI RANAJIT TALAPATRA
HONY. SECRETARY - MGMI

MINUTES OF THE 903RD MEETING OF THE COUNCIL

(Held through Hybrid mode in Physical and Virtual Platform through Zoom)

Date & Time : Saturday , 22nd June 2024 at 02.30 p.m.

The report of the **903rd Council Meeting** (3rd meeting of the 118th Session) at MGMI Building, GN-38/4, Sector – V, Saltlake, Kolkata – 700091 on **Saturday, 22nd June 2024 at 02.30 p.m.** (duly approved in the 904th Council Meeting held on 01st September 2024).

Present : Dr. B Veera Reddy, President in the Chair. The meeting was attended by S/Shri R P Ritolia, R.K.Saha, N C Jha, J P Goenka, Thomas Cherian (Virtual), Prasanta Roy, Dr. Chandra Shekhar Singh, V K Arora, Dr. Amalendu Sinha, Prof. Bhabesh Chandra Sarkar, Awadh Kishore Pandey (Virtual), Prof. G.P. Karmakar, N N Gautam (Virtual), J V Dattatreyulu (Virtual), Prof. (Dr.) Rajib Dey, T K Nag, Dr. J P Barnwal (Virtual) and Ranajit Talapatra.

ITEM No. 0 Opening of the Meeting

0.1 Sri Ranajit Talapatra, Honorary Secretary welcomed all members present physically as well as virtually and requested the President, who was present in person, to call the 'meeting to order' and address the council members.

0.2 The President welcomed all those present physically and virtually in the meeting and granted leave of absence to those who could not be present.

He informed about the recent activities that included the 19th Foundation Day lecture delivered by the CMD of DVC, which took place on 15th June 2024 in Sanctoria, helped by the Asansol Chapter and ECL. This event was attended by a large number of people and was a grand success, with Chairman, CIL and CMD, ECL present on this occasion along with senior officials of ECL, CIL, BCCL and DVC.

He also informed that the Asansol Chapter of MGMI has been revived, with Shri Niladri Rai, Director Technical, ECL, serving as the Chairman of the branch. Almost 40 memberships complete in all respects were received on that day. President thanked and congratulated Sri Niladri Roy for the membership drive and thanked him and CMD, ECL for being the host for the Lecture event.

He proposed one national conference in-Delhi with the Hon'ble Minister, Coal & Mines as Chief Guest sometime in August.

He thanked the Honorary Secretary, Honorary Joint Secretary & Immediate Past Honorary Secretary for actively helping in organising the 19th Foundation Day Lecture and making the program a success.

He also thanked Shri J P Goenka for successfully conducting the MGMI President Cup Golf Tournament, that was held at the RCGC on 24th April 2024.

He then requested Honorary Secretary to start with the agenda of the meeting.

Honorary Secretary thanked the President and proceeded with the meeting following the agenda items.

903.1.0 To confirm the Minutes of the 902nd meeting of the Council held in Hybrid platform at MGMI Hqs, Sector- V, Salt Lake, Kolkata on 27th April, 2024 at 3:00 P.M.

The minutes of the 902nd meeting of the Council had already been circulated earlier over mail to all Council Members and no comment was received on the same from any member.

Resolution : The Minutes of the 902nd meeting (2nd Meeting of the 118th Session) of the Council held on 27th April, 2024 at 03.00 P.M. be confirmed.

903.1.1 To consider matters arising out of the Minutes.

The Honorary Secretary read out the ATR (Action Taken Report) in respect of the Minutes of the 902nd Council meeting.

The Council considered the Action Taken Report in respect of the Minutes of 902nd Council Meeting held on 27th April, 2024 in Hybrid platform and concurred.

Honorary Secretary also informed about Asansol Chapter has been revived, with Shri Niladri Rai, Director Technical, serving as the Chairman of the branch. Additionally, he also mentioned that the Chapter has successfully forwarded over 40 life membership applications for approval in this Council meeting.

902.4.0 To consider and constitute a Board of Scrutineers to conduct the Election of Council Members for the period 2024 -27

Honorary Secretary informed the Council Members that C.S. had already contacted with CDSL who has agreed to conduct the Election & they are charging the same rate as that in 2022.

902.5.0 To consider applications for membership and membership position of the Institute

Honorary Secretary informed the Council members that the membership position as on 27.04.2024 as per the ATR of 902nd Council Meeting is 2306. The council agreed to all the 40 life membership applications and with these additions, the no of members stand at 2348.

902.6.0 Any other matter with the permission of the Chair.

Honorary Secretary had earlier informed the Council that there needs a parity in the name of the Institute.

Shri Prasanta Roy enquired about the status that was discussed in the earlier Council meeting regarding publication of MGMI Journal through Springer with reference to point no 902.1.1 of the 902nd Council Meeting. To this Honorary Secretary informed that he had requested Honorary Treasurer & Honorary Editor have taken up the work together along with Dr. Amalendu Sinha, Prof. Bhabesh Sarkar & others. It may be noted that both Honorary Treasurer & Honorary Editor were not present in the 903rd Council meeting.

Discussion took place & Honorary Secretary informed that if possible, he would arrange a meeting virtually or physically on 27th July 2024 at Dhanbad along with Honorary Editor & also for revival of Dhanbad Chapter taking into confidence of Chairman, BCCL.

903.2.0 To discuss about the forthcoming events of the Institute

i) Half Day National Seminar

Honorary Secretary informed that Dr. Rajib Dey had been unanimously selected Convenor during the last Council Meeting & requested him to inform the Council members of his proposal. To this Dr. Rajib Dey informed the Council that the name of the Seminar – "Augmentation of Metal Production- journey towards Green". He had informed that a skeleton framework has been made and key speakers will be there. To this President opined to make some changes in the name of the Half Day Seminar and expressed his views to hold a discussion on the same later. Prof Rajib Dey also opined that the subject line could be "Augmentation in Metal Production for journey towards green".

ii) 65th Holland Memorial Lecture on 21st Sept 2024 with AGM.

It was proposed to hold the Lecture along with the AGM. Honorary Secretary informed that Chairman, WBPCCB was agreeable for the Foundation Day Lecture but was changed due to his unavailability on the then proposed date of 16th January, and so he will be requested again for the Holland Memorial Lecture.

903.3.0 To consider and appoint a Judging Committee for MGMI Awards of Excellence.

The first meeting of the Committee was held to find out whether to have the same number of awards or to increase in number or decrease in number. During last time it was suggested by Shri Prasanta Roy that Geology & Metallurgy should be given more prominence & Review Committee of MGMI Award of Excellence was held prior to 903rd Council Meeting on the same date and it was decided during that meeting that there will be some changes in the Awards - there will be reduction in one award & another award will be added, the minutes had not been made yet. He suggested that names will be given as per the last Judging Committee. President expressed his view that the existing Committee should continue & whatever amendment is required will be placed in the AGM and the Modified M & AoA can be published mentioning the last amendment date.

The Council agreed to Secretary's proposal to go ahead with the present committee members for the different Judging Committee as per last year.

903.4.0 To consider applications for membership & the membership position of the Institute

Honorary Secretary informed the Council Members that this time there are 42 applicants – 40 for Life Members & 1 who has applied for LM but as he has only 2 years of work experience in Mining & Geology- he could not be a LM as per the rules laid down in the MoA/AoA of MGMI. There were two such cases and both applicants were asked about their choice & one of them has asked for refund of the money he had paid and accordingly the money would be refunded and the other one had agreed to become an Associate Member as of now and after 3 years, he will become a Life Member & the excess amount will be returned back. Thus the Total 42 bona fide applications received mainly from ECL, NLC, including 2 Associate members, were agreed to by the Council for induction as MGMI Members.

The details of the Membership are given below :

Membership Position
(As on 22.06.2024)

	27.04.2024	Add	Trans	Loss	22.06.2024
Member	**45**	**-**	**-**	**-**	**45**
Life Member	**191**	**40**	**-**	**-**	**2231**
Associate	**20**	**02**	**-**	**-**	**22**
Student Associate	**06**	**-**	**-**	**-**	**06**
Life Subscriber	**27**	**-**	**-**	**-**	**27**
Subscriber	**01**	**-**	**-**	**-**	**01**
Life Donor	**01**	**-**	**-**	**-**	**01**
Donor	**01**	**-**	**-**	**-**	**01**
Patron	**05**	**-**	**-**	**-**	**05**
Corporate	**07**	**-**	**-**	**-**	**07**
Life Corporate	**02**	**-**	**-**	**-**	**02**
	2306	**42**			**2348**

903.5.0 Any other matter with the permission of the Chair.

Dr. Barnwall appreciated a flawless meeting in Zoom was held and both offline and online meeting took place effectively.

Honorary Secretary informed the Council that he has no points to discuss in hand and requested the President to give a formal address & conclude the meeting.

The President asked Shri Prasanta Roy, who was earlier chosen as the Convener, that regarding National Conference which was proposed to be held at New Delhi, whether he has finalised a topic for that

Shri Prasanta Roy named the topic – Challenges & Opportunities in mineral sector. It would be a one-day seminar and the technical sessions would be held on three topics –

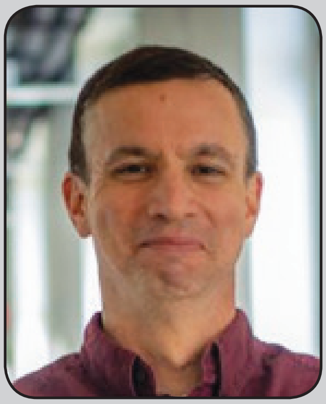
- ❖ Challenges & Opportunities in Coal Mining
- ❖ Challenges & Opportunities in Non-Coal Mining
- ❖ Challenges & Opportunities in Critical Mineral.

There was a committee formed with the Council Members along with members of Delhi & Kolkata chapters comprising Shri N C Jha, Shri U. Kumar, Shri N N Gautam. The date was to be finalised.

The President concluded the 903rd Council Meeting thanking all those present.

The meeting ended with Vote of Thanks to the Chair and others present both physically and virtually by the President and Honorary Secretary.

CATALYZING A SUSTAINABLE FUTURE



For this issue of MGMI News Journal, we caught up with Professor William S Epling. Currently, he holds the Ann Warrick Lacy Distinguished Professorship and is the Department Chair of Chemical Engineering at the University of Virginia. His prior appointments have been at two universities (University of Waterloo, University of Houston), two companies (Emera Chem and Cummins) and the Pacific Northwest National Laboratory. His research has been extensively funded by the U.S. National Science Foundation and the Department of Energy, Canada's Natural Sciences and Engineering Research Council, along with support from the private sector. Professor Epling has co-authored over 150 peer-reviewed articles with more than 12,000 citations on environmental catalysis. He holds a BS in Chemical Engineering from Virginia Polytechnic Institute and State University, and a PhD in Chemical Engineering from the University of Florida.

Could you describe your career trajectory across industry, research labs and academia?

I graduated with bachelor's and a PhD in chemical engineering. Then, I went and did a postdoc at the Pacific Northwest National Laboratory studying ultra-high vacuum surface science of catalysts. The project was looking at radioactive materials in waste storage tanks from the days of the bomb (from the Manhattan project) and making the bomb parts. So, I did photocatalysis, where the theory was if something was activated via a photocatalytic route, then it would probably be activated via radio-catalytic route. So, you could take the catalyst and dump it in a tank, and it would decompose some of the materials in there to reduce the volume of the radioactive material that they had to dispose of. I did this for about a year and soon recognized that ultra vacuum surface science was really expensive and good for national labs, but may be not good for people outside of national labs.

After this, I went and worked for a catalyst company that was making catalysts to clean up carbon monoxide and nitrogen oxides from natural gas power plants. There, we were trying to break into the transportation market with these catalysts we had, which were pretty novel. And so, Cummins, the engine company, contracted me out from that company to move there to help them build reactors to test transportation style catalysts for diesel engines. And then they ended up hiring me away from that company. I worked there for a couple of years. I make a joke - but I think it's actually kind of true - I recognized the fact that I didn't like working for people. So, I figured academics was the way to go.

I'd always planned on going back to academia. I just planned on waiting a little bit longer than I did, but decided to go back, and so I joined the faculty of the University of Waterloo, up in Ontario. It was close to Detroit, which gave me a lot of opportunity to work with the with the car companies.

Canada is very cold, so I moved to the University of Houston. After a while Houston felt very hot, so I moved to the University of Virginia which is a nice middle spot in terms of temperature and climate. Here, I've been Chair of the chemical engineering department for the last eight years.

How does serving as Department Chair differ from a regular faculty position?

As a professor, you are still dealing with a lot of interpersonal dynamics when you're running a research group. And that is probably true for any job. But I think as chair, you just have to be more aware of the people around you. I am not saying you don't with your grad students, but you interact with them so much more every day in the lab, every day working with them and helping their training. As Chair, I am not trying to train my colleagues, rather I am trying to be the liaison between the Dean and the department and so it's tricky to try to navigate all these different personalities, all the different things going on above you and below you. I am looking forward to next summer when I am not chair and can just go back to research and teaching and not have to think about administration!

What role does catalysis play in designing processes and systems of interest in the industry? Would you be able to provide any examples that we see in the industry or our day-to-day lives?

I haven't looked at the data very recently, but it used to be that you could find numbers anywhere between 75 and 90% of all the products we buy and/or use have a catalyst somewhere in the process. If you think of pharmaceuticals, they use catalysis regularly in making drugs. We wouldn't normally think about pharma as a catalysis pathway. But then, going to the more traditional things is, the gasoline that you use in your car is processed through a variety of catalytic routes to get there. The most common example by far, the highest volume catalyst made is the catalytic converter, because it is on every car globally, and something that everybody would recognize as a catalyst. It is that little piece of equipment that's underneath the car cleaning the exhaust gas. It's probably recognized as one of the technologies that saves more lives than anything else out there.

Would you say catalysis has inherently made things more sustainable, or does there need to be extra tailoring on conventional catalysts to make them more sustainable?

Typically, yes, you need extra tailoring. For example, there's a lot of people studying catalysis in Academia. If I take the summation of the papers in the various journals that have catalysis-related articles, it would be a large number. But a new catalyst that is going to make it into industry globally is probably once a year, out of the thousands of papers. Part of it is when we do these studies, we study them in the lab under very idealized conditions, and the catalyst works for the minute that we study it. But for the catalyst to last a long time, to not make all the byproducts, to be efficient in what it does, to actually handle the real feed that is coming in, is more nuanced. It is hard to think about all those things when you're down in a lab as you have limited resources. But the sustainability aspect for a catalyst, to make it last, and to make sure that you don't make byproducts is critical for the industry. When you think about the Principles of Green Chemistry, one of the rules is use every atom. From a catalytic standpoint, it is imperative to lower the energy needed, to make as many of the products as you can, and generate less byproducts through selectivity changes.

Chemical engineers have seen refineries as a big employer over the last several decades. If refinery capacity begins to reduce as the world moves away from fossil fuels, what alternatives would be likely to emerge?

If you go back some number of years or even decades, oil and gas refineries were the bread and butter in terms of money making. The fluidized catalytic cracker was deemed the moneymaker of the chemical engineering industry some decades back. But that is historically so. Refineries don't actually hire chemical engineers that frequently anymore. And part of it is, they are very automated, and people like working there, so don't leave. There hasn't been a new refinery built in the United

States, I think, since the 1970s. At one point, there were ~170 refineries, and there are only ~130 running now. Even as the refineries have expanded, and become more efficient, the employment opportunities at such places have done nothing but decline for many, many years.

Where has the transition gone? By the late eighties, it was the materials revolution. Intel came in and hired more chemical engineers than Exxon did as an example. Electrical engineers could make a new chip, chemical engineers could make a million chips by incorporating all of the reactions and separations that go on. In the last decade or so, the transition has been into the bio area. We have more of our students going into biopharma than we do into oil and gas or chemicals. There's a lot of interesting technologies being developed. and the biopharma areas had the growth over the last several years.

Now, where are they going to go is tougher to predict. When I think about the big things that chemical engineers could be working on, climate change is a big opportunity. I don't quite understand why I am not seeing more in the United States on dedicated jobs committed towards mitigating climate change. There are some avenues there, but they are not as well highlighted or advertised. I am hoping that's a growth area.

Another important area is likely going to be artificial intelligence (AI) and machine learning for chemical engineers. We are building these classes into our curricula because all of our employers are demanding it. Employers could either hire computer scientists and try to teach them chemical engineering, or they hire a chemical engineer to try to teach them coding. At least in my network, because I am in chemical engineering, they prefer the latter.

Looking into the crystal ball, do you foresee a role for fossil fuels in the decades to come?

While I think that there is going to be a significant reduction in the use of fossil fuels for transportation and for power generation, we will still see fossil fuels remain in our economy.

When I think about the transportation sector, particularly in light-duty vehicles, I think fuel cells and electric vehicles are going to take over sooner or later. But heavier duty sectors like trucks, freight and marine transport would likely remain constant in North America and actually increase globally. Part of that is just the benefits enjoyed by a growing middle class in the growing economies. When we think about the Amazons and the Alibabas of the world, or whoever else it is, they have to be able to deliver their goods. That is not likely going to come from a battery powered semi-truck. Thus, I think fossil fuels are here for a while until some kind of breakthrough technologies occur on the moving freight side of things. I think aviation stands a chance right of going to biofuels from sustainable aviation fuels. But the volumes are so high that aviation would then take all of the biomass that we have in order to transition.

In the chemical production sector, most plastics and chemicals originate from fossil fuels as well. It is hard to imagine that we could transform all of this production from fossil fuels to biomass because of the volumes of consumption.

In your view, what stands in the way of scaling up of commercial-scale CO_2 capture and storage?

Primarily costs remain the biggest deterrent. I say this in class all the time - we have all the technologies we need today to cap our temperature rise but it will cost us a lot. There's an investment to make this happen that is massive. In the United States alone, it is in terms of trillions of dollars. Another aspect is that of scale. The scale is just so massive. Whether in terms of solar panels, or wind turbines or CCS infrastructure, we would have to be building plant after plant today.

There is also a behavioral dimension to this. Say if CCS were to be adopted, an individual household's electricity bill would go up by 30%. Nobody wants to pay 30% more for their electric bill! People think, "I am entitled to cheap electricity. I am entitled to cheap power. I am entitled to cheap fuel". As individuals, we feel entitled to these prices and not having to pay for the future damages.

For the longest time, there weren't as many who were thinking about climate mitigation. I would say that climate change is much more at the forefront of the minds for the current generation. So, I think there is a possibility that real change can happen at an accelerated time scale. But I am also worried about a sense of apathy because it is just too late. And if it is too late (including as per IPCC projections), we would need to rely on negative emissions, which for one of the more news-making ones, the direct air capture approach, it seems to be antithesis of engineering as it is completely economically and energy inefficient, making no money.

Industries and governments are making a big push towards green hydrogen. Do you see green hydrogen as a realistic way forward?

If we want to produce large amounts of green hydrogen, that would mean having a lot of electrolysis capacity in conjunction with a lot of clean energy to split water. If there is such a large amount of clean energy, the question becomes if hydrogen is the best available option to use it? My colleague, Professor Bob Davis has summarized it nicely. If we have this energy, these free electrons, it could be used to power my building or a chemical plant, or displace a coal-fired power plant. It could be used to make ammonia or fertilizers. It could be used to make hydrogen as a chemical precursor or as an energy source for a gas turbine to mix in with natural gas. In places like the Southwestern United States, where there is an excess of solar at certain times of the year, it could be used for direct air capture. But it could also be used to make hydrogen to do things. Out of all of these pathways, which one makes the most sense?

I think that there are places where energy should be used before making green hydrogen, depending on how that green hydrogen is goingto be used. But I do ultimately think that we will get to a place where green hydrogen makes sense. That would probably take a path via many things in between that make more sense for the energy instead of making hydrogen. But once we have enough renewables, I think hydrogen is definitely a pathway that we will use for energy. In the meantime, we should be thinking about using it for more direct things like power generation.

In the Global South, we are seeing a push towards production of chemicals from coal/biomass to reduce import dependence. What research gaps come to mind in this area?

I think there have been a lot of technologies that have been developed to address the research gaps for using biomass to derive chemicals. One key issue is that this pathway involves a lot of waste generation. If we could figure out how to use those byproducts or reduce the waste, I think those are where many of the gaps would be. Another issue is that biomass is heterogeneous. If we had a nice homogeneous source, then I could develop a technology that would give me great efficiencies and product yields. But biomass is heterogeneous. If you come up with ways that either use byproducts or have more than one product coming out, that would be ideal to maximize the resource.

Coal to chemicals is a tough one because of the carbon intensity. Also, you would need to source hydrogen from somewhere else. At the same time, coal is so abundant that it is hard to ignore as a potential resource. I think coal-to-chemicals makes more sense than continuous coal for power generation that entails continuous CO_2 emissions. If you could take the carbon from coal, and that carbon is used in some kind of product to make plastics, it could definitely be valuable.

In the Indian context, we often see air pollution as the biggest environmental/social challenge. What lessons can be learnt from North America to reduce criteria air pollutants, either in terms of technology or policy?

I think the best example is that of the Los Angeles Basin with the mountains on one side and the ocean on the other. During the day you could have a buildup of things, which would then be swept away in the evenings. So, you could see very dramatic differences in concentrations of gases as a function of time during a 24-hour period. When it became possible to monitor these dynamics, see the visuals of the smog, the science that was coming out in terms of human health, and the impacts these pollutants were having on human health, it made a real impact. Plenty of anecdotal evidence was out there on particulate matter but studies confirmed these impacts with dilute streams in urban settings. All this translated into a social push to make it happen. Again, going to the example of a catalytic converter in a car, it does nothing to make your car run better in terms of engine performance. As a matter of fact, it technically hurts your fuel economy because of the way it wants to run. The car companies have to put it on there because emissions are regulated by the government. You have to meet these mandates or regulations in terms of the emissions. These regulations, in turn, came about because there was social pressure around cleaner air and human health.

The lesson learned, specifically in terms of air pollution, was that it took a social uprising of some sort, driven by knowledge and people becoming aware of the impacts on their health. Until people think about it, they are not going do anything about it and influence governments to make change. I think that is what really worked in the past at a local level or at a community level, to push on community leaders who then pushed above and above to the State and to the Federal Governments. How does that happen in the global South? I don't know necessarily because it is a very different set of social dynamics. But I think it starts locally and then the push just gets too much for the top to ignore.

How can the gap between basic science, applied research and industrial deployment of clean technologies be bridged?

This is one of the toughest things out there. It is called the Valley of Death. There are the things that go on a lab and then there is the application we put into practice. But what about the middle. This is where most technologies are locked. I think that more diversity in academia has occurred in the last several years that has led to more and more interactions with the industry. Yes, we are still called the Ivory Tower. A lot of us still do very fundamental research that most people would never understand how it is going to be translated into practice. However, fundamental research is so critical for us to be learning things. And from that fundamental research, usable ideas emerge. On the academic side, we are seeing more interactions with industry than we probably did a couple of decades ago. I am also seeing a lot of graduate students who want to come in and they want to do an internship while they are in grad school. They want to go see what it is like to be doing research in industry. As such, I think there are more bridges happening. However, to actual using it, I still think little has changed. I still think it is the same success rates. We are just learning more and more about what to think about.

What would your advice be to young scientists and engineers who are interested in pursuing careers in energy and sustainability?

I would remind them that they have spent a lot of time, energy and resources to get where they are today. So, I encourage them to do things that they enjoy doing. I think there is too much emphasis on finding a career that is going to change the world. That is great because it gives you a nice sense of satisfaction - I understand that. But I also think there is a lot of value in finding people you want to work with. I think there was a time during my career that I would have truly been happier getting paid less working with people who are fun to work with than being an engineer (though that was a different instance in time). My point is that finding a team you want to work with, that you enjoy working with, on a problem that you think is important is really what is important. It doesn't have to be a world-changing problem. If I come up with a catalyst that operates 10 degrees cooler, it will save the company a significant amount of money. It also conserves energy, leading to reduced CO_2 emissions. I am not asking you to focus on trivial things just that some of the things you work on don't have to be world-changing. Incremental changes are still needed. And they're way more important than some people give them credit for. I enjoy trouble shooting in my lab, some people enjoy calculus, others enjoy coding. You know everybody has their different things that they enjoy. Hopefully, you can find a place on a team where you get to continue to use skills that you enjoy using working with people you want to work with and working on a problem that you understand means something to somebody. Don't hyper focus on too big of things and too small of things. We tend to do both!

PERSPECTIVE PIECE

ROLE OF CARBON CAPTURE, UTILIZATION, AND STORAGE IN INDIA'S CLIMATE POLICY

Omkar S Patange[1] and Amit Garg[2]

Abstract

India has a rapidly growing economy with a coal-dominant energy system. Its global commitment to net-zero emissions by 2070 and national priorities for sustainable development present a challenge for climate and economic policies. At present, electricity generation, steel, cement, and other fossil-fuel dependent sectors have limited commercially viable and affordable options available for their decarbonization. To deal with these 'difficult to decarbonize' sectors, global and national scenarios aiming for net-zero emissions often rely on carbon capture, utilization, and storage (CCUS) technologies for abatement and removal of CO_2 from the energy systems. Here, we evaluate the role of CCUS in India's climate policy by understanding the projected demand for these technologies in net-zero scenarios, the technological alternatives in the context of India and international and national policies available for their deployment. The Paris agreement, through Article 6, enables parties to use voluntary cooperation for carbon trading to meet national climate goals. India also recently notified a list of mitigation and carbon removal activities (CCUS) that could be implemented under carbon credits mechanism of Articles 6.2 and 6.4 of the Paris agreement. Further, the establishment of carbon markets in India would pave the way for innovations and financing of upcoming CCUS technologies. We conclude with a recommendation to integrate the upcoming Indian Carbon Market (ICM) with relevant policies in energy and industrial sectors to promote experimentation, research, and commercialization of selected CCUS technologies, based on projected demands in net-zero scenarios. The early experimentation and deployment would also help in testing the multidimensional feasibility of these technologies and build socio-political acceptance for techno-economically viable alternatives.

Introduction

India is the fastest growing, large emerging economy, home to 17% of the world population, and has witnessed an economic growth rate of around 6% in the past three decades (World Bank, 2020). However, India's per capita income (measured as gross domestic product in terms of purchasing power parity) is still one-third as compared to the world average (World Bank, 2020). In terms of energy profile, around 17% of world's population consumes just 6% of the world's primary energy, 800 million people lack reliable access to modern cooking fuels, and the access to electricity is still unreliable in many rural areas (Sankhyayan & Dasgupta, 2019). Although, energy demand in India is expected to double by 2040 to become a quarter of the global demand, its per-capita energy consumption may remain 40% below the world average (IEA, 2019). The primary source of fuel for electricity is coal which is abundantly available in India. Coal production has grown an annual rate of 3.8% in the past decade and is expected to increase further to meet the rising energy demand (MoEFCC, 2023). Due to its dependence on coal and other fossil

[1]Economic Frontiers Program, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria
[2]Public Systems Group, Indian Institute of Management Ahmedabad (IIMA), Vastrapur, Ahmedabad, India

fuels, greenhouse gas (GHG) emissions from India have doubled to around 3.1 $GtCO_2e$ in 2019 as compared to their 2000 levels (MoEFCC, 2023). These emissions are projected to reach 4.6 to 5 $GtCO_2e$ per year by 2050 in a medium to high economic growth current policy scenario (Garg *et al., 2024).*

As a coal-dependent, fast growing, major economy, India's emissions trajectory is important for the global goal of net-zero energy systems. As a signatory to the Paris agreement, India has commitment to reach net-zero emissions by 2070. As part of the nationally determined contributions (NDCs), government of India has pledged to reduce the emissions intensity of its economy by 45% by 2030 as compared to the 2005 levels (MoEFCC, 2023). At the same time, India also wants to achieve affordable housing, health and education, clean energy and water access, food security and a better standard of living for all its citizens in the near future as outlined in United Nations' sustainable development goals (SDGs) (UN, 2015). The NDCs committed by India, endeavor to strike a balance between the development and climate goals. However, achieving 'net-zero' emissions in the latter half of this century, primarily from a fossil-fuel dependent electricity sector, pose additional challenges to balance the global climate targets and domestic development goals.

As the extant literature suggests, one of the biggest hurdles in reaching net-zero emissions from energy systems are the 'difficult to decarbonize' sectors. These sectors include energy intensive industries like steel and cement, long distance transport, aviation and reliable electricity generation (Davis *et al., 2018*). They are considered as 'difficult to decarbonize' due to the lack of commercially viable cleaner fuels and technologies that can affordably replace the fossil fuels currently used in these sectors. In this context, India's electricity generation, steel, cement, and other energy-intensive sectors are also dependent on fossil fuels with limited commercially viable and affordable options available at present for their decarbonization. To deal with these 'difficult to decarbonize' sectors, scenarios aiming for net-zero emissions often rely on carbon capture, utilization, and storage (CCUS) along with carbon dioxide removal (CDR) through technologies like bioenergy with carbon capture and storage (BECCS) and afforestation/reforestation (AR) to meet the climate goals (IPCC, 2018). An extension of CCUS, CDRs are defined as human efforts to remove carbon dioxide (CO_2) directly from the atmosphere (negative emissions), either through the enhancement of natural carbon sinks or by way of chemical engineering to reduce atmospheric CO_2 (Fuss et al., 2018; IPCC, 2022). The term "net-zero" is used to indicate zero emissions, achieved after accounting for the negative emissions from CDRs. The mainstreaming of CDRs in climate mitigation discussions has started only recently with integrated assessment models (IAMs) banking on negative emissions from BECCS and AR to achieve the below 2^{o}C pathways (Fuss et al., 2018; Minx et al., 2018). The role of CDRs was first summarized in the Intergovernmental Panel for Climate Change (IPCC)'s 4th assessment (AR4) followed by AR5 highlighting the importance of negative emissions in achieving the 2^{o}C goals. In the latest assessments (1.5^{o}C Special Report and the AR6), pathwaysthat restrict the global temperature rise to 1.5^{o}C by the end of this century rely on CDRs in the range of 150-1200 Gt-CO_2 (IPCC, 2018, 2022).

Recent research in India has also highlighted the need to explore carbon capture, utilization, and storage (CCUS) and carbon dioxide removal (CDR) technologies to decarbonize the energy sector and attain net-zero emissions (Garg *et al., 2017;* Patange *et al., 2022*; Singh *et al., 2024*; Vishal, Chandra, *et al., 2021)*. In this paper, we assess the role of CCUS and CDR in India's climate policies.

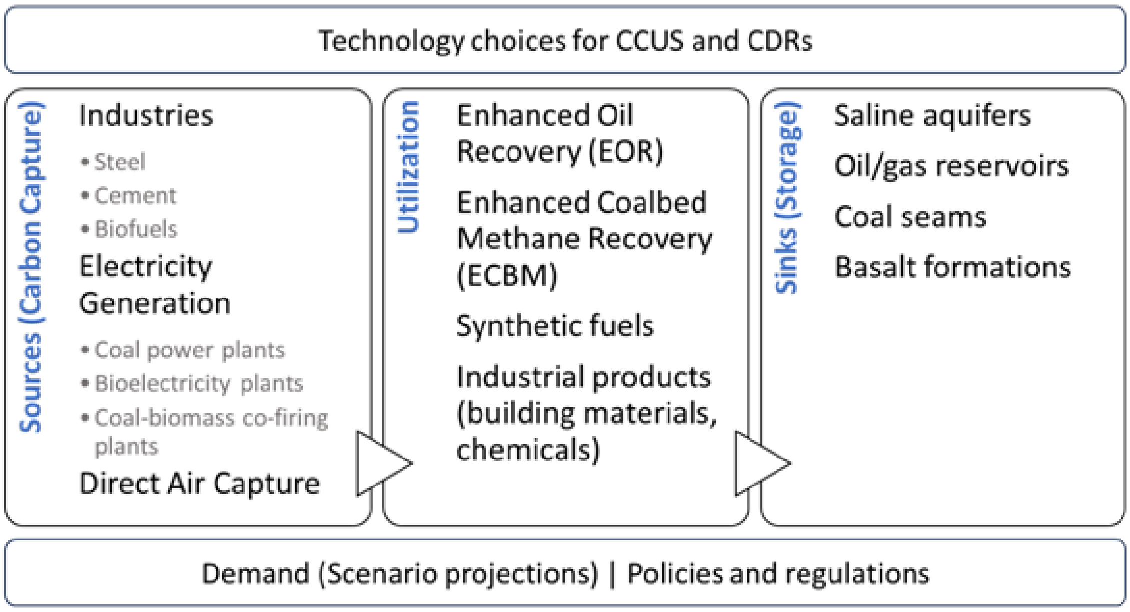


Figure 1 : Key elements to evaluate the role of CCUS in climate policy.

As illustrated in figure 1, we evaluate the role of CCUS and CDR technologies based on three key factors. First, the projected demand for these technologies in the near and long-term, second, the availability and feasibility of carbon capture, utilization, and storage technologies with possibility for carbon dioxide removal in the Indian context, and third, the policies and regulations to support and scale up these technologies to meet the projected demand for CCUS and CDR. By examining these three factors, we endeavor to inform the policy discussions on the deployment of CCUS and CDR technologies in India.

Carbon dioxide removal in global and national scenarios

According to the latest IPCC assessment, between 1850 and 2019, a total of 2390 (±240) $GtCO_2$ of anthropogenic emissions were emitted. This has resulted in a global temperature rise ranging between 0.8 to 1.3°C. The remaining carbon budget to restrict the temperature rise between 1.5 to 2°C with more than 50 per cent likelihood is estimated to range between 300 $GtCO_2$ (1.5°C, 83% likelihood) and 1350 $GtCO_2$ (2°C, 50% likelihood) (IPCC, 2022). This remaining budget is reducing at the rate of 40-50 Gt-CO_2 per year, as suggested by the recent trends (Crippa *et al., 2020;* Olivier & Peters, 2020). The long term climate goals require total CO_2 emissions from fossil fuel combustion to reach zero between 2045 to 2065 (IPCC, 2018) and the transition of energy systems towards 'net-zero' emissions is an important step to meet these climate goals.

In climate policy literature, systems modelling is often employed to study various baseline and alternate policy scenarios to meet the integrated goals of climate, environment, and economic development. In the context of climate policy analysis, scenarios are tools that help in the development of alternative images of an uncertain future and to evaluate the energy system transitions and resultant emissions in an internally consistent manner (IPCC, 2000; Mietzner & Reger, 2005; O'Neill & Nakicenovic, 2008). Climate scenarios from integrated assessment models (IAMs) are periodically compared and analyzed in IPCC's assessment reports. The latest, sixth assessment report (AR6) on climate change mitigation, published in 2022, includes global emissions projections along with deployment of mitigation technologies like renewables, CCUS, and CDRs to meet the net-zero targets. In IPCC 2022 assessment of the modelled mitigation pathways, scenarios that limit global warming to 1.5 °C (>50% probability) with no or limited overshoot, result in cumulative net emissionsin the range of 330–710 $GtCO_2$. In these pathways, the remaining fossil fuels (coal, oil, and gas) in the energy systems are either phased out or abated using CCUS. Further,during 2020-2100,the global cumulative net negative emissions from CDR technologies are projected to be 20-660 $GtCO_2$ (IPCC, 2022). However, the current implementation of CDR stands at 2.2 $GtCO_2$/year, 99.9% of which is through conventional routes like afforestation/reforestation (S. Smith *et al., 2024).* Although afforestation/reforestation is an established methods for CO_2 removal, its negative emissions potential is constrained by the limited and temporary capacity of sequestering carbon in the above ground biomass (EASAC, 2018; Lal, 2004; Minx *et al., 2018*; P. Smith, 2016). In addition, evidence suggests that as temperatures rise, the ability of forests to sequester carbon reduces (Lal, 2004). Emerging CDR technologies like bioenergy with CCS and direct air capture account for 1.3 Mt Co_2/yr and less than half of this is currently stored in geological reserves (S. Smith et al., 2024). Although these emerging CDR technologies are growing rapidly, they also face implementation challenges due to technology risks, costs, and scaling issues (IPCC, 2022).

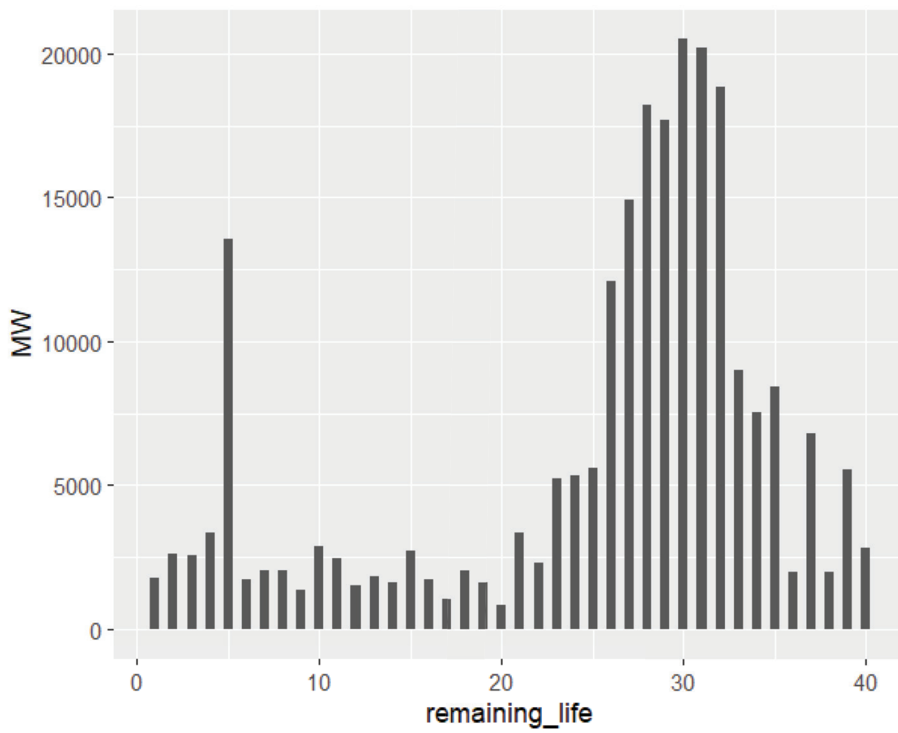


Figure 2 : Age structure of Indian coal power plants as of July 2024 (Source: Authors 'illustration based on Global Coal Plant Tracker, Global Energy Monitor, July 2024 release)

In the Indian context, a recent modelling assessment of mitigation scenarios to achieve net-zero emissions by 2070 considers different technology options like nuclear, renewables and fossil fuels with CCUS. In the pathway that relies on CCUS, capacity of coal plants with CCUS reaches 207 GW by 2070 (Garg *et al., 2024).* Recent research also projects the demand of 400–800 Mt-CO_2/year by 2050 for India to meet its share of the 1.5°C carbon budget (Singh *et al., 2024).* Another study analyzing the net-zero scenarios for India found that the share of fossil fuels in primary energy mix declines to 5.5% by 2070 without CCUS but remains in the range of 19-30% with the deployment of CCUS technologies (Chaturvedi & Malyan, 2022). Given the nascent stage of CCUS deployment at present, these net-zero scenarios would require rapid deployment and scaling up of CCUS infrastructure in the country. In addition, majority of India's coal power plants are young with about 70% of total capacity installed after 2010 (Figure 2). Around 8 GW of new capacity has become operational in past two years after the announcement of the net-zero target by India which highlights the government's commitment to energy security and affordable electricity with reliance on coal-based generation. With India's NDCs and climate mitigation targets, the younger fleet of coal plants without CCUS face the risk of becoming stranded assets after 2050 in the net-zero scenarios (Garg *et al., 2024)*.

CCUS and CDR technologies

As Figure 1 illustrates, the available technologies for CCUS and CDR can be categorized as sources for carbon capture, utilization, and sinks for permanent storage of captured CO_2. Carbon Capture, Utilization and Storage (CCUS) is broadly defined as industrial CO_2 removal through carbon capture, compression, transportation, utilization and storage in geological storage sites (Berend et al., 2014). As illustrated in figure 2, a large potential source for CO_2 in the future will be coal power plants. Another major source of CO_2 with potential for negative emissions is bioenergy with carbon capture and storage (BECCS). The technology involves burning of biomass in standalone or coal power plants (co-firing), to produce electricity and then use the CCS process to capture and store the CO_2 produced during the biomass combustion in geological reserves (Minx *et al., 2018)*. Biomass fuel is different from fossil fuels in the sense that CO_2 released from biomass combustion can be completely offset by capture of the same amount of CO_2 by growing new biomass in the given period. Therefore, if we capture the CO_2 released from burning of biomass through a technical intervention such as CCS, it will result in net removal of CO_2 from the atmosphere. The rising demand for steel and cement for housing and infrastructure also make these industries a major source of carbon capture in the future. When compared to coal power plants, flue gases from industrial processes for steel and cement production are a concentrated source of CO_2 (Pilorgé *et al., 2020)*. Further, biofuels processes like ethanol fermentation offer the purest stream of CO_2 and may become an important source of carbon capture following the biofuels policy in India (MoPNG, 2018). The biofuel production using renewable biomass feedstock also open avenues for CDR through BECCS. In addition, direct air carbon capture and storage (DACCS) is another potential source of CO_2 with abundant potential but high cost and energy penalty. DACCS is still in the research and development phase with many government and commercial parties trying to explore its commercial potential for future deployment (IPCC, 2022; Sutherland, 2019).

The captured carbon through different routes may be utilized for enhanced oil and gas extraction, synthetic fuel production or for various industrial purposes. In some cases, such as enhanced oil recovery (EOR), CO_2 is first utilized for oil recovery and then stored permanently in the oil wells constituting CCUS. If the source of CO_2 is atmospheric, like renewable biomass from energy plantations, this may also result in CDR. In other cases, like using CO_2 for producing building materials, the utilized CO_2 may not be stored permanently in the materials and would be considered as CCU. With emerging demand for carbon-neutral alternate fuels and materials, CCU can become a key route in India's climate policy (Singh et al., 2024; Vishal, Chandra, *et al., 2021)*.

In terms of storage potential, there are different estimates with a lot of uncertainty in case of India. According to Viebahn *et al. (2014)*, the high, intermediate, and low-quality storage potential estimates are 143, 63 and 45 Gt-CO_2 divided among saline aquifers, relinquished oil wells and coal mines. However, based on expert consultations, the potential in coal mines (also with the alternative for coal bed methane recovery) will not be available for the next 10-20 years. Earlier studies have estimated the storage potential in the range of 572 to 105 Gt-CO_2 (Dooley *et al., 2005*; Singh, 2013). According to another study, the good quality potential lies between 47-48 Gt-CO_2 (Holloway *et al., 2009)*. The most recent assessment for India estimates a total potential of 395-614 Gt-CO_2 (Vishal, Verma, *et al., 2021)*. This wide range of estimates needs further evaluation and site-specific studies to ascertain the realistic potential of CO_2 storage in India.

International and national policies supporting the deployment of CCUS

Article 6 of the Paris agreement enable countries to establish voluntary cooperation in implementation of their NDCs . This voluntary cooperation includes (1) use of Internationally transferred mitigation outcomes (ITMOs), a market provision to trade carbon credits among countries (Article 6.2), (2) mechanisms to contribute to GHG mitigation and support sustainable development (Article 6.4) and, (3) non-market approaches (Article 6.8). Section 6.4 of the agreement also sets out the rules and procedures for Carbon Crediting Mechanism . These procedures include activity design for emissions reduction in host parties and to set baselines to demonstrate additionality, ensure accurate monitoring and calculate emission reductions achieved by the activity. The selected activity is then followed by development of mechanism methodology, approval, and authorization of the activity by a Supervisory Body, validation, registration, monitoring, verification, and certification. Public and private entities with surplus potential for emissions reduction and negative emissions through CCUS and CDR activities may consider using the Carbon Credit Mechanism for registering these projects and earn carbon credits from the international voluntary carbon markets.

At a national level, government of India has notified a list of activities that will be considered for trading of carbon credits under the voluntary cooperation as part of Article 6.2 and 6.4 of the Paris agreement. These include mitigation activities like green hydrogen, compressed biogas, sustainable aviation fuels and energy efficient technologies for difficult to decarbonize sectors. These mitigation activities offer scope for experimenting with innovative CCU technologies. In addition, CCUS is included as part of removal activities and may be explored for CDR projects in the future. Further, the Bureau of Energy Efficiency (BEE) recently announced the establishment of Indian Carbon Market (ICM) framework to promote carbon trading under compliance and voluntary mechanisms. The regulatory framework for ICM was incorporated in the Energy Conservation (Amendment) Act 2022. On the lines of BEE's Perform, Achieve and Trade (PAT) scheme, government will set emissions targets for large industrial entities (a.k.a. obligated entities) from selected sectors. These obligated entities will have to comply to certain GHG emissions intensities and will be issued carbon credit certificates (CCC) for emissions reduction beyond the set target in a compliance year. On the other hand, obligated entities not meeting their emissions intensity target can purchase the CCCs to meet their compliance targets. Similarly, non-obligated entities can register their projects under the voluntary mechanism. Projects on CCUS and other removals are proposed under Phase II of the voluntary offset mechanisms. Further, under the compliance mechanism, obligated entities from sectors like electricity, steel, and cement can consider CCUS and CDR as abatement technologies to reduce their emissions intensities and earn carbon credits. However, development of CCUS under the ICM will depend on future costs of these technologies and carbon prices that can support their commercialization and scale-up to meet the projected demands under various net-zero scenarios. In addition, government may also need to support infrastructure development and promotion of research and innovation in these sectors.

In line with the Paris climate goals, the cost of carbon to achieve net-zero emissions fall in the range of USD 40–80/tCO_2 by 2020 and USD 50–100/tCO_2 by 2050 (Stiglitz *et al., 2017)*. At present, carbon is priced in India through a coal cess of INR 400/ tonne of coal. A NITI Aayog estimate suggests that

[3] *https://unfccc.int/process/the-paris-agreement/cooperative-implementation*

[4] *https://unfccc.int/process-and-meetings/the-paris-agreement/article-64-mechanism*

[5] https://unfccc.int/sites/default/files/resource/cma2021_10a01E.pdf?download

[6] https://moef.gov.in/uploads/pdf/revised_list_article_6.2.pdf

[7] https://beeindia.gov.in/en/programmes/carbon-market

this can raise up to INR 53 thousand crores in 2050 and finance around 31% of the carbon capture. Another recent assessment of net-zero scenarios for India estimates that a carbon price of INR 1700/ tCO_2 (approximately USD 25/tCO_2) may support the decarbonization of the electricity sector. Policies for pricing carbon could also be used to support the development of CDR technologies which could lead to their early-stage deployment and testing in the near-term. In addition, the introduction of carbon pricing could also make CO_2-EOR competitive with conventional oil, which is mostly imported in case of India. The carbon pricing instruments could also be used to finance CO_2 pipeline infrastructure and to research on geological sinks to reduce the uncertainties on CO_2 sequestration potential in India. According to a recent study of bioenergy-based CO_2-EOR at the mature oil fields of Ankleshwar, Gujarat, a carbon price of USD 40 to 60/t CO_2 may make this route competitive when compared to the conventional oil (Patange *et al., 2022).*

Apart from carbon pricing, an integrated approach to policy making could offer near-term opportunities to experiment with CCUS and CDR technologies. Early experimentation with new technologies like BECCS and DACCS using near-term opportunities could offer insights into their feasibility potential as long-term mitigation strategies. To explore such opportunities, the current policies and their corresponding institutions will have to be aligned towards the larger goal of net-zero energy systems. In India, there are policies in place to govern different sectors. For instance, the policies on energy access, doubling of farmers income, water conservation in agriculture, promotion of first and second-generation biofuels could be aligned with the schemes supporting enhanced oil recovery and the CCUS in the industrial sectors to explore CDR and negative emissions through the BECCS route. CO_2 capture is an expensive and energy intensive endeavor and could be made affordable through economies of scale. An alignment of energy sector policies towards the long-term goal of net-zero emissions could help in building systems with zero to negative emissions.

Finally, it is important to consider multi-dimensional feasibility of CCUS and CDR deployment in emission scenarios and discuss it with relevant stakeholders. The feasibility of realizing the projected emission reductions in the net-zero scenarios by 2050 is based on the techno-economic assumptions about CCUS, CDR and other clean energy technologies. However, other dimensions of feasibility such as institutional capabilities, social acceptance and national and international politics are also important to get a realistic picture of climate goals under a given scenario (Jewell & Cherp, 2020; Peng et al., 2021; Spencer *et al., 2018).* A recent study suggests that the net-zero or 1.5°C pathways may face issues in implementation due to institutional constraints (Brutschin et al., 2021). In case of India, the social and political feasibility of mitigation strategies to phase out coal from the energy system needs further evaluation. Replacing unabated coal with cleaner fuels would be technologically and economically feasible due to the rapid commercialization and falling costs of renewables. However, transitions without due consideration for governments and people dependent on coal for income and livelihood could create social and political issues in phasing out coal from the energy systems (Vishwanathan et al., 2018). Similarly, deployment of CCUS and CDR technologies would require governments to come up with appropriate regulations and get the relevant stakeholders and communities on board to ensure smooth and just transitions as envisaged by the scenario results. One way to achieve this is by investing in research, development, and demonstration of newer and less explored technologies to test their techno-economic feasibility as well as understand the socio-political issues that could arise from their large-scale deployment.

Conclusions

India's global commitment to net-zero emissions and national priorities for sustainable development present a challenge for its climate and economic policies. With a coal dominant energy sector and rising demand for carbon-neutral alternate fuels to replace imported oil and gas, various routes of CCUS and CDR technologies may be considered as an alternative to achieve net-zero emissions from Indian energy systems. In the context of net-zero emissions and climate policy targets set by India, CCUS and CDR can serve two purposes. First, to given time for just transitions out of fossil fuel-based industries and electricity generation, ensuring energy security and avoiding stranded assets ins second half of the century. Second, as a source of negative emissions in second half of the century to compensate for residual emissions from difficult to decarbonize sectors. In this paper, we propose three key steps to understand the role of CCUS and CDR technologies in achieving net-zero emissions. First, the assessment of global and national scenarios to project the future demand for these technologies. Second, an assessment of available technologies for CO_2 mitigation and removal from the atmosphere. Third, evaluation of national and international policies to support the deployment of CCUS and CDR technologies in line with their projected demands under net-zero scenarios. The Paris agreement, through Article 6, enables parties to use voluntary cooperation for carbon trading to meet national climate goals. India also recently notified a list of mitigation and carbon removal activities (CCUS) that could be implemented under carbon credits mechanism of Articles 6.2 and 6.4 of the Paris agreement. Further, India has recently initiated a carbon market which could be integrated with existing sectoral policies to support the research and commercialization of new and upcoming technologies for net-zero emissions with due consideration for multi-dimensional feasibility of these alternatives.

References

Berend, S., Reimer, J. A., Olderburg, C. M., & Bourg, I. C. (2014). Introduction to carbon capture and sequestration (Vol. 1). World Scientific.

Brutschin, E., Pianta, S., Tavoni, M., Riahi, K., Bosetti, V., Marangoni, G., & Ruijven, B. J. van. (2021). A multidimensional feasibility evaluation of low-carbon scenarios. Environmental Research Letters, 16(6), 064069. https://doi.org/10.1088/1748-9326/abf0ce

Chaturvedi, V., & Malyan, A. (2022). Implications of a net-zero target for India's sectoral energy transitions and climate policy. Oxford Open Climate Change, 2(1), kgac001. https://doi.org/10.1093/oxfclm/kgac001

Crippa, M., Guizzardi, D., Muntean, M., Schaaf, E., Solazzo, E., Monforti-Ferrario, F., Olivier, J., & Vignati, E. (2020). Fossil CO_2 emissions of all world countries—2020 Report, EUR 30358 EN. Publications Office of the European Union, Luxembourg, ISBN 978-92-76-21515-8, 1–244. https://doi.org/10.2760/143674, JRC121460

Davis, S. J., Lewis, N. S., Shaner, M., Aggarwal, S., Arent, D., Azevedo, I. L., Benson, S. M., Bradley, T., Brouwer, J., Chiang, Y.-M., Clack, C. T. M., Cohen, A., Doig, S., Edmonds, J., Fennell, P., Field, C. B., Hannegan, B., Hodge, B.-M., Hoffert, M. I., … Caldeira, K. (2018). Net-zero emissions energy systems. Science, 360(6396), eaas9793. https://doi.org/10.1126/science.aas9793

Dooley, J. J., Kim, S. H., Edmonds, J. A., Friedman, S. J., & Wise, M. A. (2005). - A first-order global geological CO_2-storage potential supply curve and its application in a global integrated assessment model. In E. S. Rubin, D. W. Keith, C. F. Gilboy, M. Wilson, T. Morris, J. Gale, & K. Thambimuthu (Eds.), Greenhouse Gas Control Technologies 7 (pp. 573–581). Elsevier Science Ltd. https://doi.org/10.1016/B978-008044704-9/50058-6

EASAC. (2018). Negative emission technologies: What role in meeting Paris Agreement targets? (ISBN 978-3-8047-3841-6; p. 45). European Academies' Science Advisory Council. www.easac.eu

Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., Hartmann, J., Khanna, T., Luderer, G., Nemet, G. F., Rogelj, J., Smith, P., Vicente, J. L. V., Wilcox, J., del Mar Zamora Dominguez, M., & Minx, J. C. (2018). Negative emissions—Part 2: Costs, potentials and side effects. Environmental Research Letters, 13(6), 063002. https://doi.org/10.1088/1748-9326/aabf9f

Garg, A., Patange, O., Vishwanathan, S., Nag, T., Singh, U., & Avashia, V. (2024). Synchronizing energy transitions toward possible Net Zero for India: Affordable and clean energy for all. Office of the Principle Scientific Advisor (PSA) to Government of India and Nuclear Power Corporation of India Limited (NPCIL). https://psa.gov.in/CMS/web/sites/default/files/publication/ESN%20Report-2024_New-21032024.pdf

Garg, A., Shukla, P., Parihar, S., Singh, U., & Kankal, B. (2017). Cost-effective architecture of carbon capture and storage (CCS) grid in India. International Journal of Greenhouse Gas Control, 66, 129–146.

Holloway, S., Garg, A., Kapshe, M., Deshpande, A., Pracha, A. S., Khan, S. R., Mahmood, M. A., Singh, T. N., Kirk, K. L., & Gale, J. (2009). An assessment of the CO2 storage potential of the Indian subcontinent. Energy Procedia, 1(1), 2607–2613. https://doi.org/10.1016/j.egypro.2009.02.027

IEA. (2019). Global Energy and CO_2 Status Report 2018 (p. 29). International Energy Agency.

IPCC. (2018). Summary for Policymakers. In: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.)].

IPCC. (2022). Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926

Jewell, J., & Cherp, A. (2020). On the political feasibility of climate change mitigation pathways: Is it too late to keep warming below 1.5°C? WIREs Climate Change, 11(1), e621. https://doi.org/10.1002/wcc.621

Lal, R. (2004). Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. Science, 304(5677), 1623–1627. https://doi.org/10.1126/science.1097396

Minx, J. C., Lamb, W. F., Callaghan, M. W., Fuss, S., Hilaire, J., Creutzig, F., Thorben Amann, Beringer, T., Garcia, W. de O., Hartmann, J., Khanna, T., Lenzi, D., Gunnar Luderer, Nemet, G. F., Rogelj, J., Smith, P., Vicente, J. L. V., Wilcox, J., & Dominguez, M. del M. Z. (2018). Negative emissions—Part 1: Research landscape and synthesis. Environmental Research Letters, 13(6), 063001. https://doi.org/10.1088/1748-9326/aabf9b

MoEFCC. (2023). India: Third National Communication and Initial Adaptation Communication to the United Nations Framework Convention on Climate Change. Ministry of Environment, Forest and Climate Change, Government of India.

MoPNG. (2018). National Policy on Biofuels. Ministry of New & Renewable Energy, Government of India. http://petroleum.nic.in/

Olivier, J. G. J., & Peters, J. A. H. W. (2020). Trend in Global CO2 and GHG Emissions – 2020 Report. PBL, Netherlands.

Patange, O. S., Garg, A., & Jayaswal, S. (2022). An integrated bottom-up optimization to investigate the role of BECCS in transitioning towards a net-zero energy system: A case study from Gujarat, India. Energy, 124508. https://doi.org/10.1016/j.energy.2022.124508

Peng, W., Kim, S. E., Purohit, P., Urpelainen, J., & Wagner, F. (2021). Incorporating political-feasibility concerns into the assessment of India's clean-air policies. One Earth. https://doi.org/10.1016/j.oneear.2021.07.004

Pilorgé, H., McQueen, N., Maynard, D., Psarras, P., He, J., Rufael, T., & Wilcox, J. (2020). Cost Analysis of Carbon Capture and Sequestration of Process Emissions from the US Industrial Sector. Environmental Science & Technology, 54(12), 7524–7532.

Sankhyayan, P., & Dasgupta, S. (2019). 'Availability'and/or 'Affordability': What matters in household energy access in India? Energy Policy, 131, 131–143.

Singh, U. (2013). Carbon capture and storage: An effective way to mitigate global warming. Current Science, 105(7), 914–922.

Singh, U., Vishal, V., & Garg, A. (2024). CCUS in India: Bridging the gap between action and ambition. Progress in Energy, 6(2), 023004. https://doi.org/10.1088/2516-1083/ad31b6

Smith, P. (2016). Soil carbon sequestration and biochar as negative emission technologies. Global Change Biology, 22(3), 1315–1324. https://doi.org/10.1111/gcb.13178

Smith, S., Geden, O., Gidden, M., Lamb, W. F., Nemet, G. F., Minx, J., Buck, H., Burke, J., Cox, E., Edwards, M., Fuss, S., Injy Johnstone, Müller-Hansen, F., Pongratz, J., Probst, B., Roe, S., Schenuit, F., Schulte, I., & Vaughan, N. (2024). The State of Carbon Dioxide Removal—2nd Edition. https://doi.org/10.17605/OSF.IO/F85QJ

Spencer, T., Colombier, M., Sartor, O., Garg, A., Tiwari, V., Burton, J., Caetano, T., Green, F., Teng, F., & Wiseman, J. (2018). The 1.5°C target and coal sector transition: At the limits of societal feasibility. Climate Policy, 18(3), 335–351. https://doi.org/10.1080/14693062.2017.1386540

Stiglitz, J. E., Stern, N., Duan, M., Edenhofer, O., Giraud, G., Heal, G. M., la Rovere, E. L., Morris, A., Moyer, E., Pangestu, M., & others. (2017). Report of the high-level commission on carbon prices.

Sutherland, B. R. (2019). Pricing CO_2 Direct Air Capture. Joule, 3(7), 1571–1573. https://doi.org/10.1016/j.joule.2019.06.025

UN. (2015). Sustainable Development Goals: 17 Goals to transform our world. United Nations. https://www.un.org/sustainabledevelopment/sustainable-development-goals/

Vishal, V., Chandra, D., Singh, U., & Verma, Y. (2021). Understanding initial opportunities and key challenges for CCUS deployment in India at scale. Resources, Conservation and Recycling, 175, 105829. https://doi.org/10.1016/j.resconrec.2021.105829

Vishal, V., Verma, Y., Chandra, D., & Ashok, D. (2021). A systematic capacity assessment and classification of geologic CO_2 storage systems in India. International Journal of Greenhouse Gas Control, 111, 103458. https://doi.org/10.1016/j.ijggc.2021.103458

Vishwanathan, S. S., Garg, A., & Tiwari, V. (2018). Coal transition in India. Assessing India's energy transition options. IDDRI and Climate Strategies. IDDRI and Climate Strategies.

World Bank. (2020). World development indicators.https://search.library.wisc.edu/catalog/999829583602121

TECHNICAL ARTICLE

RESERVOIR ENGINEERING DIMENSIONS IN LARGE-SCALE CO_2 SEQUESTRATION

Dinesh Joshi[1] and Vikram Vishal[1]

Abstract

CO_2 geo-sequestration is a critical technology in the global effort to reduce greenhouse gas emissions and mitigate climate change. This article explores large-scale geological CO_2 sequestration (GCS) through the lens of reservoir engineering, focusing on geological formations such as saline aquifers and depleted hydrocarbon reservoirs, including application in enhanced oil recovery (EOR). The process involves capturing CO_2 from industrial sources and securely storing it underground to prevent atmospheric release. Key considerations include characterization of reservoirs, which requires detailed analysis of porosity, permeability, and cap rock integrity, and the use of advanced modelling techniques to predict CO_2 plume migration, and assess risks such as leakage. Despite the promise and potential that GCS offers, several challenges persist, including those in reservoir heter ogeneity, long-term storage uncertainty, and the high cost of implementation. Monitoring techniques, particularly seismic and 4D imaging, are crucial in ensuring the integrity of storage sites. The potential storage capacity of saline aquifers is vast, estimated at tens of thousands of gigatons globally, providing a significant opportunity for large-scale sequestration. However, economic incentives and regulatory frameworks are necessary to accelerate adoption. This paper highlights the role of reservoir engineering aspects in overcoming challenges and ensuring the safe, long-term storage of CO_2.

Introduction

The increasing concentration of carbon dioxide (CO_2) in the atmosphere, driven largely by human activities such as fossil fuel combustion, has become a critical contributor to global climate change. According to the Global Carbon Project, annual CO_2 emissions reached 36.8 gigatonnes in 2022, a significant rise from the pre-industrial level of 280 parts per million (ppm) to over 417 ppm in 2023 (Chen *et al., 2022)*. In response, CO_2 geo-sequestration has emerged as a key strategy to mitigate these emissions by capturing and storing CO_2 in subsurface geological formations. This process, known as carbon capture and storage (CCS), involves capturing CO_2 from industrial sources, transporting it, and injecting it into underground formations such as saline aquifers, depleted oil and gas reservoirs, basalts and unmineable coal beds (Vishal and Singh, 2016). Among these, saline aquifers and depleted hydrocarbon reservoirs, particularly through enhanced oil recovery (EOR), have shown significant promise (Vishal *et al.*, 2021; Prakash *et al., 2024*). The Global CCS Institute reports that the current operational CCS projects have a combined capacity of capturing over 49 million tonnes (Mt) of CO_2 per year whereas the commitments for doing so in the coming years is over 350 Mt, demonstrating the potential of this technology to scale (Saouter and Gibon, 2024).

Reservoir engineering plays a pivotal role in ensuring the successful implementation of CO_2

[1]DST-National Centre of Excellence in CCUS, Department of Earth Sciences, Indian Institute of Technology Bombay, Mumbai, India

Email : rldineshjoshi@gmail.com (Dr. Dinesh Joshi) v.vishal@iitb.ac.in (Prof. Vikram Vishal)

geo-sequestration. It focuses on the comprehensive characterization of reservoirs to determine their capacity, injectivity, and containment potential. This includes analysing key factors such as reservoir porosity, permeability, and cap rock integrity, which are essential for long-term CO_2 storage. For instance, saline aquifers alone have been estimated to hold as much as 10,000 gigatonnes of CO_2 globally, offering immense potential for large-scale storage (Singh, 2024). Additionally, advanced modelling and simulation techniques are employed to predict CO_2 plume migration and assess the risks associated with pressure buildup and potential leakage. Further more, seismic and geophysical monitoring technologies, such as 4D seismic surveys, are critical for tracking CO_2 movement and ensuring the integrity of the storage site over time.

Despite the potential benefits of CO_2 geo-sequestration, several challenges and limitations remain. Heterogeneity in subsurface formations complicates predictions of CO_2 migration, as geological formations often vary in porosity and permeability. Studies have shown that such heterogeneity can lead to uneven CO_2 distribution, reducing the efficiency of storage in some cases by up to 30%. Additionally, risks of CO_2 leakage through faults, fractures, or poorly sealed wellbores remain a significant concern, with leakage rates of even 1% annually potentially undermining long-term storage effectiveness. Economic and regulatory challenges also pose significant barriers to widespread adoption, particularly in regions without strong carbon pricing mechanisms. Nevertheless, as the world continues to search for effective solutions to reduce greenhouse gas emissions, CO_2 geo-sequestration offers a viable and scalable method to store CO_2 securely underground while contributing to enhanced oil recovery and long-term climate mitigation efforts.

2. Reservoir Characterization for CO_2 Sequestration

Reservoir characterization is a critical step in the successful implementation of CO_2 geo-sequestration. It involves a detailed analysis of the geological and petrophysical properties of a subsurface reservoir to determine its suitability for long-term CO_2 storage. The primary objective is to understand the reservoir's capacity, injectivity, and containment potential, ensuring that the injected CO_2 remains securely trapped without leakage.

Key factors that are examined during reservoir characterization include porosity, permeability, cap rock integrity, fluid saturation, and the geomechanical properties of the rock formation. Detailed geological and geophysical studies are required to map the subsurface, define reservoir boundaries, and monitor CO_2 behaviour after injection.

CO_2 sequestration can occur in various geological reservoirs, each offering unique benefits and challenges. Saline aquifers are extensive porous rock formations saturated with highly saline water. These aquifers are among the most favorable candidates for CO_2 storage because of their vast distribution and significant storage capacity. Unlike depleted reservoirs, saline aquifers have not been exploited, allowing for larger volumes of CO_2 to be injected without the constraints of previous use. Their potential for large-scale sequestration makes them a key focus for carbon capture and storage (CCS) projects. On the other hand, depleted oil and gas reservoirs offer proven reliability for long-term storage, having retained hydrocarbons for millions of years. The existing infrastructure from previous extraction activities, such as pipelines and wells, can be repurposed for CO_2 injection, lowering operational costs and reducing the time required for new developments. However, the storage capacity of these reservoirs is typically more limited compared to saline aquifers, given their prior exploitation. Both types of reservoirs provide viable options for CO_2 sequestration, with saline aquifers offering greater capacity and depleted reservoirs benefiting from established infrastructure.

2.1. Key Elements of Reservoir Characterization

2.1.1. Gravity Override in CO_2 Injection

Gravity override is a critical issue encountered in gas injection processes, especially in CO_2 sequestration, where the injected gas is less dense than the displacing fluid, such as brine. This phenomenon occurs when the injected CO_2 migrates to the top of the reservoir due to gravitational segregation, bypassing lower portions of the reservoir, thus reducing the overall sweep efficiency (Abdulrahman and Foroozesh, 2022). The severity of gravity override is influenced by the vertical communication in the reservoir and the density contrast between CO_2 and brine. In reservoirs with low vertical permeability or stratified layers, gravity override poses less of a challenge. However, in reservoirs with high vertical communication, the density difference between CO_2 and brine can result in pronounced gravity segregation, causing CO_2 to accumulate at the top of the formation.

A critical characteristic of CO_2-brine systems is the substantial density contrast, which can cause CO_2 to flow along the top of the reservoir, leaving significant volumes of brine undisturbed at lower levels. Vertical equilibrium (VE) models are often employed to describe the pressure profiles in such systems, simplifying the governing equations by focusing only on the horizontal direction (Bandilla *et al., 2015).* Gravity's impact on the gas injection process can be assessed using the gravity number (Ng) and the dimensionless density difference. A low gravity number indicates that gravitational effects are minimal, whereas a high gravity number enhances viscous fingering, with gas rising more quickly in the upper portions of the reservoir (Peysson et al., 2011). This can lead to uneven CO_2 distribution and limited sweep efficiency, especially in the lower sections of the reservoir, which has schematically shown in Figure 1.

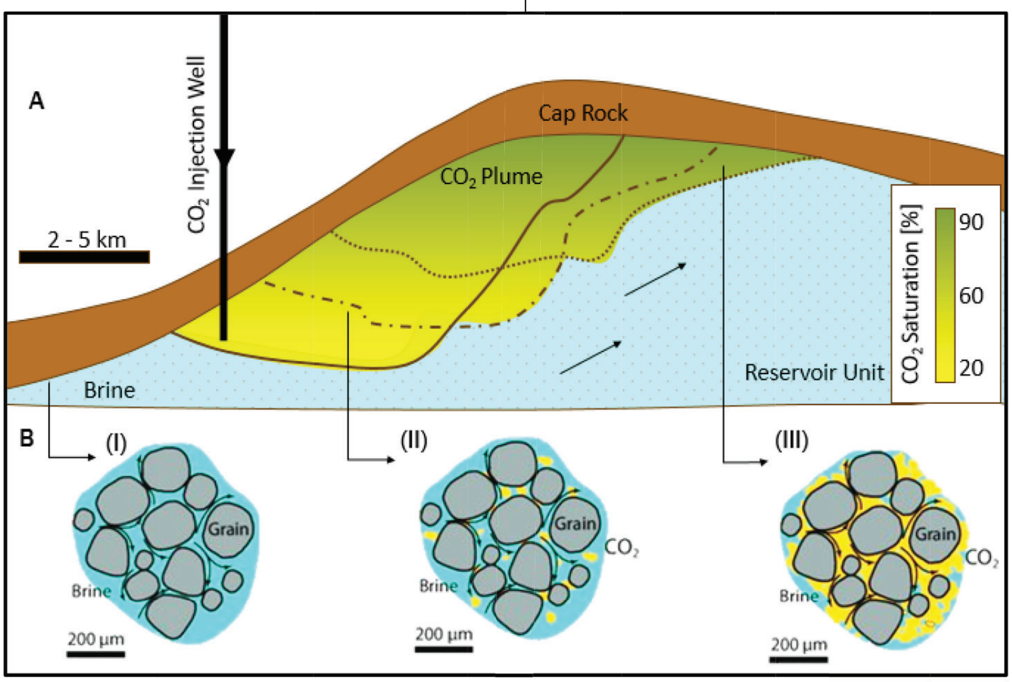


Figure 1. [A] Schematic representation of CO_2 migration in a saline formation. Due to the non-horizontal nature of caprocks, injected CO_2 typically moves updip. After the injection process concludes, the CO_2 plume continues to migrate updip. [B] Pore-scale fluid distribution patterns at different pore-space saturations(updated from Hefny *et al., 2020).*

Mitigating gravity override is essential to improving CO_2 storage efficiency. One strategy is to reduce the gravity-to-viscous force ratio (Ngv), promoting lateral migration of CO_2 and enhancing capillary trapping, which immobilizes the gas within the pore spaces. In low Ngvconditions, CO_2 is more likely to become residually trapped before reaching the upper layers of the reservoir, thus improving storage efficiency (*Mo et al., 2005).* Conversely, in high Ngvconditions, gravity forces dominate, leading to the formation of a narrow gravity tongue near the top of the reservoir, limiting the extent of CO_2 trapping (Singh et al., 2019). Recent advancements, such as the use of high-density nanoparticles and foam co-injection, have been proposed to counteract gravity override by stabilizing fluid dynamics and reducing the effects of gravitational instabilities (Lyu et al., 2021; Rathnaweera and Ranjith, 2020). These innovations aim to improve CO_2 trapping and overall sequestration efficiency in large-scale CO_2 injection projects.

2.1.2. Cap Rock Integrity

Cap-rock integrity is a critical factor in ensuring the long-term safety and effectiveness of CO_2 geo-sequestration. The primary risks associated with cap-rock failure include the reactivation of faults due to pressure changes, hydraulic connectivity between the reservoir and overlying formations, cap-rock fracturing, and the risk of CO_2 injection-induced fractures. Over - pressurization of the capillary membrane seal can also compromise its ability to contain CO_2, leading to potential leakage (Shukla *et al., 2010).* For successful CO_2 storage, the cap-rock must exhibit several key characteristics: it should be dense, have low permeability, and remain unfractured to prevent any leakage. Additionally, it must maintain CO_2 in a supercritical state, ensuring that the gas remains trapped within the reservoir (Watson and Gibson-Poole, 2005).

The mechanical strength of the cap-rock is another crucial consideration, as it must withstand changes in the stress field that occur before and after CO_2 injection. It must be strong in both tension and compression to resist deformation or failure under the pressure changes caused by CO_2 injection. Without these properties, the integrity of the cap-rock could be compromised, increasing the risk of CO_2 leakage into overlying formations or even the atmosphere. Therefore, each CO_2 sequestration project must carefully assess the cap-rock's mechanical properties, ensuring that the formation can withstand the operational pressures involved in the injection process (Shukla *et al., 2010).* Figure 2 illustrates the potential risks to cap-rock integrity from CO_2 injection (Azin *et al., 2022).*

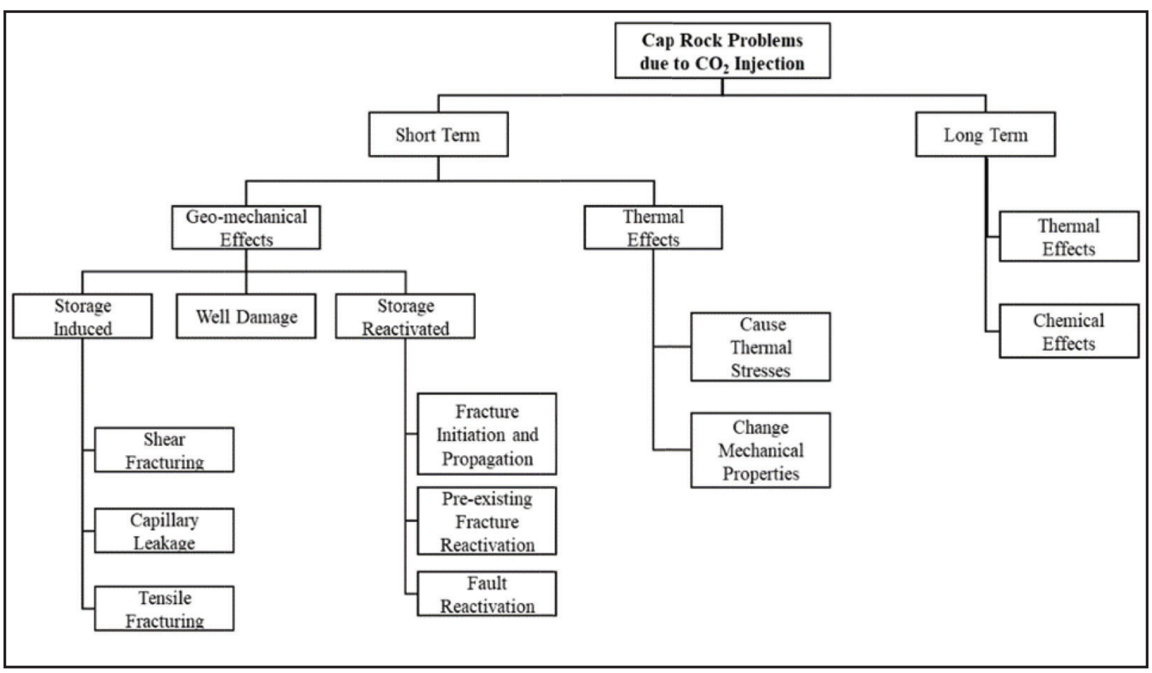


Figure 2. Potential cap rock integrity issues resulting from CO_2 injection, illustrating both short-term and long-term effects (Azin *et al., 2022*).

Injecting CO_2 into the reservoir alters pore pressures, which can lead to changes in effective stress both within the storage formation and the cap-rock. Significant fluctuations in these stresses may induce fractures, allowing CO_2 to escape. To prevent such scenarios, it is essential to account for the interaction between multiphase fluid flow and geomechanical factors, which influence stress distribution. These factors help predict potential leakage pathways, such as the creation of new fractures or the reactivation of existing faults (Rutqvist, 2012). Additionally, the geological characteristics of the cap-rock, including the geometry, orientation, frequency, and distribution of fractures, play a major role in determining its stability. These characteristics are influenced by in situ stress fields, fault orientations, and fluid pressures (Peacock and Mann, 2005).

Numerical models that integrate fluid flow and geomechanical simulations are often used to assess the risk of cap-rock failure. These models evaluate how poro-elastic effects from CO_2 injection, fracturing potential, fault slippage, and hydraulic fracturing impact the overall storage capacity and integrity of the system (Raziperchikolaee *et al., 2013)*. By simulating in situ stress changes, these models help identify potential weaknesses in the reservoir-cap-rock system, guiding the design and management of CO_2 storage projects to minimize leakage risks.

2.1.3. Salt Precipitation in CO_2 Sequestration

Salt precipitation is a significant phenomenon that can alter the absolute permeability of a reservoir during CO_2 injection, particularly in saline aquifers. This process arises from the interaction of physical and chemical processes, with physical processes—such as fluid dynamics and evaporation—playing a more dominant role than chemical reactions in causing dry-out and salt crystallization (Miri and Hellevang, 2016). As CO_2 is injected into the reservoir, the evaporation of formation water in the near-well region causes salt to precipitate and accumulate, which can reduce the reservoir's permeability and, consequently, the efficiency of CO_2 injection illustrated in the Figure 3. This process is complex and influenced by several factors, including injection schemes, well completion strategies, and the reservoir's rock and fluid properties such as permeability, porosity, and thermodynamic conditions like salinity, temperature, pressure, and the composition of CO_2 and brine.

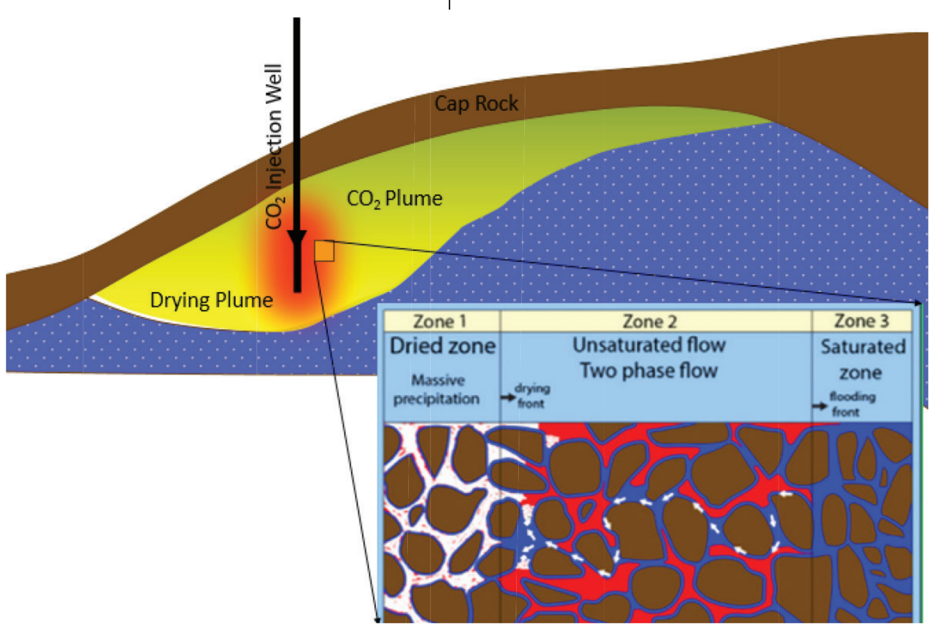


Figure 3. Schematic illustrating CO_2 injection into a saline aquifer, highlighting potential phase configurations in the near-well region (Modified from Miri and Hellevang, 2016).

The rate at which CO_2 is injected is particularly critical to the occurrence of salt precipitation. At low injection rates, gravity tends to dominate the CO_2 flow, and the heterogeneity of the formation can prevent significant salt buildup in the injection well. Conversely, at higher injection rates, the CO_2 flow is driven by viscous forces, and in more homogeneous formations, these viscous forces prevent salt precipitation near the wellbore. Salt crystallization occurs primarily due to the evaporation of formation water, gas-liquid seepage, and salt migration. In saline aquifers with poor permeability, additional factors such as brine capillary pressure and water backflow contribute to the dynamics of salt precipitation, potentially leading to localized blockages that reduce the efficiency of CO_2 injection.

Predicting the extent and impact of salt precipitation requires consideration of several key factors, including the rate of evaporation of formation water, changes in brine composition due to gas-liquid interactions, and the backflow of formation water. These factors, combined with reservoir heterogeneity, make salt precipitation a critical challenge in the design and management of CO_2 injection projects. Effective strategies to mitigate salt precipitation may involve optimizing injection rates, adjusting wellbore completions, and considering the thermodynamic conditions of the specific saline aquifer being used for storage.

2.1.4. Reservoir Geometry and Heterogeneity

The geometry of the reservoir, including its thickness, lateral extent, and structural features such as faults and folds, influences CO_2 storage capacity and distribution. Structural traps, which are geological formations that naturally trap fluids, are ideal for CO_2 storage. However, any faults or fractures present in the reservoir must be carefully mapped, as they can either enhance CO_2 migration or provide potential leakage pathways.

Heterogeneity within the reservoir, such as variations in rock type, grain size, and cementation, can affect the flow of CO_2. Highly heterogeneous reservoirs may present challenges for uniform CO_2 distribution and storage. Reservoir models are developed using seismic and well data to account for this variability.

2.1.5. Fluid Saturation

Understanding the initial saturation of fluids within the reservoir (e.g., oil, gas, or water) is essential. In saline aquifers, for instance, the reservoir will primarily be water-saturated, and CO_2 will displace this brine. Monitoring the interaction between CO_2 and the existing fluids is critical to assessing how the CO_2 will migrate and where it will ultimately be stored. The movement of CO_2 can be predicted using reservoir simulation software, which models fluid flow under various injection scenarios.

2.1.6. Geomechanical Properties

The injection of CO_2 into a reservoir alters the pressure within the formation, which can affect its geomechanical properties. It is important to evaluate the strength and stability of the reservoir and cap rock to ensure they can withstand the pressure changes induced by CO_2 injection. If the injection pressure is too high, it could fracture the cap rock, leading to potential leakage. Geomechanical studies involve testing the strength, stress, and strain characteristics of the rock, which are incorporated into reservoir models to predict safe injection parameters (Verma *et al., 2021).*

3. Planning Challenges

3.1. Capacity Estimation

Accurate storage capacity estimation is crucial for the successful implementation of carbon capture and storage (CCS) projects. Calculating the CO_2 storage capacity involves understanding the volume of sedimentary rock formations suitable for CO_2 injection and considering factors such as geological storage conditions and infrastructure. Bachu (2008) emphasized the importance of financial, legal, and operational constraints, such as groundwater protection and injection well regulations, in determining storage capacity. Key parameters affecting CO_2 storage efficiency include aquifer thickness, permeability, porosity, temperature, and injection strategy (Bachu, 2015). Various methods, from static volumetric models to dynamic numerical simulations, have been applied to estimate the capacity, with static methods being more prevalent in large-scale assessments (Wei *et al., 2022)*. A detailed assessment of potential for CO_2 storage in India by IIT Bombay presents it in a range of 395 – 614 Gt of CO_2 (Vishal *et al., 2021*).

3.1.1. CSLF - Proposed Methodology

The Carbon Sequestration Leadership Forum (CSLF) methodology provides a framework for estimating the effective capacity available in structural traps for CO_2 storage. This approach, formulated by Bachu *et al., (2007)* calculates the volume of CO_2 that can be stored in geological formations based on parameters such as area (A), thickness (h), porosity (ø), irreducible water saturation (S_{wirr}), and the density of CO_2 (ρ_{CO2}). The capacity coefficient (Cc), which accounts for factors like sweep efficiency and trap heterogeneity, is also integrated into the calculation. The method is versatile, allowing for estimations of both residual and solubility trapping through detailed equations that include variables such as pore space and saturation levels. However, long-term storage mechanisms like mineral trapping are more complex, and their capacity estimation remains challenging due to the extended timescales involved in the process. The relationships of this effective capacity for an open boundary aquifer are as follows :

$$V_{CO_2} = Ah\varphi(1 - S_{w_{irr}})C_c$$

$$M_{CO_2} = Ah\varphi(1 - S_{w_{irr}})\rho_{CO_2}C_c$$

3.1.2. USDOE-Proposed Volumetric Methodology

The U.S. Department of Energy (DOE) has developed a simplified volumetric equation for estimating CO_2 storage capacity in saline aquifers. This method assumes that CO_2 occupies pore space within a permeable rock, and it calculates the mass estimate of CO_2 that can be stored by considering parameters such as aquifer area, thickness, porosity, and CO_2 density (Goodman *et al., 2011).*

$$G_{CO_2} = Ah_g\varphi_{tot}\rho E \qquad (3)$$

In this context, G_{CO2}) represents the mass estimate of CO_2 storage capacity in saline formations, which quantifies the amount of CO_2 that can be effectively stored. The term A, measured in square units, refers to the geographical area defining the basin or region being considered for CO_2 storage. h_g denotes the gross thickness of the saline formations targeted for storage. The variable φ_{tot} represents the average total porosity of the entire saline formation over this thickness. The CO_2 density, symbolized by ρ, is expressed in terms of mass per unit volume and is evaluated under conditions specific to the storage environment for the given geological unit, averaged over the depth corresponding to h_g. Lastly, the CO_2 storage efficiency factor, denoted by E, is a dimensionless parameter that accounts for the portion of the total pore volume in the saline formation that is effectively occupied by CO_2, thereby influencing the total storage capacity.

In Equation (6), the storage efficiency factor EEE adjusts various parameters—such as the total area to net area, gross thickness to net thickness, and total porosity to effective porosity that actually stores CO_2 based on the information available and any uncertainties in specific characteristics. The efficiency factor typically ranges from 0.4% to 5.5% (Goodman *et al., 2011)*. This factor allows for an approximation of the maximum potential storage volume, assuming that CO_2 injection wells are densely drilled. The ratio of effective to total porosity, net to gross thickness, and net to total area are used to define the overall pore volume. Other factors like areal displacement efficiency, gravity, vertical displacement efficiency, and microscopic displacement efficiency also help define the fraction of pore volume reached by CO_2 from injection wells (Yang *et al., 2010*).

3.1.3. Compressibility Method

The compressibility method, also proposed by the USDOE, focuses on closed aquifer models, where the amount of pore space available for CO_2 storage is influenced by the compressibility of both the rock and the fluids present in the formation. This method, outlined by Obdam, (2006) and van der Meer, (1993) is based on the maximum pressure increase allowed in the system, and it provides a conservative estimate for storage capacity. By considering the pressure changes in a closed boundary, the compressibility method yields a time-dependent injection rate, allowing for the prediction of CO_2 storage capacity over time. This technique is particularly useful for determining the long-term storage potential in reservoirs with complex geomechanical properties.

3.1.4. Dynamic Methods

Dynamic models are essential when system attributes fluctuate due to pressure and temperature changes. Dynamic estimates of CO_2 storage capacity rely on analytical and numerical simulations of CO_2 injection over time (Bachu, 2015). These models are especially useful in basin- and field-scale assessments, incorporating time-dependent factors like pore pressure and fluid characteristics (Frailey and Finley, 2009). The material-balance technique and fractional flow theory are common methods for determining CO_2 storage capacity, providing rapid assessments with minimal data but may require assumptions that exclude critical storage mechanisms (Ajayi *et al., 2019)*.

3.1.5. Analytical Methods

Analytical methods are favoured for large-scale evaluations requiring quick assessments, as they often produce results with acceptable resolution using limited data. However, these methods must make assumptions about key mechanisms such as rock-brine CO_2 interactions, injection strategies, and formation heterogeneity. As such, they are divided into deterministic and stochastic approaches based on the site data (Han and Kim, 2018). For instance Ghanbarnezhad Moghanloo *et al., (2015)* demonstrated the applicability of fractional flow theory in predicting the CO_2 storage capacity of saline formations, while Zhu *et al., (2017*) used relative permeability curve analysis (RPCA) to calculate capillary storage potential, achieving results consistent with numerical simulations. Tools like EASiTool (Ganjdanesh and Hosseini, 2018) and SCO2T (Middleton *et al., 2020)* enhance these analytical techniques by providing rapid estimates of CO_2 storage capacity for formations.

3.1.6. Numerical Methods

Numerical simulations offer greater flexibility and accuracy than analytical methods by integrating complex geological data and capturing multi-phase fluid properties across varying time scales (Zulqarnain *et al., 2017)*. These simulations incorporate 3D geological models based on well log data, core samples, and production data, allowing for detailed investigation of CO_2 storage capacity under different conditions. Factors such as porosity, permeability, phase saturations, and injection rate significantly affect the results of dynamic capacity estimates (Ajayi *et al., 2019*).

Advanced simulation tools like ECLIPSE (Schlumberger), GEM CMG, and TOUGH use finite difference (FD), finite element (FE), and finite volume (FV) discretization techniques to model CO_2 injection, storage, and flow across geological. By including all relevant physics, including heterogeneity and anticipated pressure effects, these simulations address some of the shortcomings of other methods, making them indispensable for large-scale CO_2 storage projects.

4. Operational Challenges

4.1. Health, Safety, and Environment (HSE)

Many studies have explored the potential health, safety, and environmental (HSE) risks associated with CO_2 geological storage (Andersson et al., 2005; Cherkaoui and Lopez, 2009; Damen et al., 2006). Short-term CO_2 leakage poses a significant risk due to potential high concentrations in small areas, but it is usually easier to detect and mitigate. Long-term leakage, though likely to be subtler, presents more difficult challenges as it can spread over larger areas and be harder to detect. HSE risks from CO_2 leakage can be categorized into local and global risks. Global risks refer to the release of CO_2 into the atmosphere, which undermines the success of geological storage efforts. It is generally accepted that CO_2 leakage rates should be kept below 0.1% per year (Bowden and Rigg, 2005). Locally, CO_2 leakage can pose risks to soil, water quality, and human health, as exposure to high concentrations can be dangerous. While CO_2 is a naturally occurring gas in the atmosphere at around 0.04%, concentrations above 2% can cause soil and water acidification, leading to ecological damage (Andersson *et al., 2005*).

CO_2 leakage also has potential impacts on groundwater supplies, primarily through acidification and the mobilization of hazardous metals such as lead and arsenic. These effects can occur via two pathways : CO_2 seeping into nearby aquifers, or the displacement of deep brine which can transport dissolved contaminants. Studies have shown that leakage can lead to the mobilization of metals such as iron, manganese, and arsenic, impacting groundwater quality (Little and Jackson, 2010; Siirila *et al., 2012).* Groundwater contamination tends to occur in long, narrow plumes, making it harder to monitor and remediate (Carroll *et al., 2014).* High levels of CO_2 also affect soil chemistry by lowering pH levels, which can reduce the availability of key nutrients like phosphorus, and mobilize toxic metals such as aluminium (Andersson *et al., 2005)*.

Monitoring, Verification, and Accounting (MV&A) Monitoring, verification, and accounting (MV&A) are essential to ensuring the safety and efficacy of CCS projects. These activities help track the movement of CO_2, detect potential leaks, and assess environmental impacts. The U.S. Department of Energy's (DoE) MV&A program focuses on improving the understanding of CO_2 storage mechanisms, validating models, and ensuring health and safety by monitoring CO_2 plume movement. Monitoring typically occurs in two phases: during and after injection. Techniques vary based on site-specific factors, such as geology and location, and include air, near-surface, and subsurface monitoring methods (Middleton *et al., 2012).* Deep-focused methods assess short-term compliance and site performance, while shallow monitoring ensures surface leak detection and baseline condition establishment.

Monitoring tools can include seismic methods, borehole pressure monitoring, remote sensing, and chemical tracers. These tools help identify leaks, validate CO_2 migration models, and assess plume behaviour. For example, perfluorocarbon tracers (PFTs) and remote sensing methods have been used to track CO_2 movement and detect potential leaks (Kharaka et al., 2009). Advances in monitoring technology will continue to refine the MV&A process, making CCS projects more cost-effective and safer. Accurate monitoring and timely detection of leaks are critical for maintaining environmental and public safety during and after CO_2 injection.

5. Discussion

This paper sheds light on the multi-faceted challenges and considerations surrounding CO_2 storage in saline aquifers and depleted reservoirs for CO_2-EOR. The application of nanoparticles and foam co-injection have been proposed to counteract gravity override by stabilizing fluid dynamics and reducing the effects of gravitational instabilities. The use of nanotechnology, which has been shown to influence fluid dynamics, represents a crucial advancement in optimizing CO_2 injection strategies (Lyu *et al., 2021*; Rathnaweera and Ranjith, 2020). As the density contrast between nano-CO_2 and brine phases diminishes, it underscores the need for highly detailed models that account for these nuanced fluid behaviours. This also applies to depleted reservoirs used for CO_2-EOR, where understanding the interaction between CO_2 and remaining hydrocarbons is essential for optimizing both oil recovery and storage potential. Enhanced oil recovery through CO_2 injection not only boosts oil output but also provides an additional avenue for carbon sequestration, making CO_2-EOR an attractive dual-purpose approach.

The delicate balance between injection strategies and caprock integrity is another pressing issue discussed in the paper. While increasing injection pressure can improve well injectivity, particularly in depleted reservoirs for EOR, there is a fine line between enhancing performance and risking caprock fracture (Azin *et al., 2022*; Shukla et al., 2010). In CO_2-EOR, higher injection pressures can mobilize residual oil, but at the cost of potentially compromising the structural integrity of the storage formation. This reflects the inherent tension in managing injection pressures to maximize efficiency while safeguarding the structural integrity of the storage site. The simultaneous consideration of caprock integrity highlights the importance of pressure management techniques to prevent fracturing and ensure the long-term containment of injected CO_2, both in saline aquifers and depleted reservoirs.

Additionally, long-term trapping and leakage factors, such as reservoir permeability, capillary entry pressures, and aquifer salinity, stress the complex interplay between geological features and fluid properties. In both saline aquifers and depleted reservoirs, factors such as capillary trapping, solubility trapping, and mineralization influence CO_2 storage effectiveness. The heterogeneous nature of depleted reservoirs adds further complexity, as residual hydrocarbons and pre-existing fractures may influence the mechanical responses of the system. Thus, a holistic understanding of the storage environment is critical in both contexts to mitigate risks of leakage and optimize storage capacity. The recognition that depleted reservoirs for CO_2-EOR involve both enhanced recovery processes and long-term storage underscores the need for meticulous modelling and management of injection practices.

The paper also discusses precipitation of salt and brine backflow, both of which pose significant challenges during CO_2 injection in saline aquifers and depleted reservoirs alike. Salt precipitation near the wellbore can hinder injection, while capillary pressure-induced brine backflow can complicate both EOR and long-term storage operations. In CO_2-EOR, managing these flow dynamics becomes even more critical due to the added complexity of oil-phase behaviour. Completion fluid selection and the impact of CO_2-saturated brine on wellbore materials like steel and cement are also crucial considerations in both saline aquifers and CO_2-EOR scenarios. Wellbore integrity remains a critical factor to prevent leaks, corrosion, and cement alteration, requiring robust materials and long-term maintenance strategies.

Numerical simulations and uncertainty reduction techniques, such as the Monte Carlo simulation, are indispensable tools for addressing the complexities of both saline aquifers and depleted reservoirs. The paper emphasizes the importance of accurate geological models and grid structures to capture the full scope of subsurface behaviours. In CO_2-EOR, simulations must account for both fluid flow dynamics and hydrocarbon displacement, while in saline aquifers, the focus is on CO_2 dissolution and mineral trapping mechanisms. Although these models are computationally expensive, they are critical for optimizing injection strategies, predicting long-term storage capacity, and mitigating risks.

Lastly, cost implications and environmental considerations are central to both saline aquifer storage and CO_2-EOR projects. The cost of CO_2 storage is influenced by factors like permeability, reservoir heterogeneity, and operational efficiency. In CO_2-EOR, the added economic benefit of enhanced oil recovery can offset some of the costs, making it a more attractive option. However, both methods must address environmental concerns, particularly CO_2-induced acidity in groundwater and soil. Proper comprehensive monitoring systems, including reservoir and wellbore leakage models, pressure monitoring, and surface-based tools, are essential for tracking CO_2 movement and ensuring environmental safety, whether in saline aquifers or depleted reservoirs.

In summary, this paper highlights that while CO_2 storage in saline aquifers and depleted reservoirs for EOR presents significant challenges, advancements in technology and modelling, along with careful planning and monitoring, can make these methods viable options for reducing atmospheric CO_2. The dual benefit of CO_2-EOR, combining enhanced hydrocarbon recovery with carbon sequestration, presents a unique opportunity to both extend the life of oil fields and mitigate climate change.

Conclusion

This paper provides a comprehensive exploration of the key challenges and considerations involved in CO_2 storage within saline aquifers and depleted petroleum reservoirs, with a particular focus on nanotechnology, injection strategies, and long-term containment. The integration of nano-modified flow technologies and the balance between viscous and gravitational forces has been identified as crucial in optimizing injection efficiency and improving the predictability of CO_2 behaviour in storage. Furthermore, careful attention to caprock integrity and injection pressure management is necessary to avoid compromising the storage structure while maximizing injectivity, especially in depleted reservoirs used for CO_2-EOR operations.

Long-term trapping mechanisms, including capillary trapping and mineralization, underscore the complexity of CO_2 storage, with geological and fluid interactions playing a significant role in storage efficiency. The potential for salt precipitation and brine backflow poses additional operational challenges, reinforcing the need for strategic site selection and robust monitoring, verification, and accounting (MVA) systems. Such comprehensive monitoring is vital for detecting leaks, ensuring environmental safety, and maintaining wellbore integrity over time.

In conclusion, while CO_2 storage in saline aquifers and depleted reservoirs for CO_2-EOR presents multifaceted challenges, the continued advancement in numerical simulations, uncertainty modelling, and material sciences offers promising avenues for improving storage capacity and safety. These methods not only contribute to mitigating climate change but also provide opportunities for enhancing oil recovery in a way that supports global energy transitions and carbon management efforts.

References

Abdulrahman, A., Foroozesh, J., 2022. Carbonated Water Injection for EOR and CO_2 Storage: A Simulation Study, in: Ibrahim, R., K. Porkumaran, Kannan, R., Mohd Nor, N., S. Prabakar (Eds.), International Conference on Artificial Intelligence for Smart Community. Springer Nature, Singapore, pp. 185–196. https://doi.org/10.1007/978-981-16-2183-3_17

Ajayi, T., Gomes, J.S., Bera, A., 2019. A review of CO_2 storage in geological formations emphasizing modeling, monitoring and capacity estimation approaches. Pet. Sci. 16, 1028–1063. https://doi.org/10.1007/s12182-019-0340-8

Andersson, A., Strand, K., Eriksson, S., 2005. - Strategic environmental assessment of CO_2 capture and storage, in: Rubin, E.S., Keith, D.W., Gilboy, C.F., Wilson, M., Morris, T., Gale, J., Thambimuthu, K. (Eds.), Greenhouse Gas Control Technologies 7. Elsevier Science Ltd, Oxford, pp. 2447–2451. https://doi.org/10.1016/B978-008044704-9/50351-7

Azin, R., Izadpanahi, A., Ranjbar, A., 2022. Challenges of Gas Injection, in : Azin, R., Izadpanahi, A. (Eds.), Fundamentals and Practical Aspects of Gas Injection. Springer International Publishing, Cham, pp. 397–413. https://doi.org/10.1007/978-3-030-77200-0_9

Bachu, S., 2015. Review of CO_2 storage efficiency in deep saline aquifers. International Journal of Greenhouse Gas Control, Special Issue commemorating the 10th year anniversary of the publication of the Intergovernmental Panel on Climate Change Special Report on CO_2 Capture and Storage 40, 188–202. https://doi.org/10.1016/j.ijggc.2015.01.007

Bachu, S., Bonijoly, D., Bradshaw, J., Burruss, R., Holloway, S., Christensen, N.P., Mathiassen, O.M., 2007. CO_2 storage capacity estimation: Methodology and gaps. International Journal of Greenhouse Gas Control 1, 430–443. https://doi.org/10.1016/S1750-5836(07)00086-2

Bandilla, K.W., Celia, M.A., Birkholzer, J.T., Cihan, A., Leister, E.C., 2015. Multiphase Modeling of Geologic Carbon Sequestration in Saline Aquifers. Groundwater 53, 362–377. https://doi.org/10.1111/gwat.12315

Bowden, A.R., Rigg, A., 2005. Assessing reservoir performance risk in CO_2 storage projects, in: Rubin, E.S., Keith, D.W., Gilboy, C.F., Wilson, M., Morris, *T., Gale, J., Thambimuthu, K. (Eds.), Greenhouse Gas Control Technologies 7. Elsevier Science Ltd, Oxford, pp. 683–691. https://doi.org/10.1016/B978-008044704-9/50069-0*

Carroll, S.A., Keating, E., Mansoor, K., Dai, Z., Sun, Y., Trainor-Guitton, W., Brown, C., Bacon, D., 2014. Key factors for determining groundwater impacts due to leakage from geologic carbon sequestration reservoirs. International Journal of Greenhouse Gas Control 29, 153–168. https://doi.org/10.1016/j.ijggc.2014.07.007

Chen, Z., Zhou, Y., Li, H., 2022. A Review of Phase Behavior Mechanisms of CO_2 EOR and Storage in Subsurface Formations. Ind. Eng. Chem. Res. https://doi.org/10.1021/acs.iecr.2c00204

Cherkaoui, A., Lopez, P., 2009. CO_2 storage risk assessment: feasibility study of the systemic method MOSAR. Presented at the SAFE 2009, Rome, Italy, pp. 173–184. https://doi.org/10.2495/SAFE090171

Damen, K., Faaij, A., Turkenburg, W., 2006. Health, Safety and Environmental Risks of Underground CO_2 Storage – Overview of Mechanisms and Current Knowledge. Climatic Change 74, 289–318. https://doi.org/10.1007/s10584-005-0425-9

Frailey, S.M., Finley, R.J., 2009. Classification of CO2 Geologic Storage: Resource and Capacity. Energy Procedia, Greenhouse Gas Control Technologies 9 1, 2623–2630. https://doi.org/10.1016/j.egypro.2009.02.029

Ganjdanesh, R., Hosseini, S.A., 2018. Development of an analytical simulation tool for storage capacity estimation of saline aquifers. International Journal of Greenhouse Gas Control 74, 142–154. https://doi.org/10.1016/j.ijggc.2018.04.017

Ghanbarnezhad Moghanloo, R., Dadmohammadi, Y., Bin, Y., Salahshoor, S., 2015. Applying fractional flow theory to evaluate CO_2 storage capacity of an aquifer. Journal of Petroleum Science and Engineering 125, 154–161. https://doi.org/10.1016/j.petrol.2014.11.013

Goodman, A., Hakala, A., Bromhal, G., Deel, D., Rodosta, T., Frailey, S., Small, M., Allen, D., Romanov, V., Fazio, J., Huerta, N., McIntyre, D., Kutchko, B., Guthrie, G., 2011. U.S. DOE methodology for the development of geologic storage potential for carbon dioxide at the national and regional scale. International Journal of Greenhouse Gas Control 5, 952–965. https://doi.org/10.1016/j.ijggc.2011.03.010

Han, W.S., Kim, K.-Y., 2018. Evaluation of CO_2 plume migration and storage under dip and sinusoidal structures in geologic formation. Journal of Petroleum Science and Engineering 169, 760–771. https://doi.org/10.1016/j.petrol.2018.03.054

Hefny, M., Qin, C., Saar, M.O., Ebigbo, A., 2020. Synchrotron-based pore-network modeling of two-phase flow in Nubian Sandstone and implications for capillary trapping of carbon dioxide. International Journal of Greenhouse Gas Control 103, 103164. https://doi.org/10.1016/j.ijggc.2020.103164

Kharaka, Y.K., Thordsen, J.J., Hovorka, S.D., Seay Nance, H., Cole, D.R., Phelps, T.J., Knauss, K.G., 2009. Potential environmental issues of CO_2 storage in deep saline aquifers: Geochemical results from the Frio-I Brine Pilot test, Texas, USA. Applied Geochemistry, IAGC Celebrates 40 Years Selected Papers from the 40th Anniversary Celebration of the International Association of GeoChemistry, Cologne, Germany, August 2007 and the Special Session at the 2007 Goldschmidt Conference in Memory of A. A. Levinson 24, 1106–1112. https://doi.org/10.1016/j.apgeochem.2009.02.010

Little, M.G., Jackson, R.B., 2010. Potential impacts of leakage from deep CO_2 geosequestration on overlying freshwater aquifers. Environ Sci Technol 44, 9225–9232. https://doi.org/10.1021/es102235w

Lyu, X., Voskov, D., Rossen, W.R., 2021. Numerical investigations of foam-assisted CO_2 storage in saline aquifers. International Journal of Greenhouse Gas Control 108, 103314. https://doi.org/10.1016/j.ijggc.2021.103314

Middleton, R.S., Chen, B., Harp, D.R., Kammer, R.M., Ogland-Hand, J.D., Bielicki, J.M., Clarens, A.F., Currier, R.P., Ellett, K.M., Hoover, B.A., McFarlane, D.N., Pawar, R.J., Stauffer, P.H., Viswanathan, H.S., Yaw, S.P., 2020. Great SCO2T! Rapid tool for carbon sequestration science, engineering, and economics. Applied Computing and Geosciences 7, 100035. https://doi.org/10.1016/j.acags.2020.100035

Middleton, R.S., Keating, G.N., Stauffer, P.H., Jordan, A.B., Viswanathan, H.S., Kang, Q.J., Carey, J.W., Mulkey, M.L., Sullivan, E.J., Chu, S.P., Esposito, R., Meckel, T.A., 2012. The cross-scale science of CO_2 capture and storage: from pore scale to regional scale. Energy Environ. Sci. 5, 7328–7345. https://doi.org/10.1039/C2EE03227A

Miri, R., Hellevang, H., 2016. Salt precipitation during CO_2 storage—A review. International Journal of Greenhouse Gas Control 51, 136–147. https://doi.org/10.1016/j.ijggc.2016.05.015

Mo, S., Zweigel, P., Lindeberg, E., Akervoll, I., 2005. Effect of Geologic Parameters on CO_2 Storage in Deep Saline Aquifers.

Obdam, A., 2006. Aquifer storage capacity of CO2.

Peacock, D.C.P., Mann, A., 2005. Evaluation of the Controls on Fracturing in Reservoir Rocks. J Petroleum Geol 28, 385–396. https://doi.org/10.1111/j.1747-5457.2005.tb00089.x

Peysson, Y., Bazin, B., Magnier, C., Kohler, E., Youssef, S., 2011. Permeability alteration due to salt precipitation driven by drying in the context of CO_2 injection. Energy Procedia, 10th International Conference on Greenhouse Gas Control Technologies 4, 4387–4394. https://doi.org/10.1016/j.egypro.2011.02.391

Prakash, S., Joshi, D., Ojha, K., Mandal, A., 2024. Enhanced Oil Recovery Using Polymer Alternating CO_2 Gas Injection: Mechanisms, Efficiency, and Environmental Benefits. Energy Fuels 38, 5676–5689. https://doi.org/10.1021/acs.energyfuels.3c04258

Rathnaweera, T.D., Ranjith, P.G., 2020. Nano-modified CO2 for enhanced deep saline CO_2 sequestration: A review and perspective study. Earth-Science Reviews 200, 103035. https://doi.org/10.1016/j.earscirev.2019.103035

Raziperchikolaee, S., Alvarado, V., Yin, S., 2013. Effect of hydraulic fracturing on long-term storage of CO_2 in stimulated saline aquifers. Applied Energy, Special Issue on Advances in sustainable biofuel production and use - XIX International Symposium on Alcohol Fuels - ISAF 102, 1091–1104. https://doi.org/10.1016/j.apenergy.2012.06.043

Rutqvist, J., 2012. The Geomechanics of CO_2 Storage in Deep Sedimentary Formations. Geotech Geol Eng 30, 525–551. https://doi.org/10.1007/s10706-011-9491-0

Saouter, E., Gibon, T., 2024. All You Need to Know About the Next Energy Revolution: Solutions for a Truly Sustainable Future. Springer Nature Switzerland, Cham. https://doi.org/10.1007/978-3-031-51332-9

Shukla, R., Ranjith, P., Haque, A., Choi, X., 2010. A review of studies on CO_2 sequestration and caprock integrity. Fuel 89, 2651–2664. https://doi.org/10.1016/j.fuel.2010.05.012

Siirila, E.R., Navarre-Sitchler, A.K., Maxwell, R.M., McCray, J.E., 2012. A quantitative methodology to assess the risks to human health from CO_2 leakage into groundwater. Advances in Water Resources, Special Issue on Uncertainty Quantification and Risk Assessment 36, 146–164. https://doi.org/10.1016/j.advwatres.2010.11.005

Singh, M., Chaudhuri, A., Chu, S.P., Stauffer, P.H., Pawar, R.J., 2019. Analysis of evolving capillary transition, gravitational fingering, and dissolution trapping of CO_2 in deep saline aquifers during continuous injection of supercritical CO_2. International Journal of Greenhouse Gas Control 82, 281–297. https://doi.org/10.1016/j.ijggc.2019.01.014

Singh, R.K., 2024. A critical meta-analysis of CO_2-water-rock interaction in basalt for CO_2 storage: A review based on global and Indian perspective. Marine and Petroleum Geology.

van der Meer, L.G.H., 1993. The conditions limiting CO_2 storage in aquifers. Energy Conversion and Management, Proceedings of the International Energy Agency Carbon Dioxide Disposal Symposium 34, 959–966. https://doi.org/10.1016/0196-8904(93)90042-9

Verma, Y., Vishal, V., Ranjith, P.G., 2021. Sensitivity Analysis of Geomechanical Constraints in CO_2 Storage to Screen Potential Sites in Deep Saline Aquifers. Front. Clim. 3. https://doi.org/10.3389/fclim.2021.720959

Vishal, V., Singh, T.N. (Eds.), 2016. Geologic Carbon Sequestration. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-27019-7

Vishal, V., Verma, Y., Chandra, D., Ashok, D., 2021. A systematic capacity assessment and classification of geologic CO_2 storage systems in India. International

Journal of Greenhouse Gas Control 111, 103458. https://doi.org/10.1016/j.ijggc.2021.103458

Watson, M., Gibson-Poole, C., 2005. Reservoir Selection for Optimised Geological Injection and Storage of Carbon Dioxide: A Combined Geochemical and Stratigraphic Perspective. Presented at the Fourth Annual Conference on Carbon Capture and Sequestration DOE/NETL.

Wei, N., Li, X., Jiao, Z., Stauffer, P.H., Liu, S., Ellett, K., Middleton, R.S., 2022. A Hierarchical Framework for CO_2 *Storage Capacity in Deep Saline Aquifer Formations. Front. Earth Sci. 9. https://doi.org/10.3389/feart.2021.777323*

Yang, F., Bai, B., Tang, D., Shari, D.-N., David, W., 2010. Characteristics of CO_2 *sequestration in saline aquifers. Pet. Sci. 7, 83–92. https://doi.org/10.1007/s12182-010-0010-3*

Zhu, L., Liao, X., Chen, Z., Mu, L., Chen, X., 2017. Analytical model for quick assessment of capillary storage capacity in saline aquifers. International Journal of Greenhouse Gas Control 65, 160–169. https://doi.org/10.1016/j.ijggc.2017.09.004

Zulqarnain, M., Zeidouni, M., Hughes, R.G., 2017. Static and Dynamic CO_2 *Storage Capacity Estimates of a Potential* CO_2 *Geological Sequestration Site in Louisiana Chemical Corridor.*

Please Note : We aim to provide with correct and reliable information about upcoming event, but cannot accept responsibility for the text announcements or the bonafides of event organizers, Please feel free to contact us if you notice incorrect or misleading information and we will attempt to correct it.

TECHNICAL ARTICLE

TRANSITION TO A SUSTAINABLE ENERGY FUTURE : THE ROLE OF COAL, GEOTHERMAL AND HYDROGEN WITH CCUS INTEGRATION

Tushar Adsul[1], Santanu Ghosh[2] and Atul Kumar Varma[1,*]

Abstract

The transition to a sustainable energy future is increasingly focused on integrating various green fuel sources and technologies to reduce greenhouse gas emissions and mitigate climate change. This paper explores several promising energy resources, including coal bed methane (CBM), shale gas, hydrogen production from coal, and geothermal energy, highlighting their potential to contribute to a low-carbon economy. CBM and shale gas, recognized for their lower CO_2 emissions than traditional fossil fuels, leverage complex geological characteristics for enhanced methane recovery. Techniques such as microbially-enhanced CBM (ME-CBM) and hydrous pyrolysis are examined, emphasizing the role of carbon capture utilization and storage (CCUS) in reducing global environmental impact. In the hydrogen sector, coal remains a cost-effective feedstock for hydrogen production through gasification and electrolysis, producing "grey" and "blue" hydrogen, respectively. Integrating renewable energy sources in coal-based hydrogen generation enhances sustainability, promoting the concept of "green coal hydrogen". Shale gas production can also be optimized through Pyrite's catalytic effects and clay minerals' adsorption capabilities, further contributing to methane recovery. Geothermal energy is presented as a stable and clean alternative source for electricity generation, especially when integrated with solar energy for enhanced efficiency in low-grade geothermal resource utilization. Despite geographical limitations, geothermal systems hold significant promise for hydrogen production, contingent upon necessary technological advancements and thermodynamic upgrades. This integrated approach underscores the potential of diverse energy resources combined with CCUS and hydrogen technologies to support the transition towards a greener future, where coal is re-envisioned not as a relic of the past but as a vital component of a sustainable energy landscape. By harnessing these innovations, we can move closer to achieving global climate goals while simultaneously addressing future energy demands.

Introduction

The Intergovernmental Panel on Climate Change (IPCC), a specialized body of the United Nations, has underscored the alarming consequences of escalating global temperatures, stressing the need to cap global warming at 1.5°C above pre-industrial levels (Agarwal and Gupta, 2021). This is pivotal for achieving 'net zero' emissions by 2050 - a critical target to mitigate climate change. A primary driver of climate alteration is the surge in anthropogenic carbon dioxide (CO_2) emissions, primarily from fossil fuel combustion (Leung *et al., 2014).* To combat this, reducing reliance on fossil fuels is paramount, as they remain a dominant source of greenhouse gases.

However, alongside the transition to cleaner energy, carbon capture and sequestration (CCUS) technologies are gaining recognition as vital tools in reducing atmospheric CO_2 levels (Ghosh *et al.,* 2023). CCUS can capture CO_2 directly from industrial processes and power generation before

[1]Department of Applied Geology, Indian Institute of Technology (Indian School of Mines) Dhanbad, Jharkhand – 826004, India
[2]Department of Geology, Mizoram University, Aizawl, Mizoram – 796004, India
* Corresponding author, atul@iitism.ac.in

it is released into the atmosphere, storing it in geological formations. This dual approach, reducing fossil fuel consumption and implementing CCUS can significantly curb greenhouse gas emissions, contributing meaningfully to the global objective of stabilizing the climate (Gupta and Paul, 2019).

Coal, a combustible organic sedimentary rock, has long been the cornerstone of the fossil fuel-driven economy in numerous countries, mainly due to its abundant reserves and relatively low cost. This has made coal an attractive energy source, particularly in regions undergoing rapid industrialization. However, the environmental costs associated with its extensive use are profound. The combustion of coal is a significant contributor to the release of greenhouse gases, CO_2, which exacerbates global warming. In addition to CO_2, coal burning also emits hazardous pollutants like polycyclic aromatic hydrocarbons (PAHs), compounds known for their carcinogenic and mutagenic properties.

Integrating CCUS technologies into coal-based industries is becoming increasingly essential to address these climate and health concerns. By capturing CO_2 at the source, CCUS can prevent significant quantities of this greenhouse gas from entering the atmosphere while sequestering it in secure geological formations (Bachu, 2000). This approach offers a pathway to mitigate the adverse climate impacts of coal, allowing for a transition toward cleaner energy systems without exacerbating atmospheric CO_2 levels. Thus, while coal remains an essential energy resource, implementing CCUS is critical for steering industrialized nations toward a more sustainable and environmentally responsible future.

As concerns about climate change intensify, the urgency to develop clean and green energy technologies has grown significantly. Among the emerging alternatives, Coal Bed Methane (CBM) has gained attention as a relatively cleaner energy source (Adsul *et al., 2023)*. Compared to conventional coal combustion, CBM extraction produces fewer volatile organic compounds (VOCs) and PAHs, making it a more environmentally friendly option. However, the sustainability of CBM is increasingly under scrutiny. The gradual depletion of coal reservoirs, coupled with the exhaustion of viable source rocks, is reducing the availability of CBM. Furthermore, many CBM wells are reaching the end of their operational life, casting doubt on the long-term viability of this resource (Ghosh et al., 2024). In light of these challenges, transitioning from CBM to more sustainable solutions are critical. One promising avenue is the integration of CCUS technologies within the CBM production framework. By capturing and storing CO_2 emissions generated during CBM extraction and use, CCUS can enhance the environmental benefits of CBM, aligning it more closely with the global push for decarbonization.

Also, hydrogen is emerging as a crucial player in transitioning to cleaner energy systems. Green hydrogen, produced through electrolysis using renewable energy, and blue hydrogen, generated from natural gas with integrated CCUS, offer a promising future for decarbonized energy. These technologies can complement the declining availability of CBM, creating a hybrid energy landscape where hydrogen, coupled with CCUS, accelerates the shift towards a carbon-neutral future. By leveraging these innovations, we can mitigate the uncertainties surrounding CBM while advancing the development of clean energy solutions.

1. Microbially Enhanced Coal Bed Methane

Microbially enhanced coal bed methane (ME-CBM) is a promising approach to boost methane production from existing and depleted coal seams (Adsul *et al., 2023)*. By leveraging microbial activity to enhance the breakdown of organic matter into methane, this technique could extend the life of aging wells (White *et al., 2005).* However, deploying ME-CBM is closely monitored to mitigate risks, particularly groundwater contamination and the introduction of biological hazards. The flowback water generated during ME-CBM production must undergo stringent treatment protocols before disposal to prevent environmental damage.

In parallel with these microbial methods, advanced laboratory techniques like hydrous pyrolysis are employed to assess and exploit undiscovered methane resources. Hydrous pyrolysis simulates natural hydrocarbon formation by heating source rocks or isolated organic matter in the presence of liquid water but without oxygen (Lewan, 1997). This method, heavily reliant on coal's molecular structure and kerogen types, shows potential for generating early mature thermogenic methane from productive kerogen (Lewan, 1993). Its efficacy in generating late-mature thermogenic methane is still under exploration.

Further advancements in methane generation are also being driven by research into pyritic sulfur's catalytic potential. Due to its electron lone pair (Ma *et al., 2016),* pyritic sulfur is being investigated as a catalyst that could promote methane production by aiding hydrogen extraction from kerogen (Hatcherian *et al., 2023).* Experimental studies utilizing hydrous pyrolysis at varying temperatures and pyrite concentrations aim to elucidate whether pyritic sulfur behaves as a catalyst or a reactant in facilitating the production of short-chain gaseous alkanes.

In conjunction with these technologies, integrating CCUS is essential for ensuring that the additional methane produced, whether through ME-CBM or hydrous pyrolysis, does not exacerbate atmospheric CO_2 levels. Moreover, the hydrogen economy offers another avenue for clean energy development. Hydrogen produced through thermochemical processes involving kerogen, combined with CCUS to handle emissions, can provide a low-carbon pathway for green fuel production (Kumar *et al., 2024)*. These innovations ME-CBM, hydrous pyrolysis, sulfur catalysis, and hydrogen- represent critical steps toward refining clean fuel production, making the transition to sustainable energy more feasible.

Enhanced methane recovery can be significantly improved through CO_2 geo-sequestration (Corum *et al., 2013)*. This dual-purpose method captures and stores excess atmospheric CO_2 from fossil fuel combustion and aids in methane extraction. This technique helps mitigate global warming by reducing CO_2 levels in the atmosphere. Bio-sedimentary rocks, such as coal and shale, are particularly suited for this process due to their ability to adsorb large amounts of CO_2 in their micropores and mesopores. When CO_2 is injected into these formations, it displaces the methane adsorbed within the rock's structure, allowing the methane to be recovered from the wells. This process, known as enhanced methane recovery (EMR), offers a sustainable alternative to conventional hydrocarbon extraction, turning CO_2 from a pollutant into a resource that facilitates energy production.

Additionally, clay minerals, especially smectite, play a vital role in the effectiveness of CO_2 sequestration. With their high cation exchange capacity, large surface area, and inherent environmental benefits, natural and synthetic smectite clays act as efficient adsorbents for CO_2. These clays enhance the geo-sequestration process by capturing CO_2 within their structure, making coal seams and shale beds more effective storage sites. This combination of CO_2 sequestration and enhanced methane recovery improves methane yield and provides a viable pathway for reducing atmospheric CO_2, aligning with global climate goals.

Furthermore, integrating this process with hydrogen production technologies could advance clean energy development. By coupling CO_2 geo-sequestration with hydrogen extraction, it is possible to create a synergistic system that supports methane recovery, sequesters carbon, and produces hydrogen as a clean fuel. Combining enhanced methane recovery, CO_2 sequestration, and hydrogen production, this holistic approach could play a pivotal role in transitioning to a low-carbon energy future.

2. Hydrogen Energy

Hydrogen fuel is rapidly emerging as a critical component of the future energy landscape due to its high energy density and versatility. With a calorific value of 141.9 kJ/g, hydrogen outperforms traditional fuels like petrol (47 kJ/g) and natural gas (54 kJ/g), making it a highly efficient energy carrier (Kumar *et al.*, 2023). Despite its association with fossil fuels, coal remains a cost-effective and abundant feedstock for hydrogen production and storage, contributing to developing what is often termed "black hydrogen." Several techniques are employed to extract hydrogen from coal, including coal gasification, pyrolysis, liquefaction, and integrated gasification combined cycle (IGCC). While gasification and pyrolysis primarily produce "grey hydrogen," their environmental impact can be mitigated by employing CCUS technologies, resulting in "blue hydrogen" with significantly reduced carbon emissions.

For a cleaner approach, "green hydrogen" can be generated from coal through innovative techniques such as coal slurry electrolysis, where hydrogen is produced in its pure form at the cathode. High-rank, vitrinite-rich coals with oxygenated functional groups are preferred for this method due to their superior hydrogen storage capabilities. Additionally, advanced materials like single-walled carbon nanotubes (SWCNTs) and carbon nanocomposites show great potential for efficient hydrogen storage (Sahoo *et al., 2023)*. However, further optimization regarding binding energy and molecular structure is needed to maximize storage efficiency. Active carbon is another viable option for hydrogen storage but requires precise moisture control to perform effectively.

Moreover, integrating coal-based hydrogen production with renewable energy sources can significantly enhance environmental sustainability. By using renewable power—such as wind or solar energy—in processes like coal gasification, the carbon footprint of hydrogen production can be minimized, giving rise to a more sustainable approach known as "green coal hydrogen." This concept blends coal's energy potential with renewables' environmental benefits, creating a more circular and less carbon-intensive system for hydrogen generation.

Thus, coal, often viewed solely as a contributor to environmental degradation, should instead be seen as a "*Black Diamond"* with untapped potential in the hydrogen economy. Coal can support the transition to a cleaner energy future while contributing to global carbon reduction goals when used responsibly and paired with CCUS and renewable energy technologies. This approach transforms coal from an outdated energy source into a strategic asset for sustainable hydrogen fuel solutions.

3. Shale Gas

Shale gas and CBM represent a promising green fuel alternative due to their comparatively lower CO_2 emissions when juxtaposed with traditional fossil fuel combustion. However, the complex interplay between shale's organic and inorganic microstructure greatly influences gas production efficiency. Key factors such as shale brittleness, pore geometry, pyrolyzable organic carbon content, aliphatic hydrogen concentration, and mineral composition are critical in determining its capacity to produce methane and other hydrocarbons (Merey and Sinuyac, 2016).

Quartz is a vital mineral that enhances the brittleness of shale formations, making them more susceptible to hydraulic fracturing (fracking). This brittleness facilitates the release of trapped methane, improving overall gas recovery. Additionally, clay minerals, particularly smectites, play a significant role in gas adsorption due to their large surface area and cation exchange capacity. Smectites act as efficient adsorbents, sequestering methane in their mineral lattice and releasing it during gas production, enhancing the overall yield.

Solid bitumen from oil shale may also contribute to early hydrocarbon production via hydrous pyrolysis. This process, which simulates natural hydrocarbon generation by heating organic matter in the presence of water, holds promise for extracting thermogenic methane. However, the efficiency of bitumen in hydrocarbon production is still under scientific review.

Integrating CCUS into shale gas operations is another crucial step in reducing the environmental footprint of this resource. Shale gas extraction can be made even more environmentally viable by capturing the CO_2 emissions generated during shale gas production and storing them in geological formations.

As with other forms of methane production, shale gas could be coupled with hydrogen technologies to reduce carbon emissions further. For example, hydrogen produced through steam reforming of methane, combined with CCUS, results in "blue hydrogen"a cleaner energy alternative. These advancements make shale gas a transitional energy resource and a vital player in a low-carbon, hydrogen-driven future.

4. Geothermal Energy

Geothermal energy is gaining recognition as a reliable and sustainable green energy source. Although its availability is geographically limited to tectonically active regions, it offers a stable and continuous method for generating electricity, heating, and cooling with minimal environmental impact. Geothermal power plants tap into high-temperature resources deep within the Earth's crust, utilizing steam or hot water to drive turbines and generate electricity. This process is immaculate, producing little to no air pollution or greenhouse gas emissions, making it an attractive alternative to fossil fuels.

The integration of geothermal energy with solar power presents an innovative approach to improving the efficiency of geothermal power plants, particularly when utilizing low-grade geothermal resources. This hybrid system can help overcome the limitations of low-temperature geothermal wells by supplementing the energy input required for electricity generation or even hydrogen production. Solar energy can raise the temperature of geothermal fluids, enhancing the efficiency of the system and reducing reliance on fossil fuels.

Hydrogen production through geothermal energy is an up-and-coming area of research. Using geothermal heat to drive processes like water electrolysis or thermochemical cycles can provide a renewable pathway for producing hydrogen, often called "green hydrogen". However, large-scale hydrogen production using geothermal energy remains economically and technologically challenging. Current geothermal systems, especially those relying on low-grade resources, require significant thermodynamic and technological upgrades to make hydrogen production viable and sustainable.

Technological improvements, such as advanced heat exchangers, enhanced geothermal systems (EGS), and optimized fluid extraction methods, are essential for maximizing energy efficiency and minimizing operational costs. Coupling geothermal with carbon CCUS technologies could further reduce emissions and improve the sustainability of hydrogen production from geothermal sources. By capturing any CO_2 emissions generated during the energy conversion processes, geothermal systems can contribute to carbon-neutral or even carbon-negative hydrogen production.

As research and development in geothermal-solar hybrids and CCUS technologies progress, geothermal energy could become a key player in the green hydrogen economy, offering a stable and environmentally friendly option for large-scale energy production. This integrated approach highlights geothermal energy's potential not just as a clean electricity source but as a cornerstone for sustainable hydrogen fuel production in the future.

Concluding Remarks

Exploring alternative energy sources, such as CBM, shale gas, hydrogen production from coal, and geothermal energy, reveals a promising pathway toward a more sustainable and low-carbon energy future. Each resource presents unique opportunities and challenges, underscoring the need for an integrated approach that combines various technologies and practices. Continued investment in research and development is crucial to advancing technologies that improve the efficiency of methane recovery and hydrogen production, prioritizing innovations such as microbially-enhanced techniques, hydrous pyrolysis, and CCUS to optimize resource extraction and reduce carbon emissions. Developing hybrid systems that combine renewable energy with fossil fuel resources can enhance energy efficiency and sustainability; for instance, integrating solar power with geothermal energy or coal-based hydrogen production can significantly reduce the carbon footprint of these processes. Governments should create supportive regulatory environments and policy frameworks that encourage the adoption of cleaner energy technologies, including incentives for companies to invest in CCUS technologies and renewable energy integrations, alongside clear guidelines for environmentally responsible practices in fossil fuel extraction. Engaging the public and stakeholders in discussions about the benefits and challenges of transitioning to greener energy sources is essential, as increased awareness can drive community support for projects prioritizing environmental sustainability and energy resilience. Ongoing monitoring and assessment of the environmental impacts of these energy sources are necessary to ensure compliance with sustainability goals, including evaluating the effectiveness of carbon capture technologies and the ecological implications of energy extraction processes. Future directions should focus on enhancing the synergy between energy sources, investigating integrating geothermal energy with hydrogen production to maximize resource utilization while minimizing emissions, and advancing carbon capture and storage technologies to ensure widespread adoption. Additionally, exploring the potential of EGS and low-temperature geothermal resources can broaden the geographic range of geothermal energy utilization, making it a more accessible option for clean energy generation. While significant challenges remain, the diverse energy resources discussed offer substantial opportunities for contributing to a sustainable energy future. By adopting a comprehensive approach that combines innovation, regulatory support, and public engagement, we can create a robust energy landscape that effectively addresses climate change while meeting the growing energy demands of our society.

References

Adsul, T., Ghosh, S., Kumar, S., Tiwari, B., Dutta, S., & Varma, A. K. (2023). Biogeochemical controls on methane generation: A review on Indian coal resources. Minerals, 13(5), 695. https://doi.org/10.3390/min13050695

Agarwal, N., & Gupta, P. (2021). Carbon capture and sequestration: A comprehensive review. International Journal of Research in Applied Science and Engineering Technology, 9, 2321–9653.

Bachu, S. (2000). Sequestration of CO_2 *in geological media: Criteria and approach for site selection in response to climate change. Energy Conversion and Management, 41, 953–970.*

Corum, M. D., Jones, K. B., & Warwick, P. D. (2013). CO2 sequestration potential of unmineable coal—State of knowledge. Energy Procedia, 37, 5134–5140.

Ghosh, S., Adsul, T., & Varma, A. K. (2023). Organic matter and mineralogical acumens in CO_2 *sequestration. In Inamuddin, & T. Altalhi (Eds.), Green sustainable process for chemical and environmental engineering and science: Carbon dioxide capture and utilization (pp. 561–594). Elsevier. https://doi.org/10.1016/B978-0-323-99429-3.00016-3*

Ghosh, S., Adsul, T., Tiwari, B., Kumar, D., & Varma, A. K. (2024). Exploring geochemical signatures in production water: Insights from coal bed methane and shale gas exploration—A brief review. Methane, 3(1), 172–190. https://doi.org/10.3390/methane3010011

Gupta, A., & Paul, A. (2019). Carbon capture and sequestration potential in India: A comprehensive review. Energy Procedia, 160, 848–855.

Hatcherian, J., Adsul, T., Hackley, P., Ghosh, S., & Varma, A. K. (2023). Impact of pyrite-sourced sulfur on catagenesis in gilsonite undergoing hydrous pyrolysis. In Bulletin of the Geological Society of Greece, Special Publication, 12, 70. Abstract published at the 2023 Joint 74th ICCP and 39th TSOP meeting, University of Patras, Greece.

Kumar, D., Adsul, T., Ghosh, S., & Varma, A. K. (2024). Coal for hydrogen production and storage. In Inamuddin, & T. Altalhi (Eds.), Solid▯gaseous biofuels production (pp. 487–524). Wiley-Scrivener. https://doi.org/10.1002/9781394204816.ch19

Leung, D. Y. C., Caramanna, G., & Maroto-Valer, M. M. (2014). An overview of the current status of carbon dioxide capture and storage technologies. Renewable and Sustainable Energy Reviews, 39, 426–443.

Lewan, M. D. (1993). Laboratory simulation of petroleum formation: Hydrous pyrolysis. In Organic geo-

chemistry: Principles and applications (pp. 419–442). Springer.

Lewan, M. D. (1997). Experiments on the role of water in petroleum formation. Geochimica et Cosmochimica Acta, 61(17), 3691–3723. https://doi.org/10.1016/S0016-7037(97)00176-2

Ma, X., Zheng, J., Zheng, G., Xu, W., Qian, Y., Xia, Y., Wang, Z., Wang, X., & Ye, X. (2016). Influence of pyrite on hydrocarbon generation during pyrolysis of type-III kerogen. Fuel, 167, 329–336. https://doi.org/10.1016/j.fuel.2015.11.069

Merey, S., &Sinuyac, C. (2016). Analysis of carbon dioxide sequestration in shale gas reservoirs by using experimental adsorption data and adsorption models. Journal of Natural Gas Science and Engineering, 36, 1087–1105.

Sahoo, A., Adsul, T., Ghosh, S., & Varma, A. K. (2024). Microstructural maneuvering for bioenergy production. In Inamuddin, & T. Altalhi (Eds.), Solid gaseous biofuels production (pp. 299–332).Wiley-Scrivener. https://doi.org/10.1002/9781394204816.ch12

White, C. M., Smith, D. H., Jones, K. L., Goodman, A. L., Jikich, S. A., LaCount, R. B., et al. (2005). Sequestration of carbon dioxide in coal with enhanced coalbed methane recovery: A review. Energy & Fuels, 19(3).

HEALTH TIPS

Sugar – the latest culprit

How to find out how much sugar you can eat ?

Its not possible to add how much sugar you are eating in your diet every day in every neal. But it is possible to acquaint with the recommendations for healthy eating, such as minimizing eating of processed foods, and eating more whole fruits and vegetables aned whole grain products.

The sugar in the whole apple results in a slow increase in our sugar levels. Bur apple juice causes a sudden spike in our sugar levels putting a strain on our insulin system. From metabolic point of view, its much easier for our body to process the sugar when it's in the form of an apple rather than juice. When sugar is released slowly, our body is able to metabolize it and does not store it as fat.

EXPLORING DECARBONIZATION STRATEGIES FOR INDIA'S INDUSTRIAL SECTORS : PATHWAYS TOWARDS SUSTAINABLE DEVELOPMENT

Sujoy Chattaraj[1,*] and Rajnish Kumar[1,2]

Abstract

The Paris Agreement, an international treaty adopted in December 2015 at the UN Climate Change Conference (COP21) in Paris, France, and which entered into force on 4thNovember 2016, aims to limit the increase in global temperature to 1.5°C above pre-industrial levels. This goal is set with the understanding that such a limitation would significantly reduce the risks and impacts of climate change. The increase in CO_2 concentration in the atmosphere is considered one of the prime reasons for global warming. The concentration of CO_2 in the atmosphere has increased from 384 ppm in the year 2007 to 425 ppm in 2024 and is expected to reach 550 ppm by the year 2050. In response, the deployment of advanced carbon capture, utilization, and storage (CCUS) technologies has become critical to achieving the decarbonization goals necessary for meeting net-zero emission targets.

CO_2 capture technology is mainly divided into three types of technologies according to the source of capturing, viz., pre-combustion, post-combustion, and oxy-fuel combustion. Each capture technology has its own set of advantages and limitations in terms of implementation and cost. However, the post-combustion CO_2 capture has shown to be the most promising in existing power plant settings. Solvent absorption, pressure and/or temperature swing adsorption, low-temperature distillation, membrane separations and synthetic hydrate formations are among the available post-combustion CO_2 capture technologies that have been discussed so far. India, currently the third-largest emitter of CO_2 globally, is projected to remain heavily reliant on fossil fuel-based energy sources for the foreseeable future. This continued dependency underscores the critical need for implementing CCUS technologies to mitigate environmental impacts. This article provides a comprehensive analysis of potential CO_2 emission sources, evaluates the technological advancements in CO_2 capture, and explores the utilization pathways and storage solutions tailored to India's unique energy and industrial landscape. By addressing the country-specific challenges and opportunities, this paper presents carbon capture as an essential tool for achieving long-term carbon neutrality and sustainable development.

Keywords : *CO_2 Capture, Sustainability, Net Zero, Scale-up, Sequestration, Utilization.*

[1]Gas Hydrate Research Laboratory, Department of Chemical Engineering, Indian Institute of Technology Madras, Chennai – 600 036, India.

[2] School of Sustainability, Indian Institute of Technology Madras, Chennai – 600 036, India

*Corresponding Author, Email: chattaraj.sujoy@gmail.com

Introduction

Climate change, driven by rapid industrialization and technological growth, is one of the greatest challenges of the past few decades. The Industrial Revolution led to heavy reliance on fossil fuels, increasing greenhouse gas (GHG) atmospheric concentrations. Since 1970, GHG levels have risen by over 115%, primarily due to human activity. Among these, CO_2 is the most significant contributor, surpassing other gases like methane (CH_4), nitrous oxide (N_2O), halocarbons, and sulphur hexafluoride (SF_6). Access to secure, reliable, and affordable energy remains critical for economic and sustainable development. Among others, CO_2 alone contributes more than 60% to the global warming. Masson- Delmotte et al., (2014) reported that CO_2 accounts for 76% of the global GHG emission among which energy sector, agriculture, forestry and other land use, industry, transport and building sectors are the major contributors of the global GHG emissions. Considering CO_2 emissions from all the sectors, 35% of the total CO_2 emission is from the energy sector only.

The atmospheric concentration of CO_2 was about 280 parts per million by volume (ppmv) in the pre-industrial era and it has increased to about 421 ppmv in the year 2022 and expected to increase 550 ppmv by the year 2050 (Yang *et al., 2016).* It will reach around 750 ppmv by the year 2100. To reduce greenhouse gas emissions and adapt to climate change, the Paris Agreement treaty was adopted in December 2015 at the UN Climate Change Conference (COP21) in Paris, France, which aims to restricting the temperature increase by 1.5°C to control the global warming over pre-industrial levels, understanding that this restriction would greatly decrease climate change risks and impacts. However, in current global deployment scenario is still not sufficient to meet the goal of net-zero CO_2 emissions by 2050 (Hong, 2022). However, to achieve the net zero emission target set by UNFCCC and to keep global CO_2 concentration below 450 ppmv by 2050, it has become necessary to capture the anthropogenic CO_2 from both high and low-concentration CO_2 sources. Hence, in this alarming scenario tree plantation, forests preservation, focus towards enhancement of renewable energy production, implementation of energy efficient technologies, implementation of carbon credit in every industrial sectors, carbon capture and storage (CCS) /carbon capture, utilisation and storage (CCUS) etc. are the viable options towards reduction of global CO_2 emissions. However, CCUS are considered as most viable option among all. CCS involves the integrated process of three stages, viz., capturing of CO_2 from the industrial sources followed by, transporting it to a storage location, and lastly long-term storage by isolating from the atmosphere (Metz *et al., 2005)* and the terms CCUS includes the utilisation of captured CO_2 for other applications (IEA, 2021). CCS (carbon capture and storage) was originally used to separate CO_2 from methane that was collected from natural gas reservoirs in the 1920s. In order to reduce anthropogenic CO_2 emissions, CCS was initially proposed in 1977. There are five different types of CO_2 capture systems that have been reported to date, including pre-combustion, post-combustion, oxygen fuel combustion, industrial separation, chemical cycle combustion, and direct air capture (DAC). All the existing capture technologies are employed based on the source and concentration of CO_2. There are a few technologies which are commonly implemented in CO_2-capture technology, including absorption method, adsorption method, membrane separation, cryogenic/low-temperature distillation and hydrate formation. Each capture technology has its own set of advantages and limitations in terms of implementation and cost.

CO_2 capture, sequestration, and utilization are all combined and integral parts of the CCUS process. Hence, the capture process individually does not provide a solution towards CO_2 mitigation unless it is stored in different geological formations or is utilized. India, following China and the United States, ranks as the third-largest emitter of carbon dioxide globally, contributing approximately

2.6 gigatonnes per annum (Gtpa) of CO_2. A significant portion—about 1.6 gigatonnes per annum (Gtpa) or 60% of these emissions is attributed to the power generation and industrial sectors. The remaining 40% arises from other sectors, such as agriculture, transportation, and construction, alongside emissions from dispersed point sources across various industries and the rapid pace of urbanization. India's industrial expansion has been a key driver of these emissions, with total CO_2 emissions from the industrial sector estimated at 2.6 Gtpa in 2020. India's continued reliance on coal for power generation—responsible for nearly 70% of the country's electricity—further exacerbates its carbon footprint. Accelerated urbanization also contributes to the country's CO_2 emissions, with India expected to add nearly 416 million people to its urban population by 2050. This rapid growth in urban areas is increasing energy consumption and transportation demands, both of which are major contributors to greenhouse gas emissions. Hence, addressing emissions from these sectors will be crucial in mitigating India's overall carbon output as the country continues to modernize and expand its industrial base. The present study discusses prospective sources of CO_2 emissions and the technologies available for CO_2 capture, utilization, and potential storage from the Indian perspective.

2. Industrial Systems for CO_2 Capture/Separation

Currently available technological pathways for CO_2 capture are industrial separation, post-combustion, pre-combustion, oxyfuel combustion, chemical looping combustion (CLC), and DAC. Among these, industrial separation and post-combustion capture are the commonly used technologies, followed by pre-combustion, oxyfuel combustion and DAC. The industrial sector is considered as the single largest source of CO_2 emission. In general, natural gas processing, fertilizer, bioethanol and ethylene oxide production are considered high concentration CO_2. However, the iron and steel-making industry, cement and Aluminium industries are considered the world's largest emitters of CO_2 in the industrial processes.

2.1. Pre-combustion CO_2 capture

The pre-combustion CO_2 capture process treats synthesis gas (syngas), primarily composed of carbon monoxide (CO) and hydrogen (H_2). This method relies on syngas production, CO_2 removal, and H_2 combustion. By adding steam and reducing temperature in the water-gas shift reaction, CO is converted to CO_2, enhancing H_2 output. Pure H_2 is then used in a combined cycle for energy generation after separating the CO_2 and H_2 streams and transferring them to the compression unit. Pre-combustion technology, which has been employed in chemical industries for nearly a century, typically involves pre-treating coal or natural gas through partial oxidation with steam and/or air to produce syngas. The CO produced subsequently undergoes a water-gas shift (WGS) reaction with steam in a catalytic reactor, yielding CO_2 and additional H_2.

Steam reforming : $CH_4 + H_2O \rightleftharpoons CO + 3H_2$

Partial oxidation: $CH4 + \frac{1}{2} O_2 \rightleftharpoons CO + 2H_2$

WGS reaction: $CO + H_2O \rightleftharpoons CO_2 + H_2$

The pre-combustion capture technology is extensively used to generate hydrogen and fertilisers. Pre-combustion capture's biggest drawback, however, is that it necessitates a chemical plant in front of the turbine. Complex chemical reactions frequently result in additional plant shutdowns, which can limit power output. Non-gaseous feedstocks, the need for a cleansed gas stream, and potentially expensive scrubbing for high NOx emission control are further drawbacks. Although pre-first combustion's fuel conversion stages are more complex and expensive, the higher CO_2 concentrations in the gas stream and higher pressure make the separation process simpler (Kanniche *et al., 2010).* In power plants using integrated gasification combined cycle (IGCC) technology, pre-combustion is extensively used.

2.2. Post-combustion CO_2 capture

Post-combustion systems capture CO_2 from flue gases produced after burning primary fuels, primarily in pulverized coal (PC) or natural gas combined cycle (NGCC) power plants, using organic solvents like amines. Flue gas streams have a high flow rate (5 to 10 times greater than typical CO_2 removal streams) but contain a low CO_2 concentration (3-33% by volume) and partial pressure (0.03 to 5 bar). These gases also include air pollutants such as SO_2, NOx, particulates, and trace metals that must be removed before CO_2 capture. In the capture process, the gas mixture contacts the solvent in the absorber. The CO_2-rich solvent then moves to a regenerator (stripper) via a heat exchanger, where it is heated to 100-120°C using steam from a reboiler. After CO_2 is desorbed, the "lean solvent" is recirculated back to the absorber. Regenerating the solvent at atmospheric pressure requires substantial thermal energy.

2.3. Oxy-fuel combustion CO_2 capture

Oxy-fuel combustion systems combust the primary fuel with oxygen rather than air to produce a flue gas that is primarily made up of water vapour and CO_2. Because of the high CO_2 concentrations in the gas stream, it is easier to separate CO_2 and requires more energy to separate oxygen from air. To regulate the temperature of the Oxy-fuel combustion CO_2 capture process, some of the flue gas might be mixed with the oxygen in place of nitrogen or air. Despite the benefits of oxy-fuel combustion capture, such as decreased NO_X emissions and higher CO_2 purity with smaller gas volumes due to greater density, the process requires a lot of energy to produce high-purity oxygen. Furthermore, the process is more expensive since it requires construction materials that can endure high temperatures and recycle flue gases.

2.4. Chemical looping combustion (CLC) CO_2 capture

In order to minimise direct contact between fuel and air, the Chemical Looping Combustion (CLC) idea relies on the transfer of oxygen from the combustion air to the fuel via an oxygen carrier in the form of a metal oxide. The CLC process was initially created for gaseous fuels, such natural gas and syngas, before being expanded to solid fuels, like coal and biomass, and subsequently liquid fuels, like oil and ethanol. Two coupled reactors, the air and fuel reactors, make up the CLC system. Fuel gas is oxidised in the fuel reactor by a metal oxide through the chemical reaction is as follow:

$$CH_4\ (CO,\ H_2) + MeO \rightarrow CO_2 + H_2O\ (CO_2,\ H_2O) + Me$$

CO_2 and H_2O are present in the fuel reactor's exit gas stream. With little energy loss during component separation, virtually pure CO_2can be obtained after water condensation. CO_2 and H_2O are present in the fuel reactor's exit gas stream. With little energy loss during component separation, virtually pure CO_2 can be obtained after water condensation.

$$Me + \tfrac{1}{2}O_2 \rightarrow MeO$$

CuO, CdO, NiO, Mn_2O_3, Fe_2O_3, and CoO are the different metal oxides that have been reported so far for the CLC CO_2 capture process. The only drawback of the overall CLC process is that the oxygen carriers are subjected to strong chemical and thermal stresses in every cycle, and the performance could be poor after enough cycles in use.

2.5. Direct air capture (DAC)

Direct air capture technologies capture CO_2 directly from the atmosphere. DAC technology is first introduced by Lackner in the year 1999 as an alternative way of conventional ways of CO_2 capture (Lackner *et al., 1999).* To date, two types of DAC technology have been employed commercially. One is liquid solvent base and other is sorbent base technology. In the liquid solvent-based method, diluted CO_2 (~ 420 ppm in the atmosphere) is first absorbed into a potent alkaline liquid solvent, such as $Ca(OH)_2$ solution, in an adsorption column to create $CaCO_3$. This $CaCO_3$ can then be separated, dried, and heated to 900 °C to create CaO and release concentrated CO_2. For $Ca(OH)_2$ regeneration, CaO is hydrated in a slaker unit. Although the solvent-based method for the DAC process is considered a proficient method in terms of adequate CO_2, it consumes high energy for $Ca(OH)_2$ regeneration. The reaction occurs during liquid solvent-based DAC method (Hong, 2022).

Absorption: $Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$

Calcination: $CaCO_3 \rightarrow CaO + CO_2$

Slaking: $CaO + H_2O \rightarrow Ca(OH)_2$

On the other hand, in solid sorbent method CO_2 molecules can be taken out of the entering gas mixture by interacting with hierarchically porous materials.

3. CO_2 Capture Technologies

To date, there are five primary technologies available for CO_2 capture, which include absorption, adsorption process, membrane separation, low-temperature distillation and hydrate formation. Among all of these, the liquid solvent-based absorption method is the most widely used method for, to date, CO_2 capture. Figure 1 shows the technologies available for CO_2. However, all the technologies have their own advantages and disadvantages depending upon the source and concentration of CO_2 to be separated and the application area. A variety of capture techniques has been applied since the ideal CO_2-capture procedure varies depending on the emission scale, concentration, pressure, and other factors at the CO_2 source site.

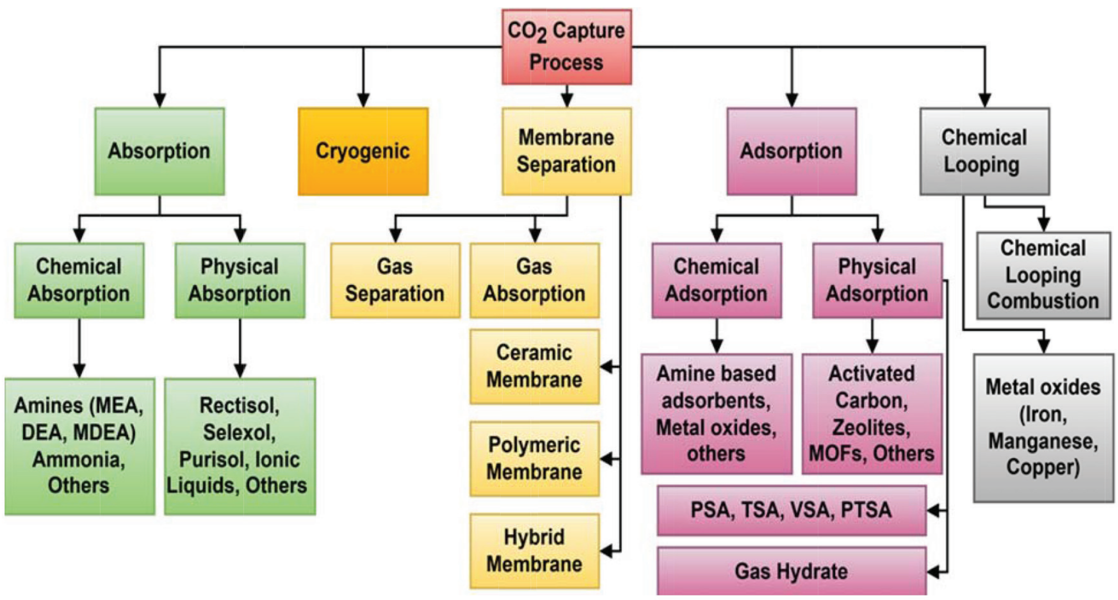


Figure 1: Different carbon capture methods

3.1. Solvent-based absorption methods

The chemical absorption is most well-known method of CO_2 capture. It depends on a chemical solvent and carbon dioxide reaction. Alkanolamines, such as monoethanolamine (MEA), diethanolamine (DEA), or methyl diethanolamine (MDEA) in aqueous solution, are often used solvents. There are two steps to the procedure. The solvent in the absorber reacts with the flue gas in the initial stage to absorb CO_2. The rich loading solution is then sent to the stripper, where it is heated to regenerate CO_2. The solution without CO_2 (lean-loading solution) is sent back to the absorber column. The desorber desorbs a high-purity carbon dioxide stream for compression, storage, or further utilization.

3.2. Adsorption

A separation is achieved through the adsorption process, in which one or more components of a gas or liquid stream are adsorbed on the surface of a solid adsorbent. The solid particles absorb gas constituents as the gas is passed through the bed. The process is exothermic, therefore by raising the temperature, it is possible to regenerate the adsorbents through desorption. In the post-combustion adsorption method, CO_2 molecules are selectively separated from a gas mixture either by forming a chemical bond with the sorbent (i.e., chemisorption is preferred at high temperatures) or by adhering to the surface of the adsorbent matrix by weak intermolecular forces (i.e., physisorption is preferred at lower temperatures) (Ünveren *et al., 2017).* Changing the sorbent's temperature or pressure to move the CO_2 adsorption equilibrium process is known as temperature swing adsorption or pressure swing adsorption, respectively. Its advantages include the ability to remove CO_2 by around 90% and lower energy and operational costs. On the other hand, its drawbacks include the complexity of the process setup. A detailed discussion on adsorption methods has been discussed later.

3.3. Membrane Separation :

Through a permeable or semipermeable medium, membrane separation can be utilised to selectively separate CO_2 from the flue gas using chemical and physical mechanisms such as solution-diffusion transport, molecular sieving, surface diffusion, and Knudsen diffusion. Compared to other existing technologies, the membrane separation process requires the least energy per unit mass of CO_2 captured, between 0.5 and 6 MJ/kg of CO_2. The fundamental benefit of this process is that, even when capacity is dropped to 10% of the original design value, it is very capable of maintaining product purity. Additionally, it is a very dependable procedure for on-stream gas separation that is very inexpensive. This process' limitations include its ineffectiveness and the low purity of CO_2 it produces (Mondal *et al., 2012).* Inorganic membranes, polymeric membranes, mixed matrix membranes (MMMs), facilitated transport membranes (FTMs), and gas-liquid membrane contactors are among the different types of membranes that have been created for CO_2 capture (Belaissaoui and Favre, 2014). Zeolite, oxides (such as Al_2O_3, titanium dioxide (TiO_2), zirconium oxide (ZrO_2), carbons, or MOFs are used as the top membrane layer in inorganic membranes, which are cast on a porous substrate (often metal or ceramic) for mechanical stability. Inorganic membranes offer good mechanical stability and great thermal stability, but their low CO_2 permeability and expensive manufacturing prevent them from being scaled up *(Spigarelli and Kawatra, 2013).*

3.4. Cryogenic Distillation/Separation :

The procedure of cryogenic separation is frequently used to remove CO_2 from streams with high CO_2 concentrations, usually greater than 50%. To create liquid CO_2 with a high purity (99.99% vol.) that is suitable for transportation and storage, CO_2 must first be separated from other components present in the flue gas through several stages of compression and cooling at very low temperatures (-100°C to -135°C) and high pressures (101 bar to 203 bar) (Leung et al., 2014). This separation method can be used with CO_2 collection systems that use oxyfuel combustion or pre-combustion. The key advantages of this method are that it can operate at atmospheric pressure and doesn't require a chemical adsorbent. Because CO_2 is produced along with other gases such SOx, NOx, and H_2O that severely interfere with cooling and cause corrosion, fouling, and plugging, it is difficult to use this technology for CO_2 capture.

3.5. Hydrate Formation :

Guest gas molecules of small size, such as nitrogen (N_2) and carbon dioxide (CO_2), are enclosed by an open lattice of water molecules in gas hydrates, solid, non-stoichiometric inclusion compounds. Most of the expanding greenhouse effect is caused by CO_2, one of the many possible guest molecules. Therefore, creating effective CO_2 capture techniques is essential to addressing this significant environmental concern and CO_2 capture by these hydrates is a viable alternative option.

4. Source of Carbon Emissions in India

India's carbon emissions are primarily driven by its energy, industrial, and transportation sectors. The power sector remains the largest contributor, accounting for nearly 40% of total CO_2 emissions due to its reliance on coal-based thermal power plants. The industrial sector is the second-largest emitter, responsible for about 25%, with the steel and cement industries being significant contributors due to energy-intensive production processes. The transportation sector also adds substantially to emissions, largely from road transport. Meanwhile, agriculture and waste management contribute to methane (CH_4) and nitrous oxide (N_2O) emissions, making them key sectors in greenhouse gas production. Together, these sectors reflect the energy-dependent nature of India's economy and the challenges of decarbonization in the coming decades.

India's per capita carbon emissions are approximately 1.4 metric tons of CO_2 (tCO_2), significantly lower than the global average of 4.5 tCO_2 per capita. The industrial sector substantially contributes to India's energy-related carbon dioxide emissions, accounting for about 25% of the total emissions, making it the second-largest source after power generation. However, the country's aggregate carbon emissions are on an upward trajectory, primarily driven by developmental activities that increasingly rely on coal-based energy. Currently, India's coal-fired power plants, which contribute over 180 gigawatts (GW) to a total installed capacity exceeding 300 GW, are a key factor in this emissions growth. While projections suggest a future decline in the share of energy generated from fossil fuels, overall energy demand is expected to rise significantly. Estimates indicate that energy consumption could increase by 25–30% by 2030 and by as much as 60–70% by 2040. This anticipated growth poses significant challenges for India in balancing economic development with the imperative to reduce carbon emissions and transition to more sustainable energy sources. According to the CO_2 emission intensity data provided by the Central Electricity Authority (CEA) for the fiscal year 2021–2022, an assessment of the power sector was conducted across approximately 271 power plants. This evaluation utilized the actual plant load factor, which was determined to be 57.02%, to compute the respective emission values accurately. Notably, the top ten states in India account for a substantial 75% of the total CO_2 emissions generated by the electricity sector, with Maharashtra being the predominant contributor. Projections indicate that thermal power plants are expected to emit an estimated 1,200 metric tons per annum (mtpa) of CO_2 by 2030.

The steel sector in India is a significant contributor to the country's total carbon dioxide (CO_2) emissions, accounting for approximately 10% of the overall emissions. In 2019, direct CO_2 emissions from steel production were estimated at 240 metric tons per annum (mtpa). This substantial output is primarily attributed to the Indian steel industry's reliance on coal-based processes, specifically the blast furnace method and coal-based direct reduction techniques. Looking ahead, it is projected that both the demand for and production of steel in India will rise significantly, reaching an estimated 190–200 mtpa by 2030. Consequently, CO_2 emissions from the steel sector are anticipated to escalate, potentially reaching around 450 million metric tons annually by 2030. In 2023, India's cement sector remains a significant contributor to carbon emissions, with approximately 337 million tonnes of cement produced annually. The sector's emissions are expected to remain high due to its reliance on fossil fuels for energy, particularly coal and petcoke, which account for about 32% of the industry's total emissions. Cement production in India is projected to emit nearly 0.66 tonnes of CO_2 per tonne of cement. However, by adopting energy efficiency measures and renewable energy sources, this intensity could be reduced by 9% to 0.60 tonnes of CO_2 per tonne. Further reductions could be achieved by integrating alternative fuels such as biomass and municipal solid waste, potentially lowering emissions to 0.44 tonnes of CO_2 per tonne of cement by 2030. As of the most recent data, the chemical industry in India contributes approximately 250 million metric tonnes (MMT) of CO_2 emissions annually. This sector is heavily involved in energy-intensive processes such as the production of ammonia, methanol, and other petrochemical products. Additionally, the gasification sector, primarily coal-based, continues to generate significant emissions due to its role in synthetic fuel production. As per the IEA and CEEW report, in 2022, coal gasification has contributed approximately 80-100 MMT of CO_2

annually, with further increases expected as the sector grows. Despite these efforts, the sector's overall emissions trajectory indicates the need for carbon capture, utilization, and storage (CCUS) technologies to reach net-zero by mid-century.

5. Progress of India's CCUS Initiatives:

India has made notable strides in its Carbon Capture, Utilisation, and Storage (CCUS) initiatives over the past few years, marked by increased stakeholder interest and several collaborative efforts. Initially, CCUS in India faced challenges due to high costs, insufficient research, and a lack of policy support. However, the landscape began to shift significantly following the launch of Mission Innovation in 2015, which aimed to accelerate clean energy innovation and included carbon capture as one of its key focus areas. The Indian government has initiated several pilot projects and collaborations to foster CCUS development. Initiatives taken in India is summarized in Figure 2.

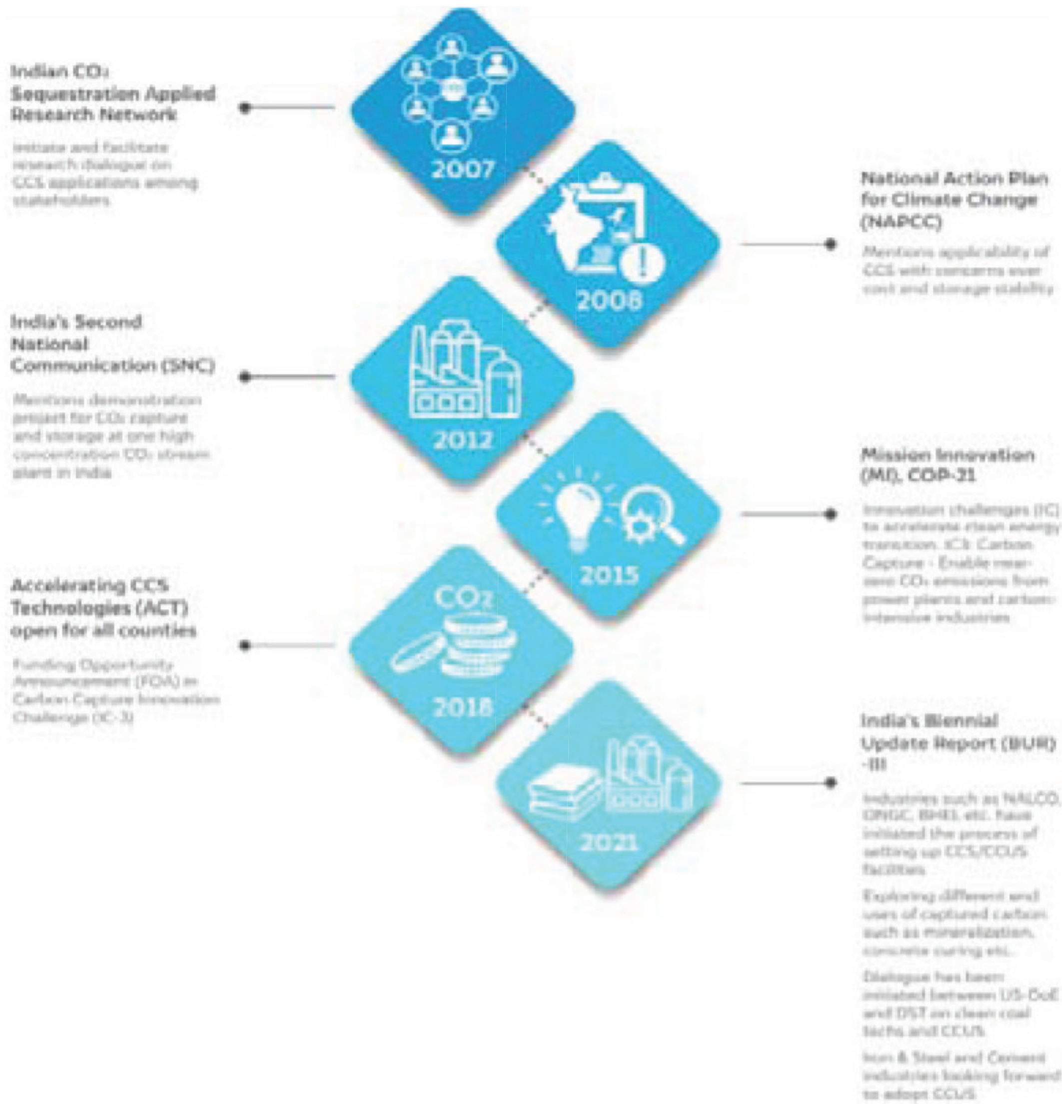


Figure 2 : Progress of CCUS initiatives in India (CEEW report, 2021)

For instance, public sector undertakings like the National Aluminium Company (NALCO) and the Oil and Natural Gas Corporation (ONGC) are actively exploring CCUS technologies. NALCO has launched a pilot sequestration plant, while ONGC is investigating enhanced oil recovery (EOR) methods using captured CO_2 from the Indian Oil Corporation's Koyali refinery. National Thermal Power Corporation (NTPC) has been at the forefront, with projects like the 300 MW coal-based power plant in Singrauli, which aims to capture 50% of its CO_2 emissions. Further, Indian government has allocated over ₹100 crores (approximately $13 million) for research and development in CCUS technologies. Collaborative efforts with international agencies and private companies have been key to accelerating this sector. The National Policy on Climate Change, launched in 2008, set the stage for carbon management technologies, with CCUS being a focal point. Furthermore, India's commitment to achieving net-zero emissions by 2070 emphasizes the importance of CCUS technologies in meeting climate goals. India aims to reduce its emissions intensity by 33-35% by 2030, based on 2005 levels, making CCUS a vital component of its strategy to achieve these targets while maintaining economic growth. The Ministry of Coal has identified the need for further research in CCUS and is collaborating with research institutes to innovate and optimize capture technologies.

6. Policy suggestions and mitigation strategies

India's total CO_2 emissions were about 2.88 gigatonnes in 2021, making it the third-largest emitter globally. By 2030, it is projected that India could emit 4.48 gigatonnes of CO_2 if no further mitigation measures are implemented. Implementing CCUS could capture up to 750 million tonnes of CO_2 annually by 2050, significantly contributing to India's net-zero emissions target. These strategies can help India transition to a low-carbon economy while promoting economic growth and ensuring energy security. To promote CCUS in India, a multi-faceted approach is needed that combines technological advancements, policy reforms, and economic incentives. Below are some policy suggestions and mitigation strategies that can drive CCUS adoption in the country.

Develop a Comprehensive CCUS Policy Framework : Indian government should establish a clear national strategy for CCUS, including defined goals, timelines, and pathways for deployment. Introduce mandatory emission reduction targets for key industrial sectors like steel, cement, and oil refining, which are major CO_2 emitters.

Subsidies and Incentives for CCUS Projects : Provide tax incentives and subsidies to industries adopting CCUS technologies. Offering capital grants or low-interest loans for pilot and commercial-scale projects can reduce the financial burden of implementing these technologies. Implement carbon pricing or carbon credits to provide financial incentives for industries to capture CO_2 rather than emitting it.

Enhance Public-Private Collaboration : Promote public-private partnerships (PPP) for CCUS research, development, and demonstration (R&D) projects. Collaborative efforts between the government, research institutes, and private players can drive technological advancements. Develop knowledge-sharing platforms to help Indian industries learn from global best practices, such as large-scale CCUS projects in the U.S., Norway, and Canada.

Infrastructure Development for CO_2 Transportation and Storage : Build the necessary infrastructure for CO_2 transportation pipelines and storage reservoirs. India should map and assess geological formations for potential CO_2 storage sites, such as unmined/abandoned coalbeds, depleted oil and gas fields and deep saline aquifers.

R & D Investment in Innovative CCUS Technologies : Invest in developing low-cost CCUS technologies tailored for India's coal-heavy energy sector. This includes advancing pre-combustion, post-combustion, and oxyfuel combustion technologies. Promote research and development into direct air capture (DAC) and the utilization of CO_2

in value-added products such as chemicals, fuels, and building materials.

International Cooperation and Technology Transfer : Leverage international agreements, such as those under the Paris Agreement, to access global funding and technical expertise for CCUS deployment. Seek financial and technical support from organizations like the Green Climate Fund and bilateral collaborations with countries like the U.S., U.K., and Japan, which are investing in CCUS technologies.

Public Awareness and Acceptance : Run public awareness campaigns to highlight the benefits of CCUS in reducing carbon emissions and its importance in meeting India's climate targets. Engage local communities in areas where CCUS infrastructure is planned to gain public acceptance and prevent opposition.

Industrial Decarbonization and Transition Support : Provide transition funds for sectors heavily reliant on fossil fuels (e.g., steel, cement) to adopt CCUS technologies. This will help them meet emission reduction targets while continuing to operate efficiently. Support decarbonization roadmaps for key industries, with sector-specific targets for CO_2 reductions by 2030 and 2050.

Carbon Market Mechanisms : Develop a domestic carbon market where industries can trade carbon credits generated by CCUS projects. This will not only incentivize reductions but also create a market-driven approach to achieving climate goals. India's domestic carbon trading market, initiated in 2023, could expand to include CCUS credits, encouraging businesses to invest in these technologies.

References :

Metz, B., Davidson, O., de Coninck, H.C., Loos, M., Meyer, L.A., Prepared by Working Group III of the Intergovernmental Panel on Climate Change (IPCC) (Eds.), 2005. IPCC Special report on carbon dioxide capture and storage. IPCC. Cambridge University Press.

Masson-Delmotte, V., Zhai, P., Pörtner, H.O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M., Waterfield, T. (Eds.), 2019. IPCC special report: Global warming of 1.5 °C. Intergovernmental Panel on Climate Change (IPCC).

Hong, W. Y., 2022. A techno-economic review on carbon capture, utilisation and storage systems for achieving a net-zero CO_2 emissions future. Carbon Capture Science & Technology 3: 100044.

Yang, G., Luo, H., Ohba, T., Kanoh, H., 2016. CO_2 capture by carbon aerogel–potassium carbonate nanocomposites. Int. J. Chem. Eng. 2016, 4012967.

IEA, 2021. About CCUS. IEA, Paris Available from: https://www.iea.org/reports/ about-CCUS (Accessed 30 October 2021).

Kanniche, M., R. Gros-Bonnivard, P. Jaud, J. Valle-Marcos, J.M. Amann and C. Bouallou, 2010. Pre-combustion, post-combustion and oxy-combustion in thermal power plant for CO_2 capture. Applied Thermal Eng., 30: 53-62.

Leung, D.Y.C., Caramanna, G., Maroto-Valer, M.M., 2014. An overview of current status of carbon dioxide capture and storage technologies. Renew. Sust. Energy Rev. 39, 426–443.

Ünveren, E.E., Monkul, B.¨O., Sarıo˘glan, S¸., Karademir, N., Alper, E., 2017. Solid amine sorbents for CO_2 capture by chemical adsorption: a review. Petroleum 3 (1), 37–50.

Mondal, M.K., H.K. Balsora and P. Varshney, 2012. Progress and trends in CO_2 capture/separation technologies: A review. Energy, 46: 431-441.

Belaissaoui, B., Favre, E., 2014. Membrane separation processes for post-combustion carbon dioxide capture: State of the art and critical overview. Oil Gas Sci. Technol. –Rev. IFP Energies nouvelles 69, 1005–1020.

REVIEW ON HIGH-TEMPERATURE CO_2 CAPTURE USING FLY ASH-INFUSED CAO-BASED SORBENT

Shishir Tiwary[1] and Soubhik Kumar Bhaumik[2]

Abstract

Global industrialization has caused rapid consumption of fossil fuels, leading to a sharp rise in CO_2 emission, thus creating an imperative environmental and geopolitical issue. Several methodologies have been developed for the last three decades to mitigate CO_2 from thermal power plant exhausts and other process industries. Among these, low-temperature capture (amine-based sorbent) is the most established and commercially employed in these sectors; however, it incurs huge energy penalties (20%–30% of the power plant output) in cooling the flue/fuel gas prior to the treatment. An emerging technique is high-temperature CO_2 capture (HTCC) using CaO-based sorbent that treats incipient gas at high temperatures of 600°C–950°C in pre & post-combustion operations. Though techno-economically in terms of uptake capacity, it suffers from sintering-induced agglomeration that reduces its performance and adversely impacts the solid inventory and plant operation under repeated carbonation and calcination cycles. Sorbent modifications using inert to inhibit sintering are being conducted to enhance morphological properties and disperse CaO particles. Infusion of coal fly ash (as inert material) to CaO has exhibited promising results in inhibiting agglomeration of particles and providing cyclic stability under multicyclic study.

Introduction

Global warming is one of the most urgent challenges faced by humanity, driven primarily by the rise in CO_2 emissions and other greenhouse gases (GHGs). Since 2022, emissions have surged to unprecedented levels, reaching 37.55 gigatons, leading to significant and far-reaching impacts. These include: (i) abnormal temperature increases causing intense heatwaves, which result in health issues, higher mortality rates, and strain on infrastructure; (ii) disruptions to agriculture due to altered precipitation patterns, leading to food insecurity in vulnerable regions; (iii) deteriorating air quality, causing respiratory problems and worsening public health; (iv) accelerated glacier and ice melt, contributing to rising sea levels and threatening coastal and low-lying areas; (v) ocean acidification, which affects marine life, particularly coral reefs and shellfish; and (vi) ecosystem disruptions, as many species struggle to adapt to these rapid changes.

[1] Senior Research Fellow, Department of Chemical Engineering, IIT (ISM) Dhanbad
Email: tiwaryshishir17@gmail.com
[2]Associate Professor, Department of Chemical Engineering, IIT (ISM) Dhanbad
Email: soubhikge@gmail.com

Table 1: Typical CO_2 concentration of flue gas from various sources [1]

Flue gas source	CO_2 concentration (%)	P (atm)
Coal-fired boilers	12-14	1
IGCC after combustion	12-14	1
Gas turbine	3-4	1
Natural gas-fired boilers	7-10	1
Hydrogen production	15-20	22-27
Steel production (blast furnace)	20-27	1-3
Aluminium production	1-2	1
Cement process	14-33	1

2.0. Existing CO_2 Capture Technologies

Several technologies exist, differing in unit operation and operating temperature. Based on temperature, these are broadly classified into cryogenic, low (LT), elevated (ET) and high temperature (HT) as described inTable 2.

A. Low Temperature :

Methods available for capturing CO_2 at low temperatures are described below :

Cryogenic Distillation: It is based on the principle of compression and cooling. This process cannot be used in post-combustion thermal power plants due to the lower CO_2 concentration (3%–20%) and an excessive amount of energy required for pre-cooling of CO_2 gas, which automatically increases the operational cost.

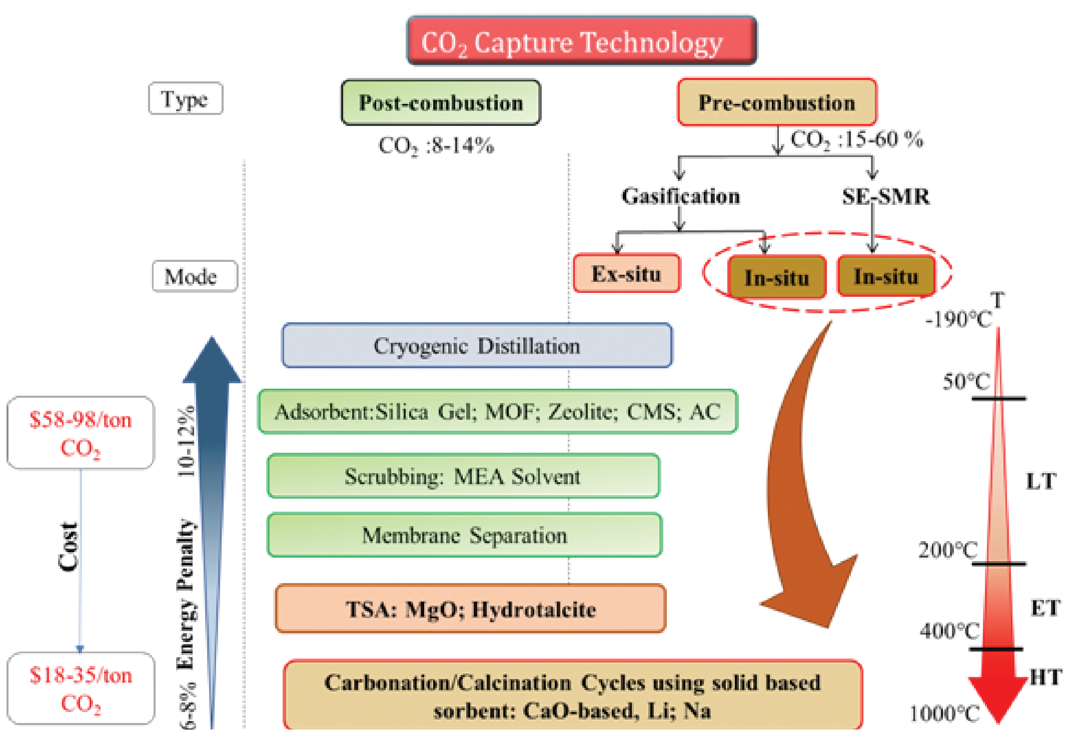


Figure 1 : Existing CO_2 capture technologies implemented at different temperatures [2]

Adsorption : There are a wide variety of adsorbents suitable for CO_2 capture, which include activated carbon, silica gel, amine-incorporated zeolites, etc. These sorbents adsorb CO_2 at low temperatures and high pressure via physical adsorption. However, they exhibit low selectivity for CO_2 during reaction and require high temperature (>300°C) for desorption.

Absorption : The conventional technology is a mono-ethanol amine (MEA) based absorption post-combustion process operating in the low (40°C–150°C) temperature range. MEA faces a severe energy penalty of 10% to 12% [3] incurred during the pre-cooling requirement of the flue gases for the absorption process and subsequent heating to 120°C–140°C for stripping off the absorbent [4], along with additional demerits of cost escalations due to corrosion, limited to small scale (102 tons/day) [5], environmental disposal issues caused by loss of solvent.

Membrane Separation : This technique employs the difference between the physical and chemical interaction occurring in a gas mixture component with the membrane material for the separation of gases.

B. Elevated Temperature

The sorbents suitable for elevated temperature capture are magnesium oxide (MgO) and hydrotalcites (HTlcs)/layered double hydroxides. Recently, the former has also been considered as a suitable candidate due to the low energy requirement for regeneration, economical and advancement in material science. However, it has low uptake capacity at elevated temperature, extremely low kinetics, poor thermal and mechanical stability in cyclability studies [15].

Table 2: Comparative study of sorbents based on operating conditions and uptake capacity[2]

Temperature	Sorbents	Operating Conditions/Enthalpy		Pros	Cons	Uptake Capacity (g/g)
		Adsorption/ Carbonation	Regeneration			
Low	Zeolite [6,7]	T = 15-35°C P= >2 bar $\Delta H^{\circ} = -(20 - 60)$ kJ/mol	T = 300°C	Suitable for post-combustion capture of CO_2 at lower temperature; High selectivity for CO_2	Operation complex for low pressure of CO_2 in the flue gas stream; Highly hydrophilic nature that reduces the adsorption performance	0.088-0.132
	Carbon molecular sieve [8]	T=20-40°C P=1 bar $\Delta H^{\circ} = -24$ kJ/mol	T=175-315°C P < 1.01325 bar	High thermal and chemical stability	Selective adsorption of $CO_2$is difficult in the presence of water; Expensive	1.474
	Solid supported amine sorbent [6,9]	T=25°C P=8 bar $\Delta H^{\circ} = -70$ kJ/mol	T=137°C P= 1 bar	High CO_2 adsorption capacity; High CO_2 selectivity	High regeneration cost; Corrosion of equipment; Oxidative degradation of amines	0.178-0.37
	Metal-organic framework [6,7,10]	T=38°C P=10 bar $\Delta H^{\circ} = -113.5$ kJ/mol	T=300-500°C	High surface area, large uptake capacity, and selectivity at high-pressure	Slower kinetics	0.559

	Carbon-based material (activated carbon) [6,11]	T=25°C P=1.01325 bar; $\Delta H^{\circ} = -14.98$ kJ/mol	T=100°C	Inexpensive; Insensitive to moisture; large surface area per unit volume	Reduced selectivity with increase in pressure; Uptake capacity highly sensitive to temperature	0.004-0.013
Elevated	Hydrotalcite [12,13]	T=200-400°C P=1 bar $\Delta H^{\circ} = -40$kJ/mol	T=500°C	High surface area and abundant basic sites	Expensive due to the complicated synthetic methods; Low adsorption capacities	0.022
	MgO [13]	T=200-400°C P=1 bar $\Delta H^{\circ} = -96$ kJ/mol	T=550°C	Lower regeneration temperature	Slow adsorption kinetics; Loss in surface area during regeneration	0.011
High	Lithium-based sorbent [14]	T=400-750°C P=1-50 bar $\Delta H^{\circ} = -141.97$ kJ/mol	T= >750°C	Higher durability and thermal stability	Poor reversibility; slow kinetics; Low surface area and large energy demand for thermal regeneration	0.33
	CaO[7]	T=650-700°C P=1-42 bar $\Delta H^{\circ} = -177.8$ kJ/mol	T=750-950°C	High-temperature capture; lower energy penalty; fast kinetics	Rapid deactivation and capacity loss due to sintering under repeated carbonation and calcination cycles.	0.78

The chemical formula of most utilized HTlcs for CO_2 capture at elevated temperatures is $(Mg)_{1-x}\cdot(Al)_x(OH)_2(CO_3)_{\frac{x}{2}}\cdot mH_2O$. This popularity is due to its better adsorption capacity, fast kinetics, hydrothermal cyclic stability, and ease of preparation over other HTlcs. Nevertheless, the enhancement of the capture capacity of HTlcs still remains a challenge, which involves searching for and optimizing the suitable alkali metal and the stabilizer [15].

C. High Temperature (Solid Sorbent)

Other technologies for post-combustion based on solid sorbent treat the nascent flue gas operating at elevated and high temperatures, by repeated cycling of capture through carbonation and regeneration via calcination. In comparison to the lithium zirconate and sodium-based sorbent and other metal oxides, CaO emerges as the foremost material as it surpasses others in uptake capacity (0.78g (CO_2) g sorbent–1); has rapid kinetics at high temperatures (600°C–1000°C), thermally stable, besides being inexpensive and abundantly available in the form of limestone [16].

3.0 . Calcium Looping Technology

It is a new, promising process for large-scale capturing CO_2 from fossil fuel-fired power plants. A schematic of a typical Calcium looping (CaL) system is given in Figure 2. It employs dual bubbling- or circulating fluidized bed systems. Temperature swing (TS) occurs during the transfer of $CaCO_3$ from the carbonator (600-700°C) to the calciner (900-950°C) and CaO from the calciner to the carbonator [17,18]. The main advantage of this process is that it utilizes the well-established fluidization technology for capturing CO_2 using an inexpensive limestone at high temperatures.

$$CBN: CO_2(g) + CaO(s) \rightarrow CaCO_3(s);\ \Delta H^{\circ} = -177.8\ \text{kJ/mol} \quad \text{(R1)}$$

$$CALC: CaCO_3(s) \rightarrow CaO(s) + CO_2(g);\ \Delta H^{\circ} = 177.8\ \text{kJ/mol} \quad \text{(R2)}$$

A continuous, stable operation maintains a constant uptake by purging sintered materials and replenishing the sorbent inventory with a fresh makeup stream. The heat required for calcination is typically supplied from an additional oxy-fuel combustion unit, leading to a 30% escalation in capital cost [19].

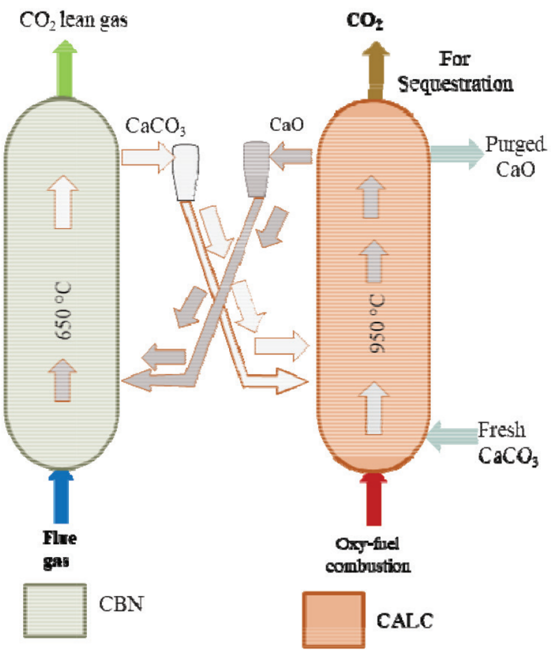


Figure 2 : Calcium looping Process [2]

The major drawback of CaO is the deterioration of uptake capacity/utilization efficiency with repeated carbonation-calcination cycle, due to the decrease in active surface area and pore volume caused by sintering [14]. It impacts the process design/operation of the plant: number of columns and trains, operation through the switching time etc. Yet, in terms of overall economic viability, this demerit is outweighed by the low cost of CaO and high capacity, attracting dedicated research to overcome sintering-induced deactivation. Strategies for enhancing the sorbent reactivity through multiple CO_2 capture-and-release cycles include: (i) thermal pre-treatment; (ii) re-carbonation and optimization of calcination conditions; (iii) sorbent hydration techniques; (iv) incorporation of inerts, dopants and porous support material; and (v) the use of nanomaterials.

4.0. Fly Ash Utilization

The incorporation of inert into CaO is carried out to increase the structural strength of the modified sorbent by the interaction of the former and latter, which might mitigate the sintering process. Several inert materials, such as SiO_2, Al_2O_3, MgO, and TiO_2, are currently employed in modifying CaO to achieve stabilized sorbent with high uptake capacity. Based on the X-ray Fluorescence (XRF) study, Fly Ash is constituted of the above-mentioned materials and possesses a high Tammann temperature. Fly ash (FA) is generated as a by-product in thermal power plants (225 Mt in India), whose disposal poses an environmental hazard affecting the local ecosystem. FA capture CO_2 with an uptake capacity of 0.141 and 0.182g CO_2/g coal fly ash at the temperature of 25°C and 45 °C [20]. However, when CO_2 gas is passed through FA at high temperatures (650-900 °C), no capture occurs, and it behaves as an inert. The constructive utilization of FA would lead to the reduction of disposal and environmental problems. Very few studies have infused FA to the different CaO precursors as given below:

i) Sreenivasulu et al. [21] work at elevated temperatures (350°–650°C) where CaO:MgO:FA sorbent was tested in the Fixed Bed Reactor (FXB) under a harsh atmosphere in which a large proportion of FA (~40%) led to lower surface area and uptake capacity.

ii) Chen and Khalili [22] conducted the carbonation reaction on the sorbent (CaO:FA) for t_{CBN}=20 min and calcination reaction in both mild (T_{CALC}=920°C, N_2=100%) and harsh (T_{CALC}=920°C, CO_2=100%) conditions to understand the effect of variation of fly ash on uptake capacity.

iii) Yan et al. [23] investigated the effect of variation of the duration of thermal pre-treatment of the sorbent (CaO:FA) in the extended carbonation period (t_{CBN}=25 min) under harsh calcination conditions (T_{CALC}=920°C, CO_2=100%) to determine the cyclic stability.

iv) Scaccia et al. [24] performed the extended carbonation study (t_{CBN}=30 min) and calcination under mild condition (T_{CALC} = 900°C, N_2=100%) on the sorbent (CaO:FA). This work reported the formation of two new crystalline phases (gehlenite-$Ca_2Al_2SiO_7$ and anorthite $CaO{\cdot}Al_2O_3{\cdot}2SiO_2$) that assisted in inhibiting the sintering phenomena.

v)Tiwary et al. [25] modified organometallic precursor of CaO with fly ash and performed the cyclability study under harsh carbonation and calcination conditions. The carbonation conversion of FA-modified sorbent was inferior to the unsupported sorbent in the 1st cycle, however, the former proved to be superior compared to the latter in the multicyclic (30 cycles) study (Figure 3).

5.0. Conclusion

There is a growing concern regarding the vast anthropogenic emissions of the greenhouse gas, especially CO_2 and associated climate change. On the other hand, the global consumption of fossil fuels for electricity

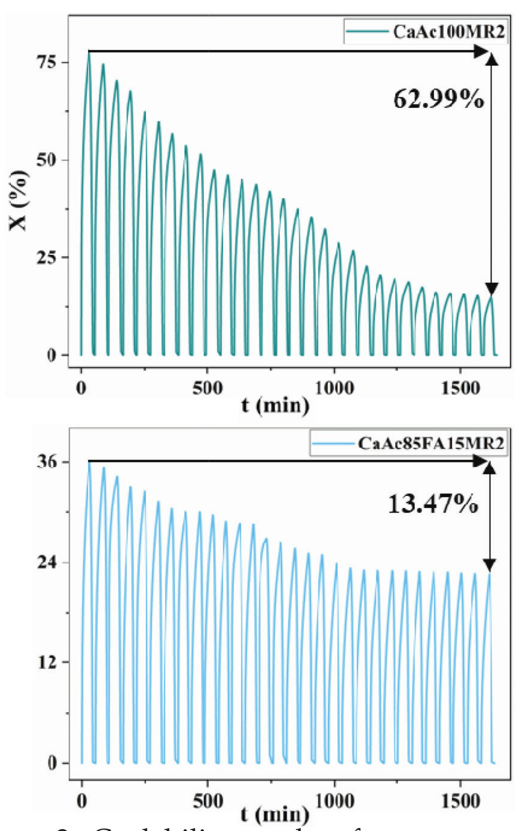


Figure 3: Cyclability study of unsupported and FA-modified sorbents (Permission taken from Tiwary et al. [25]).

generation, transportation, and process industries is continuously increasing. An improved and cost-efficient process for CO_2 capture could be a bridging technology, allowing the use of fossil fuels in a "sustainable" manner, that is, without CO_2 emission into the atmosphere. However, the costs currently associated with low-temperature-based amine scrubbing are high, thus making research into developing new CO_2 sorbents a high priority. Calcium Looping is a promising 2nd generation carbon capture technology that utilizes the theoretically reversible carbonation and calcination reactions of CaO. Among several proposed sorbents, CaO-based sorbent has gained importance due to its techno-economic feasibility. However, the technology suffers from sorbent degradation under repeated cycles, impacting commercial-scale usage. The review showcases FA-infusion to CaO- as a viable route to develop stable modified sorbents with considerable uptake capacity.

References

[1] *Wang X, Song C. Carbon Capture From Flue Gas and the Atmosphere: A Perspective. Front Energy Res 2020;8. https://doi.org/10.3389/fenrg.2020.560849.*

[2] *Tiwary S, Bhaumik SK. Theoretical approaches in hot CO_2 capture using modified CaO-based sorbents: Review. J CO_2 Util 2022;57. https://doi.org/10.1016/j.jcou.2021.101875.*

[3] *Florin N, Fennell P. Synthetic CaO-based Sorbent for CO_2 Capture. Energy Procedia 2011;4:830–8. https://doi.org/10.1016/j.egypro.2011.01.126.*

[4] *Chen Z, Song HS, Portillo M, Lim CJ, Grace JR, Anthony EJ. Long-term calcination/carbonation cycling and thermal pretreatment for CO_2 capture by limestone and dolomite. Energy Fuels 2009;23:1437–44.*

[5] *Lu H, Khan A, Smirniotis PG. Relationship between structural properties and CO_2 capture performance of CaO-based sorbents obtained from different organometallic precursors. Ind Eng Chem Res 2008;47:6216–20. https://doi.org/10.1021/ie8002182.*

[6] *D'Alessandro DM, Smit B, Long JR. Carbon dioxide capture: Prospects for new materials. Angew Chemie - Int Ed 2010;49:6058–82.*

[7] Boot-Handford ME, Abanades JC, Anthony EJ, Blunt MJ, Brandani S, Mac Dowell N, et al. Carbon capture and storage update. Energy Environ Sci 2014;7:130–89. https://doi.org/10.1039/c3ee42350f.

[8] Abanades JC, Arias B, Lyngfelt A, Mattisson T, Wiley DE, Li H, et al. Emerging CO_2 capture systems. Int J Greenh Gas Con 2015;40:126–66.

[9] Ünveren EE, Monkul BÖ, Sarıoğlan Ş, Karademir N, Alper E. Solid amine sorbents for CO_2 capture by chemical adsorption: A review. Petroleum 2017;3:37–50. https://doi.org/10.1016/j.petlm.2016.11.001.

[10]Wu D, Gassensmith JJ, Gouveîa D, Ushakov S, Stoddart JF, Navrotsky A. Direct calorimetric measurement of enthalpy of adsorption of carbon dioxide on CD-MOF-2, a green metal-organic framework. J Am Chem Soc 2013;135:6790–3. https://doi.org/10.1021/ja402315d.

[11]Hauchhum L, Mahanta P. Carbon dioxide adsorption on zeolites and activated carbon by pressure swing adsorption in a fixed bed. Int J Energy Environ Eng 2014;5:349–56. https://doi.org/10.1007/s40095-014-0131-3.

[12]Halabi MH, De Croon MHJM, Van Der Schaaf J, Cobden PD, Schouten JC. High capacity potassium-promoted hydrotalcite for CO_2 capture in H2 production. Int J Hydrogen Energy 2012;37:4516–25. https://doi.org/10.1016/j.ijhydene.2011.12.003.

[13]Wang J, Huang L, Yang R, Zhang Z, Wu J, Gao Y, et al. Recent advances in solid sorbents for CO_2 capture and new development trends. Energy Env Sci 2014;7:3478–518.

[14]Amorim SM, Domenico MD, Dantas TLP, Jose HJ, Moreira RFPM. Lithium orthosilicate for CO_2 capture with high regeneration capacity: Kinetic study and modelling of carbonation and decarbonation reactions. Chem Eng J 2016;283:388–96.

[15]Bhatta LK., Subramanyam S, Chengala MD, Olivera S, Venkatesh K. Progress in hydrotalcite-like compounds and metal-based oxides for CO_2 capture:a review. J Clean Prod 2015;103:171–96.

[16]Antzara A, Heracleous E, Lemonidou AA. Improving the stability of synthetic CaO-based CO_2 sorbents by structural promoters. Appl Energy 2015;156:331–43.

[17]Shimizu T, Hirama T, Hosoda H, Kitano K, Inagaki M, Tejima K. A twin fluid-bed reactor for removal of CO_2 from combustion processes. Chem Eng Res Des 1999;77:62–8.

[18]Charitos A, Rodríguez N, Hawthorne C, Alonso M, Zieba M, Arias B, et al. Experimental validation of the calcium looping CO_2 capture process with two circulating fluidized bed carbonator reactors. Ind Eng Chem Res 2011;50:9685–95.

[19]Petrescu L, Cormos C-C. Environmental assessment of IGCC power plants with pre-combustion CO_2 capture by chemical & calcium looping methods. J Clean Prod 2017;158:233–44.

[20]Mazzella A, Errico M, Spiga D. CO_2 uptake capacity of coal fly ash: Influence of pressure and temperature on direct gas-solid carbonation. J Environ Chem Eng 2016;4:4120–8.

[21]Sreenivasulu B, Sreedhar I, Reddy BM, Raghavan K V. Stability and carbon capture enhancement by coal-fly-ash-doped sorbents at a high temperature. Energy and Fuels 2017;31:785–94. https://doi.org/10.1021/acs.energyfuels.6b02721.

[22]Chen H, Khalili N. Fly-Ash-Modified Calcium-Based Sorbents Tailored to CO_2 Capture. Ind Eng Chem Res 2017;56:1888–94. https://doi.org/10.1021/acs.iecr.6b04234.

[23]Yan F, Jiang J, Zhao M, Tian S, Li K, Li T. A green and scalable synthesis of highly stable Ca-based sorbents for CO_2 capture. J Mater Chem A 2015;3:7966–73. https://doi.org/10.1039/c4ta06639a.

[24]Scaccia S, Vanga G, Gattia DM, Stendardo S. Preparation of CaO-based sorbent from coal fly ash cenospheres for calcium looping process. J Alloys Compd 2019;801:123–9. https://doi.org/10.1016/j.jallcom.2019.06.064.

[25]Tiwary S, Saha S, Sahu G, Chavan PD, Bhaumik SK. Infusion of Fly Ash/MgO in CaO-based sorbent for high-temperature CO_2 capture: Precursor selection and its effect on uptake kinetics. Mater Today Sustain 2024;27:100933. https://doi.org/10.1016/j.mtsust.2024.100933.

TECHNICAL ARTICLE

RAMSAR RECOGNITION OF EAST KOLKATA WETLAND

Dr. Anupendu Gupta[1]

Introduction

In 1971 a convention took place in a small Iranian little-known city of Ramsar to designate unique worldwide wetlands that are important for conservation of biological diversity. Once identified, these wetlands were designated as Ramsar sites and all signatory countries were advised and agreed to establish and oversee a management system aimed at conservation of the ecological character of these wetlands and to ensure wise use in future. Since then it is an international agreement to abide by the advice of Ramsar Convention, which was the first modern treaty between nations aimed at conserving natural resources. Wetlands can be included on the List of Wetlands of International Importance because of their ecological, botanical, zoological, immunological or hydrological importance.

Australia was the world's first country to enlist Wetland of International Importance as Ramsar Sites in 1974. Since then there are now more than 170 countries, which have designated more than 2400 wetland sites throughout the world to the Ramsar List of Wetlands of International Importance. India first entered the Ramsar List in 1982.

Nature of Ramsar Sites

Under the Ramsar Convention, a wide variety of natural and human-made habitat types ranging from rivers to coral reefs can be classified as wetlands. Wetlands include swamps, marshes, billabongs, lakes, salt marshes, mudflats, mangroves, coral reefs, fens, peat bogs, or bodies of water - whether natural or artificial, permanent or temporary. Water within these areas can be static or flowing; fresh, brackish or saline; and can include inland rivers and coastal or marine water to a depth of six metres at low tide. There are even underground wetlands.

In 2014, there were 26 Ramsar sites across India. Since 2014 till date 59 new Ramsar sites have been added across India, total sites being 85. According to The Wetlands (Conservation and Management) Rules of 2017, the Indian government excluded river channels, paddy fields, or other areas utilized for commercial activities from the definition of wetlands.

As on date there are two Ramsar wetland sites in West Bengal, East Calcutta (Kolkata) Wetland and Sunderban Wetland. The East Calcutta (Kolkata) Wetland (ECW) is the earliest Ramsar site in West Bengal which is still officially enlisted after its old name Calcutta. It was designated as Ramsar site in 2004.

Eastern Kolkata Wetland (EKW)

Kolkata (Erstwhile Calcutta) is located in the east of River Hooghly, which is the south bound channel of River Ganges flowing from downstream of-Farakka after bifurcation of east bound channel flowing into Bangladesh as Padma. Howrah is on the west of Hooghly. Like any large river, prominent natural levee (a ridge of sediments deposited naturally alongside a river by over flowing water) is developed all along the eastern bank of Hooghly. The north-south aligned megacity of Kolkata situated along the levee and to its east has a general ground slope towards the east causing eastward flow of surface water and drainage.

[1] Former Dy Director General, Geological Survey of India, BB 45/3. Salt Lake, Kolkata – 700 064
Email: anupendu@yahoo.com

This geomorphic aspect has created a vast wetland along the east of the megacity receiving surface drainage and sewerage. The natural wetland was added with the making of shallow lakes (bheri) for fishery and some partially submerged land, seasonally cultivated for vegetables. The combination of natural and manmade swampy wetland of eastern Kolkata has been acting as a natural treatment plant for incredible quantity of sewerage and supporting fish culture and vegetable production, not realized by either the government authorities or public at large.

The development of Salt Lake City by reclaiming land from a large area of EKL in the north-eastern parts during 1960-70 for creating additional residential provision for the citizens of Kolkata City was an example of large scale organized urban encroachment into the wetland. Understandably neither the government nor the environmentalists had a real clue to the overall damage done to the habitat and population. However, awareness developed soon afterwards in 1980s when filling up of any more wetland in southern extents of Salt Lake and elsewhere was strictly prohibited.

In spite of the prohibition, EKW once again became venerable when in 1991 the West Bengal Government accepted an offer by a non-resident Indian to build a World Trade Centre and allotted 227 acres of wetlands for this purpose. However, a PIL was filed in Calcutta High Court by a NGO against the decision of the Government and in a landmark judgment in 1992 Justice U.C. Banerjee disallowed the proposal and highlighted the reasons for which the EKW should be left as it was without any interference. There have been many later attempts by small developers to encroach EKW but these attempts failed.

Now the Eastern Kolkata Wetlands cover 125 square kilometers and include salt marshes, agricultural fields, sewage farms and settling ponds. The wetlands are also used to treat Kolkata's sewage, and the nutrients contained in the wastewater sustain fish farms and agriculture.

Contribution of Late Dr Dhrubojyoti Ghosh for making us aware of the value of EKL and need for its protection

Late Dr. Dhrubojyoti Ghosh, while working as an Engineer for the Government of West Bengal's Water & Sanitation Department, reached this incredible but neglected part of the city and started searching for an answer to the question: What exactly happens to the city sewage? Through life long research he got the answer and largely made the scientific community aware of the process which undergoes in a swampy terrain like EKL and benefits reaped.

These natural water bodies which were known just as fisheries provided the answer. Devised by local fishermen and farmers, these wetlands served, in effect, as the natural sewage treatment plant for the city. The East Kolkata Wetlands host the largest sewage fed aquaculture in the world. EKW helps transform sewage into clean water through natural process.

EKW supplies paddy, fish and vegetables to Kolkata at low logistic costand represents world’s largest assembly of waste and water fish ponds. EKW represents perhaps the largest waste neutralization ‘factory’ in India.

The Sewage from city are sent to the East Kolkata Wetland and treated to solar purification followed by natural oxidation and therefore, water become suitable for algal and phytoplankton’s growth which act as producer of an aquatic ecosystem. East Kolkata Wetland has 272 bheries which are spread over an area of 4000 hectares. The sewage sent to the wetland through channels, reaches natural swamps and bheries through several secondary canals having dense vegetation of water hyacinth, which plays vital role in phytoremidiation of city sewage. The bheries with shallow depth act as big natural oxidation pond that favours extensive purification of waste water along with integrated resource recovery. The oxidation pond overflows water which is used in agriculture area where paddy is cultivated and finally the excess water from the paddy fields is collected at the far end and finally released.

EKW transforms 5% faecal matter into 0.01% at zero cost and transforms sewage into clean water through a natural process. Dr. Ghosh deserves our hearty gratitude as because his work has indirectly touched every Kolkatan.

IF Kolkata is to survive, EKW must be protected at any cost.

NATIONAL SEMINAR
On
"Challenges and Opportunities in Mineral Sector"
on 8th August 2024
at the Oberoi Hotel, New Delhi
Organised by
Mining Geological and Metallurgical institute of India, Kolkata.

Highlights

India is home to a diverse world's wealth of minerals. The country has significant sources of coal (fourth-largest reserves in the world) bauxite, titanium ore, chromite, natural gas, diamonds, petroleum, and limestone and is the second largest producer and consumer of coal after China. It also ranks in the top five globally as a significant producer of bauxite, iron, and zinc ore. However, despite this abundance, the mining sector's contribution to the GDP hovers between 2.2% to 2.5%. Moreover, the global commitment of India to work on "Climate Change" and Net Zero Carbon emission by 2070 calls for low-carbon and clean technologies which would increase the demand for critical minerals.

In this backdrop, Mining Geological and Metallurgical institute of India (MGMI) organised this seminar. Hon'ble Minister of Coal and Mines, Hon'ble Minister of State of Coal and Mines, Govt. of India along with Secretaries and Addl. Secretaries of these ministries graced the occasion. A large number of CEOs and Directors including Chairman, Coal India Limited also spoke on this occasion.

Inaugural Session

Following dignitaries delivered their addresses in the Inaugural Session :

Chief Guest : Shri G. Kishan Reddy, Hon'ble Minister of Coal, Mines Govt. of India

Guests of Honour : Shri Satish Chandra Dubey, Hon'ble Minister of State, Govt. of India

Shri V L Kantha Rao. Secretary, Ministry of Mines

Shri M Nagaraju, Additional Secretary, Ministry of Coal

Also present on the dais were - Smt. Vismita Tej, Additional Secretary, Ministry of Coal

Smt. Rupinder Brar, Additional Secretary, Ministry of Coal

Shri P M Prasad, Chairman, Coal India Limited

Dr B Veera Reddy, President, MGMI & DT, CIL

Shri Ranajit Talapatra, Secretary, MGMI

Shri Amrit Lal Meena, Secretary, Ministry of Coal, Govt. of India, who could not be present in this Session because of pressing engagement, spoke in the post-lunch Session expressing the Government's expectations from the coal industry.

The Inaugural Session started with the usual Indian tradition of "Lighting the Lamp" followed by Dr B Veera Reddy, President, MGMI, welcoming all dignitaries on the dais, MGMI members present, attending delegates, invitees, other participants and members of the press. In his address he briefed about the mandate of MGMI and its past activities.

Shri P M Prasad, Chairman, CIL, highlighted the ambitious future plan of CIL, emphasising the need for diversification beyond coal. He also praised MGMI for regularly organising programmes and events pertinent to mineral and mining sectors.

The Guests of Honour and other dignitaries on dais, in their addresses mentioned the major issues facedby the mining and mineral industries. They also expressed the hope that MGMI would play a pivotal role by providing suitable platforms to stakeholders through organisation of technical programmes so that major issues are discussed in different forums and concerted efforts are put in to make these sectors more efficient with state-of-the-art technologies.

In his address as the Chief Guest, Hon'ble Minister of Coal and Mines, Shri G. Kishan Reddy said that the vast natural resources of India will prove to be an essential game-changer to the nation's journey to wards Viksit Bharat-2047 that would lead to Atmanirbharta in the true sense. He further added that under the able leadership of Hon'ble Prime Minister, Shri Narendra Modi, the Government has brought a paradigm shift in coal and mineral sectors, making them transparent and competitive. He called on all the industry leaders to become part of this unfolding growth story of India. He further informed that the Government has undertaken several measures to enhance ease of doing business to encourage their participation and also to mitigate the associated risks. Initiatives taken such as reimbursement of 50 per cent exploration expenditure for Exploration License and Composite Licence holders is a move in this direction. He deliberated in detail on the steps being taken by the Government to reduce dependence on imported coal and measures to augment domestic coal producing capacity of the country.

Hon'ble Minister further stated that Critical Minerals have emerged as drivers of modern economy and the Government of India has ensured that the country taps into this global opportunity through the launch of the National Critical Minerals Mission.

The Session ended with the Vote of Thanks delivered by Shri Ranajit Talapatra, Secretary, MGMI.

Technical Sessions

The Inaugural Session was followed by three Technical Sessions, viz. I- Challenges and Opportunities in Coal Mining, II-Challenges and Opportunities in Non-Coal Mining and III-Challenges & Opportunities in Critical Minerals. The details are as follows :

Technical Session I : Challenges and Opportunities in Coal Mining

Chairpersons of this session were :

Shri U Kumar, Past President, MGMI and ii) Shri N N Gautam, Former Advisor, UNDP.

Rapporteur- Shri S K Jha, Dy. Mgr, CMC ECL

The Speakers present were -

i. *Shri Achyut Ghatak, DT, CMPDIL*

He deliberated upon a) Global prospective of Coal, b) Total demand of primary energy, c) Contribution of fossil fuel in the whole energy basket and d) The Indian scenario.

ii. *Shri A K Singh, DT, WCL*

He mainly gave an Overview of WCL and discussed about a) Challenges faced by WCL and b) Opportunities for WCL in the changed scenario.

iii. *Shri Niladri Roy DT, ECL*

Shri Roy discussed on a) The vital role of coal mining, b) Challenges before the coal mining sector, and c) Opportunities for growth and improvement in this sector.

iv. *Shri Neeraj Patel, GM, Coal (Mkt), GMDC*

He mainly presented a) Statistics of GMDC covering its market capitalisation, performance turnaround statistics, existing and upcoming projects, b) Coal sector review c) Challenges in the sector from mine allotment to mine opening and d) Export incentives.

iv. *Shri Ajit Kr. Saxena, CMD, MOIL*

v. Shri Saxena's presentation on non-coal mining was shifted to this session as he had to leave early. He talked on a) Reliability of exploration, b) Mining processes, and c) Standard Operating Procedure for extracting minerals.

In their closing remarks, Shri U Kumar, Past President, MGMI and Shri N N Gautam, Former Advisor, UNDP, emphasised on cleaner technologies and hydrogen economy.

Technical Session II : Challenges and Opportunities in Non-Coal Mining

Chairperson of this session was:

Shri Anil K Jha, Past President, MGMI

Rapporteur- Shri Ajit Singh Choudhary. MD, Elitech

The Speakers present were –

i) Dr. H S Venkatesh, Director NIRM

He mainly spoke on the importance of a) Rock mechanics studies, and b) Continuous monitoring and data analysis for safe mining practices.

ii) *Shri Debashish Nanda, Director BD, CIL*

He highlighted issues related to a) Critical mineral sector in India and b) Initiatives taken by CIL, NTPC, HZL, Deccan Gold, etc. in critical mineral sector.

iii) *Dr. Deependra Singh, CMD – IREL*

He focused on a) Critical minerals in various sectors. and b) Major challenges in this sector.

iv) *Shri Piyush Srivastava Chief – NRD, Tata Steel*

He mainly addressed about a) Technical and administrative challenges in mining, b) Importance of scientific research. and c) Royalty structuring.

v) *Shri B.R.V Susheel Kumar, DMG, Telangana*

He spoke on a) Exploration of minerals, b) Telangana having more than 300 leases and all are georeferenced, to have close monitoring of the mines under operation, and c) Supportive policy framework.

At the end, Shri Anil K Jha, Chairman of the Session, shared his valuable ideas and thoughts.

Technical Session III : Challenges and Opportunities in Critical Mineral

Chairperson of this session was :

Dr Amalendu Sinha, Former Director CSIR-CIMFR,

Rapporteur - Dr Murari Prasad Roy, Chief Scientist, CSIR-CIMFR,

This was a Panel Discussion Session and the panellists were-

i) *Dr D K Sinha, CEO, GMRICS/GMDC*

Dr Sinha initiated the discussion with the Mines and Minerals (Development and Regulation) Amendment Act, 2023 for identification of 24 critical and strategic minerals. He also raised concern about the dependency on import, particularly for lithium, cobalt, nickel, phosphorus, potash, etc. The difficulties of extracting critical minerals from pegmatite host rocks, and issues like limited tonnage and complex beneficiation processes were also discussed.

ii) *Prof Arvind K Mishra, Director, CSIR-CIMFR*

Prof Mishra emphasized on the security about supply chains of Critical Minerals listed in India and boosting domestic production to reduce import dependence and enhance technological self-reliance. He informed about the initiatives of Council of Scientific and Industrial Research (CSIR) in exploration, identification, characterization, beneficiation, enrichment, separation and waste utilization for Critical Minerals.

iii) *Dr Muduru Lachna Dora, Director (G), DGCO*

Dr Dora talked about the importance of critical and deep-seated minerals in carbon emission economy as India has a global commitment to work on "Climate Change". He highlighted the role of Critical Minerals for economic development and National Security and hoped that critical mineral deposits may be auctioned by the Central Government in fast-track mode. He also mentioned about the signing of recent agreement for lithium exploration and mining pact for 5 lithium blocks with Argentina by Khanij Bidesh India Limited (KABIL), Ministry of Mines. Lastly, he informed about the role of GSI on offshore survey and exploration of Critical Minerals which were the major initiatives of the new strategy known as Critical Mineral Assessment Programme (CMAP).

Subsequent to these deliberations, lively discussions on many important issues related to Critical Minerals added value to the subject.

The chairperson, Dr. Amalendu Sinha, finally, expressed his views and opinions and thanked the panellists and audience for their contributions.


SPEAKER
CMD
SPEAKER


NMDC
SHRI AMRIT LAL MEENA


CMD

Recommendations

Challenges & Opportunities in Coal Sector

a. Despite the global shift towards renewable energy, coal remains essential for meeting India's current energy demands and industrialization goals, serving as a cornerstone of the nation's economic stability and progress,

b. Multiple radical reforms are required if the coal sector has to grow in a sustainable manner,

c. To comply with socio-environmental norms, encouraging Underground (UG) mining is a better solution and it requires a UG specific coal pricing regime, which may include cross-subsidisation/ composite pricing/total E-auction for the PSUs,

d. The blocks being allocated for UG mining may be allowed concessions in revenue share and part reimbursement for exploration expenses,

e. Suitable enablers like PLIs, subsidies and radical market policies need to be put in place,

f. The Government may consider telescopic freight charges similar to telescopic fare system for the multi modal transport system,

g. To resolve the 'Hug Movement', PPP models for development of evacuation infrastructure may be required to transport about 1100 Million Tonnes (80% of the total production) of Coal through rail by 2030,

g. It is important for the coal suppliers to integrate with the Sagarmala project of GOI and develop adequate berthing capacities at the ports,

h. Wherever possible, Solar Power Plants should be installed by Coal Companies -WCL has already installed such plant of 2MW capacity till date,

i. Pump Storage energy projects making use of abandoned mines need to be initiated by the mining companies,

j. Gasification projects need to be executed on priority basis,

k. Addressing occupational hazards through advanced technologies, regular health screenings, and comprehensive safety training is essential,

l. The complex regulatory environment is bringing up challenges in adhering to environmental laws and managing land acquisition processes. It is required to streamline these processes maintaining high standards for crucial sustainable growth.

m. Socio-political dynamics should be suitably assessed and addressed through transparent dialogue and community engagement to foster a supportive environment.

Challenges & Opportunities in Non-Coal Sector

a. Technical and administrative challenges, scientific research and technological advancements need special attention in steel sector.

b. Investment in hard rock tunnelling needs to be enhanced and advanced drilling, remote-controlled equipment and drone technology should be suitably implemented to enhance productivity and safety.

c. Special consideration called for in PLI scheme and better Royalty structuring,

d. More supportive policy framework may be considered to facilitate exploration and extraction,

e. Rock mechanics engineering solutions for the design of mining, energy, and infrastructure projects should be adopted right from the initial stage. Proactive scientific design is crucial to avoid failures of rock structures.

a. Participation of stakeholders in resource expansion, recycling and substitution. Enrichment of lean grade, flowsheet development, availability of testing facilities, maintaining purity levels, mitigating environmental hazards, and ecosystem development are major requirements,

b. Critical mineral sector in India has to play a significant role to meet energy demand, particularly for electric vehicles. India aims for a 30% growth by 2030 in this sector,

c. India has identified 30 critical minerals essential for battery storage, aerospace, and defence. It is required to develop exploration programmes, processing technology, and policy frameworks. Companies like CIL, NTPC, HZL, Deccan Gold, etc. have already taken initiatives for development of critical mineral sector,

d. Dependency on import from foreign countries, particularly for lithium, cobalt, nickel, phosp horus, potash etc. is a major concern,

e. Lack of exploration expertise, limited tonnage and complex beneficiation processes need to be addressed on priority basis.

f. Expertise is needed for extraction of critical minerals from pegmatite host rocks,

g. Council of Scientific and Industrial Research (CSIR) has proactively taken R&D initiatives in the fields of exploration, identification, characterization, beneficiation, enrichment, separation and waste utilization of critical minerals. Presently, CSIR is working on 19 critical minerals, including capacity building for a few of them,

h. It is pertinent to understand the importance of critical and deep-seated minerals in carbon emission economy as India has a global commitment to work on "Climate Change" (Net Zero Carbon emission by 2070).

i. In the foreseeable future, Critical Minerals are going to play a very important role for India's economic development and National Security,

j. The recent signing of an agreement for lithium exploration and mining for 5 lithium blocks with Argentina by Khanij Bidesh India Limited (KABIL), Ministry of Mines, is a very determined move of the Government in this direction.

VALEDICTORY SESSION

The concluding session of the National Seminar commenced with the following guests and office-bearers on the dais.

Shri P M Prasad, Chairman, Coal India Limited, Dr B Veera Reddy, President, MGMI & DT, CIL, Shri Ranajit Talapatra, Secretary, MGMI & Former GM, CIL, Dr C S Singh, Jt. Secretary, MGMI & GM, CIL, Shri Prasanta Roy, Convenor, Seminar.

In this session Shri P M Prasad, Chairman, Coal India Ltd. praised MGMI for organising this seminar on a topic which is very relevant in today's context. He also talked about the future of coal and role of Coal India Ltd. Dr B Veera Reddy, President, MGMI, thanked members of MGMI for their untiring efforts in organising this well attended seminar in a very short time. Finally, Shri Prasanta Roy, Convenor of this seminar delivered the Vote of Thanks, thanking everyone who was associated with this event directly or indirectly.


NATIONAL SEMINAR ON MINERAL SECTOR
8th August 2024
Challenges and Opportunities in Mineral Sector
Venue: The Oberoi, New Delhi
Organised by:
THE MINING, GEOLOGICAL AND
METALLURGICAL INSTITUTE OF INDIA
PRINCIPAL SPONSOR
Coal India
PLATINUM SPONSORS
NMDC
MOIL
MOIL LTD.
GOLD SPONSOR
नालको NALCO
SPECIAL THANKS TO
CCL
cmpdi
ECL
MCL
NCL
SECL
WCL

NEW MEMBERS

(Life Members enrolled in 904th Council Meeting)

LM- 11199
Shri Rewati Raman Kant
Chief Manager (Mining), ECL
Eastern Coalfields Ltd
Qtr.No. D-11, Gopalpura Colony,
Post-Mugma, Dist – Dhanbad-828204
Jharkhand
(M) 9434795163/9775393549
Email : rewatiraman_kant@rediffmail.com

LM- 11200
Shri Sanjeev Kumar
Dy. Manager (Mining), ECL
Eastern Coalfields Ltd
Qtr.No. CK/05/020, Gopalpura Colony,
Post-Mugma, Dist – Dhanbad
Jharkhand – 828204
(M) 9771444962/9931881101
Email : sanjeev080848@gmail.com

LM-11201
Shri Ajoy Bhowmik
General Manager (E&M), ECL
Eastern Coalfields Ltd
D/4, Area Coplex, Salanpur,
Gourande Road, Asansol – 713359
(M) 8910177825/9434795297
Email : ajoybhowmik19@gmail.com

LM-11202
Shri Satanand Sharma
Chief Manager (Mining), ECL
Eastern Coalfields Ltd
Duplex-A, Sun Shivay Apartment,
Near St. Xavier School,
Nawadeh, Dhanbad – 828130
(M) 9771444842/9934193383
Email : satanandsharma.cil@gmail.com
satanand.sharma@coalindia.in

LM-11203
Shri Anil Kumar Pandey
Chief Manager (Mining), ECL
Eastern Coalfields Ltd
Shankarpur Colliery, P.O. Ukhra
Dist - Paschim Burdwan–713363, WB
(M) 9434796267
Email : akpandey6667@gmail.com

LM-11204
Shri Sushil Kumar Das
Sr. Manager (Mining), ECL
Eastern Coalfield Ltd
Kumardubi Colliery, Mugma Area,
PO. Chirkunda, Dhanbad– 828202, Jharkhand
(M) 9434796949/9470597325
Email : sushilkumardas7325@gmail.com

LM-11205
Shri Shailendra Kumar Gaikwad
GM (Mining), ECL
Eastern Coalfield Ltd
Office of General Manager, Mugma Area
Post-Mugma, Dist – Dhanbad-828204, Jharkhand
(M) 9771447255
Email : skmishra.gayakwad@coalindia.in

LM-11206
Shri Sandeep Kumar
Sr. Manager (Mining), ECL
Eastern Coalfields Ltd
C-5/15, Gopalpura Colony, P.O. Mugma,
Dist – Dhanbad – 828204, Jharkhand
(M) 9771444853/8210667356
Email : sandeepkmr1969@gmail.com
sandeep.k9016@coalindia.in

LM-11207
Shri Arbind Kumar
Manager (Mining), ECL
Eastern Coalfields Ltd
C Type Qtr, At Chora 7/9 Pit Colony

Near PNB Haripur, P.O. Haripur
Dist : Paschim Bardhaman – 713378, WB
(M) 9434796463/8617884335
Email : arvindkr69@rediffmail.com

LM-11208
Shri Rohit Putatunda
Dy. Manager (Mining), ECL
Eastern Coalfields Ltd
C-15/83, Jhanjra Officers Colony,
P.O. Jhanjra BO, Dist: Burdwan (West),
West Bengal -713385
(M) 9434795906/903810660
Email : rohit.lyf@gmail.com
rohit.putatunda@coalindia.in

LM-11209
Shri Diwakar Abhijeet Tiwari
Safety Officer, ECL
Eastern Coalfields Ltd
CEQ 02/03, Officer's Colony,
Nimcha Colliery, Post – Bidhanbag,
Paschim Bardhaman-713337, WB
(M) 9434795709/6294799058
Email : tiwaridiwakar8@gmail.com

LM-11210
Shri Sanjay Kumar
Sr. Manager (Mining), ECL
Eastern Coalfields Ltd
Qtr. No. C/8-27 (Riverside) Pandaveswar
Colliery, Fulbagan, PO & PS Pandaveswar
Dist : Paschim Bardhaman – 713346, WB
(M) 9434796007 /9474540391
Email : sanjayyajnas.kumar023@gmail.com

LM-11211
Shri Dharmendra Kumar Saha
Manager (Mining), ECL
Eastern Coalfields Ltd
Khottadih Colliery, PO. Bilpahari
Dist : Paschim Bardhaman – 713378, WB
(M) 9434795981 / 8597153307
Email : dharmendrakumarsaha@gmail.com

LM-11212
Shri Radha Gobinda Kar
Chief Manager (Mining), ECL
Eastern Coalfields Ltd
Office of the Agent, Khottadih Colliery
Dist : Paschim Bardhaman-713378, WB
(M) 9434796163 / 9932267282
Email : rgkar1974@gmail.com
agentktd2021@gmail.com

LM-11213
Shri Ravi Bhushan Tirkey
Dy. Manager (Mining), ECL
Eastern Coalfields Ltd
Madhaipur Colliery, Nutundanga
Dis Paschim Bardhaman – 713381
(M) 9434796016 / 9475897802
Ememail : ravibhushan04@gmail.com
mgrmdpug@gmail.com

LM-11214
Shri Chinmay Mondal
MT (Mining), ECL
Eastern Coalfields Ltd
Qtr. No. C/8/44, Jhanjra Officer's Colony,
Dist : Paschim Bardhaman – 713363, WB
(M) 9046972916 /8910412603
Email : mondalchinmay2010@gmail.com
chinmay.mondal@coalindia.in

LM-11215
Shri Satyendra Prasad Singh
Chief Manager (Mining), ECL
Eastern Coalfields Ltd
Qtr. No. D-01/01, Panthnagar,
AT+P.O. Pandaveshwar,
Dist : Paschim Bardhaman – 713346, WB
(M) 9771444951
Email : satyendra521965@gmail.com

LM-11216
Shri Subhashish Dash
Dy. Manager (Mining), ECL
Eastern Coalfields Ltd
At – Manderboni Colony, P.O. Gogla

Dist : Paschim Bardhaman – 713381, WB
(M) 9434795512 /9337735629
Email : subasis.manu@gmail.com

LM-11217
Shri Prabhat Kumar
Chief Manager (Mining), ECL
Eastern Coalfields Ltd
B-25 (1&30), Town House, Shristi Nagar
Asansol, P.O. R.K. Mission
Dist : Paschim Bardhaman – 713305
(M) 7001648182
Email : pk26min@gmail.com

LM-11218
Shri Dawarika Prasad Ahirwar
Manager, ECL
Eastern Coalfields Ltd
Dalurband Colliery, PO & PS Pandaveshwar
Dist : Paschim Bardhaman – 713346, WB
(M) 9434795522 / 9755731160
Email : dalurbandcolliery@gmail.com

LM- 11219
Shri Manoj Kumar Singh
Chief Manager (Mining), ECL
Eastern Coalfields Ltd
D/13, Jhanjra Officer's Colony
P.O. Jhanjra (B.O), Dist – Paschim Bardhaman
West Bengal – 713385
(M) 9434795869 / 9134590801
Email : manojcil7@gmail.com
manoj62.singh@coalindia.in

LM-11220
Md. Zakir Hussain Ansari
Sr. Officer (Mining), ECL
Eastern Coalfields Ltd
VTC, Kenda Area, ECL
PO. Haripur, Dist – Paschim Bardhaman
West Bengal -713378
(M) 8709568757 / 8709568757
Email : zakirhussain117@gmail.com

LM-11221
Shri Sudip Sahoo
Manager, JMS Mining Pvt. Ltd
JMS Mining Pvt. Ltd
Kumardihi – B Guest House, 11No. Pit, Ukhra,
Dist: Paschim Bardhaman – 713363
(M) 6296411557
Email : sudip.jms@gmail.com
sudip.sahoo@jmsmining.com

LM-11222
Akil Ansari
Sr. Manager (Mining), JMS Mining Pvt. Ltd
JMS Mining Pvt. Ltd
Flat No. 3A, GDR Appartment, Jabbarpally
Ichapur, Durgapur – 713363, WB
(M) 9589629496
Email : akilbees@gmail.com
akil.ansari@jmsmining.com

LM-11223
Shri Asim Kumar Mondal
Chief Manager (Mining), ECL
Eastern Coalfields Ltd
House No. 29, Kabiguru, Sail Co-operative,
City Centre, City – Durgapur – 713216, WB
(M) 9434796966 /9434675373
Email : mondalasim568@gmail.com
asim.mondal@coalindia.in

LM-11224
Shri Achinta Halder
General Manager (Mining), ECL
Eastern Coalfields Ltd
D-2, Jhanjra Officer's Colony, PO. Jhanjra BO
Dist – Paschim Bardhaman– 713385, WB
(M) 9434796307 / 9474181523
Email : achinta.halder@gmail.com
achinta.haldar@coalindia.in

LM-11225
Shri Lokeswara Rao Chitikireddy
Dy. Manager (Excavation), MCL
Mahanadi Coalfields Ltd
Qtr. No. C-39, Lingaraj Township

Near Handidhua, P.O. Deulbera, Talcher
Odisha – 759100
(M) 9939868168 /8639253407
Email : lokeshch6993@gmail.com
lokeshwara.rao@coalindia.in

LM-11226
Shri Kaushik Kumar Khan
Chief Manger (Mining), ECL
Eastern Coalfields Ltd
Qtr-D-08, P.O. Jhanjra,
West Burdwan – 713385 WB
(M) 8918880165
Email : asojhanjra@gmail.com
kaushik_khan91@yahoo.co.in

LM-11227
Shri Ramesh Chandra Meena
Sr. Manager (Mining), ECL
Eastern Coalfields Ltd
C-04/14, Officer's Colony, J.K. Nagar
Near High School, P.O. Bidhanbag
Paschim Bardhaman – 713337, WB
(M) 9434796942 /8052506379
Email : rcm2010ncl@yahoo.in
rc.meena7666@coalindia.in

LM-11228
Shri Sandip Kundu
Chief Manager (Mining), ECL
Eastern Coalfields Ltd
Flat No. 4A, Amardeep Housing Estate, Budha, Bathe Road, Asansol
Paschim Bardhaman – 713301, WB
(M) 9434796943 / 7001560299
Email : sandipkundu2017@gmail.com
sandip.kundu@coalindia.in

LM-11229
Shri Ramesh Chandra Mohapatra
General Manager (Mining), ECL
Eastern Coalfields Ltd
D-01, Jhanjra Officer's Colony,
P.O. Jhanjra BO, Dist – Paschim Bardhaman,
West Bengal – 713385
(M) 9434790163 / 9382432726
Email : ramesh.mohapatra.cil@gmail.com
rc.mahapatra@coalindia.in

LM-11230
Shri Pradip Biswas
Chief Manager (Mining), ECL
Eastern Coalfields Ltd
Qtr.No. D-2, Haripur Colliery Complex
PO. Haripur,
Dist: Paschim Bardhaman-713378, West Bengal
(M) 8653837811/ 9434795812
Email : pbiswassbp@gmail.com

LM-11231
Shri Raj Kishore Prasad Singh
Chief Manager (Mining), ECL
Eastern Coalfields Ltd
D Type Bunglow, Near Chora 10 Pit
Post – Haripur,
Dist – Paschim Bardhaman– 713378, WB
(M) 9434796472 / 8597153456
Email : rkpsingh.911@gmail.com

LM-11232
Dr. Satya Prakash Sahu
Dy. Manager (Mining), MCL
Mahanadi Coalfields Ltd
QtrNo. C/13, Anand Vihar,
Burla -768020, Orissa
(M) 9064080116
Email : satya.prakash42@gmail.com
sp.sahu1643@coalindia.in

LM-11233
Shri Sumit Datta
Sr. Manager (Mining), CMPDIL
Flat No. 3A Aashtha Khushi Apartment, Moti Nagar, Karmik Nagar (Near Delhi Public School), Post-ISM, Dist – Dhanbad
Jharkhand – 826004
(M) 9471516616
Email : dattasumit1972@gmail.com

LM-11234
Prof (Dr.) Kripamoy Sarkar
Associate Professor, IIT, ISM Dhanbad
Department of Applied Geology, IIT

(Indian School of Mines)
Dhanbad – 826 004, Jharkhand
(M) 9570145254
Email : kripamoy@iitism.ac.in

LM-11235
Dr. Ranjit Kumar Paswan
Sr. Scientist, CSIR-CIMFR
Central Institute of Mining & Fuel Research
Qtr. No. MSA/II/39, Scientist Apartment, CIMFR Colony, CSIR-CIMFR, Barwa Road,
Dhanbad – 826 001, Jharkhand
(M) 9631726815
Email : ranjitkp.cimfr@yahoo.co.in

LM-11236
Shri Ashok Kumar
Chief Strategy Officer - -Govt Business,
Marsh India
K1201, Amrapali Sapphire, Sector 45,
Noida, UP – 201303
(M) 9999291480
Email : mailidashok@yahoo.com

LM-11237
Shri Suvrajit Dash
Manager, Geo Enterprises
Geo Enterprises
C/o. M/s. Geo Enterprises, Prabhagiripatnam Village, Podalakur Mandal, SPSR Nellore District
Andhra Pradesh – 524345
(M) 8917411859
Email : suvrajitlipu@gmail.com

LM-11238
Dr. Deepak Kumar Sinha
CEO, GMRICS
Gujarat Mineral Research Industrial Consultancy Society/GMDC
GMDC Annexe, 2nd Floor, 8 Mills Officers Colony, Ashram Road, Navrangpura
Ahmedabad – 380009, Gujarat
(M) 9490749961
Email : dksajal@gmail.com
dksinha.amd@gov.in

LM-11239
Shri Deepak Kumar
DGM (Mining) BSL Collieries, SAIL
BSL Collieries – Steel Authority of India Ltd
2nd Floor, Leena Niwas, Shankar Colony
(Opp. Meera Towers) Kali Mandir Road
Bekarbandh, Dhanbad – 826001, Jharkhand
(M) 9470194914/9523594914
Email : deepakkr4@yahoo.com
deepakkrsail@gmail.com

LM-11240
Dr. Arnold Luwang Usham
Scientist, CSIR-CIMFR
CSIR-Central Institute of Mining & Fuel Research
Type IV/63, CSIR-CIMFR Digwadih Campus,
P.O. Fri, Dist-Dhanbad, Jharkhand- 826001
(M) 9990436744
Email : arnoldluwang@gmail.com
arnoldluwang@cimfr.nic.in

LM-11241
Dr. Deepak Kumar
Dy. Manager (Mining), BCCL
Bharat Coking Coal Ltd
Bunglow No.4/3, Old Doctors Colony,
Jagjivan Nagar, Dhanbad, Jharkhand-826003
(M) 9470597327 / 8709244125
Email : deepakkumar.12021@gmail.com

LM-11242
Dr. Manas Kumar Mallick
Asstt. Professor, BIT Sindri
Department of Mining Engineering
BIT Sindri, P.O. Sindri Institute
Dist : Dhanbad, Jharkhand – 828123
(M) 8555916172
Email : mallick.manas2@gmail.com

LM-11243
Shri Sudhansu Sekhar Singh
Manager (E&M), MCL
Mahanadi Coalfields Ltd
Jagruti Vihar, Burla, Sambalpur, Odisha – 768020
(M) 9438877365
Email : sssingh@coalindia.in

NATIONAL SEMINAR AMPG 2024

Mining, Geological & Metallurgical Institute of India (MGMI) organised a National Seminar on **'Augmentation in Metal Production : Journey Towards Green' (AMPG-2024)** on 21st September 2024. It was held at Williamson Magor Hall, Bengal Chamber of Commerce & Industry, Royal Exchange Building, 6, Netaji Subhas Road, Kolkata. The event was arranged in two sessions – inaugural and a technical session.

Inaugural Session

The session commenced with the compere welcoming the guests, delegates and participants with a brief introduction of MGMI and inviting **Shri P M Prasad,** Chairman, Coal India Limited (CIL) and Chief Guest of the event, **Shri Brijendra Pratap Singh,** Director-in-Charge, DSP & IISCO-SAIL, Guest of Honour, **Dr B Veera Reddy,** President, MGMI and Former Director (T), CIL, **Dr Rajib Dey,** Convenor, AMPG and Professor, Jadavpur University, **Shri Ranajit Talapatra**, Honorary Secretary, MGMI and Former GM, CIL on the dais. **Shri Sanjiv Kumar Singh**, Director (Mining), Hindustan Copper Ltd, Guest of Honour, could not attend the inaugural session for being stuck-up on road due to flood. The dignitaries participated in the lighting of the ceremonial lamp. They were then felicitated with flower bouquets.

Dr Rajib Dey welcomed the guests and delegates. Introducing the theme of the seminar, he mentioned that metals are gaining importance of which steel is the most. The per capita production of steel in India is well below the world average and we need to increase the production capacity. Besides, for production of electrical vehicles, lithium, cobalt, nickel are required. The enhancement of production of metals is a necessity, but the mining and extraction is not an environment-friendly process, Dr Dey mentioned. Steel production accounts for 10%-12% of total global emission. Our aim should be to make the metal production process environment-friendly and sustainable as also cost-effective. The aim of this seminar is to discuss ways of metal production in a much greener way.

Dr B Veera Reddy mentioned the topic on metal mining is a different one from the topics of the 10-12 seminars conducted by MGMI in last few years. Since steel production needs to be doubled to 300 mt by 2030 and to 500 mt by 2047, Ministry of Coal has enhanced the target of coking coal production. Metal extraction (bauxite to aluminium) and preparation (steel) are power-intensive processes and we should try to find some energy-efficient measures for going green. Recycling of metals needs less energy. Coal India has taken a lot of environment initiatives. He feels lot of exploration needs to be done in our country. For growth of country's economy, growth of metal industry is a necessity. He concluded by mentioning that the topic is very apt and by wishing the seminar a success from which knowledgeable inputs would hopefully come out.

Shri Brijendra Pratap Singh began his address by commenting that MGMI is actively involved in exchanging knowledge on mineral and metal industry and in taking role in collaboration between industry leaders, technology suppliers, power centres and policy makers. According to him the topic of seminar is very apt in the current scenario. India's economy is growing @ 6-7%. For the mission 'Viksit Bharat 2047', Indian Government is putting thrust on infrastructure development and capital investment and for this, consumption of metal is set to increase. Shri Singh spoke on Government of India's National Steel Policy framed in 2017 that states per capita demand to increase; indigenous production of high strength, value added steel to minimise import; sustainability; reducing CO_2 emission. All steel majors are planning to introduce new technologies in their expansion plan. He urged that coal companies may increase supply of low-ash coking coals to curb imports. Iron ores in India are mostly of low grade and improved beneficiation technology is a necessity. He emphasized on metal scrap recycling. Shri Singh concluded by suggesting alternative fuels and ways to reduce CO_2 emission in steel production.

Shri P M Prasad told sustainable mining practices are the need of the day, whether it is coal mining or metal mining. Coking coals are a basic need for steel industry and to lower the price of steel, availability of coking coal at low cost is required. After a long time, dedicated coking coal mine, like Kotre-Basantpur (West Bokaro Coalfield), is coming up in the country. Coals from this mine, after washing, would be of good quality. Keeping eye towards sustainability, mining equipment are being designed, as also high efficiency, low emission power plants. Mine closure plans are being modified with technical assistance from World Bank. Shri Prasad concluded by wishing the seminar a success.

Shri Sanjiv Kumar Singh, who reached at the fag end of the session, expressed thanks to MGMI for inviting him. He talked of HCL, the only copper miner of the nation, mining and processing copper concentrate. India has only 0.3% of world copper reserve. He mentioned a few steps that HCL is planning to take for expansionin coming 5 years.

The session concluded with presentation of mementoes to the dignitaries. The event was attended by 121 dignitaries, delegates and invitees.

Technical Session

The Chairman of the session was **Prof N R Bandyopadhyay,** Ex-Director, School of Material Science and Technology, IIEST Shibpur. Dr Rajib Dey introduced him. The Co-chairman was Shri **Pradip Kumar Thakur,** Ex-Senior General Manager, CET, SAIL, who was introduced by the Chairman. With a few introductory words, the chairman called the following speakers for presentation.

Shri Tirtha Prasad Saptoka, Senior Area manager, Corporate Sustainability, Tata Steel spoke on ***'Decarbonizing Steel making'*** after being introduced by Dr Rajib Dey. He told global risk landscape is dominated by sustainability risks. 2.5-3.0 gegatons of CO_2 is emitted every year in India, of which 30% is from steel, cement and other metal industries. Steel is a permanent recyclable material, whose demand and production will grow. Challenges for decarbonization are – capital intensive assets, net zero technology, infrastructure development, varying regulation, willingness of customer to bear higher price. Then he discussed transition towards net zero, green route and plans and progress of Tata Steel.

Shri Subharthi Das, General Manager presented the paper of Arunava Banerjee, Chief Operating Officer, Primetals Technologies India entitled ***'Primetals Solution for Suatainability in Steel Industry'***. He suggested there are technologies like hydrogen-based one, to reduce pollution in steel industry, but buyers need to be ready to purchase those. He discussed Maximized Emission Reduction of Sintering (MEROS), Waste Heat Recovery (WHR) for Electric Earth Furnace, Automation systems popular in Europe.

Shri Rajib Maitra, Partner, Mining & Metals, Deloitte Touche Tohmatsu India LLP, talked on ***'Augmenting Copper Sector Growth in India'.*** He mentioned copper is a critical mineral almost globally, presenting global demand scenario, supply scenario, leading producers of copper concentrate across major copper economies.There are global initiatives on producing low-carbon copper. He discussed usage segments in India, its resource position which is 12.20 Mt. Recent thrust in exploration activities in onshore and offshore areas is on. Then he spoke about major producers in our country, recycling of the metal, projected demands and productions by 2030 and 2047, which may grow 5 to 6 times. He felt Government should take initiatives for growth of copper industry.

The topic of discussions of **Dr Ranjeet Kumar Singh,** Principal Scientist, Mineral Processing Division, CSIR-NML was ***'Augmentation of Iron Ore Resources'.*** He talked of production, consumption and future demand of steel, mentioning good quality raw material and processes involving reduced energy consumption and carbon emission needed for achievement. The steps for augmentation, challenges of beneficiation were discussed. He concluded by presenting a few case studies and beneficiation strategy.

Shri Sam N Mitra, Director, Tuffstone Resources Pvt Ltdand Former VP (Minerals), Tata International Ltd delivered presentation on ***'Productivity and Prosperity in Mining Industry'***. He felt key themes linked to productivity are augmentation, atmanirbhar and green mining and discussed productive technology mentioning that depletion is the biggest threat in mining industry. He quoted a FICCI-Deloitte report that said less than 10% of India's Obvious Geological Potential (OGP) has been explored yet and less than 2% has been presently mined, and concluded that we could be self-reliant only through cost-competitiveness, and not by merely having large reserves.

Shri Anirban Biswas, Sr Principal Engineer, Project Management, M N Dastur & Co (P) Ltd, spoke on '***Possibility of Production of Green Steel in India'.*** He presented production and consumption figures of different types of steel and iron. According to him the green path to steel production is dependent on – energy efficiency, use of renewable energy, material efficiency, green hydrogen, CCUS. Steel and Iron industries emit 12% of total CO_2 emission. He discussed cleaner technologies and some innovative methods explored by various entrepreneurs towards and major challenges for production of green steel.

Dr Gopal Ghosh Roy, Ex-Chief General Manager, RINL & Ex-Advisor, NMDC, talked on ***'Augmentation in Metal Production; Journey towards Green'***. He showed world steel production figure mentioning that per capita consumption in India is very less. Steel making is a carbon intensive process and some strategy towards net zero was suggested. According to him there should be short term, mid-term and long-term goals. He discussed some areas of concern and felt lots of R & D initiative are required.

The topic of **Dr Arup Mukherjee,** President, Design & Quality, Tata Hitachi Construction Machinery Co Pvt Ltd, was ***'Engineering Technology for Construction & Mining Equipment towards Green Solution'.*** He spoke on Tata Hitachi Company, its journey, its facilities and its products. He discussed zero emission technology development roadmap with innovative greener solutions.

Queries from audience were replied by the speakers after each presentation. The session ended with presentation of mementoes to the chairmen and speakers.


NATIONAL SEMINAR ON
"AUGMENTATION IN METAL PRODUCTION: JOURNEY TOWARDS GREEN"
(AMPG - 2024)
Saturday 21st September 2024
The Mining, Geological & Metallurgical Institute of India (MGMI)
Gold Sponsor
Supported by
TATA STEEL
#WeAlsoMakeTomorrow
PROF. (DR.) N R BANDYOPADHYAY
CHAIRMAN - TECHNICAL SESSION

TECHNICAL NOTE

DEVELOPMENT OF VIRGIN MINERAL DEPOSITS – SOME SUGGESTIONS

D.N. Bhargava

This technical note presents some suggestions how the "Development of Virgin Mineral Deposits" could be achieved in an environment of peace and harmony, and regulation of the mining activity could be done in an effective and efficient manner so as to simplify the regulating mechanism yet maintain the scope of regulation.

It takes into account the current practice of auction of Mineral bearing areas, allotting each to the highest bidder. Also, there are indefinite delays in grant of various approvals which retard the commencement of production of minerals These factors are bound to inflate the cost of production of the respective minerals; this inflation may eventually be passed on to the consumers. Keeping the above factors in view, certain views and suggestions are being offered below; if adopted these may simplify the procedures, promote "Ease of doing mining" and guard against inflation.

The current situation and suggestions offered for adoption

1. A mineral deposit is first identified in the course of geological mapping of a region by the Geological Survey of India (GSI). Just then mutual consultation between the Ministry of Mines and the Ministry of Environment & Forests is necessary about the future clearance of such an area for the grant of mining lease even before the detailed exploration of the mineral deposit is undertaken. This will ensure the availability of the sites for detailed exploration and subsequent mining operations subject to observance of certain conditions for the conservation of the Mineral resources and the protection of Environment. It will do away with the need for further approvals by the Ministry of Environment or the Ministry of Mines and save valuable time during the start-up of mining operations.
2. The detailed exploration of the mineral deposit is being undertaken by a number of Agencies. It includes the GSI and Directorates of Geology of different States. Certain Agencies of the Central Government such as the Mineral Exploration and Consultancy Limited (MECL), Coal Mine Planning and Design Institute (CMPDI) also undertake detailed exploration. The mining lease holders are required to pay a mineral exploration cess which in a way makes up for the expenses made by the Governments or their agencies on exploration.
3. In case a viable mineral deposit is identified for the grant of mining lease, the concerned Government may rehabilitate in advance the persons, who are likely to be displaced as a result of the grant of mining lease, at another suitable site; the Government may recover the cost of such rehabilitation from the applicant who is subsequently granted the mining lease of the said area. The M.L. Holder would gladly reimburse the cost of rehabilitation, because it will save him valuable time before the commencement of the mining operations.
4. Once the decision of clearing an area for future mining is taken as discussed at (1.) above, the Ministry of Environment may specify the environmental conditions which should be met, keeping in mind that during the conduct of mining operations, some amount of degrada-

[1]Former Controller General, Indian Bureau of Mines; Email : deokinandanbhargava31@gmail.com

tion of environment would be inevitable. It may also specify the extent to which the environment may be restored in the course of the mining operations and before the closure of the mine.

5. The concerned officers of Ministry of Environment may monitor the mining operations there after, but the need for any grant of approval for the mining operation should not arise. Since the Officers of the Indian Bureau of Mines are also the authorized officers under the Environment Act, the Ministry of Environment may point out, if necessary, any lacuna to IBM. Then it will be IBM's responsibility to ensure that the lacuna is removed by the Mine Owner. Even otherwise IBM may on its own do so.

6. Whenever mining lease is granted of an area which had already been explored by a Government Agency in the past before the provision for payment of exploration cess was made, it may be made mandatory for the applicant for mining lease to reimburse the cost of exploration, and he may be provided the detailed exploration report. Thereafter he may be permitted not to pay the exploration cess until such time that the original payment made is fully adjusted. Thereafter he may be required to pay the exploration cess for exploration in the same way as is obligatory for the others.

7. It is experienced that the displaced communities are often antagonistic to mining. To gain their goodwill and change their mind-set it may be advisable to let the Gram Panchayat of the mineral bearing area also take up mining. They may be encouraged to form a cooperative and hold the administration of the mine; they may engage the Mining Corporation of the concerned State as the Consultant in technical matters relating to Mining Operations; Indeed, the Corporation may be assigned the supervision of technical work involving the management of the mining operations.

8. The grant of Mining lease should be delinked with the practice of granting it to the highest bidder. Instead the applications for the grant of lease may be considered on the basis of how the applicant would serve the public interest by the way of rehabilitation of the displaced people or indicating the concrete steps he would take to serve any other public interest. The offers may be transparently scrutinized for taking decision regarding the grant of mining lease. The existing procedure of auctioning lease to the highest bidder may adversely affect the consumer of minerals due to automatic inflation in the prices of the mineral.

It is hoped that the above-mentioned suggestions may be found helpful in the governance of the Mineral Sector and be of benefit to all stakeholders.

Mangalore

27th September 2024

2025 Global Metals & Mining Conference

May 20 - 22, 2025

Henderson, NV

Metals and mining are at the core of what we do. With a history of proven success, our skilled and global team knows the value of an internationally coordinated approach in this specialized field. Members may like to join for 4th Annual Global Metals and Mining Conference, where leading companies across this essential and diverse industry will come together.

Methane Mitigation Europe Summit

25 – 27 February 2025

Novotel Amsterdam City, Netherlands

This will give operators a structured timeline to develop new protocols, expand resources, and integrate cutting-edge technology for compliance. It may be an ideal moment to connect with industry colleagues to overcome the hurdles.

The members mayengage in open conversations about the obstacles and achievements in this journey, leaving them energized and well-prepared.

Featured speakers include:

- Cristina Lopez, Process Research Engineer in Methane Emissions and Renewable Gases, GRTgaz
- Murès Zarea, President, GERG
- Rebecca Allison, COO, Net Zero Technology Centre
- Isabella Stocker, Methane Advisor, bp
- Rosalía Vázquez, Senior Advisor for Energy Transition & Climate Change, Repsol
- Ludovic Donnat, Environmental Modeling Research Engineer, Total Energies

MGMI PRESIDENT GOLF TOURNAMENT 2024

The MGMI Golf Tournament 2024, held on April 24th at the prestigious Royal Calcutta Golf Club, was a resounding success. Despite the scorching temperatures reaching around 42°C, the event witnessed enthusiastic participation from approximately 18 avid golfers, including individuals from MCL who travelled to participate.

Ahead of the tournament, outside players engaged in practice sessions on April 23rd to familiarize themselves with the course. The heat did little to dampen the players' spirits, who displayed commendable enthusiasm throughout the event.

The prize distribution ceremony and after-party took place at the opulent Royal Platinum Lounge. Attendees were treated to a delightful ambience, accompanied by delectable cuisine, and music that received widespread appreciation.

Dr.B V Reddy – Director Technical CIL/ President MGMI graced the occasion as the chief guest of the tournament. Among the distinguished dignitaries present were Mr. R.P. Ritolia, the Chairman, Mr. D.B. Nayak - DDG (Mech); and Mr. Talapatra, Secretary of MGMI.

PRIZE WINNERS :	
Champion - Best Net Score:	Mr. J. Kumar (MCL)
Runner-up :	Mr. M.S. Sharma (MCL)
Gross Winner :	Mr. Vikash Jain
Best Outstation Player :	Mr. D.B. Nayak - DDG (Mech)
Best Senior Player (Above 70) :	Mr. O.P. Killa
Best Nine-Hole Senior Player :	Mr. J.P. Goenka
Best Stableford Point :	Mr. Jatin Mehta
Nearest to the Pin:	Mr. T.K. Banerjee
Longest Drive :	Mr. Anil Karmakar
Best Ladies Golfer :	Mrs. Shobha Karmakar
Lucky Draw Winner :	Mr. Rajkumar

The event concluded on a high note, leaving participants and attendees eagerly anticipating the next edition of the MGMI President Golf Tournament.

LIST OF MGMI SPECIAL PUBLICATIONS

Name of the Publications	Year	US$	Rs
Progress of the Mineral Industry * (Golden Jubilee Vol.1906-1956)	1956	12	60
Dr. D.N. Wadia Commemorative Volume*	1965	15	100
Small Scale Mining in India and abroad *	1991	45	450
New Finds of Coal In India – Resource potential and Mining Possibilities	1993	30	300
Computer Applications in Mineral Industry	1993	40	400
Indian Mining Directory (4th Edition)*	1993	40	400
Asian Mining 1993	1993	85	850
Mine Productivity & Technology	1994	75	500
Maintenance Management for Mining Machinery*	1995	60	600
High Production Technology for underground Mines*	1996	50	500
Mineral Industry Development in India – Issues, Perspective & Policy	1996	20	200
Disaster Prevention Management for Coal Mines, Vol I	1996	50	500
Disaster Prevention Management for Coal Mines, Vol II	1996	50	500
Business and Investment opportunities in Mining Industries (BIMI '96)*	1996	40	400
Indian Mining Directory (5th Edition)*	1996	50	500
Information Technology in Mineral Industry(MGMIT'97)*	1997	50	500
Technological Advances in Opencast Mining(Opencast'98)*	1998	80	800
Management of Mining Machinery (MMM 1999)	1999	80	800
Mining & Marketing of Minerals (MMM 2000)	2000	80	800
Mechanisation and Automation in Mineral Industry(MAMI 2001)	2001	80	800
Mineral Industry : Issues on Economics, Environment and Technology (MEET 2002)	2002	80	800
Development of Indian Mineral Industry Looking Ahead(DIMI 2003)	2003	20	200
Emerging Challenges in Mining Industry (ECMI 2003)	2003	50	500
Future of Indian Mineral Industry (FIMI 2004)	2004	80	800
Bridging the Demand Supply Gap in Indian Coal Industry*	2005	30	300
Asian Mining Towards A New Resurgence (Vol. I & II)	2006	175	2400
Indian Mining Directory (6th Edition)*	2006	60	600
Turnaround Stories of Coal Companies and Future Strategies	2006	20	200
Reprints of Holland Memorial Lecture	2006	40	400
Glimpses from Transactions	2006	30	300
Coal Beneficiation & Development of Coal Derivatives*	2007	40	400
2nd Asian Mining Congress*	2008	200	2000
Glimpses of Hundred years of MGMI of India (1906 – 2006)	2008	50	500
3rd Asian Mining Congress	2010	160	2000
4th Asian Mining Congress	2012	100	1000
5th Asian Mining Congress	2014 (CD)	100	1000
National Seminar on Indian Mining Industry-Challenges Ahead (IMICA)	2015	15	150
6th Asian Mining Congress (Pen Drive)	2016	100	1000
6th Asian Mining Congress (Proceeding Vol)	2016	500	5000
7th Asian Mining Congress (Pen Drive)	2017	100	1000
8th Asian Mining Congress (Green Mining: The Way Forward)	2019	250	2500
9th Asian Mining Congress (Technological Advancements in Mining Industy : Status and Challenges)	2022	25	2500
10th Asian Mining Congress (Roadmap for Best Mining Practices vis-a-vis Global Transformation)	2023	35	3500
Regular Publications	a) News Letter (published quarterly) b) Transactions (published Annually)		

*** out of stock**

MGMI TRANSIT HOUSE

The Mining, Geological and Metallurgical Institute of India

GN-38/4, Sector V, Salt Lake, Kolkata 700 091
Phones : +91 33 4000 5168, +91 33 2357 3482
Email : office@mgmiindia.in, mgmisecretary@gmail.com
Website : www.mgmiindia.in

Rules & Regulations

1.

Accommodation	Room Rent	Accommodation	Room Rent
Single Occupancy	Rs. 1,500/-	Triple Occupancy	Rs. 2,500/-
Double Occupancy	Rs. 2,000/-	Extra Bed	Rs. 600/-

2. 50% discount will be offered to MGMI member for self occupancy only.
3. Full tariff will be applicable for the nominee of MGMI member.
4. Full tariff for the employees of the Corporate Member or Patron Member.
5. 50% advance has to be deposited for confirmation of **block booking** (three or more rooms for two or more days). Caution money @Rs. 500/- per day, per room has to be deposited along with room rent in advance. This will be refunded in full or part thereof depending on the damage caused by the Guests.
6. Cancellation of confirmed booking Period Prior to date of Occupancy Cancellation fee to be deducted from advance

   a. Cancellation before Seven days 5%
   b. Cancellation before Three days 10%
   c. Cancellation before One day 25%
7. 24 Hours Check-in and Check-out
8. GST : @12% Extra

LIFT Facility Available

Complimentary Breakfast Available

For Booking Please Contact MGMI Office at the Numbers and Email Addresses given above

THE MINING GEOLOGICAL & METALLURGICAL INSTITUTE OF INDIA Established 1906

Published by : **Honorary Secretary, The Mining, Geological and Metallurgical Institute of India**
GN-38/4, Sector V, Salt Lake, Kolkata 700 091, Phones : +91 33 4000 5168, +91 33 2357 3482 / 3987
E-mail : office@mgmiindia.in, mgmisecretary@gmail.com
Website : www.mgmiindia.in
Price : Free to Members : ₹ 200.00 or US$ 10.00 per copy to others
Printed at : Graphique International, Kolkata - 700 015, Phone : (033) 2251 1407