ACBCCS 2013

Awareness and Capacity Building in Carbon Capture and Storage: Earth Processes

15th -19th January, 2013, New Delhi

Pre-Workshop Bulletin of Lecture Notes

Workshop Highlights

- CCS Status & Overview - 2 Sessions
- CO_2 Reduction in Power Sector - 3 Sessions
- Earth Processes in CO_2 Storage & Recycling - 4 Sessions
- CO_2 in Industry - 4 Sessions
- Panel Discussion

Supported by

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Ministry of Earth Sciences
Government of India

Organized by

CCRI

Climate Change Research Institute
New Delhi

Awareness and Capacity Building in Carbon Capture and Storage: Earth Processes

ACBCCS-2013

IIC Convention Center, January 15-19, 2013

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Convener
Dr. (Mrs.) Malti Goel
CSIR Emeritus Scientist, Jawaharlal Nehru University, New Delhi & former Adviser and Scientist 'G', Department of Science & Technology, New Delhi

R.V. SHAHI
Chairman, Energy Infratech
Former Power Secretary, Govt. of India

Foreword

I am pleased to know that a workshop on '*Awareness and Capacity Building in Carbon Capture and Storage: Earth Processes*' is planned to be held in New Delhi from January 15-19, 2013.

India being the founder member of Carbon Sequestration Leadership Forum, USA, an initiative with which I was closely associated as Secretary Power, Govt. of India, and Global Carbon Capture and Storage Institute, Australia, it is timely that an interaction is organised to enhance understanding on CO_2 recycling. Issues need to be elaborated for broadening the perspectives on CCS. Acceptance of Carbon Capture and Storage (CCS) under Clean Development Mechanism has aroused special interest among industry. It has become necessary to review the CCS scenario, particularly in India for a possible change in its social acceptance. It is also necessary to develop a road map on the research needs in CCS and submit the recommendations to the concerned agencies.

Internationally research has been growing exponentially and I am told that very recently a new scientific 'Journal of CO_2 Utilization' has been launched by international publishers like Elsevier. India is among major coal based economies in the world. Therefore I appreciate this initiative to synergize the research efforts in India and to organize a capacity building workshop. Industry has to come forward to take the challenge.

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

(**R. V. Shahi**)

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Awareness and Capacity Building in Carbon Capture and Storage: Earth Processes (ACBCCS 2013)

Pre Workshop Lecture Notes

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Pre-Workshop Bulletin of Lecture Notes

Awareness and Capacity Building in Carbon Capture and Storage: Earth Processes (ACBCCS-2013), January 15-19, 2013

PREFACE

India's energy is majorly dependent on 'King Coal'. The coal combustion also causes the highest CO_2 emissions of all fossil fuels. With the growing concerns for climate change threats in the 21st century there has been increasing interest in carbon sequestration technology as insurance for continuation of coal use in our energy supply.

According to IPCC assessments the carbon dioxide concentrations have increased from pre industrial value of 280ppm to 386 ppm at present and a safe limit of 450 ppm has been set for the year 2050 to save the Planet Earth. To respond the complex dynamics of climate change predictions, both mitigation and adaption approaches are being developed. Capturing of excess carbon dioxide, its utilization and permanent fixation away from the atmosphere are emerging technology worldwide for mitigation. The challenges are immense and need to be addressed by scientific & technological means.

We need to create awareness not only on the research issues of carbon capture, utilization and storage options, but also the options for clean energy development in a sustainable manner. It is hoped that the five day national level workshop on Awareness and Capacity Building in Carbon Capture and Storage: Earth Processes (ACBCCS-2013) being held from January 15-19, 2013, New Delhi will provide a platform for the young researchers to learn more about the about the scientific & technological challenges faced by us in CCS and CCUS in the context of global climate change. .

On this occasion I would like to thank Shri R.V. Shahi, Chairman, National Advisory Board for his support and encouragement. I feel indebted to overwhelming response from the eminent experts and delegates from various institutions across the country. The support from Ministry of Earth Sciences, Government of India for this capacity building workshop is highly acknowledged.

Dr. (Mrs.) Malti Goel
Convener (ACBCCS-2013)
CSIR Emeritus Scientist & Former Adviser, DST

डॉ. के. कस्तूरीरंगन
सदस्य
Dr. K. KASTURIRANGAN
MEMBER

सत्यमेव जयते

भारत सरकार
योजना आयोग
योजना भवन
नई दिल्ली-११०००१
GOVERNMENT OF INDIA
PLANNING COMMISSION
YOJANA BHAWAN
NEW DELHI-110 001

No. PC/M(KK)/I.10/2013,
January 08, 2013

MESSAGE

I am happy to learn that a five day national level workshop is being held on 'Awareness and Capacity Building on Carbon Capture and Storage: Earth Processes' from January 15-19, 2013 at IIC Convention Centre, New Delhi.

The carbon capture and storage has emerged as a challenging field of science & technology. I understand that Indian Scientific Community has evinced considerable interest in pursuing research in this field, so as to keep pace with the international research. It is timely that an exposure is provided and understanding about the various options of recycling of carbon dioxide in the earth processes is created for broadening the perspectives on CCS. There is a need for creating awareness and capacity building among the young engineers and scientists from the industry and academia, to take actions and technological interventions for climate change mitigation.

I congratulate the Organizers for the initiative taken for the ACBCCS-2013 and wish them a grand success.

(K. Kasturirangan)

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डॉ. शैलेश नायक
DR. SHAILESH NAYAK

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

MESSAGE

I am happy that a national level *Workshop on Awareness and Capacity Building on Carbon Capture and Storage: Earth Processes (ACBCCS2013)* is being organized during January 15-19, 2013 at IIC Convention Centre, New Delhi.

India's energy portfolio is coal dominant. Carbon sequestration no doubt is an important research area. It is a complex set of technologies in multi-disciplinary areas viz., capturing CO_2 from its point sources; direct or indirect utilization of CO_2 in chemical or bio industry; transport of CO_2 in case it is to be trapped in the subsurface and finally the process of CO_2 storage.

I see a plethora of scientific challenges in the study of CO_2 interactions in the earth system. Sub-surface injection of CO_2 into deep saline aquifers, depleted oil & gas reservoirs, un-mineable coal seams, the basalt rocks and possibly in the oceans has been conceptualized. Safety, permanence of storage and leakage across the boundaries are the main concerns. Geosciences can play a major role and we need modeling studies of active and passive CO_2 interactions to understand these processes.

I am confident that this workshop will help to provide a useful knowledge base in the developing science of climate change mitigation.

(Shailesh Nayak)

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सत्यमेव जयते

केन्द्रीय विद्युत विनियामक आयोग

CENTRAL ELECTRICITY REGULATORY COMMISSION

C.E.R.C.

V.S. VERMA
MEMBER

Former Member (Planning), CEA
Former Director General,
Bureau of Energy Efficiency

MESSAGE

It gives me a great pleasure to learn that The Climate Change Research Institute (India) is organizing a national level workshop on "Awareness and capacity building on Carbon Capture and Storage - Earth Process" from January 15 to 19th, 2013 at IIC Convention Centre, New Delhi. The subject of Carbon Capture and Storage has been under discussion and active consideration of the International community and specially in Europe for last about 8-10 years. A few experimental and research Installations have also been tried in US, Germany, UK and a few other countries. The various aspects of CCS Technology need in-depth deliberations with a view to adopting it in the Indian context specially when there lies a great deal of areas which needs to be more clearly understood.

The various principles of the processes and its impact on efficiency and availability of the energy sector, in particular, have had to prove on commercial considerations. More clarity of thought and process can be achieved by deliberations amongst the various experts in a Conference like this. The CCS technology has to be understood from the point of view of considerations of International acceptance and proveness at commercial scale with special reference to priorities at the national level in India for adoption of the same in the industries and the Power Sector along with other priorities. The various pros and cons of such installations must be discussed and deliberated at length before a considered view could be taken for applications in our country.

The vast unexplored area relating to the Capture of CO_2 and its conversion into useful products such as building materials and other also needs to be given due priority by the scientists and technologists who are associated in one way or the other with the development of this area. This is particularly important since in the distant future time to come the electricity generation in our country would continue to be mainly based on coal, with consequent large production of CO_2. However, it is now decided for sure that the CO_2 footprint of India has to be brought down in a systematic phased manner by adoption of various techniques, methodologies and technologies. I am confident that the above Workshop would prove to be more relevant and focused in this direction.

I wish the Workshop great success and indeed look forward for its recommendations at the end of the concluding sessions.

(V.S. VERMA)

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Awareness and Capacity Building Workshop on Carbon Capture and Storage: Earth Processes

Jan 15-19, 2013, India International Centre, New Delhi

Tentative Programme

Day 1: 15.01.2013 (CCS Status & Overview)

F/N : INAUGURATION

Afternoon Session

2:00 PM Current Status of CCS Research - National & International
- Dr. (Mrs.) Malti Goel, CSIR Emeritus Scientist

3:00 PM CCS Corporate Sector Initiatives in India
- Shri D. K. Agarawal, ED, NTPC

4:00 PM CCS Scoping Study in Indian Context
- Dr. Agneev Mukherjee, TERI

Day 2: 16.01.2013 (CO_2 Reduction in Power Sector)

Forenoon Session

10:00 AM Pre Combustion and Combustion- CO_2 Reduction in Power Sector
- Dr. Anshu Nanoti, IIP, Dehradun

11:30 AM Capturing CO_2 by Physical and Chemical Means
- Prof. A.K. Ghoshal, IIT Guwahati

Afternoon Session

Field Visit

Day 3: 17.01.2013 (Earth Processes in CO_2 Storage & Recycling)

Forenoon Session

10:00 AM Geological Sequestration of CO_2 in Saline Aquifers- An Indian Perspective
- Dr. A.K. Bhandari, Ministry of Mines

11:30 AM Options for CO_2 Storage and Role of Unconventional Gas in Reducing Carbon Dioxide Emissions
- Dr. Balesh Kumar, GERMI & Ex-NGRI

Afternoon Session

2:00 PM Carbon Sequestration Potential of the Forests of North- Eastern India
- Prof. P.S. Yadava, Manipur University

3:30 PM Prospects in Biomimetic Carbon Sequestration

- Prof. Satyanarayana Tulasi, Delhi University

Bio-sequestration of Carbon Dioxide— Potential and Challenges

- Prof. K. Uma Devi, Anna University

<u>Day 4</u>: 18.01.2013 (CO_2 in Industry & Value addition)

<u>Forenoon Session</u>

10:00 AM Opportunity of CO_2 Storage in Coal Beds

- Dr. A. K. Singh, CIMFR

11:30 AM Real Term Implications of Carbon Sequestration in Coal Seams

- Mr. Vikram Vishal, IIT Bombay

<u>Afternoon Session</u>

2:00 PM Reservoirs for CO_2 Storage & Value Addition – EOR process

- Dr. D.M. Kale, ONGC Energy Centre

3:30 PM Carbon Dioxide Storage and Enhanced Oil Recovery

- Mr. Gautam Sen, Ex- Oil & Gas Consultant, ONGC

<u>Day 5</u>: 19.01.2013 (Panel Discussion and Summing Up)

19th January, 2013

10:00 AM Assembly & Tea

10:30 AM Guest Lecture: Policy and Regulatory Interventions in Abatement of CO2 Footprints

- Shri. V. S. Verma, Member, Central Electricity Regulatory, Commission

11:15 AM Round Table Discussions:

Suggested Topics

- Need for a regulatory / institutional framework in India
- CCS in power and Industry sector
- CCS capacity building needs
- Impact on international development on developing countries

12:00 Concluding Remarks

12:15 Presentation by delegates and Awarding Certificates of Participation

Workshop on Awareness and Capacity Building in Carbon Capture and Storage: Earth Processes (ACBCCS-2013), January 15-19, 2013

Seminar Hall-3, IIC Convention Centre, F.F. (entry from Gate 1), New Delhi – 110003

<u>Programme of Inaugural Session: 10:30 – 12:00 Noon</u>

10:30	hrs.	Assembly & Tea	
11:00	hrs.	Welcome	Ms Karishma Vohra, Student TERI
11:05	hrs.	Introduction to Theme	Dr. (Mrs.) Malti Goel, Convener and CSIR Emeritus Scientist, JNU
11:15	hrs	Special Address:	Shri M. P. Narayanan, Former Chairman, Coal India Ltd.
11:35	hrs.	Presidential Address:	Sh. D.K. Agarwal, Executive Director, NTPC and Head NTPC-NETRA
11:50	hrs.	Inaugural Address:	Dr. Harsh K. Gupta, Member, National Disaster Management Authority and Former Secretary, DoD
12:00	hrs.	Vote of Thanks	General Secretary, CCRS

12:05 - 12:35 hrs. Introductory lecture on Carbon Capture and Storage:

CO_2 SEQUESTRATION AND EARTH PROCESSES*

Dr. (Mrs.) Malti Goel
CSIR Emeritus Scientist, Centre for Studies in Science Policy,
Jawaharlal Nehru University, New Delhi-110067, India

Abstract

This paper is dealing with the emerging topic of CO_2 Sequestration, which is among the advanced energy technologies. CO_2 Sequestration is being discussed in national and international forums and is of particular importance to coal based economies. Various processes for CO_2 utilization and recycling in the Earth System are discussed in detail. Highlights of international large scale projects and current status in India including future challenges and objectives of ACBCCS-2013 are presented.

1. Introduction

> *"The most beautiful experience we can have is the mysterious. It is fundamental emotion, which stands at the cradle of true art and true science."*
>
> *- Albert Einstein*

Capturing carbon dioxide is an end-of-pipe solution for pollution mitigation in fossil fuel based energy systems. Significant strides are being made in understanding carbon capture and storage - CO_2 Sequestration in fossil fuel based economies. The CO_2 Sequestration involves capture of excess CO_2 from its point sources and its permanent fixation away from the atmosphere. The various techniques of CO_2 capture are derived from gas separation techniques, which include chemical absorption, membrane separation, physical adsorption, and cryogenic separation at source[1]. Captured CO_2 is then sequestrated by means of surface processes, by sub surface storage and/or by recovery of energy fuels & minerals (Fig. 1). If the source and the underground fixation sites are not near to each other, transport of CO_2 in liquid form over longer distances is required. To achieve a carbon balance in the atmosphere in an enhanced CO_2 scenario, science & technology gaps exist in CO_2 capture processes and materials as well as site specific models for its fixation[2,3].

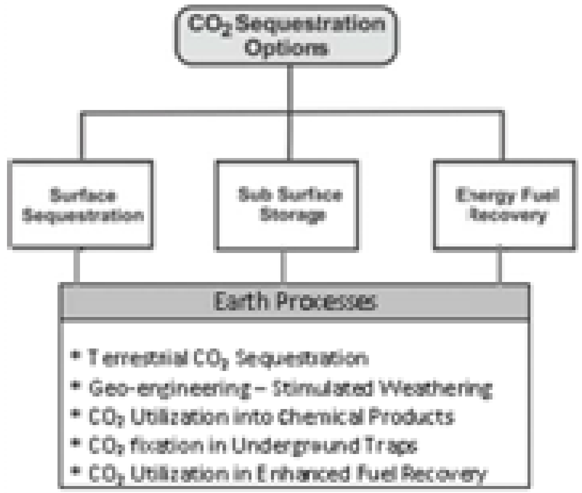

Fig. 1 The CO_2 Sequestration options

2. Earth Processes

Development of technologies for quantifying carbon stored in a given ecosystem and manipulation of ecosystem to increase the carbon sequestration rate beyond current conditions requires modeling research[4]. Whereas, CO_2 sequestration in earth processes in the surface and subsurface levels can be understood as follows:

2.1 CO_2 Fixation in Terrestrial Ecosystems

The terrestrial sequestration approach is having significant potential for terrestrial sequestration i.e., plant & soil sequestration, microbial and micro-algae fixation to stabilize atmospheric concentration of CO_2.

2.1.1 Plants and Soil

The terrestrial biosphere is capable of sequestering large amount of carbon dioxide. Plants absorb CO_2 in the photosynthesis process. Carbon assimilation occurs in forests, trees, crops and soil and these are CO_2 sinks. Terrestrial CO_2 storage can lead to afforestation in forest areas and can enhance crop productivity in rural areas. Advanced crop species and cultivation practices could be designed to increase the uptake of CO_2 through an enhanced photosynthesis rate.

The primary ways that carbon is stored in plants or in the soil as soil organic matter (SOM), which is a complex mixture of carbon compounds, consisting of decomposing plant and animal tissue, microbes (protozoa, nematodes, fungi, and bacteria) and carbon associated with soil minerals. Soils contain three times more carbon than the amount stored in living plants and animals.

It is estimated that increasing the soil organic carbon (SOC) by 0.01 per cent could nullify the annual increase in atmospheric carbon due to anthropogenic CO_2 emissions. The soil carbon pool and emissions of CO_2 are also influenced by vegetation types and local environmental factors[5, 6]. Enhanced CO_2 absorption rate in vegetation and cropland can lead to active storage whereas in wetlands, mined or un-mined forest sites and highway construction sites it can be a form of passive storage. Development of techniques for enhanced absorption of CO_2 while using least forest area and to understand the feedback mechanisms with a view to undertake agro-forestry modeling are needed.

2.1.2 Bio Sequestration

A further biological route can be to capture CO_2 from the flue gas using an algae pond in the vicinity of a thermal power plant. Development of algal strains with high productivity appears to be the most cost-effective solution with value addition. But the greatest challenge is to isolate algae and genetically improve algal strain for both higher oil content and overall productivity. Marine algae forms a possible solution for thermal power plants situated along the sea coast. Enhanced biological CO_2 capture has become possible by designing photo-bio reactors. Controlled micro organism activation methods using photo bio reactors are under development as biofixation option of CO_2. Solar bioreactors have been proposed for warm and sunny climatic regions. Bio-mimetic approaches using immobilized carbonic anhydrase are being studied in bioreactors for assessing CO_2 sequestration potential.

Further studies of carbon concentrating mechanisms in photoautotrophic organisms and non-photosynthetic organisms, standardization and creation of data bank can potentially lead to the development of cost-effective large scale operation of CO_2 sequestration[7].

2.2 Geo-engineering - Stimulated Weathering

Mafic and Ultramafic rock minerals, olivine, pyroxene and anorthite are present in large quantities in the subsurface environment. These minerals play an important role in the natural *carbon cycle.* Natural weathering occurs over geological time scales. Accelerating the natural process of CO_2 absorption by enhanced mineralization of olivine/ silicate rocks offers another potentially low cost solution for CO_2 sequestration[8]. The effects of CO_2 fugacity and salinity on the kinetics of diffusion of CO_2 into olivine have been investigated. Several studies have been made to study mineral reactivity, energy balance, intense grinding in presence of gaseous CO_2 and dynamics of CO_2 in pores. Accelerated rate of precipitation of mineral carbonate with industrial wastewater as a cation source has been demonstrated[9] in presence of a catalyst.

Silicates and compounds of magnesium and iron are present in small quantities in mineral industry waste. By using the geo-engineering approach for stimulated weathering of mining and industrial wastes, it is possible to sequester excess CO_2 from the atmosphere. Large scale sequestration by such means requires further and more detailed modeling research and understanding of field processes.

2.3 CO_2 Utilization and Value Added Products

The CO_2 has low chemical activity but it is possible to activate it towards chemical reactions by application of temperature or pressure or by use of catalysts. A variety of chemicals can be produced from CO_2. These can be subdivided into a number of important areas; i) Synthetic fuel products from CO_2 could be regarded as energy vectors or energy stores, utilizing renewable energy sources at off-peak hours with temporarily stored local CO_2. ii) By hydrogenation of CO_2 over a wide range of catalysts, synthetic hydrocarbons as transportation fuel can be produced. Hydrogen is required in considerable quantity and selectively to produce a single fraction of commercially vehicular fuels. iii) Synthesis gas can be produced by reforming reactions, sometimes in multiple steps. One of the benefits of reforming reactions is the simplicity of the catalysts used, including nickel and cobalt catalysts. iv) The synthesis gas produced can then be used in the transition metal catalyzed Fischer-Tropsch (F-T) synthesis.

Challenge exists to develop not only the F-T process conditions, but also to design new effective and selective catalysts. Use of enzyme carbonic anhydrase has been suggested as most efficient catalyst in CO_2 reaction with water. A pilot plant for multi-fuel generation has been designed and fabricated at Rajiv Gandhi Prodiyiki Vidyalaya, Bhopal[10].

2.4 CO_2 Fixation in Underground Traps

Permanence of storage and no risk from leakage are main safety criteria for sub-surface storage. As a CO_2 plume migrates, some of it may react with formation minerals to precipitate carbonates. When CO_2 reacts with in-situ fluids and gels dissolved geo chemical trapping occurs. The CO_2 laden water becomes denser and sinks to bottom. Chemical reactions with rock minerals can lead to formation of solid carbonates minerals. Mineral trapping is more permanent as Silicate minerals are converted to secondary Carbonates. Under suitable conditions of pressure and temperatures, minerals trapping capacity is high. Sequestration potential is high. On the whole, the nature of dissolution, mixing and segregation of CO_2 is dependent on reservoir characteristics and required scientific understanding of local geology[11].

The US Department of Energy has classified eleven major types of reservoirs for knowledge development pathways of CO_2 Sequestration. Each has unique characteristics and requires considerable research on their performance analysis[12]. In the sub-surface CO_2 is normally stored in the supercritical phase, which is attained at the temperature of 304.1K and pressure 73.8 bars. Injection of CO_2 into deep saline aquifers, depleted oil & gas reservoirs, un-mineable coal seams and in basalts has been conceptualized. Physical trapping is expected to occur where there is a good cap rock with a low permeability. Engineered geological traps are also expected to provide a permanent storage for CO_2. Both active and passive underground trapping mechanisms have been studied extensively.

2.4.1 Underground Solution Trapping

CO_2 fixation in deep saline aquifers, both on shore and offshore and are expected to provide the largest storage capacity at below 800m depth. At this depth, CO_2 is in liquid or supercritical state and has density less than water. The buoyant forces tend to drive upwards and therefore good cap rock is essential, in a manner similar to a soda water bottle where CO_2 occupies the space by partially displacing the fluid. In Saline formations, estimates of potential storage volume are low up to 30% of the total rock volume. The storage efficiency would depend on its structure as well as storage strategies and purity of captured CO_2.

2.4.2 Large scale Stratigraphic Trapping

Upward migration of CO_2 is blocked by the stratigraphic structure of clay rocks above the storage formation. Lateral migration of CO_2 can also take place beneath the cap rock isolated within anticline structures bound by the shale cap and capillary forces may also retain CO_2 in the pore spaces of the formation.

2.4.3 Mineralogical Trapping

Basalt formations are attractive storage media as ancient hot lava sites. Pacific Northwest National Laboratory (PNNL), USA has identified carbon dioxide sequestration research priorities in flood basalts in the Columbia River region [13]. Field research carried out in these formations suggests that lateral dispersions and vertical transport of CO_2 to overlaying basalt flows are expected to be important limiting factors controlling in-situ processes.

Will clay and calcium carbonate precipitation clog the available pore space at the injection site? Considerable further research is needed to understand the kinetics of rapid mineralization reaction rates that may occur in different basalts across the world. The area of Deccan flood basalts in India is estimated to be 0.5 million km^2. Consisting of the thick Mesozoic sediments, its thickness varies from a few hundred m to 1.5km, it could show accelerated reaction with CO_2 and its conversion into mineral carbonates possibly below sediments. It comprises of reactive Fe-Mg-Ca and Na rich silicon minerals. A preliminary feasibly study in Deccan Volcanic Province has been conducted at National Geophysical Research Laboratory, Hyderabad to study nature of secondary carbonation that takes place upon reaction with CO_2 in supercritical conditions[14].

2.4.4 Residual Gas trapping

Residual gas trapping can occur in any sub-surface reservoir. When free-phase CO_2 migrates, it forms a plume, the CO_2 concentration towards the tail of the plume can get trapped by capillary pressure from the water present in the pore spaces between the rocks. Similar to solution trapping CO_2 either forms residual - droplets in the pore spaces or gets dissolved in the formation water. This is similar to oil molecules trapped in the sub-surface for millions of years.

2.5 CO_2 Utilization in Recovery of Energy Fuels

An important aspect of carbon sequestration is recovery of value added products. Active underground storage of CO_2 in oil, gas or coal fields for enhanced fuel recovery can provide an economic synergy to CO_2 sequestration process.

2.5.1 Enhanced Oil Recovery (EOR)

The CO_2 has been injected in depleting oil fields for enhanced recovery of oil. Scientific research for testing of storage of anthropogenic CO_2 in EOR has also been carried out depending on the pressure of injection gas into the reservoir. The CO_2 in an oil well can either be in miscible or in immiscible phase. In the miscible phase, injected CO_2 mixes with the viscous crude causing it to swell. It reduces its viscosity in the reservoir causing a flow to produce more oil. In the immiscible phase CO_2 does not dissolve in the crude. It raises the pressure and helps to sweep the oil towards the production well. A combination of both miscible and immiscible phases normally occurs. How much oil is displaced depends on various parameters such as; oil swelling, viscosity reduction, miscibility generation and reduction in residual oil saturation. Relative contribution of various parameters depends on the reservoir conditions as well as crude oil quantity. Dynamic modeling tools are needed to study migration, flow / behavior of stored CO_2 and actual performance prediction for enhanced oil recovery.

2.5.2 Enhanced Coal Bed Methane Recovery (ECBM)

Coal beds have absorption capacity for CO_2 which is two to three times that of methane. Like oil fields, an un-mineable coal seam can also prove to be a potential reservoir for enhanced coal bed methane recovery (ECBM). Physical adsorption of CO_2 occurs on the internal surface and micro pores in coal beds and replacing methane. The CO_2 remains trapped as long as pressure and temperature remain stable. The absorption isotherms for CO_2 are important. Sorption capacity of coal decreases significantly with increasing temperature. Normally temperature in the range of 12^o to 26^oC is preferred. High moisture content in coal also decreases sorption capacity. Model predictions suggest that injection of CO_2 can achieve 70-90 percent recovery of CBM as against 40 percent without it. CO_2 storage in coal beds takes place at shallower depth than in Saline and oil reservoirs.

The key parameters which need to be monitored are moisture, ash content of coal, Vitrinite reflectance, temperature and pressure[15]. Mineral matter acts an inert diluting agent in the coal and contributes to gas desorption, therefore the areas of coal having relative low ash yield are more favorable to CO_2 sequestration. Presence of large-scale faults can be harmful as the gas may escape or remain trapped. Further studies are needed for assessing CO_2 Sequestration potential in coal beds are: i) Coal quality, ii) Sorption capacity, iii) Intra-molecular structure of coal, iv) Hydrodynamics v) dynamics of CO_2 flow.

3. International Large Scale Sequestration Projects

Global field experimentation is being pursued to determine benchmarks. According to Global Carbon Capture and Storage Institute (GCCSI) 74 large-scale projects are in various stages of operation, construction and in planning stages. Among these eight projects have lead to 20 Mt of CO_2 sequestered per annum.

Among the large scale demonstration noteworthy is Weyburn oil fields in Southern Saskatehewan, Canada for enhanced oil recovery. By injecting about 6000 tons of CO_2 per day, a total of 20Mt of CO_2 is expected to be sequestered[16]. During its life, such an operation could produce 122 million barrels of incremental oil, which is about 30 percent enhancement over the recoveries so far. The emphasis is on measuring and monitoring of leakage, risks, etc, to develop a best practice manual for CO_2-EOR.

In Salah in Algeria is another international project of CO_2 Sequestration in depleted gas fields. It is expected that 17Mt of CO_2 could be injected in the gas leg of the reservoir till the project completion in 2020. Since 2004 about 1 Mt of CO_2 has been sequestered per year at a depth of 1800 m in the Krechba reservoir, a geological formation with low permeability sandstone. Scientific monitoring of CO_2 plume inside the well has been developed. Using satellite based Interferometric Synthetic Aperture Radar (InSAR) remote sensing imagery techniques. CO_2 ground movement is being tracked.

The earliest CO_2 storage project has been Sleipner West in Norway, began in 1996 in Norway. The Sleipner reservoir is situated in the Utsira formation comprises a 200-250m thick fluid saturated sandstone formation at a depth of 1,000 metres beneath the seabed. More than 15 million of CO_2 has been injected and images of the CO_2 plume at Sleipner from the time-lapse 3D seismic data have been obtained[16]. The changes in seismic impedance have been monitored from new seismic data produced at regular intervals.

The CO_2 sequestration project at Reykjavik, Iceland aims to study feasibility of permanent storage of CO_2 captured from geothermal waters into basaltic rocks. Located in the vicinity of a geothermal power plant, geochemical modeling of the CO_2 in waters as a natural analogue in CarbFix pilot is expected to throw some light on its feasibility despite limited pores that are present in basalts.

Gorgon CO_2 Injection is another large scale project in Australia and New Zealand. Built on the success of Otway pilot project it targets 3.4 and 4 million tonnes of CO_2 to be stored per year to a depth of approximately 2.3 km into a deep saline formation below Barrow Island. One of the largest CCS projects in the execution stage in the world, it also includes integrated monitoring, reservoir management and risk minimization strategies.

Medium to large-scale field tests for enhanced coal bed methane recovery have been reported in San Juan field of USA, Yubari Iskari coal fields in Japan, Silesian basin in Poland and Fenn Big Valley, Canada. A dual porosity model based on idealization of fracture media is adopted and two phase flow of gas and water has been proposed.

These developments and CCS Research is leading coal based economies will be reviewed in the presentation.

4. Current Energy Status in India and Future Challenges

In the future economic profile of India accelerated growth in energy demand is on the anvil. In the electricity generation fossil fuels are predominant having a share of 69 percent in the total installed capacity and there are concerns for increasing CO_2 emissions. From the very beginning energy planning in India has been essentially resource based and cost economics has been the main consideration. Being rich in coal and mineral resources, thrust on thermal and nuclear generation began early along with hydropower development. Energy security and pollution abatement have been important goals. As a result of these early policies, Indian economy has relatively low carbon footprints.

In the climate change scenario it is imperative that alternate energy technology options are given greater thrust, which can lead to sustainability of the energy environment system. The renewable energy sources are receiving accelerated support as clean energy sources. India has adopted a National Action Plan on Climate Change having eight mission programmes. Among these the National Solar Mission has attracted greatest attention for foreign direct investment to achieve increasing share of solar energy. Renewable Energy Certificates have been introduced for trade and transactions. However, according to a modest growth scenario for India to reach 2000 kWh/ capita energy consumption in 2070, the renewable energy sources can provide at the most 30 percent share [45].

Energy security being the prime concern, dependence on fossil fuels is expected to continue for the next few decades. With this in view future capacity addition has been planned through deployment of supercritical and ultra supercritical coal technologies with a projected increase in energy efficiency of power generation. The CO_2 footprints in the power sector are targeted to be reduced and a new mission on clean coal technology is in pipe line. India's policy does not support CCS deployment[20]. However research on carbon sequestration has begun. A number of government Departments & Ministries like DST, DBT and MOES as well as industries like ONGC, NTPC and Reliance are supporting research. A National Programme on CO_2 Sequestration (NPCS) research had been launched by the Department of Science & Technology (DST), Government of India in 2007 from the perspective of pure and applied research, with the participation from academic institutions and R&D laboratories across the country. Four Thrust areas under for the programme are identified as; (i) CO_2 Sequestration through Micro-algae Bio-fixation Technique (ii) Carbon Capture Process & Materials Development (iii) Terrestrial Agro-forestry Sequestration Modeling Network (iv) Policy development studies[21].

ACBCCS-2013 is the acronym for 'Awareness and Capacity Building in Carbon Capture and Storage: Earth Processes' being organized from January 15-19, 2013, as a sequel to ACBCCS-2009 held at Indian National Science Academy, New Delhi in 2009. Acceptance of CCS in CDM in Durban Meeting of Conference of Parties held in December 2011 has aroused interest of industry to earn certified reduction credits and would require a change in social acceptance of CCS. A number of issues including implications of CCS, modalities and technology transfer, understanding the processes and boundaries as social and economic burden have emerged.

The objectives of the workshop on ACBCCS-2013 are; (i) provide an opportunity to create awareness and enhance understanding of CCS and earth processes in carbon fixation, (ii) share experience and knowledge in carbon capture and storage technologies and address research needs, and (iii) put forth perspectives on carbon recycling and earth processes in knowledge domain and submit recommendations to concerned agencies.

5. Conclusions

The CO_2 sequestration is a large-scale infrastructure intensive emerging energy technology for mitigation of climate change. Advancements made in CO_2 sequestration in the surface or subsurface – be it terrestrial plantation or algae or a coal mine or oil reservoir or mineral rocks – are a scientific necessity in developing the knowledge base about its disposal. CO_2 sequestration in the long run can offer an opportunity to recover clean energy fuels only when technology is proven. The studies so far are site specific and need to be evaluated on case to case basis. Considerable additional geological investigation and modeling research would be needed to create a comprehensive data base for effective mapping of various reservoirs and test the efficacy in the long run. The future challenges and research needs in CO_2 sequestration and Earth Processes can be grouped as follows;

i) Site assessments from physical and geological conditions
ii) Data up gradation for geochemical and geophysical information about reservoirs
iii) Geo-modeling studies of complex reactive transport & geo-mechanics
iv) Geostrategic acceptance; source-sink matching
v) Safety, security and risk assessment of CO_2 sequestration
vi) Development of techniques for geophysical monitoring & verification of CO_2 migration

References

1. B. Davidson Metz, H.O. Coninck, M. Meyer Loos, L. Eds., IPCC Special Report on Carbon Capture and Storage, *Working Group III*, 2005.
2. Malti Goel, Carbon Capture and Storage, Energy Future and Sustainable Development: Indian Perspective, in: Goel Malti, B. Kumar & S. N. Charan, Eds.. *Carbon Capture and Storage : R&D Technology for Sustainable Energy Future*, Narosa Publishing House, Delhi, pp 3-14, 2008.
3. Malti Goel, Carbon Capture and Storage Technology for Sustainable Energy Future, *Current Science*, **92**, pp 1201-2, 2009a.
4. Joc Wisniewski, R. K. Dixon, J. D. Kinswan, R. N. Sampson, A. E. Lugo, Carbon Dioxide Sequestration in Terrestrial Ecosystem, *Climate Research*, **3**, pp 1-5, 1993.
5. P.S. Yadava, CO_2 Mitigation: Issues and strategies, in CO_2 Sequestration Technologies for Clean Energy Future, eds. Qasim S. Z., Goel Malti, Daya Publishing House, Delhi, 2010, 163-170, 2010.
6. R. Reddy, G. K. Rasineni and A. S. Raghavendra, The impact of global elevated CO_2 concentration on photosynthesis and plant productivity, *Current Science*, **99**, No. 1, pp 46-54, 2010.
7. Adarsh K. Puri, T. Satyanarayana, Enzyme and microbe mediated carbon sequestration, in CO_2 Sequestration Technologies for Clean Energy Future,

eds. Qasim S. Z., Goel Malti, Daya Publishing House, Delhi, 2010, pp 119-130, 2010.

8. R. D. Schuling and P. Kigjsman, Enhanced Weathering: an effective and cheap tool to sequester CO_2, *Climate Change*, **74**, pp 349-354, 2006.
9. J. Zhana, R. Zhana, H. Geerlings and J. Bi, A novel indirect wallastonite carbonation route for CO_2 sequestration, *Chemical Engineering and Technology*, **33** (7), pp 1177-1183, 2010.
10. V. K. Sethi et al., A Novel Approach for CO_2 Sequestration and Conversion in to Useful Multipurpose Fuel, *International Journal ICER*, JERAD, 2010
11. Malti Goel, S.N. Charan, A. K. Bhandari, CO_2 Sequestration: Recent Indian Research, IUGS Indian Report of INSA 2004-2008, in: A. K. Singhvi, A. Bhattacharya and S. Guha, eds., INSA *Platinum Jublee publication*, pp 56-60, 2008.
12. Buchanan R. Carr T. R. Geologic Sequestration of Carbon Dioxide in Kansas, Kansas Geological Survey, *Public Information Circular (PIC)*, **27**, 2011.
13. MacGrail B. Peter, Schaef H. Todd, and Spane Frank A, New Findings Regarding Carbon Dioxide Sequestration in Flood Basalts, in: Goel Malti, Kumar B. and Charan S. N., eds., *Carbon Capture and Storage : R&D Technology for Sustainable Energy Future*, Narosa Publishing House ,Delhi, 2008, 15-22.
14. P. S. R. Prasad, D. Sarma, L. Sudhakar, U. Basavaraju, R.S. Singh, Z. Begum, K.B. Archana, C. D. Chavan, S. N. Charan, Geological sequestration of carbon dioxide in Deccan Basalts: Preliminary laboratory study, *Current Science*, **996**, pp 288-291, 2009.
15. J.C. Pastin, R.H. Groshong and R.E. Carroll, Enhanced Coal bed Methane recovery through CO_2 sequestration of carbon dioxide: *Potential a market based Environmental solution in the Black warrior Basin of Alabana*, www.netl.doe.gov/publications
16. K. J. Vargas, Multiple tasks finalize Weyburn CO_2 injection modification, *Oil & Gas Journal*, **107**(44), pp 44-49, 2009.
17. Bickle, M., Chadwick, A., Huppert, H., Hallworth, M., Lyle S., Modelling carbon dioxide accumulation at Sleipner: Implications for underground carbon storage,*Earth and Planetary Science Letters*, 2007, 255 (1-2), p 164-176.

18. E. Murphy, A. Bonneviller, M. White and K. Rossa, *Carbon Sequestration Initiative*, Pacific Northwest National Laboratory, USA, 2010.

19. S.P. Sukahtme, Meeting India's Future Needs of Electricity through Renewable Energy Sources, Current Science, 2011, 101, 624-29.

20. R. V. Shahi, Carbon Capture and Storage Technology: a possible long-term solution to climate change challenge, Qazim S. Z. and Goel Malti, Eds., in CO2 Sequestration Technologies for Clean Energy, Daya Publishing House, Delhi, 2010, pp. 13-22.

21. Malti Goel, Recent approaches in CO_2 fixation research in India and future perspective towards zero emission coal based power generation, Current Science, Vol. 97, 2009b, pp1625-1633.

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TERI'S SCOPING STUDY ON CCS IN AN INDIAN CONTEXT

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Extended Summary

1. Introduction

Carbon Capture and Storage (CCS) refers to "the separation of CO_2 from industrial and energy-related sources, transport to a storage location and long-term isolation from the atmosphere" [1]. It is one among the portfolio of measures being considered for reducing Greenhouse Gas (GHG) emissions with a view to mitigating climate change.

TERI recently conducted a scoping study for CCS in India, with support from the Global CCS Institute (GCCSI). The study was conducted to identify the potential role for CCS in India's GHG mitigation strategies through an examination of issues, opportunities and barriers to the deployment of CCS. The conclusions of the report should help in drawing a roadmap for CCS implementation in India.

2. Present and Future CO_2 Emissions

India's total GHG emissions in 2007, inclusive of Land use, land-use change and forestry (LULUCF), were 1727.71 million tonnes of CO_2 equivalent, and gross CO_2 emissions were 1497.03 million tonnes. The CO_2 generation per capita was 1.3 tonnes/capita, when not considering LULUCF [2].

Around 66% of India's gross CO_2 emissions came from the energy sector in 2007, with electricity generation alone accounting for almost 48% of the gross emissions. The industrial sector accounted for most of the remaining CO_2 emissions, with 27% of the total emissions.

As per India's Integrated Energy Policy [3], India's CO_2 generation in 2031-32 is expected to be in the range of 3.9 and 5.5 billion tonnes, depending on India's economic growth, energy and carbon intensity of the economy, the share of renewables in India's energy mix, and other factors. This, when combined with India's estimated population of 1468 million in that year, means that India's per capita CO_2 emissions in 2031-32 are projected to be between 2.6 and 3.6 tonnes/capita.

3. Economic Analysis

Coal is expected to remain the mainstay of India's power sector in the near future too, with most of the 100 GW of power capacity addition planned in the 12th Five Year Plan period (2012-17) based on coal based power. This means that the electricity sector will remain a major source of CO_2 emissions for decades to come. This coupled with the fact that CCS deployment is most suited to large scale point sources of emissions, means that it is likely that in an Indian scenario, some of the earliest CO_2 capture units are likely to be set up in large power plants. An economic analysis for such a unit has been carried out as a part of the study.

While there have been a number of studies conducted regarding the cost of both CCS retrofit and built-in capture, the fact that these studies have used widely divergent assumptions regarding plant and other costs, year of installation, capture technology used, type of storage sink, and other parameters, means that it is often not possible to compare the results of the studies meaningfully. To deal with this issue, three different cases were developed. In Case 1, the basic inputs required were adapted from the study conducted by Mott MacDonald in 2008 [4], with various parameters and assumptions supplemented by other references. This analysis was further refined based on consultation with NTPC Ltd. and other stakeholders, and the findings used to create the Case 2. Finally, the results were compared with those arrived at in Case 3 using the GCCSI figures given in [5]. For each case, a separate analysis was conducted for imported and domestic coal as feedstock.

For the three cases, the base case power plant was considered to have either 5 units, each of gross power output 800 MW, or 6 units with gross power output 660 MW each. The cumulative gross power output was therefore taken to be close to 4 GW. Since carbon capture is an energy intensive process, for a constant gross power output, the net power output will be significantly reduced when compared to the base case scenario. To compensate for this, an additional unit has been considered to be added, so that the net power output remains reasonably constant. This additional unit, however, adds to the capital cost of CCS.

Due to the high capital expenses involved in CCS, especially in the capture stage, and the energy penalty that carbon capture entails, there is a marked increase in the cost of the final product in whichever industry CCS is deployed. For the power sector, a key measure of the affordability of CCS is the increase in the Levelised Cost of Electricity (LCOE) entailed.The LCOE calculated for each case is shown in Figure 1. It has been estimated that the LCOE is likely to rise by up to 47% for a plant of this size, with a greater increase likely for deployment on smaller units.

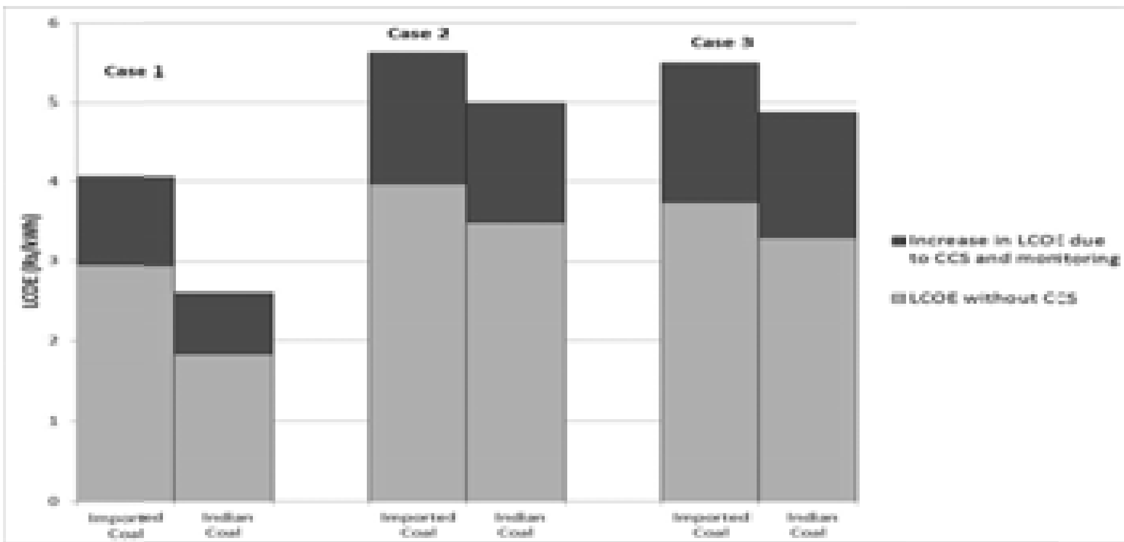

Figure 1: Comparison of the Levelised Cost of Electricity (LCOE) and the increase in LCOE for the different cases

4. Capacity Development Needs

The study concludes that, broadly, the following capacity development needs related to CCS require to be addressed so as to create an enabling environment for CCS deployment in India.

1. Knowledge building and capacity development of policy makers and regulators
2. Capacity development for storage site assessment, development, operation and monitoring and verification
3. Technology sharing and transfer
4. Capacity development of Financial Institutions
5. Public Engagement
6. Knowledge sharing among different CCS groups

References

1. Intergovernmental Panel on Climate Change (IPCC), 2005. *Special Report on Carbon Dioxide Capture and Storage*. Intergovernmental Panel on Climate Change.
2. Ministry of Environment and Forests, Government of India, 2010. *India: Greenhouse Gas Emissions 2007.* Ministry of Environment and Forests, Government of India.
3. Planning Commission, Government of India, 2006. *Integrated Energy Policy: Report of the Expert Committee*. Planning Commission, Government of India.
4. Mott MacDonald, 2008. CO2 Capture-Ready UMPPs, India. Mott MacDonald.
5. Global CCS Institute, 2011. Economic Assessment of Carbon Capture and Storage Technologies: 2011 update. Global CCS Institute.

CO_2 RECOVERY FROM POWER PLANTS BY ADSORPTION: ISSUES, CHALLENGES AND APPROACHES

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Extended Summary#

Rising levels of CO_2 in the atmosphere due to burning of fossil fuel have been recognized to be the main contributor of global warming and associated climate change phenomenon. Fossil fuel combustion for power generation is the major source of increased CO_2 levels in the atmosphere.

There are three generic methodologies that can be used for CO_2 capture from a power plant. These are Post Combustion CO_2 capture, Pre Combustion CO_2 capture and Oxy-fuel combustion capture. Each methodology has its own merits and demerits.

In pre-combustion approach, gasification of feed stock (Coal) produce a hot multi-component gas stream containing acidic gases like H_2S, CO_2 along with H_2. Conventional solvent based technology for removal of acid gases operates at low temperatures, hence the gas cleanup train requires cyclic heating and cooling steps to produce clean H. These temperature swings lead to over all thermal lower efficiency of the process. Developing an alternative adsorption based technologies using adsorbents which can work at high temperature for CO_2 and H_2S removal will be a step change towards increasing the thermal efficiency of the process.

Post combustion is an end of pipe treatment of the flue gases for removal of the CO_2 present prior to discharge through the stack. CO_2 levels are generally in the range of 5 % to 15% depending on the type of fuel undergoing combustion and the CO_2 must be removed from mixtures with N_2, O_2, moisture and SOx /NOx if present.

In post combustion approach, solid adsorbents like zeolites and activated carbons can be used to recover CO_2 from flue gas mixtures by pressure swing adsorption technique. Several adsorbent materials have been investigated for CO_2 recovery by PSA/VSA. The general consensus appears to be that Zeolite 13X materials performs better than activated carbons or silica gels. Both capacities and selectivities for separation of CO_2/N_2 mixtures (representative of flue gases from power plants) are superior. However, power requirement during regeneration can be high and there is for this reason a large scope for developing new adsorbents which will show better selectivity and regenerability.

Metal Organic Framework (MOF) is a new class of adsorbents attracting interest for selective CO_2 separation. These are materials in which metal ions or clusters are connected via organic linkers to form highly porous network structures. Several MOF's have been proposed as adsorbents for CO_2 recovery. However, the several studies that have been reported so far on CO_2 adsorption on MOF's have been limited mostly to equilibrium isotherm and diffusion measurements with pure components. Not much data is available on adsorption processes such as PVSA.

The focus of this paper is to project the R&D challenges being faced during pre / post combustion CO_2 capture and also to highlight recent R&D developments being made in adsorption based capture technologies to address these issues. An experimental study is presented for the removal of CO_2 from two types of gas feeds representing pre-combustion and post-combustion process streams. Hydrotalcite and MOFs adsorbents for CO_2 recovery were evaluated by measuring their equilibrium loading capacities in a gravimetric microbalance. Breakthrough, PVSA experiments were performed in a single column micro-absorber unit. The results are compared with performance data generated with commercial adsorbent materials under comparable operating conditions.

CAPTURING CO_2 BY PHYSICAL AND CHEMICAL MEANS

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Extended Summary

India primarily depends on coal to meet the energy demands of the nation. Under such circumstances, emission of CO_2 is unavoidable and thus, to overcome the threat of global warming, reduction of emissions of CO_2 to the environment is mandatory by means of capturing the emitted CO_2 also termed as post-combustion capture. Post-combustion capture operates typically at atmospheric pressure by unit operations like absorption, adsorption, etc. In an alternate process (oxy-fuel process: mostly in R&D stage), the fuel is burnt in an oxygen rich environment so that mostly CO_2 is emitted and the need for CO_2 separation is eliminated. In pre-combustion capture, the fuel is not burnt directly but is converted at suitable temperature and pressure into synthesis gas (mixture of CO, CO_2 and H_2). Thereafter, CO is further converted to CO_2 and H_2 and then CO_2 is captured to get H_2 (the major constituent) as fuel. Membrane Reforming, Sorption-enhanced water-gas-shift (SEWGS) and Integrated Gasification Combined Cycle (IGCC) are typical examples of pre-combustion capture technologies.

CO_2 capture technologies can be broadly classified into two categories namely, physical means and chemical means. It is need of the hour to be thorough with the advancements, merits and demerits of traditional and potential areas like absorptive, adsorptive and other emerging technology based CO_2 capture processes as well as the pre-capture technologies. Chemical absorption processes for CO_2 capture is divided into two categories distinguished by the rate of reaction of solvent with CO_2. The first category, also termed as CO_2 treating processes in bulk, is applied when the partial pressure of CO_2 in the feed is relatively low and/or the product purity is high. CO_2 is removed to very low levels using faster reacting solvents such as primary and secondary alkanolamines and promoted hot carbonate salts.

The second category, termed as hybrid category, attains increased CO_2 removals by controlling the reaction rate of CO_2 with the suitably blended amine

solvents. Improvement of efficiency of a contactor also demands investigation on the effects various operating parameters and materials characteristics. Monoethanolamine (MEA) is used for separation of CO_2 from flue gases from power plants due to its ability to absorb CO_2 under low partial pressure conditions. The flue gas usually contains SO_2, NOx, O_2, N_2, H_2O and particulates apart from CO_2. Their presence affect CO_2 capture performance and hence additional measures are taken to remove SO_2, NOx, and particulates before the flue gas flow into the CO_2 capture system. CO_2 removal/separation by adsorption has drawn renewed attention because of development of potential adsorbents such as zeolites, activated carbon, carbon molecular sieves, SBA 16 and metal organic frame works and modification of the existing adsorptive separation technologies. However, successful commercialization of adsorptive separation technologies for CO_2 capture is yet to be in place. Hydrogen Membrane Reforming (HMR), a combination of steam reforming (SR) and water-gas shift (WGS) reaction modelled into a single unit, is also referred to as membrane water gas shift reaction (MWGSR). SEWGS is used to shift the equilibrium conversion of CO for its complete conversion and H_2 production maximization. IGCC turns high-sulphur coal, heavy petroleum residue, biomass or municipal waste into low heating value, high-hydrogen synthesis gas and then removes impurities before it is used as a primary fuel for a gas turbine.

Growing concerns over climate change have led to a strong emphasis on the research and development of high-efficiency and economic CO_2 capture technologies. The R&D activities are focused on refinement of current capture technologies in one side and development of novel capture technologies that can deliver significant benefits on the other side.

CO_2 STORAGE OPTIONS: OCEAN PERSPECTIVES

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Extended Summary

Increasing rate of carbon dioxide (CO_2) release to atmosphere after industrial revolution had triggered the studies on green house gases effect and its impact on global warming. Based on the information available it is an established fact that the human activity is rapidly changing the composition of the earth's atmosphere, contributing to warming from excess carbon dioxide (CO_2) along with other trace gases such as water vapor, chlorofluorocarbons, methane and nitrous oxide. Sustained worldwide growth in population and economic activity has increased anthropogenic CO_2 emissions and are beginning to stress the natural carbon cycle. More CO_2 is being exhausted than can be taken up by trees, grasses, and the oceans, and the excess is accumulating in the atmosphere. The Intergovernmental Panel on Climate Change (IPCC), a group established by the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP), reports that the average surface temperature of the earth has increased during the twentieth century by about 0.6° ± 0.2°C. Estimates of warming expected through the 21^{st} century vary among models, but all are responsive to levels of carbon dioxide in the atmosphere. As point sources the Oil refineries, coal-fired power plants, iron and steel works, cement, lime and natural gas production are the largest concentrated sources of anthropogenic CO_2emissions. The current potential to reuse CO_2 in industry is limited, so most of the captured CO_2 would have to be stored. Although CO_2 can be stored in aquifers and utilized in depleted oil and gas fields, the distances to the CO_2 producer site can be thousands of kilometers, which raise the overall storage costs significantly. The disposal of CO_2 in Ocean is another potential option for long-term storage of CO_2. But many questions are to be answered to proceed in this line.

National Institute of Ocean Technology had expertise in a wide spectrum of ocean technology development, including deep sea applications up to 6000 m water depth, coastal engineering and offshore structures, ocean observations, marine bio technology, etc., with experience in exploitation of renewable and non-renewable

ocean resources in a sustainable manner. With the proven ability of the institute in technology development for marine applications, the institute had recently initiated studies to understand the global scenario and possibilities of developing innovative eco-friendly ocean CO_2 sequestration technology for marine applications.

Based on the P-T conditions of the ocean basins CO_2 can be effectively stored on the ocean floor beyond 2800 m water depth where it will be dense enough to further. The details of the measurement platform for monitoring the disposal could be worked out, feasible technology shall be worked out for the transportation and storage based on the available capture technology from the industries lying on coastal regions of India. But the issue on ecology and environmental concern is alarming to proceed on direct disposal and we initiated the activities on indirect optimization methodology by means of carbonation techniques and utilize as coastal protective measures, artificial reef growth, island formation etc. CO_2 can also be utilized for micro-algal growth in identified species for the extraction of bio-diesel etc.

Details of the storage options will be discussed in the workshop and the subject needs capacity building in the country to understand and take forward in large scale from the policy level to R&D for implementation perspective.

GEOLOGICAL SEQUESTRATION OF CO_2 IN SALINE AQUIFERS-AN INDIAN PERSPECTIVE

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Extended Summary

India has set a goal of sustained economic growth of 8-9%. To achieve this our energy needs will grow rapidly in future. The scientific evidence is now overwhelming that the increased concentration of CO_2 in the atmosphere result primarily from the combustion of fossil fuel to meet energy needs of different sectors. Since fossil fuels would be the main stay for energy generation in India, CO_2 emissions are likely to increase exponentially. To contain and ultimately reduce its emission it will be important to adopt cleaner technologies, capture, reuse and storage of CO_2 in geological sinks.

In little over a decade, geological storage of CO_2 has growth from a concept to a potentially important mitigation option. Geological storage of CO_2 in saline aquifers seems to be a viable option. Saline aquifers occur almost in all sedimentary basins are much more wide spread and lie in the proximity of stationary emitting sources. It has other advantages i.e.

- ***The estimated storage is large enough to make them viable for long-term solutions.***
- ***Usually due to there high salinity and depth they cannot be technically and economically exploited for surface use.***
- ***Scenarios for negative impacts and unintended damages are limited.***
- ***Mechanism for storage of CO_2 in deep saline aquifer includes physical trapping below*** **low permeable cap rocks, dissolutions and mineralization.**

Since Saline Aquifers are generally unused and of no economic significance, little is known about the presence of deep saline aquifer in different geological formation in India. However, deep exploratory drilling and geophysical surveys carried out for oil and gas by ONGC and oil companies, water development projects

by CGWB some sub-surface data about saline aquifers has been made available. The main constraints in deployment of CCS in India are the lack of detailed knowledge about potential storage sites. A precondition for opting for CCS would be its commercial viability.

Studies have been undertaken to understand the rubrics of geological storage in saline aquifers to make a beginning.

OPTIONS FOR CO_2 STORAGE AND ROLE OF UNCONVENTIONAL GAS IN REDUCING CARBON DIOXIDE EMISSIONS

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Extended Summary

The viable options for carbon dioxide storage are: CO_2-EOR (Enhanced Oil Recovery); CO_2-EGR (Enhanced Gas Recovery); geological CO_2 sequestration in basalt formations and saline aquifers. Oil & Natural Gas Corporation Ltd. have already initiated a project on CO_2-EOR in Ankleshwar oil field of Western India and CO_2-EGR is still in research and development stage.

Indian basalts may not be attractive proposition for carbon storage, as areas having basaltic rocks are prone to increased seismicity. Further, these rocks are underlain by thick Mesozoic sediments, which are light gaseous hydrocarbon bearing. The reports on occurrence of deep saline aquifers away from the coastal zones are scanty and R&D efforts in this area need to be focused.

The innovative carbon storage advances have been: Bio- Carbon Capture and Storage (Bio-CCS); Getting geothermal power with CO_2 instead of water in the arid areas where water is scarce; and increasing the fertility of ocean and soil by carbon dioxide uptake.

Growing role of unconventional gas, which is least carbon intensive, in the global energy scenario and initiatives towards carbon storage for mitigating the CO_2 emissions are the key challenges for sustainable energy future of World and even India (Global Energy Assessment, 2012). The exploration and development of unconventional gas (coal bed methane, shale gas & gas hydrate) have gained / is gaining importance in the country. The expanding role of carbon storage in reducing the impact of climate change will require reducing its cost and transformation towards integrated fossil fuel based energy efficient system.

Coal bed methane production in India has not met the estimated production targets and the technology for exploitation of methane from gas hydrates is yet to

be developed. Therefore, there is need to explore and exploit shale gas, which have risk recoverable potential of > 180 tcf. for India.

Gas is a cleaner source of energy than coal and releases about 6 % of carbon dioxide to the atmosphere, while coal adds to about 12 %. The key technologies behind shale gas exploration & exploitation are horizontal drilling and multi-stage fracturing. India has taken initiatives towards shale gas development and the Government of India policy towards shale gas exploration and exploitation will be announced soon.

Potential shale gas bearing basins of India are: Assam-Arakan; Cambay; Cauvery; Krishna-Godavari; Gondwana & Vindhyan etc. The basins have shale horizons with suitable thickness, maturity, organic carbon content & porosity and geochemical, petrophysical and optical characteristics of these basins are similar to producing basins from other parts of world.

Status of India's R& D initiatives for carbon storage and unconventional gas exploration and exploitation will be presented and discussed. The monitoring & modeling methodology for sequestered CO_2 will also be deliberated.

CARBON SEQUESTRATION POTENTIAL OF THE FORESTS OF NORTH-EASTERN INDIA

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Extended Summary

Carbon management in forests is one of the important agenda in India to reduce emission of carbon dioxide (CO_2) and to mitigate global climate change. In the context North-Eastern region forest comprises of Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim, Tripura is 1,73,219 km^2 which is 66.07 percent of its geographical are in comparison to the national forest cover 21.5 percent. However according to recent assessment there was a loss of 549 km^2 of forest cover during 2009-2011 in the northeastern states. Manipur and Nagaland have lost the highest forest cover of 190 km^2 and 146 km^2 respectively which is attributed to shifting cultivation and biotic disturbances. In the overall there is a decrease of 367 km^2 of forest cover in the country during the same period. The North-eastern region constitutes only 7.98% the geographical area of the country but account for nearly 25% of the forest cover of the country.

The North-Eastern region is very rich biodiversity and has been identified as part of hot spots of world biodiversity. Therefore carbon sequestration potential of North-eastern forests is an important component of an overall carbon management strategy to reduce and to mitigate CO_2 emission mainly because of long grand growth period due to high rainfall area and high productivity of forest ecosystems.

Recently Indian Space Research organization – Geosphere Biosphere program (ISRO-GBP) under National Carbon Project has initiated to assess the carbon pools in the forest vegetation, soil and atmospheric carbon fluxes in the country to understand the role of forest in carbon capture and storage under anthropogenic change. There is limited information on carbon sequestration in the soil and forest vegetation of North-Eastern region.

Carbon stock in the aboveground biomass varied from 65.1 to 127.5 t C ha^{-1} in sub-tropical forests, 86.7 to 295.5 t C ha^{-1} in pine plantation and 93.5 to 105.8 t C ha^{-1} in Montane wet temperate forest of Manipur. However carbon storage in the biomass of humid tropical forest of Meghalaya and Barak valley of Assam was

reported to be 161.2 and 103.8 t C ha^{-1} respectively. In bamboo forests of Assam and Manipur carbon stock in aboveground biomass was recorded to be 61.1 t C ha^{-1} and 65.35 t C ha^{-1} respectively. The rate for carbon sequestration in forest biomass is highly variable depending upon species composition, age of tree, nutrient status of soil and level of biotic disturbances.

The rate of carbon sequestration ranged from 13.7 to 15.9 t C ha^{-1} yr^{-1} in sub-tropical broad leaved hills forests and 6.3 to 13.7 t C ha^{-1} yr^{-1} in pine plantation in the state of Manipur. Soil carbon storage was estimated to be 27.73 to 48.03 t C ha^{-1} in upper layer of soil (0-30cm) in the different type of forests of Manipur which is under estimated and forest soils may contain 2 to 3 time more carbon. In bamboo forests the soil carbon was reported to be 57.3 t C ha^{-1} in 0-30 cm soil depth in Barak valley in Assam.

There is an urgent need to quantity the carbon stock and rate of carbon sequestration in different types of forests at micro-level to assess potential of C-sequestration and sustainable managements of forests in North-East India. Estimation of carbon stock forests of North-East India may become operational to carbon trading future.

Thus the forests of North-eastern region have a great potential to store carbon due to high rate of productivity as well as highest percentage of the forest cover in the country. The declining trend in forest cover in the region is matter of great concern and may be taken care in the future. Large tract of open forests in various North-Eastern states provide a great opportunity for carbon sequestration through mass scale afforestation and restoration programme in open forest, wasteland and shifting cultivation areas to reduce the carbon dioxide level in the atmosphere and to mitigate the climate change.

PROSPECTS IN BIOMIMETIC CARBON SEQUESTRATION

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Extended Summary

The thermal radiation from the Earth, in the form of long-wavelength infrared rays, lies in the absorption spectrum of carbon dioxide and other green house gases (GHGs). These GHGs absorb radiation primarily in a very narrow frequency band (7-13µm), while CO_2 absorbs over a much larger (13-19µm) spectral range. Thus CO_2 accounts for 21% of the greenhouse effect (after water vapour that accounts for 64%), which is higher than ozone (6%) and other trace gases (9%). Moreover, carbon dioxide makes up 68% of the total greenhouse gas emissions.

The atmospheric CO_2 concentration has increased from 280 ppm in 1800, the beginning of industrial age, to 396 ppm today. Without any mitigation, it could reach levels of 700-900 ppm by the end of the 21st century, which could bring about severe devastating impacts. This imbalance of CO_2 concentration has disturbed the Earth's carbon cycle that is naturally in balance maintained by the oceans, vegetation, soil and the forests.

The most pressing technical and economic challenge of the present time is to supply energy demand for the world economic growth without affecting the Earth's climate. That is why the current focus is on reducing fossil fuel usage and minimizing the emission of CO_2 in atmosphere. In spite of the advances made in the field of renewable energy, it has not been possible to replace gas, coal and oil to meet the current energy needs. If fossil fuels, particularly coal, remain the dominant energy source of the 21st century, then stabilizing the concentration of atmospheric CO_2 will require development of the capability to capture CO_2 from the combustion of fossil fuels and store it safely away from the atmosphere. The hazards of global warming have reached to a magnitude that irreversible changes in the functioning of the planet are seriously feared. It is, therefore, necessary for the whole scientific community to restore permissible levels of CO_2 by using the existing knowledge.

Carbon sequestration or carbon capture and storage (CCS) has emerged as a potentially promising technology to deal with the problem of global warming. Several approaches are being considered, including geological, oceanic, and terrestrial sequestration, as well as CO_2 conversion into useful materials. Biological systems have solutions to the most dreaded problems of all times. The photosynthetic fixation of atmospheric CO_2 in plants and trees could be of great value in maintaining a CO_2 balance in the atmosphere. Algal systems, on the other hand, being more efficient in photosynthetic capabilities are the choice of research for solving global warming problem. The biomass thus produced could be used as fuel for various heating and power purposes.

Mankind is indebted to microbes for bringing and maintaining stable oxygenic conditions on Earth. A proper understanding of microbial systems and their processes will help in stabilizing atmospheric conditions in future too. Investigations are underway for exploiting carbonic anhydrase and other carboxylating enzymes to develop a promising CO_2 mitigation strategy. The recent work on biomimetic approaches using immobilized carbonic anhydrase in bioreactors has a big hope for the safe future.

The process of carbon assimilation by photosynthesis has made forests, trees and crops as the major biological scrubbers of CO_2. Terrestrial biomes are potential CO_2 sinks. Microbes such as fungi and bacteria have been found to be responsible for most of the carbon transformations and long-term storage of carbon in soils. The chances of persistent C storage are high in fungi due to their complex chemical composition and higher carbon utilization efficiency. In fact, increased fungal to bacterial activity has been shown to be associated with increased carbon stored in soil.

Photoautotropic organisms ranging from bacteria to higher plants have evolved unique carbon concentrating mechanism (CCM) in response to the declining levels of CO_2 in their surrounding environment. Photosynthesis is much more efficient in microalgae than in terrestrial C_3 and C_4 plants. This high efficiency is due to the presence of both intracellular and extracellular carbonic anhydrases and the CO_2 concentrating mechanism. The present focus is on exploiting the ability of microalgae to convert solar energy and CO_2 into O_2 and carbohydrates. Microalgal mass cultures can use CO_2 from power plant flue gases for the production of biomass. The algal biomass thus produced can directly be used as health food for human consumption, as animal feed or in aquaculture, for biodiesel production or as fertilizer for agriculture.

A fast growing marine green alga *Chlorococcum littorale* is reported to tolerate high concentrations of CO_2. The wastewater containing phosphate (46 g m^{-3}) from a steel plant has been used to raise cultures of the photosynthetic microalga *Chlorella vulgaris*. Flue gas containing 15% CO_2 was supplemented further to get a CO_2 fixation rate of 26 g CO_2 m^{-3} h^{-1}. Research is in progress on the development of novel photobioreactors for enhanced CO_2 fixation and $CaCO_3$ formation. CO_2 fixation rate has increased from 80 to 260 mg $l^{-1}h^{-1}$ by using *Chlorella vulgaris* in a newly developed membrane-photobioreactor. A novel multidisciplinary process has recently been proposed that uses algal biomass in a photobioreator to produce H_2 besides sequestering CO_2.

Non-photosynthetic CO_2 fixation occurs widely in nature by the methanogenic archaebacteria. These are obligate anaerobes that grow in freshwater and marine sediments, peats, swamps and wetlands, rice paddies, landfills, sewage sludge, manure piles, and the gut of animals. Methanogens are responsible for more than half of the methane released to the atmosphere. These methanogenic bacteria grow optimally at temperatures between 20 and 95 ^oC. Carbon monoxide dehydrogenase and/or acetyl-CoA synthase aid them to use carbon monoxide or carbon dioxide along with hydrogen as their sole energy source. Waste gases from blast furnaces containing oxides of carbon were used for converting them into higher- Btu (more calorific value) methane using thermophilic methanogens. A column bioreactor operated at 55 °C and pH 7.4 was employed for the process. A mixture of three cultures of bacteria (*Rhodospirillum rubrum, Methanobacterium formidium* and *Methanosarcina barkeri*) was used for complete bioconversion of oxides of carbon to methane.

Heterotrophic bacteria having efficient carbonic anhydrase and phosphoenolpyruvate carboxylase and/or pyruvate carboxylase may be raised in fermentors, and these can be flushed with flue gases with CO_2 concentration to produce useful metabolites such as aspartate family of amino acids. Dual benefit of carbon sequestration along with useful product formation by employing microbes such as *Corynebacterium glutamicum* makes this approach very attractive.

Biomimetic approach involves identification of a biological process or structure and its application to solve a non-biological problem. Carbonic anhydrases are the fastest enzymes known for their efficiency in converting carbon dioxide into bicarbonate. Efforts are underway for using carbonic anhydrases from various microbial sources for CO_2 sequestration. The possibility of an on-site scrubber that would provide a plant-by-plant solution to CO_2 sequestration, apart from eliminating the concentration and transportation costs, is the potential advantage of the biomimetic approach. The recent developments in immobilization of microbial carbonic anhydrases for its recycling and biological carbon sequestration will be discussed.

BIOSEQUESTRATION OF CARBON DIOXIDE— POTENTIAL AND CHALLENGES

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Extended Summary

Anthropogenic activities leading to release of carbon dioxide and other green house gases have been directly linked to the increase in global temperature and consequent climate change. Methods to manage the release of CO_2 through sequestration by physical and chemical methods have been worked out. These techniques of CO_2 containment are prohibitively expensive. Of late, the prospect of biological carbon fixation for remediation of CO_2 is being explored. Plants are CO_2 sinks – they fix CO_2 during daytime. Tiny (microscopic) aquatic plants – the microalgae have even more efficient CO_2 fixing ability than large plants and trees. They have a very quick growth rate. Some of these species are rich in oil suitable for converting to diesel (fuel) and with nutrient properties (with omega fatty acids). Some species have carotenes and other pigments; some are rich in proteins. They can be mass cultured in lands not suitable for agriculture and their biomass can be beneficially used in production of biodiesel, nutracueticals for humans and as animal feed. Flue gas (a mixture of CO_2 and the other green house gas NO_X) released from Industries can be used to ferrigate the mass culture units of microalgae thus effectively sequester them. The proof of concept experiments of this biosequestration option have been demonstrated in 2005. Large scale industries based on this principle are yet to take off – despite the lure of biodiesel. The challenges in this technology are many— both technical and fiscal. Technical issues relate to mode of transfer of flue gases to the algal culture medium and means of harvest of microalgae. Fiscal concerns are with regard to the cost of set up of the facility and the running costs. The various options to meet these challenges will be discussed.

CO_2 SEQUESTRATION POTENTIAL OF INDIAN COALFIELDS

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Abstract

India has abundant coal reserves, including the Gondwana and Tertiary coals and lignite deposits. These can serve as storage sites for CO_2 limited by permeability and other controlling parameters such as sorption capacity and porosity. In this paper the information on coal availability, storage capacity and coal characteristics are used from the best published data sets for assessment of CO_2 sequestration potential of unmineable coalbeds in India. The scientific assessment of CO_2 storage potential in coal bearing sedimentary basins may serve as a basis for research, planning and policy to enable carbon capture and storage technology deployment in Indian coalfields.

1. Introduction

Capturing carbon dioxide and storing it in unmineable coal seams in combination with enhanced coalbed methane recovery provide an opportunity to stabilize the CO_2 emission level and harness a clean source of energy. It is particularly important for countries like India endowed with large coal deposits. Carbon dioxide storage potential of coal seams is yet to be established. Friedmann [1] suggested that injection of CO_2 within the coal beds to replace methane and thereby enhance Coalbed Methane (CBM) recovery are likely to minimize methane release in the environment while the CO_2 is stored in place of methane.

Coal in India occurs in two stratigraphic horizons viz., Permian sediments mostly deposited in intracratonic Gondwana basins and early Tertiary near-shore peri-cratonic basins and shelves in the northern and northeastern hilly regions of the Eocene-Miocene age. Gondwana basins of Peninsular India are disposed in four linear belts following several prominent lineaments in the Precambrian craton. In the extra-Peninsular region, (Darjeeling and Arunachal Pradesh) Lower Gondwana sediments occur as thrust sheets overriding Siwalik sediments. Besides coal, lignite deposits in younger formations also occur in the western and southern part of India.

Assessment of CO_2 sequestration potential based on carbon dioxide and methane sorption capacities of coalbeds in Indian sedimentary basins is presented in this paper.

2. Coal and Lignite Deposits in India

Coal formation in India is continuation of Great Gondwana formation extending over Antarctica, Australia, South Africa and South America called Gondwana Super group of the Indian Peninsula comprising 6-7 km thick clastic sequence formed in Paleozoic to Mesozoic era during Permian to Cretaceous period. Originating from highlands of Central India, the Gondwana sedimentation occurred in graben or half graben trough alignment due west to east and two parallel drainage channels north west to south east. Singarauli basin of Son valley occupies the junction between the E-W trending Damodar Koel graben and the NE–SW trending rift zone of Son Mahanadi valley. Son valley lies to the immediate west of Damodar and North West of Mahanadi valleys. The Wardha, Godavari and Satpura Gondwana valleys lie in the southern and central part of India respectively. A brief account of the pattern of sedimentation in Gondwana basins has been presented by Casshyap [2].

Gondwana sedimentation, the main repository of coal in India is divided in Lower Gondwana corresponding to Lower and Upper Permian and Upper Gondwana corresponding to Lower Cretaceous and Lower Jurassic age. Acharyya [3] has reported that the Lower Gondwana belts are controlled by Pre-Cambrian crustal structure like Archean cratonic sutures and Protozoic mobile belts. The formation lineament followed E–W trending zone occupied by Damodar, Koel, Son and Narmada rivers. NW-SE trending zone is occupied by Mahanadi river in the north and Godavari Wardha rivers in the south. Another N-S trending zone north of river Damodar delineate Rajmahal group of coalfields that flank the Rajmahal hills. The coal and lignite deposits in Indian sedimentary basins are exhibited in Fig. 1.

Fig. 1: Coal and lignite distribution in India

Nearly 99.7 per cent sub-bituminous to bituminous coal of India is available in the Lower Gondwana in the eastern region of India located in West Bengal, Jharkhand, Madhya Pradesh, Chhattisgarh, Orissa, Andhra Pradesh and Maharashtra provinces. There are more than 65 known basins in Lower Gondwana sediments spread over nearly 64000 sq. km. Excluding unproductive part and small detached outliers, the potential coal bearing area is about 14,500 sq. km [4].

Tertiary formation spread over the periphery of peninsula along the coast in Tamilnadu, Kerala, Gujarat and Himalayan foothills from Pir Panjal of Jammu and Kashmir to Abor Hills and Kuen Bhum range of Arunanchal Pradesh. Deep seated occurrence of lignite indicating substantial reserve of lignite at depth in region of Kalol of Cambay basin, Barmer and Sanchor basin seems to be exceptional in nature.

3. Coal Inventory of India

Coal inventory of India is based on data made available from Geological Survey of India, Central Mine Planning and Design Institute, Mineral exploration Corporation Ltd., Singareni Collieries Co. Ltd. and some other agencies. The coal seams over 0.5m thickness and down to the depth of 1200m are included for resource evaluation. Depth wise reserve position in different states as available on 1st April 2012 [5] is given in Table 1.

Table 1: Depth wise Gondwana coal resources of different states of India as on 1st April 2012

State	Resource estimate under depth			Total Reserve
	0-300m	300-600m	600-1200m	
Andhra Pradesh	9654.17	8754.74	3745.95	22154.86
Bihar	160.00	---	---	160.00
Chhattisgarh	37755.15	11609.08	1481.92	50846.15
Jharkhand	41118.05	16321.79	8703.94	80356.20**
**Jharia	-------14212.42---------------			
Maharashtra	7522.32	3165.28	194.49	10882.09
Madhya Pradesh	15367.65	8656.20	352.41	24376.26
N E States	1394.66	202.00	---	1596.66
Orissa	46653.67	23086.73	1707.01	71447.41
Uttar Pradesh	1061.80	---	---	1061.80
W Bengal	13155.05	12127.36	5333.31	30615.72
Grand Total	173842.52	83923.18	21519.03	293497.15
**Jharia	-------14212.42---------------			
% share	59.23	28.60	7.33	100
**Jharia	-------4.84 %------------------			

** Jharia coalfield reserve position is available in group of 0-600 m depth range only. The reserve position within 300m depth over is found in all the active coalfields except a few hidden pockets under basaltic flow or soil cover.

4. Extraneous Coal Deposits of India

Large tract of land in India is still not covered for regional exploration even in well delineated basins. Many a times, surface exposures are misleading, terrain is unfriendly or exploration is technically difficult and hence not included in potential coal basins. They are often identified by chance or in the process of exploration for oil and natural gases and coal bed methane. The coal reserve of such areas is not covered in National Coal Inventory by the Geological Survey of India.

The areas not covered under regional exploration for resource estimation could be the Grey area thrown deep by way of faulting or concealed deposits under deep cover, loose alluvial or igneous traps. Some of these areas have been included in the present exercise because of their potential usage for CO_2 sequestration in days to come.

5. Grey Areas of Coalfields

Well-delineated coalfields of nearly 37000 sq km area have a few patches under deep cover beyond the resource estimation and eventual mining limits. Such blocks occur under the influence of intrabasinal faults or subsidence of the basal formation. In some of the patches whole of Damuda series are found when the main coal repository – the Barakar formation occurs below 1500 m, while in other patches, even the top coal bearing formation – Raniganj is overlain by Upper Gondwana formations. The coals of such patches are not included in resource estimation. The details of these blocks are of interest because of location, likely characteristics and their availability for coalbed methane (CBM) exploitation and may be for carbon dioxide sequestration.

5.1 Jharia Coalfield

Jharia coalfield, the most extensively explored coalfield with nearly 95% proved reserve within 300 m depth cover is explored up to 1200m depth cover, with prime coking coal availability within 1050 m depth cover only [6]. Development of Moonidih mine just within the fringe area of barren measure to 510m depth cover is intersecting XV seam while the coking coal seam IX may be intersected in the shaft line at 830m depth cover.

Barren measure up to nearly full thickness of 730m may have to be crossed to touch the coking coal seams along the periphery of Mahuda block, while within the Mahuda block overlain by Raniganj formation, the depth of the top most Barakar seam may be 1800-2000 m deep; beyond mining limit as per any imagination.

5.2 Raniganj Coalfield

Because of thick fully developed Raniganj formation to 1035 m thickness in Raniganj coalfield, hardly any effort has been made to touch Barakar formation underneath 350 m thick Barren Measure along the northern periphery of Raniganj formation exposure.

5.3 Sohagpur Coalfield

Sohagpur coalfield is divided in northern and southern sections by Chilpa Bahmani Fault of maximum 600m throw trending E to W running from Burhar to Sonhat coalfields. As a result, exposed Barakar formation in the southern part is thrown down in the northern portion of the coalfield. The portion is further complicated with the exposure of Supra Barakar, Lameta and Deccan trap flow of Upper Cretaceous age in the north western part [7]. Raniganj formation of 525m thickness has a number of thin coal seams and dolerite sill of variable thickness [8].

The Barakar formation in this section is buried below 1200 m to 2000 m and its geological details are not available. Middle Barakar of 150-250 m, the main repository contains all the important coal seams. The cumulative thickness of the seams is 15-20m, while in Upper Barakar, the seams in the eastern part has gained 60m thickness at places.

5.4 South Karanpura Coalfield

South Karanpura coalfield in narrow elongated form is developed along the south boundary fault in folded basin with Bundi Basaria metamorphic inliers. The coalfield is a half-graben trough in semi-elliptical shape, traversed by basin margin fault and a number of intrabasinal faults. Central part of the basin has all the sediments of Damuda group including 600m thick Raniganj and nearly 300m thick barren measure over the Barakar formation.

5.5 East Bokaro Coalfield

Bokaro coalfield extending over 64 km in east west direction and maximum width of 11 km in the north south direction is divided in two parts by Lugu Hills in East and West Bokaro coalfields. The coalfield is traversed by a number of strike and oblique faults including prominent Gobind pur Pichri Fault.

5.6 Talcher Coalfield

The Talcher coalfield, the southern-most member of the northwest-southeast trending Mahanadi valley, is the most important coalfield of the Orissa state. It falls mostly in the Dhenkenal district, with a small part in the Sambalpur district of Orissa.

6. Concealed coalfields

Concealed areas are of recent discovery and invariably under deep cover, underneath basalt or alluvial cover. The exact extension of most of these basins is just indicative by way of geophysical prospective and with skeleton boreholes drilled for oil and natural gas exploration. The reserve estimates need correction with every new drilling record. The search for concealed coalfields is made with respect to Damuda sequence of formations within Gondwana sediments. It is however not certain that every patch with Raniganj formation will definitely have Barakar formation in sequence after crossing Barren measure.

In most of the cases, the deposits follow established lineament and appear to be extension of active coal mining areas. Presence of South Gondwana formation in Bangladesh and intersection of thick coal seams at Singur under 1600 m depth cover does support the extension of Damodar valley lineament beyond the present Raniganj coalfield. Concealed coalfields in major Gondwana lineament in Wardha and Godavari Valley follow identical trend. This has been supported by geophysical logging and deep hole drilling for oil exploration. The details, i.e. area, seam distribution and reserve estimate of coal in case of deposits concealed under basaltic bed or alluvium are not available but the process of their exploration by non mining agencies in near future is not ruled out.

7. Unmineable coal beds in well-delineated coalfields

The mining limit is decided with due consideration to quality, fuel value, market demand, market price, basin location and abundance of coal. The limit as such varies for different grades of coal and location of the coalfields. There is no decided guideline for making futuristic extrapolation for mining limit but in the light of past experience and future projection of global technological input, following conservative suggestions are made. A buffer zone of 100m cap rock is suggested between the mineable seams and unmineable coal beds to contain gas injected in the coal beds.

The mining in any basin will be marginally affected by distribution of different grades of coal and accordingly the operational limit will shift. For example, in case of Jharia coalfield, the coking nature of bottom most Zero seam may attract mining beyond the non coking coal seams I-V. Superior grade coal in lower seams of Raniganj has always encouraged going deeper leaving aside the upper coal seams. Similarly, the operational limit of power grade coal; accepted to be mined by open cast may alter in case of coalescing of seam.

The storage characteristic of different beds, the possibility of CO_2 injection along with methane drainage and potential of gas sequestration should be estimated for unmineable coal seams.

8. Comparative Adsorption of CO_2 and Methane

The coal mass has methane in micropores invariably less than its adsorption capacity. Injection of CO_2 in such coal beds has the option of occupying the void and or occupies the total surface area by even displacing the methane molecules. The studies conducted so far support the latter option because of stronger affinity of CO_2 to the coal molecule. It has been found that with the displacement of each methane molecule, 2 to 3 molecules of CO_2 are accommodated and thus its adsorption reaches closer to near complete.

The adsorption, storage and generation of methane are also known to depend upon the surface area of micro-porous system, thickness of coal seams and the confining pressure. Methane sorption capacity for Indian coals has been investigated [8]. Based on the research of the last two decades, it has been generally accepted that coal can adsorb more carbon dioxide than methane and that carbon dioxide is preferentially adsorbed onto the coal structure over methane. The 2:1 ratio has been widely reported in the literature [9].

9. Potential Coalbeds for CO_2 Storage in India

The potential sites for CO_2 storage in coal beds of Indian Territory have been identified with due consideration of accepted exploration norms, depth wise resource distribution quality wise abundance and mining status of coal. The following areas appeared to be promising sites for CO_2 storage (Table 2).

Table 2: Identified candidates for CO_2 storage in India

Category of coal beds	Grade of coal	Candidates /Basins
Unmineable coalbeds in well-delineated Coalfields	Power Grade coal	Singrauli, Mand Raigarh, Talcher, Godavari
Grey Areas	Coking coal	Jharia, East Bokaro, Sohagpur, S Karanpura
	Superior non coking coal	Raniganj South Karanpura
	Power grade coal	Talcher
Concealed Coalfields	Tertiary age coal	Cambay basin Barmer Sanchor basin*
	Power grade coal	West Bengal Gangetic Plain Birbhum, Domra Panagarh, Wardha Valley Extension, Kamptee basin Extension

10. Properties of Potential Coalbeds

In the absence of knowledge of methane adsorption capacity with CO_2 injection, empirical equations may be used for estimation of gas quantity in a particular coalbed. Coal characterization properties such as vitrinite reflectance percentage and proximate analysis are found to be the relevant parameters affecting the gas recovery and subsequently CO_2 storage in coal beds. These properties for the coal fields targeted for the said exercise is summarized in Table 3 and 4. Some of the properties in the same coal fields varied in non coking to coking coals and average figure has been taken for approximate estimate.

Table 3: Proximate analysis and rank of unmineable and grey area coalbeds

Coalfields	Basic parameters (mmf basis)		Virinite reflectance Av. Ro (%)
	VM (%)	FC (%)	
East Bokaro	28-36	85-90	0.85-1.05
South Karanpura	37-40	80-84	0.60-0.80
Jharia –Barakar	17-35	87-93	0.90-1.30
Raniganj	39-44	79-90	0.70-0.85
Rajmahal-Barakar	38-40	78-81	0.45-0.50
Singrauli- Barakar	37-45	78-81	0.45-0.50
Sohagpur	34-40	80-87	0.55-0.65
Pench valley	32-40	82-89	0.50-0.60
Wardha valley	35-40	78-82	0.55-0.60
Godavari Valley	35-42	78-83	0.55-0.60
Talcher	35-45	79-82	0.50-0.55

*mmf - Mineral matter free basis

Table 4: Proximate analysis and rank of concealed coalbeds

Coalfields	Basic parameters (mmf basis)		Virinite reflectance Av. Ro (%)
	VM (%)	FC (%)	
Cambay basin	45-58	52-68	0.32-0.44
Barmer Sanchor Basin	47-60	48-66	0.26-0.40
Birbhum	16-38	68-86	1.10-1.86
Wardha valley	24-35	72-88	0.54-0.68
Kamptee Kanhan valley	26-36	75-92	0.52-0.66

*mmf - Mineral matter free basis

11. Storage Capacity of Coalbeds

CO_2 storage capacity of unmineable coal seams for different categories of coalfields have been discussed below:

11.1 Unmineable Coal Beds in Well-delineated Coalfields

In depth coal resource analysis of Indian territory as per quality, depth wise distribution and status of exploration has supported in identification of suitable sites for CO_2 sequestration. The resources reported by GSI and other agencies have been classed as mineable and unmineable on the basis of the following factors.

- Exploration limit of coal has been to 1200m depth cover.

- Coking and superior grade non coking up to the explored limit has been classed as mineable.
- Inferior grade non coking coal (Grade E-G) below 600m depth cover.
- Damodar and Mahanadi Valleys have been taken as within mineable limit.
- Mineable limit for inferior grade non coking coal of Godavari and Wardha Valleys have been taken as 800m due to premium pricing structure.

The coal beds of Singrauli, Mand Raigarh, Talcher and Godavari valley come under this class where the coal reserve is available below the mining limit. With a view to capping injected CO_2 in the coal beds, minimum 100m thick top formation is proposed to be left between the working horizon and non mining zone. The vitrinite percentage of these sites is low in the range of 40 to 60%, vitrinite reflectance (VRo%) within 0.4-0.6% and ash within 15-45%, average 35%. The seams according to these properties are sub bituminous in rank with poor cleat frequency and aperture. The coal reserve, methane reserve and CO_2 storage capacity for these sites is summarized in Table 5.

Table 5: Unmineable coal reserve and CO_2 storage capacity

Coalfield	Estimated adsorption capacity of CO_2 (m^3/t)	Coal Reserve (Mt)	CO_2 storage capacity (Bm^3)	CO_2 storage capacity (Mt)	CO_2 storage capacity (90%) (Mt)
Singrauli	Average 20.0	37.0	0.74	1.46	1.32
Mand Raigarh	Range 16.0-23.0 average 19.0	79.0	1.50	2.97	2.67
Talcher	Range 17.2-24.8 Average 20.4	1017.0	20.80	41.18	37.06
Godavari	Range 16.8-22.2 Average 19.2	1976.0	38.02	75.28	67.75

11.2 Grey Area Coalbeds

The extension of coal beds below 1200m depth cover in coking and superior grade non coking coal have not been explored even though the continuity of the coal beds was well indicated within the lineament. The coal beds of such zones beyond mineable limit have been classed as Grey Area reserve. These reserves in case of East Bokaro, South Karanpura, Jharia and Raniganj and Sohagpur are below 1200m depth cover while in case of inferior grade non coking the limit is 600m for Son Mahanadi Valley and 800m for Wardha Godavari Valley coal fields. The coal and CBM, recoverable CBM and CO_2 storage capacity for these areas is summarized in Table 6.

Table 6: Estimated CO_2 adsorption capacity in grey area coalbeds

Coalfield	Estimated CO_2 adsorption capacity (m^3/t)	Cumulative Coal seam thickness (m)	Block Area (km^2)	Coal Reserve (Bt)	CO_2 storage capacity (Bm^3)	CO_2 storage capacity (Mt)	CO_2 storage capacity (90%) (Mt)
South Karanpura	Range 19.5-28.0 mean 24.5	73.0	76.0	0.75	18.35	36.33	21.80
East Bokaro	Range 22.3-33.5 mean 28.1	100.0	113.0	1.53	42.90	84.94	76.45
Jharia	Range 22.0-56.0 mean 34.5	40.0	193.0	1.04	35.96	71.20	64.08
Raniganj	Range 20.8-29.0 mean 24.0	30.0	240.0	0.97	23.33	46.19	41.57
Sohagpur	Range 18.9-26.4 mean 22.6	15.0	450.0	0.91	20.59	40.76	36.69
Talcher	Range 17.2-24.8 mean 20.4	120.0	149.0	2.41	49.24	97.49	87.75

The methane reserve in these locations is within 3.15 to 11 Bm^3 in 76 to 450 sq.km area. Cumulative seam thickness is very high within 15m to 120m and average gas content within 2.4 to 7.6 m^3/t of coal. Some of the seams of Damodar valley coal basins have gas concentration above 19m^3/t of coal. Total CO_2 sequestration even with 60% methane recovery is estimated over 114 BCM or Mt. approximately.

11.3 Concealed Coalbeds

These coal beds left in resource estimation exercise because of the basalt trap or thick alluvium beds are classed as concealed coalbeds. The bottom most coal bearing Barakar formation in such operations has been located within 300m to 3km depth cover over Nagaland to Cambay Basin of Gujarat. For the CO_2 sequestration or even ECBM recovery, the beds below 2000m have not been included in concealed potential sites. In case such sites are indicated roughly and the boundary and lithology is not defined, are also excluded from the present exercise for the time being. The representative gas content, coal rank and CO_2 storage potential for these fields are based on information available for the nearest coalbed of the lineament or from different sources (Table 7).

Table 7: Concealed area coal reserve and CO_2 storage capacity

Coalfield	Estimated adsorption capacity (m^3/t)	Cumulative Thickness of the coal seams (m)	Area of the block (km^2)	Coal reserve (Bt)	CO_2 storage capacity (Bm^3)	CO_2 storage capacity (Mt)	CO_2 storage capacity (90%) (Mt)
Cambay basin	Range 13.8-19.6 average 16.7	102.0	6900	63.0	1057.81	2094.45	1885.02
Barmer Sanchor Basin	Range 128-18.4 average 15.6	100.0	6700	60.0	936.00	1853.28	1667.95
W.B. Gangetic plain	Range 16.4-23.2 average 18.3	---	---	7.2	131.76	260.88	234.80
Birbhum coalfield	Range 17.2-24.8 average 20.2	100.0	312.0	4.2	85.08	168.46	151.61
Domra Panagarh	Range 18.6-25.8 average 21.8	48.0	116.0	0.751	16.39	32.45	29.20
Wardha Valley extension	Range 15.7-22.8 average 17.8	13.0	212.0	0.37	6.62	13.11	11.80
Kamptee Extension	Range 7.2-9.2 average 8.1	14.0	300	0.57	9.81	19.42	17.48

The gas resources of the above coalfields as estimated are based on presumption that the saturation level of the coal mass will be nearly 90% during the life time of the bore wells, with recovery of methane as per best practice. The storage capacity of some of the candidates are insignificant particularly those of Wardha Kamptee extensions and unless the limit is precisely delineated, may not be of any use. Similarly the storage potentials of unmineable beds of Mand Raigarh and Singrauli are also insignificant and even if ignored may not materially change the situation. Delineation of concealed coal basins not yet well defined may make difference in CO_2 storage capacity in future. The Barmer Sanchor basin finding is clear example the latest finding of which has improved the CO_2 storage potential.

12. Conclusions

Deeper unmineable coals are prospective candidates for methane recovery with simultaneous sequestration of CO_2 in coalbeds thereby reducing the atmospheric GHG level and providing a clean source of fuel. Indian coalbeds may be classified into grey, concealed and unmineable based on its depth of occurrence and grade characteristics. CO_2 sequestration potential in Indian coalbeds is estimated to be 4459 Mt. However, further research on selection of suitable candidates for CO_2

storage at a specific site demands for a detailed economic appraisal taking into consideration the daily CO_2 generation from the point sources and total gas likely to be generated during the life time of the power station with the present rate of consumption of coal.

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References

1. Friedmann SJ, Dooley JJ, Held H, Edenhofer O. The low cost of geological assessment for underground CO_2 storage: Policy and economic implications. *Energy Conversion Management* 2006; 1894: 47.
2. Casshyap SM. Patterns of sedimentation in Gondwana basins: *Fourth International Gondwana Symposium.*, Geological Survey of India, Calcutta, India January 1977; 525: 2, Hindustan Pub. Corp (India), 1979.
3. Acharyya SK. Comment on``Crustal structure based on gravity-magnetic modelling constrained from seismic studies under Lambert Rift, Antarctica and Godavari and Mahanadi rifts, India and their interrelationship'' by DC Mishra et al. *Earth and Planetary Science Letters* 2000; 595: 179.
4. Coal Atlas of India. CMPDI, Ranchi (India), 1993.
5. Inventory of Coal and Lignite resources of India as on 01.04.2012. http://www.portal.gsi.gov.in/gsiDoc/pub/coal_resource.zip
6. Chandra D. *Jharia coalfield*, Geological Society of India, Bangalore, 1992.
7. Chandra D., Singh RM and Singh MP. *Text book of Coal*, Tara book Agency, Varanasi, 2000.
8. Singh AK. Opportunities for Coalbed Methane Exploitation in India, *Proc. of Int. Conf. on Mining Challenges of the 21st Century*, New Delhi, November 1999, The Institution of Engineers (India), 369.
9. Chikatamarla L, Bustin MR. Sequestration potential of acid gases in Western Canadian Coals. *Proceedings of the 2003 International Coalbed Methane Symposium*, University of Alabama, Tuscaloosa, Alabama, 5-8 May, 2003, 1.

REAL TERM IMPLICATIONS OF CARBON SEQUESTRATION IN COAL SEAMS

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Extended Summary

Coal is the source and reservoir of methane gas; the volume of methane stored is each coal is dependent on many factors. Methane is retained in coals as: adsorbed molecules on the organic micropores, free gas in pores, cleats and fractures, dissolved in solution within the coal bed. Injection of CO_2 in coal seams may be carried out to extract methane through the fracture network in the coal. CO_2 has an additional effect compared to other gases that it is preferentially adsorbed onto coal surfaces, displacing methane from adsorption sites. CO_2-ECBM sequestration is a value addition project in management of increasing atmospheric concentration of GHGs as it recovers the cost of capture, processing, transportation and storage of CO_2 by production of methane. Therefore, coal seam sequestration may be defined as the storage of CO_2 from anthropogenic sources into deep, unmineable coal seams for geologically significant limits with or without concomitant recovery of natural gas (White et al., 2005).

The challenges in coal seam sequestration are many folds and various research works on field and laboratory scale are being carried out to understand the reservoir behaviour. Several pilot scale studies for injection of CO_2 is under operation in different fields like Ishikari Basin, Japan and North Dakota, USA. Most of these basins have experienced loss in injectivity due to reduction in coal permeability with time. The decline may be attributed to the CO_2 adsorption induced swelling in coal mass which leads to closure of macroporosity (i.e. cleats) since CO_2 in supercritical form induces maximum volumetric deformation in coal (Peters et al., 2000). It is important to understand the response of coal in detail before implementation of the sequestration process on a field scale. Not many studies have been carried out on investigating the behaviour of Indian coal with CO_2 in terms of the real term coal-CO_2 interactions. The role of effective stresses, confining stresses, coal matrix deformation etc. on CO_2 permeability of Indian bituminous coal was found in a recent article by Vishal et al. (2013a). The results

reveal that coal undergoes swelling and at higher depths, permeability reduces significantly, thereby altering the complete process of sequestration. Phase transformation of injected CO_2 at such depths may also lead to changes in coal-CO_2 interactions, finally influencing the injectivity of gases. Further, the influence of gas injection on the strength characteristics of coal as well as surrounding rock must be investigated for overall stability and safety of the system. Cap rock integrity is one of the most important parameters for sequestration of green house gases and must be understood in greater details before actual implementation.

However, applications of carbon capture and storage (CCS) in coal seams have its own advantages and thus, focus on coal research for sequestration has gained attention over time. The mechanism of storage in coal being adsorption is safer as compared to the compressional mechanism in conventional hydrocarbon reservoirs. The preferred affinity of coal for CO_2 over methane may be utilized for enhanced recovery of CBM from the coal blocks. Simulation works have indicated that injection of CO_2 may be used to recover more than 90% of coalbed methane which during primary recovery only enable upto 40-50% of gas extraction. Vishal et al. (2013b) worked out the CO_2-ECBM recovery for a block of coal seam in Raniganj coalfield for a preliminary investigation of the process using numerical simulation. The results indicate a positive connotation for the feasibility of the process, with keeping in mind the assumptions and the constraints in their work.

Therefore, to meet the growing energy needs, CCS in coal not only provides opportunity for capturing low carbon fuel, i.e. methane but also partly meets with the commitment of reduction of greenhouse gases (GHG) emission into the atmosphere. The process of ECBMR shall also partly offset the cost of carbon capture, transportation and storage in coal and hence, CCS in coal may be a value-addition process as compared to other storage methods in saline aquifers or basaltic formations. Understanding the behaviour of coal in underground scenarios is the key to successful operations and if established, coal seam sequestration would lead its way to GHG release mitigation in future.

References

1. Peters, J., Punjrath, N.K., Singh, S.K., 2000, Development of coalbed methane resources–challenges in the new millennium, Indian Geol Cong, KDMIPE, Dehradun.

2. Vishal, V., Ranjith, P.G., Singh, T. N., 2013a, CO_2 permeability of Indian bituminous coals: Implications for carbon sequestration, International Journal of Coal Geology. doi: 10.1016/j.bbr.2011.03.031
3. Vishal, V., Singh, L., Pradhan, S. P., Singh, T. N., Ranjith, P.G., 2013b, Analog modeling of Gondwana coal seams in India as coalbed methane reservoirs substituted for carbon dioxide sequestration, Energy, doi: 10.1016/j.energy.2012.09.045
4. White, C.M., Smith, D.H., Jones, K.L., Goodman, A.L., Jikich, S.A., LaCount, R.B., DuBose, S.B., Ozdemir, E., Morsi, B.I., Schroeder K.T., 2005, Sequestration of carbon dioxide in coal with enhanced coalbed methane recovery: a review, Energy Fuel, 19(3), 659–724.

CARBON DIOXIDE STORAGE AND ENHANCED OIL RECOVERY

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Abstract

Capturing and storing CO_2 from the atmosphere is becoming essential in view of the large increase of CO_2 from anthropogenic activities. Sub-surface geology provides the best medium for storage of excess CO_2 either in depleted oil and gas fields or in saline aquifers. EOR or enhanced oil recovery is a tertiary method after natural depletion and water injection methods have been applied to the oil field. Carbon Dioxide is injected into an oil bearing stratum under high pressure. Miscible CO_2 interacts with the reservoir oil resulting in low viscocity, low interfacial tension and therefore higher mobility. This therefore reduces the residual oil saturation.

Recent changes in EOR technology incorporate very large volume of injected carbon dioxide (1 to 1.5 Hydrocarbon pore volume HCPV), better mobility control through alternate use of gas and water, advanced and optimized infill well drilling and completion to target reservoir above oil water contact and bypassed oil zones left unswept during the secondary water injection stage. Rigorous monitoring of reservoir fluid either through pressure studies in slim hole for thinner reservoirs or time lapse seismic for seismically resolvable reservoirs is a significant approach in recent times.

139 Gega tones of CO_2 has been injected in the subsurface with an average of 0.30 tonnes/bbl as the CO_2/oil ratio at the time of report in 2009.India needs to take up EOR methods more vigorously though ONGC has initiated the process. Gujarat, Assam and Rajasthan can be the pioneers in this effort depending on the type of oil.

1. Introduction

Carbon Dioxide –enhanced oil recovery technology have been commercially deployed in old oil fields mainly in the United States of America [1] for the last three decades. Anthropogenic sources of CO_2 are steadily increasing in developed countries as the source in contrast to the natural sources, which were the only source historically. Pipeline network of CO_2 and identification of CO_2 sink i.e. the old oil field or saline aquifer in subsurface if storage is the only objective, is necessary for deployment of this technology. Ability to produce incremental oil and therefore enhanced revenue, through injection of high pressure CO_2 gas has made this option financially attractive.

Sedimentary basins across the globe are the habitat for oil and gas fields and coal seams. Deeper saline aquifers can also be found in Sedimentary basins. Basin is a depocentre in the Earth's crust formed due to tectonic forces either in extensional or compressional or in Strike slip regime. Sedimentary rocks transported from highlands by water system deposits in this basin and the process continues with increased subsidence either by gravity or by renewed tectonic activity. Insitu, organic growth of carbonate reefs is also possible under favorable environment. Sandstones, Carbonates rocks usually have pores and they are either filled with saline aquifers or in some cases hydrocarbons. Coal also gets deposited in sedimentary basins and coal seams can entrap fluids particularly gases. It is important that this fluid do not escape back into the atmosphere and therefore top and lateral seals are necessary and usually impermeable rocks like shale/ salts/evaporates or tight limestone provides seal. Depleted Oil fields and saline aquifers thus provide habitat for injected CO_2 in a sedimentary basin. Seismic data provides the subsurface image of sedimentary basin and can indicate possible habitats for injected CO_2.

A recent global study carried out using analog from US experience indicate that over fifty [2] large oil basins have reservoirs amenable for miscible CO_2 injection which can potentially produce 470 billion barrel of additional oil and store 140 billion metric tons of carbon dioxide. Half of these basins are in Africa and Middle East. Around 300,000 barrels of oil per day is being produced in USA mainly in Permian Basin located around Texas from enhanced oil recovery through 60 MM tones of CO_2 injection of which 20% is from anthropogenic sources. Extensive CO_2 pipeline network exists and the sinks i.e. candidate for injection is well defined including replacements. The process of water alternating gas injection manages the supply demand of CO_2 at individual field level by and shuts off CO_2 injection incase supply exceeds demand. European Union, Canada, Australia and even some of the BRICS countries are also following suit.

Saline aquifers can store much larger volumes of CO_2, due to its abundance, but the ability to produce incremental oil with injection of carbon dioxide in a matured oil field offsets the costs associated with carbon capture and storage.

Additionally the geology of oil reservoirs is well understood unlike reservoirs with saline aquifers where leakage of CO_2 back into the atmosphere can pose a serious problem, unless trapping mechanism exists. However estimating performance of injected carbon dioxide in enhancing oil recovery is complex and data intensive and each oil field could be very different.

EOR or enhanced oil recovery is a tertiary method after natural depletion and water injection methods have been applied to the oil field. Carbon Dioxide is injected into an oil bearing stratum under high pressure. Miscible CO_2 interacts with the reservoir oil resulting in low viscosity, low interfacial tension and therefore higher mobility. This therefore reduces the residual oil saturation. The challenge is to increase area of contact of the two phases. In case of immiscible CO_2 with reservoir oil, due to low reservoir pressure or heavy or too light oil, mobility still increase due to oil phase swelling and viscosity reduction of the mixture in some instances. CO_2 produced along with hydrocarbon particularly in miscible case is separated and recycled back into the oil reservoir.

Recent changes in EOR technology incorporate very large volume of injected carbon dioxide (1 to 1.5 Hydrocarbon pore volume HCPV), better mobility control through alternate use of gas and water, advanced and optimized infill well drilling and completion to target reservoir above oil water contact and bypassed oil zones left unswept during the secondary water injection stage. Rigorous monitoring of reservoir fluid either through pressure studies in slim hole for thinner reservoirs or time lapse seismic for seismically resolvable reservoirs is a significant approach in recent times. There is also a possibility of increasing geological storage of CO_2 into the saline aquifer once the oil has been produced. Industrializing the process would include a steady supply of CO_2 through pipelines and selection of large number of oil fields as sink candidates, including identification of their replacements when oil production from a field becomes financially unviable.

2. Case Studies from USA and Canada (source: Global Technology Roadmap)

The Permian Basin of southwest Texas and southeast New Mexico [3] is one of the largest and most active oil basins in the United States, with the entire basin accounting for approximately 17 percent of the total United States oil production with OXY as the main operator. Approximately two-thirds of Oxy's Permian Basin oil production is from fields that actively employ carbon dioxide (CO_2) flooding, an enhanced oil recovery (EOR) technique in which CO_2 is injected into oil reservoirs, causing the trapped oil to flow more easily and efficiently. Oxy is an industry leader in applying this technology, which can increase ultimate oil recovery by 15 to 25 percent in the fields where it is employed in the Permian. Each year, Oxy inject more than 550 billion cubic feet of CO_2 into oil reservoirs in the Permian, making Oxy the largest injector of CO_2 for EOR in the United States and a world leader in this technology.

To ensure an adequate supply of CO_2 for EOR operations in the Permian, Oxy relies upon several sources. These include carbon dioxide produced from the Oxy-operated Bravo Dome field in northeastern New Mexico, and additional supplies from methane fields in the southwestern Permian. The Century Plant in Pecos County, Texas, further expands Oxy's EOR infrastructure in the Permian Basin. The plant processes natural gas with high-CO_2 content, resulting in methane gas for the market as well as a major new source of CO_2 for Oxy's Permian operations.

The principal reservoirs are Carbonate shelf and platform strata with variable porosity and low permeability. Primary recovery efficiencies were low between 10 to 20% of OOIP. Water flooding started in 1950's and CO_2 injection commenced in large fields in 1970s. Recovery has gone up to 50% in some of the large fields with CO_2 injection. A recent USGS analysis indicates that the largest reservoirs –the San Andres, Grayburg and Canyon have contributed to this growth in oil reserves in the preceding decade. Deeper and smaller reservoirs can also be taken up but with lower gain. The main reservoirs studied by USGS have a potential to further add a mean of 2.68BBO of reserves through water flooding and CO_2 injection.

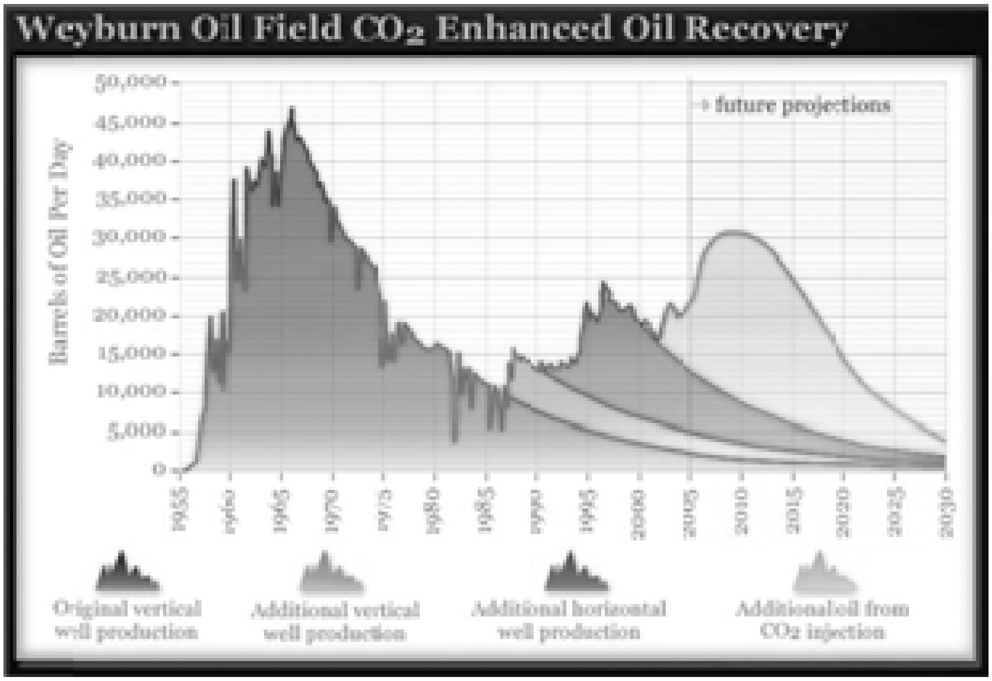


Fig 1: Enhanced oil recovery and future predictions from Weyburn oil field

The Weyburn oil field [4], operated by EnCana, Canada's largest oil company, is 130 km (80 mi) southeast of the city of Regina in Saskatchewan province. The Weyburn oil field was discovered in 1954 with an estimated 1.4 billion barrels of original oil in place. Oil production started in 1955 and rose to about 31,500 barrels of oil per day in 1963. Starting in 1964, water was pumped into injection wells in order to increase oil production. By 1966 production peaked at about 47,200 barrels per day (Fig 1). Over the next 20 years, production declined steadily, dropping to just 9,400 barrels per day by 1986. Additional vertical and horizontal wells were drilled. This increased production to approximately 22,000 barrels per day.

By 1998, roughly 330 million barrels of oil had been produced. This amounted to about 23% of the oil in the reservoir. Production again started declining rapidly. It was predicted that, unless a new solution could be found to enhance oil recovery, total production would be no more than 350 million barrels—just 25% of the original oil in place.

3. The Great Plains Synfuels Plant

To encourage the development of alternative fuel sources, the United States government supported the building of the Great Plains Synfuels Plant near Beulah, North Dakota. Commercial operations started in 1984. The goal was to produce methane (CH_4) from coal. Every day, more than 16,000 tons of crushed lignite coal is fed into "gasifiers" where it is mixed with steam and oxygen and then partially burned at a temperature of 1200°C (2200°F). This breaks down the coal to produce a mixture of gases. The gas is cooled to condense tar, water, and other impurities. Then it is passed through methanol at -70°C (-94°F). This separates the synthetic natural gas (SNG)—mostly CH_4—from other compounds—mostly carbon dioxide (CO_2).

The daily production is 3,050 tons of SNG, which is fed through gas pipelines to customers, and 13,000 tons of waste gas, 96% of which is CO_2. Many Synfuels plants release their waste gas into the atmosphere, contributing to the greenhouse effect and global warming. Waste gas from the Great Plains plant is fed into a 330 km (205 mi) pipeline to Weyburn, where it not only is disposed of safely but also helps to produce more oil (Fig 2).

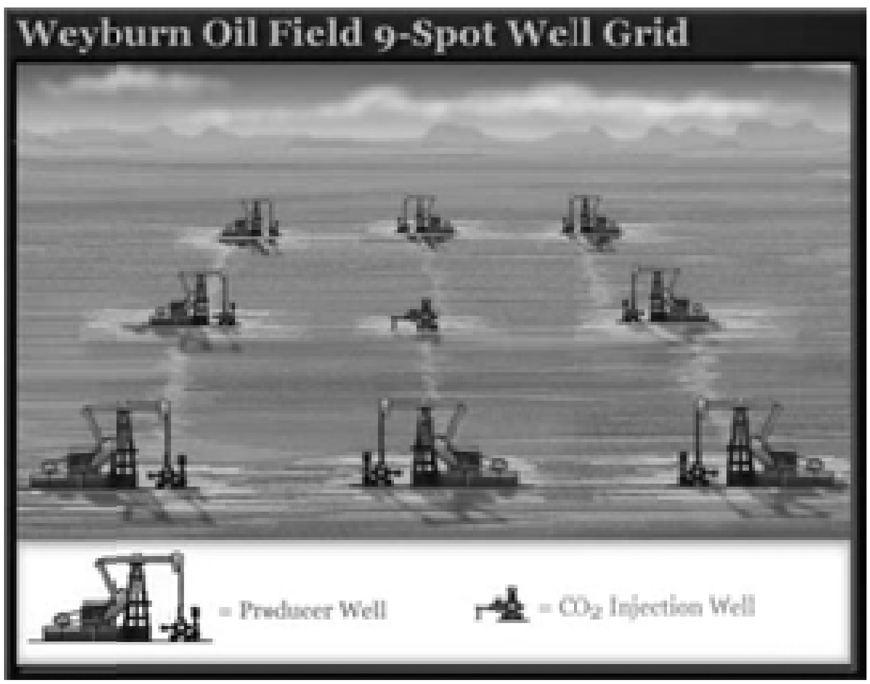


Fig 2: Well grid structure in Wyeburn project

4. The Weyburn CO_2 Enhanced Oil Recovery Operation

In 1997, the Dakota Gasification Company (DGC) agreed to send all of the waste gas (96% CO_2) from its Great Plains Synfuels Plant through a pipeline to the Weyburn oil field.

Delivery of the first CO_2 to Weyburn commenced in September 2000. The gas in the pipeline is at very high pressure (about 152 bars), which makes it a supercritical fluid. Supercritical fluids are gases under such high pressures that the vapor (gas) phase becomes as dense as the liquid phase. Supercritical fluids have high density but flow easily like gases, and so are ideal for transporting through pipelines. The Weyburn oil field has a total of 720 wells. The vertical wells were drilled in a "9-spot" grid pattern—eight producing wells in a square around an injection well—and typically have a spacing of around 150 m (500 ft). The high-pressure CO_2 is being pumped into 37 injection wells, helping oil to flow toward 145 active producer wells (Fig 3).

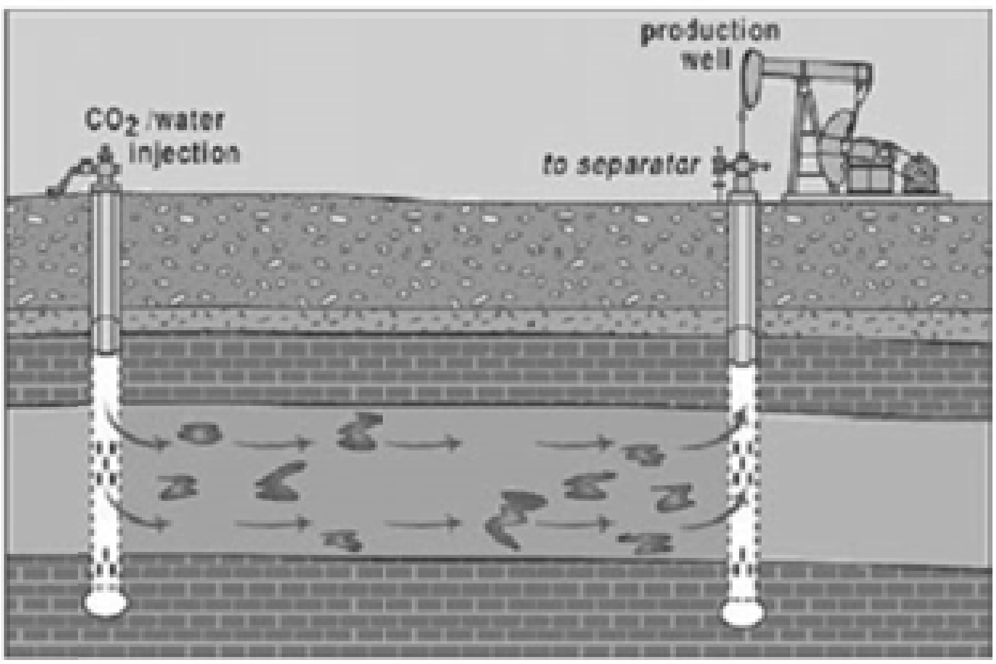


Fig 3: CO_2 injection and oil recovery process

The level of purity of the CO_2 supplied is ideal for use in enhanced oil recovery (EOR). This is because CO_2 dissolves more readily into oil when small impurities are present. Hydrogen sulfide (H_2S), which makes up 2.5% of the injection gas, is particularly beneficial at helping CO_2 to mix with oil.

When CO_2 supercritical fluid is pumped at high pressure into the reservoir, the CO_2 mixes with the oil, causing it to swell and become less viscous (Fig 3). The swelling forces oil out of the pores in the rocks, so that it can flow more easily. Water is pumped into the injection wells, alternating with CO_2, to push the released oil toward producer wells. Some CO_2 comes back out of the ground at producer wells. This is recycled, compressed, and reinjected along with gas from the pipeline.

It is predicted that the CO_2 EOR operation will enable an additional 130 million barrels of oil to be produced, extending the field's commercial life by approximately 25 years. It is also anticipated that about 20 million tons of CO_2 will be injected and become permanently stored 1,400 m (4,600 ft) underground over the lifetime of this project. There is worldwide interest in this test of the viability of underground storage for large-scale reduction in CO_2 emissions to the atmosphere. The Weyburn CO_2 Monitoring and Storage Project is funded by several international energy companies, the U.S. and Canadian governments, and the European Union. The main concern is whether the CO_2 will stay in place.

Weyburn is an excellent test site because, since 1955, thorough geological tests have been made and the results stored. There are rock core samples from 1,200 boreholes, plus time-lapse seismic analysis and borehole logging. Researchers are also sampling groundwater to test for CO_2 leaks in wells. So far, no leaks have been detected and none of the gas has escaped to the surface. The Canadian government believes that CO_2 storage deep underground will help it to meet its targets under the 1997 Kyoto Protocol, which requires a reduction in greenhouse gas emissions by an average of 5% between 2008 and 2012. In the case of Weyburn, the CO_2 is from coal that came from under the ground, so it is effectively being put back where it came from.

Another CO_2 capture and storage project currently under way is in the Sleipner field [5] in the North Sea in the Norwegian region. Injection commenced in 1996 with CO_2 separated from natural gas and injected into the Utisara sand a saline aquifer of late Cenozoic age at a depth of 1012m below sea bed, around 200m below reservoir top with a storage of over 11 mmt. Time lapse surveys have been carried out with 3D surveys in 1994, 1999, 2001, 2002, 2004, 2006, 2008 etc. The CO_2 plume is seen in seismic as a number of sub horizontal reflectors of tuned wavelets arising from thin layers of CO_2 trapped beneath thin intrareservoir mudstone and the reservoir cap rock and growing in time. There is also a velocity pull down in reflectors below the plume. A post stack Stratigraphic inversion of the 1994 and 1996 provided p wave impedance. Prestack inversion of the 1994 and 2006 data sets (after injecting 8.4mmt) with 50 iteration in the window 750-1400 ms provided s wave impedance and refined p wave impedance. This results when combined with spectral decomposition gave an idea of the thickness of CO_2 layers thus making it possible to make a volumetric estimate of CO_2 in the subsurface.

5. Monitoring / Flow Surveillance

Acoustic and elastic impedance contrast between the overlying and underlying rock strata and the reservoir rock provides the basis for subsurface imaging of the reservoir. While the longitudinal wave (P wave) is sensitive to the pore fluid, the transverse wave (shear wave) bypasses the pore and therefore is insensitive to presence of fluid. Gassman's equation provides a relationship between P wave velocity, S wave velocity, average density of matrix and fluid, porosity and elastic constants of rock matrix and fluid. Fluid substitution assuming constant shear modulus and constant porosity can help in modeling the change in p wave velocity with injected CO_2.

Laboratory studies along with well calibrated seismic parameters and using Gassman's equation can provide sensitivity analysis of seismic velocity (p wave) with pressure and saturation of injected CO_2. Thus with a baseline 3D survey prior to CO_2 injection, and then with 3D survey repeated periodically along with injected CO_2 and production and interpreting changes in subsurface as per the template designed as above, calibrated with saturation logs in time lapse mode, it is possible to quantify enhance oil recovered, both above the oil water contact as well as in bypassed zones in isolated pools. Additionally, inversion of pre stack seismic data composed of reflections from different offsets can throw further light into the change in subsurface with injected CO_2 and enhanced production.

Reflection coefficient of non zero offset seismic wave at an interface depends on the contrast in acoustic impedance along with the contrast in Poisson's ratio (which is essentially a function of the ratio of p wave and shear wave velocity) of the overlying and underlying bed. Thus AVO (amplitude VS offset of P waves) behavior of the reservoir also changes with injected CO_2 and production of oil. Incase this behavior is calibrated with well data and based on rock physics modeling; the changes could help in understanding fluid movement.

However this is easier said than done for artifacts in acquisition of seismic data and processing of seismic data can easily mar the assumption of repeatability. Three factors namely Earth effects, acquisition related effects and noise, changes seismic amplitudes.

Earth effects [6] include spherical divergence, absorption, transmission losses, interbed multiples, converted waves, tuning, anisotropy and structure. Acquisition related effects include source and receiver arrays and receiver sensitivity. Noise can be ambient or source generated, coherent or random. Processing attempts to alleviate problems of non repeatability, but can in the process create amplitude distortion and even now algorithms used are still not without their limitation in preserving amplitudes. 3D surveys done at different time are processed with the same processing parameters and same sequence. At each step at the non reservoir zone data is matched through time and space variant amplitude and spectral trace matching after correcting for time shifts if any due to variation in near surface between the surveys.

This process can reasonably ensure that at the non reservoir level, the time lapse surveys match and differences over and above this at the reservoir level can only be ascribed as signal attributed to injected CO_2 and enhanced production. Quantification of enhanced production and the economics can then only be on a firmer footing. Disadvantages of carbon sequestration through EOR vis a vie injecting CO_2 in saline aquifer is their geographic distribution of old oil fields and their limited capacity as well as the fact that subsequent burning of the additional oil so recovered will offset much or all of the reduction in CO_2 emissions. Flat spots in Seismic if detectable, created due to oil water contact pre injection of CO_2 can also be of great help for this will move vertically in repeated seismic, along with enhanced recovery

The discussion so far assumed that CO_2 is inert [7] and it does not affect the rock matrix. However this is not always the case and its effect also needs to be discussed. Temperature and pressure conditions in subsurface will keep CO_2 in a liquid state. Under this condition if CO_2 replaces water without dissolving in it the bulk modulus and density would decrease. When supercritical CO_2 migrates upward it moves to sub critical state and this may alter the free and dissolved gas ratio, affecting fluid saturation and distribution of patchy VS homogenous saturation. Changes in p wave velocity with increase in saturation of CO_2 are very different for the two cases below 70 deg saturation. Reduction in velocity of P wave is much faster for homogenous saturation as compared to patchy saturation, and therefore unless lab studies of core provide type of saturation data, interpretation of lowering of VP to saturation of CO_2 directly can be vastly erroneous. A 3% enhancement in porosity due to dissolution of mineral in CO_2 causes the same reduction in VP as

70% enhancement in CO_2 saturation. Thus non inert CO_2 is a difficult case for a Quantative estimation of injected CO_2.

Shear wave data may help to differentiate dissolution from saturation effects. With injection of CO_2 there is an increase in VS due to lowering of density in the inert case while chemical dissolution causes a decrease in VS due to lowering of rigidity modulus. Also the behavior of VS is independent of type of saturation, patchy vs. uniform for shear wave bypasses fluid. The challenge is to acquire good quality shear wave data, particularly in 4D sense. Combining both V p and Vs particularly using time lapse survey, backed up with extensive core data can provide a better quantitative estimation. Vertical Seismic profiling i.e. VSP carried out in 3D sense can provide a higher resolution data for it involves only one way wave propagation unlike surface seismic which has two way wave propagation. Static errors due to near surface irregularities are also much more pronounced in surface seismic data for shear wave acquisition.

We can conclude by stating that monitoring of multiphase subsurface flow associated with CO_2 injection poses new challenges because of complex seismic response of CO_2 water rock systems. Conventional models for seismic signatures like Gassman's model, based on fluid substitution, are mechanical and cannot incorporate chemical changes to host rock thereby altering porosity or formation of patchy porosity on account of change of state from super critical to sub critical. Thus magnitude and sense of changes in VP and Vs together, in time lapse seismic/VSP backed up with laboratory studies of core may help in Quantative estimate of injected CO_2 and each case can be unique depending on the interaction of CO_2 with water and host rock.

IEA [2] has prepared a detailed compilation of the estimates of original oil in place, ultimate primary and secondary recovery, incrementally technically recoverable oil from CO_2-EOR and the volume of CO_2 stored in association with this process in fifty world basins with favorable conditions for miscible CO_2. Basins are located in USA, Canada, Russia, China, Middle East, Africa, Latin America, and Australia. This process is cheaper in onshore but large oil field in offshore like Brazil can be ideal candidates in storing CO_2 in pre salt reservoir.

139 Gega tones of CO_2 has been injected in the subsurface with an average of 0.30 tonnes/bbl as the CO_2/oil ratio at the time of report in 2009. India needs to take up EOR methods more vigorously, though ONGC has initiated the process.

Gujarat, Assam and Rajasthan can be the pioneers in this effort depending on the type of oil.

6. Conclusions

Capturing and storing CO_2 from atmosphere is essential for saving the planet in view of the large increase of CO_2 through anthropogenic source. This naturally upsets the normal Carbon cycle. Subsurface Geology provides the best medium for storage of excess CO_2 either in old oil and gas field or in saline aquifer. Depleted fields have an advantage for the geology is well known, infrastructure exists and injected CO_2 can enhance recovery, thereby making the project financially attractive. It has to be ensured that injected CO_2 does not leak back to the atmosphere and entrapment mechanism is known for oil and gas field unlike saline aquifer. However the potential to store CO_2 is far greater in the saline aquifer and is ubiqtous.

Monitoring movement of injected CO_2 can be done by using time lapse surface or down hole survey carried out in 3D sense and both P wave and shear wave studies would be required to make a volumetric estimate. Incase CO_2 is inert the interpretation would be relatively simpler else alteration of petro physical characteristic of the host rock and the type of porosity data from extensive cores using SEM studies would be required as input for interpreting time lapse data. It can be concluded [8] that Quantative interpretation of repeated 3D data for monitoring and volumetric computation of the stored CO_2 depends on the rock physics model. VP and VS and amplitude changes with respect to CO_2 saturation in reservoir condition of temperature and pressure, needs to be studied and each case is unique in its own way.

References

1. National Energy Technical Laboratory (2010) Carbon Dioxide Enhanced Oil Recovery, US Department of Energy Report.
2. Michael L Godec et al (2011) Global Technology Roadmap for CCS in industry Sectorial Assessment, CO_2 Enhanced Oil Recovery Advanced Resources International Inc Report.
3. Marilyn E Tennyson et al (2012) Assessment of Remaining recoverable Oil in selected major Oil fields of Permian basin, Texas and New Mexico, USGS Report.

4. Jinfeng MA (2010) AVO modeling of pressure saturation effects in Weyburn CO_2 sequestration, Leading edge, SEG publication.
5. Andy Chadwick et al (2010) Quantative analysis of time lapse seismic monitoring data at the Sleipner CO_2 storage operation, Leading edge, SEG publication.
6. M Bacon, R Simm, and T Redshaw (2003) 3-D seismic interpretation, Cambridge University press.
7. TizanaVanoria et al (2010) The Rock Physics basis for 4D monitoring of CO_2 fate: Are we there yet, Leading edge, SEG publication.
8. Per Avseth, Tapan Mukherji, and Gary Mavko (2008) Quantative Seismic Interpretation, Cambridge University Press.

CO_2 Capture & Sequestration Project

An Impact Project of DST at RGPV Bhopal

MODELING & SIMULATION OF CARBON RECYCLING TECHNOLOGY THROUGH CONVERSION OF CO_2 INTO USEFUL MULTIPURPOSE PRODUCTS: CO,H2, & METHANOL

Dr V K Sethi
Director-UIT, Rector RGPV
& Head, Energy Deptt

The Four Dimensions of Low Carbon Technologies

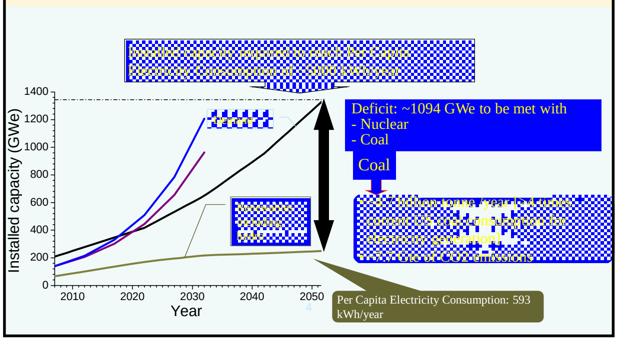
- 1: ***Low Carbon Technologies (LCT)***
  Renewable Energy Technologies- Planning for Energy security and Environmental Sustainability
- 2: ***Clean Development Mechanisms (CDM)***
  Barriers, Policy & Action Plan and Roles of Market Players- Impact of Low-Carbon Life Style on Climate Change
- 3: ***Clean Coal Technology (CCT)***
  Mega Power Projects based on Supercritical & IGCC Technologies – Plans in Power Sector.
- 4: ***Carbon Capture& Sequestration (CCS)***
  Impact R & D Projects & Technology Issues – Technology Transfer Strategies.

Issues in LCT & CCS

- **Promotion of Clean Coal Technologies**
- **Technology break thoughts in the areas like CO_2 capture & Sequestration and Clean Coal Technologies**
- **Development of low cost solar photo voltaic cells**
- **Bringing Energy Efficiency & Energy Conservation on the top of the National Agenda**
- **Promotion of Carbon Trading on the strength of Energy Efficiency and Green Environment initiatives.**
- **Base line methodologies for variety of Clean and Green Technologies need to be redefined.**

India's long-term Energy Security can me met primarily from Coal & Nuclear

India Fifth Largest Producer (1,82,700 MW)
Low Per Capita Consumption (704 U)



Comparison of CO_2 capture & Sequestration Technologies with other leading mid-to long-term option

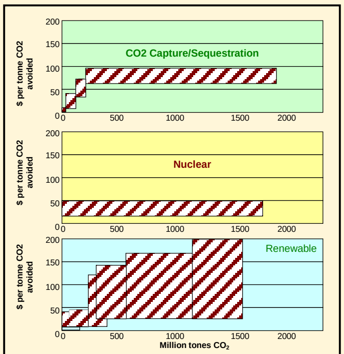


Figure: Comparison of CO_2 capture & Sequestration Technologies with other leading mid-to long-term option

1. Project Details:

a. ***Title of the project:***
"MODELING & SIMULATION OF CARBON RECYCLING TECHNOLOGY THROUGH CONVERSION OF CO2 INTO USEFUL MULTIPURPOSE FUEL"

b. ***DST File No.:*** ***DST /IS-STAC / CO2-SR-31 /07 Dt. 11-01-2008***

c. ***PI details*** Principal Investigator's): **Prof. P.B. Sharma, V.C., DTU, Delhi, Dr. V. K. Sethi, Director- UIT-RGPV, Bhopal, Dr. Mukesh Pandey, Dean, RGPV, Bhopal, Dr. J.P. Kesari, Prof. Mech., DTU**
Patron: **Prof. Piyush Trivedi, Vice Chancellor, RGPV, Bhopal, M.P.**

d. ***Date of start :*** ***1st April 2008***

e. ***Date of completion:*** ***30th June 2010*** **(II stage in progress)**

f. ***Total cost of project:*** **25.324 Lakhs**

Broad area of Research:

CO_2 SEQUESTRATION (Under the National Program on Carbon Sequestration – NPCS of DST)
Sub Area – Project Title: **Modeling & Simulation of Carbon Recycling Technology Through Conversion of CO_2 Into Multipurpose Fuels.**

g. Approved Objectives of the Proposal:

1. **To establish a pilot plant for CO2 sequestration and conversion in to multipurpose fuel.**
2. **To develop Zero Emission Technology Projects and recycle Carbon-di-oxide to add value to clean energy projects by adopting two pathways:**

- Sequester CO_2 and convert the same into fuel molecules.
- Use CO_2 to grow micro algae to produce Bio-diesel and Methane Gas.

3. **To develop mathematical & chemical models for CO_2 sequestration, Hydro Gasifier, Catalytic conversion & Algae pond systems.**

Methodology

Description of the Pilot Plant:-

Rated Capacity of the Capture of CO_2 : 500 kg/ day

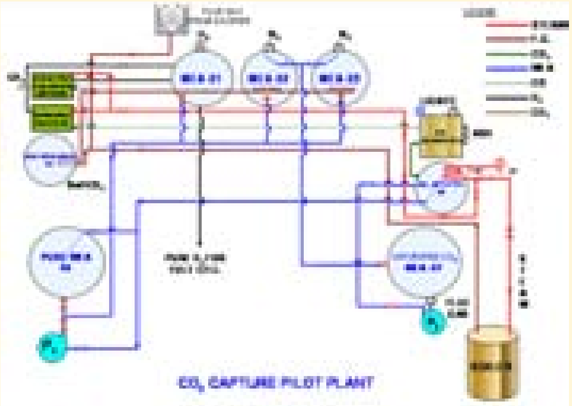
Source of CO_2: Boiler of capacity 100kg/hr. steam & Biomass Gasifier of 10kWe

Solvent used for capture of CO_2 : Mono Ethanol Amine (MEA)

SOx & NOx Removal: Na H CO_3, NaOH & Lime.

Catalytic Converters / Reduction Unit

- For Methane.... Input CO and H_2, Catalyst "R - 01 *
- For Hydrogen.... Input CO and Steam, Catalyst "R - 02 *
- For CO ... Input CO_2 and Lignite /charcoals


Scheme Diagram of CO_2 Capture Pilot Plant

2.Salient Research Achievements

The following four systems have been incorporated in the Pilot Plant:

1. **CO2 Capture & sequestration system – Indigenous Development**
2. **Catalytic Flash Reduction of CO2 using charcoal from gasifier/lignite. Production of Hydrogen from CO**
3. **Production of Methane using Catalytic Conversion process**
4. **Production of Algae from CO2 Sequestration with Solar flux.**

- **This project revalidated the useful application of the Amine absorption system to strip the CO2 from the flue gasses but also validated the data on its efficiency for a Power Plant.**
- **The simulation study further revealed that in a Thermal Power Plant, if a slip stream of the Flue gasses is recycled then a 30% reduction of CO2 would be achieved by direct abatement and recycle would result in a decline of fuel consumption by at least 7% and thereby reducing the CO2 emissions by about 36% in the most cost effective manner.**

Innovations:

- **Capture of CO_2 from Biomass and a Boiler on Pilot Scale and achieving capture efficiency of the order of 78%**
- **Production of CO in stable form and Water Gas shift reaction to produce fuel molecules like H_2**
- **Catalyst development to produce Methane from the captured CO_2**
- **Enhancing productivity of selected Micro-Algae for production of Bio- diesel**
- **Plant Cost optimization through in-house designing and erection work**

Long Term Application:
Deployment of the Technology to Actual Power Plants

Immediate Application
Green Energy Technology Centre (GETC) has been set-up for R&D and purpose

The pilot plant installed at RGPV can be utilized variety of application such as:-

- Study of CO_2 capture in Mono – Ethanol Amine (MEA) ranging from 1 molar to 3 molar solutions.
- Sequestration of CO_2 released from the stripper unit to variety of Algae and Development of lipid content for Bio-diesel production.
- The pilot plant can be used for recycling of CO in stable form to the boiler for reduction in Green Home Gas Emission.
- The pilot plant as well as table top plant shall be used for development of low cost catalysts for production of fuel elements like H_2, CH_4 etc.
- The plant is being used for academic purpose like M.Tech. Projects/ practical and dissertations for Ph.D.

THE ROAD MAP AHEAD

- Government of India has declared its policy on CO_2 abatement by the announcement and adoption of the 'National Action Plan on Climate Change'.
- It has also made voluntary commitment at the Copenhagen Summit that the Country shall decrease its Carbon Intensity by 20% by 2020 and 50% by 2050.
- The bulk of CO_2 is emitted by the Thermal Plants in the Power Sector. For EPA regulations to be implemented there have to be a road map as to how this can be done without major impact on the cost or efficiency of the Thermal Plants

Solution lies in…

- The thermal plants in India have a thermal efficiency of 35% and an emission ratio of 0.90Kg/kWh of CO_2 emissions as published by CEA. The reduction of 30% intensity would translate to a decrease of 0.27Kg/kWh of CO_2 emissions i.e. below 0.63Kg/kWh CO_2 emissions by 2020.
- This decrease is possible by a combination of abatement and recycling measures. The CO_2 reduction by an Amine system of 30% CO_2 capture would mean a decrease of Thermal Efficiency by a minimum of 2%.
- Energy penalty because of CCS is a major issue

Recycling of CO_2

- The CO_2 so captured needs to be either compressed to be used in Enhanced Oil Recovery or recycled. The better option would be that the same be recycled.
- The system additions to the existing thermal plants would be a two stage gasifier to use up this CO_2. This would help recycle the Carbon of the CO_2 and the treated/ converted CO would be re-fed into the Boiler by means of a Gas Burner.

The Chemistry of Recycling
Energy in various molecules:

- Carbon Dioxide production is exothermic reaction having energy (-) 393.5 kJ/mol there is no energy in this molecule after its formation and the value of the exhaust CO_2 is in fact zero. The CO_2 here in heat balance is seen as a waste, which it is.
- Hydrogen has a heat value of 141.8 MJ/Kg or the heat value would be 33875 kcal/Kg or in terms of power 1 kWh = 860 kCal would be 39.40 kWh/Kg.
- Like wise the Methanol has 22.7 MJ/Kg. this would mean a heat value of 5423 kcal/Kg or in terms of power would be equivalent to 6.30 kWh/Kg.
- Carbon monoxide has a heat value of 10.112 MJ/Kg, this would mean a heat value of 2416 kcal/Kg or in terms of Power would be equivalent to 2.8 kWh/Kg.

The Chemistry of Recycling

- The coal based power plant data for existing power plants to be retrofitted with CO_2 capture was studied; there are a number of projects using Amine Based System.
- For every 44 kg of CO_2 captured the CO produced would be 56kg with 12 kg of Carbon which has a heat value of 7840 kcal/kg or a total of heat of value of 94080 kcal.
- This would result in a total production of 56kg of CO which has a heat value of 2414 kcal and the total heat value of 1,35,184 kcal.
- In percentage terms it is 43.80% increase, but heat input to this endothermic reaction should be accounted for.
- The heat input (endothermic as %age of input heat value) of 21.92% should be accounted for i. e. 43.80 – 21.92 = 21.88%

THUS THE HEAT GAIN IS 21.88% IF WE PRODUCE CO FROM CO_2

Thus in nutshell

(A) PRODUCING CO FROM CO2 :-

- 21.88 % is the heat gain if we produce only CO from CO_2.

(B) PRODUCING HYDROGEN FROM RECYCLED CO_2 :-

$CO + H_2O = CO_2 + H_2$

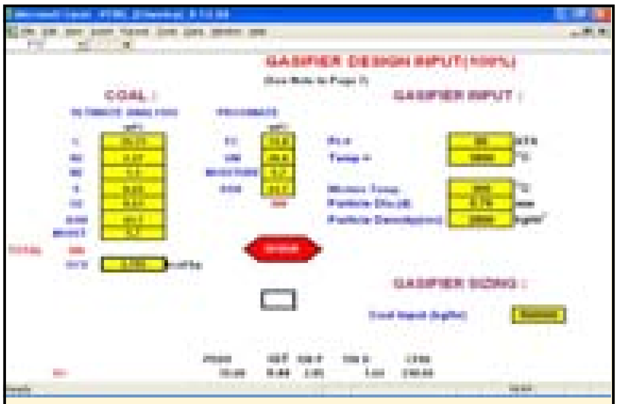
- Net heat energy gain of 18.72%

(C) METHANOLE PRODUCTION FROM RECYCLED CO2 :-

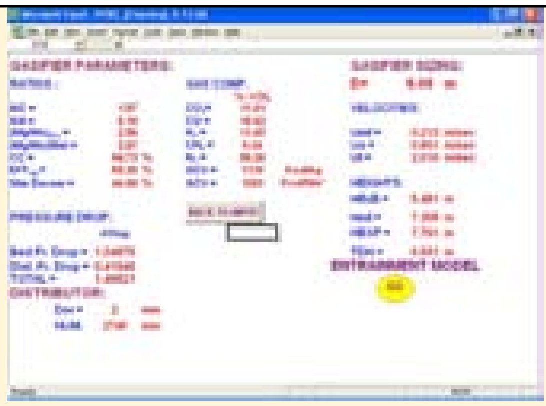
$2H_2 + CO = CH_3OH$

- When using recycled inputs there is a net gain in Heat value terms of 14.58%

(D) 30% CO_2 Capture & Recycling reduces 7.79% Coal



Gasifier Design - Input



Gasifier Design - output

Application Potential:

Long Term

- Deployment of the Technology to Actual Power Plants of NTPC through BHEL / TOSHIBA or any other major player

Immediate

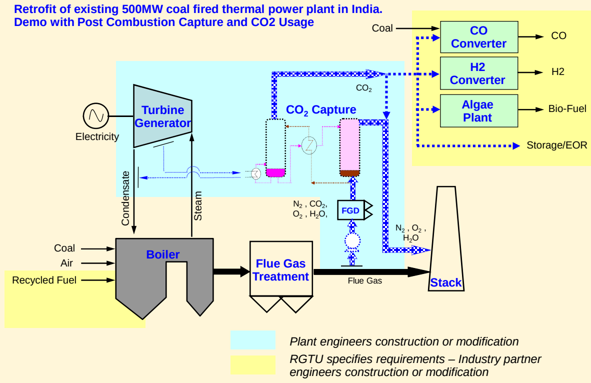
- Green Energy Technology Centre (GETC) being set-up for Teaching & Research (M. Tech & PhD)

Future action plan:

- Efforts are underway to extend the scope of the process by incorporation a Coal gasifier and recycling of carbon through collaborative research and Distributive Research Initiatives (DRI) with Research Organizations and Power Industries.

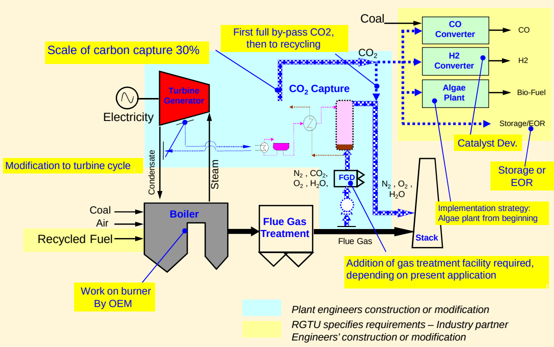
Schematic of Demo Project (Idea)

Retrofit of existing 500MW coal fired thermal power plant in India.
Demo with Post Combustion Capture and CO2 Usage



Demo Project –Strategy Plan

- Retrofit of existing 500MW coal fired thermal power plant in India.
- Demo with Post Combustion Capture and CO2 Usage



If the technology of CO2 Capture Recycling & Sequestration is applied on a 500 MW Coal based Thermal Power Plant with 30% capture we will get benefits like:-

- **Levelised Cost of Electricity or LCOE on a long term basis calculated for retrofitting would be Re. 1.05 per kWh. The energy penalty for 30% abatement would be 3% and the Loss in generation due to use of steam in MEA process would be 15000 kWh/hr for 30% CO2 reduction. The Capital cost would be Rs. 1.50 Crs. per MW.**
- **The Net emission reduction when the Recycling of CO2 is used in tandem with abatement would be down from 0.9kgmCO2/kWh to 0.63kgmCO2/kWh.**

CO_2 Sequestration Pilot Plant installed under the DST Project