Chapter 13
Coalbed Methane: Present Status and Scope of Enhanced Recovery Through CO_2 Sequestration in India

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Abstract Enhancing coalbed methane recovery through injection of CO_2 in depleted low pressure coal reservoir is a potential, economic and environmentally suitable solution to reduce greenhouse gas emissions. In India, commercial coalbed methane (CBM) production has been started since 2007 at Raniganj and Sohagpur basins and subsequently to Jharia and Bokaro coalfields. CBM reservoirs are at low pressure, and after some years of production through primary reduction of hydrostatic pressure, rate of recovery declines and harms the well economics. In a secondary drive, the CO_2 or $CO_2 + N_2$ or other mixture of gases can be injected to enhance the methane recovery and to maintain reservoir pressure. Studies conducted so far support stronger affinity of CO_2 to the coal molecule, displacing each methane molecule by 2–3 molecules of CO_2. Coal may adsorb more carbon dioxide than methane and that carbon dioxide is preferentially adsorbed onto the coal structure over methane (with 2:1 ratio). High-pressure methane and CO_2 sorption measurements were carried out for various coal seams in India. On the basis of CO_2 sorption capacity, seam thickness and extension, the suitable sites and their storage capacities estimated to be 4459 Mt for CO_2. It is assumed that this quantity of storage is sufficient to store over 20% of total gas emission from the present power plants over their lifetime. The sites close to the operating thermal power units may be the most appropriate for CO_2 sequestration as the transportation cost of the gas will be minimum. The rate of CO_2 generation and total CO_2 generated within the life span of a thermal power station presuming 20 years more from the date will be helpful for enhanced coalbed methane (ECBM) process in the close vicinity of CBM blocks. It is also required that geologic data and experimentally determined

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mineralization reaction rates and kinetics should be incorporated into geochemical models to predict the permanent storage of CO_2 in unmineable deep coals after ECBM recovery.

Keywords Enhanced coalbed methane · Recovery · CO_2 sequestration · Sorption isotherm · Storage estimates · Unmineable coal seams

Abbreviations

CBM	Coalbed methane
ECBM	Enhanced coalbed methane
ONGC	Oil and Natural Gas Corporation
GEECL	Great Eastern Energy Corporation Ltd
CSIR	Council of Scientific and Industrial Research
CIMFR	Central Institute of Mining and Fuel Research
CDM	Clean Development Mechanism
bcf	Billion cubic feet
IGCC	Integrated Gasification Combined Cycle
PFBC	Pressurized Fluidized Bed Combustion
CSLF	Carbon Sequestration Leadership Forum
IWCCS	International Workshop on Carbon Capture and Storage
DGH	Directorate of Hydrocarbons
HBJ	Hazira Bijaipur Jagdishpur
IPHE	International patnership for hydrogen economy
TCF	Trillion cubic feet
ICOSAR	Indian CO_2 sequestration applied research
VR	Vitrinite reflectance
BCM	Billion cubic meters

1 Introduction

In India, the Coalbed methane (CBM) recovery and utilization on large commercial scale is gaining importance. After few years of primary recovery, the rate of production declines and harms the well economics. At this stage injection of CO_2 into coal beds, enhanced methane recovery helps to tackle the dual challenges of reducing carbon dioxide and improving quality of life through clean energy exploitation (Reichle et al. 1999). There are many technological barriers and different challenges have to be overcome in the initial stages such as land acquisition, complex geologic conditions, drilling in heterogeneous formations, multiple hydrofrac and economic recovery techniques.

Coal seams can hold large amounts of carbon dioxide in comparison to the amounts of methane gas that they contain (Burruss 2003). However, before commercial sequestration projects are undertaken, it is necessary to evaluate the consequences of the geologic sequestration of carbon dioxide. Several efforts have been made in the past to investigate different technical issues related to carbon dioxide sequestration in unmineable coal seams (Bromhal et al. 2003; Mavor et al. 2004; Gorucu et al. 2005; Reeves and Oudinot 2005; Siriwardane et al. 2006). Coal swelling and shrinkage is considered as one of the potential problems during the carbon dioxide sequestration (Reeves and Oudinot 2005; Smith et al. 2005; Kelemen et al. 2006; Mazumder et al. 2006a, b; Pan and Connell 2005). Several laboratory experiments and numerical studies indicate that coal undergoes simultaneous swelling and shrinkage when the carbon dioxide is injected into a coal seam while the methane is produced. The large CO_2 adsorption capacities of coals and the CO_2-induced swelling of coals are two properties that were documented early (Mahajan 1991; Levine 1996). The research priorities for coal seam sequestration are sorption of CO_2 and coal swelling behaviour caused by CO_2 adsorption (Reichle et al. 1999). Studies in these and related areas will help define the CO_2 trapping mechanisms. Amoco has studied the adsorption of nitrogen, methane, carbon dioxide, and their mixtures to provide data for the modelling of gas recovery from coalbed methane reservoirs (Chaback et al. 1996; DeGance et al. 1993). Burlington Resources, the largest producer of coalbed methane, has been injecting CO_2 to enhance methane production since 1996 (Stevens et al. 1998). The experiences gained from enhanced oil and gas recovery of conventional reservoirs can be used for Enhanced Coalbed Methane (ECBM) recovery and also to the long-term disposal of CO_2.

Coal is an especially attractive target for sequestration not only because it can store large quantities of gas, but because CO_2 can be used to enhance recovery of coalbed methane, thereby offsetting the costs associated with sequestration of CO_2 (Byrer and Guthrie 2000; Gentzis 2000; White et al. 2005). It is essential, before finalization of CO_2 disposal sites that under what environmental conditions the sequestered CO_2 would remain stable, a better understanding is needed of the chemistry of the coal-CO_2 and methane displacement. One of the earliest studies of the adsorption of CO_2 on coal used the BET equation to calculate the CO_2 surface areas of anthracites (Walker and Geller 1956). The diffusion of CO_2 through coals of various ranks as an activated process was established not long afterward (Nandi and Walker 1965). Despite the fact that these, and many studies since then, have been performed at low pressure and of tenet low temperature in order to investigate the surface area of the coal (Mahajan 1991), they have provided information which is relevant to today's sequestration projects.

Coalbed methane reservoirs in the lower Gondwana and Tertiary Formations are extremely heterogeneous and this heterogeneity must be considered to screen areas for the application of CO_2 sequestration and ECBM recovery technology. Major screening factors include stratigraphy, geologic structure, geothermic, hydrogeology, coal quality, sorption capacity, technology and infrastructure. Results of this investigation indicate that the potential for CO_2 sequestration and enhanced coalbed methane recovery in the Indian coal bearing basin is substantial and can result in significant reduction of greenhouse gas emissions while increasing natural gas reserves.

2 Coalbed Methane Status in India

CBM has a very bright future in India if proper steps are taken in this direction. Currently, seven CBM blocks have been operated by Oil and Natural Gas Corporation (ONGC), Essar, Reliance and Great Eastern Energy Corporation Ltd. (GEECL) producing methane commercially. India, having the fourth largest proven coal reserves (306 billion tonnes) and being the third largest coal producer in the world, holds significant prospects for commercial recovery of CBM on large scale, it is anticipated that by 2022, CBM may contribute 10–16% of natural gas requirement.

The prognosticated CBM resource based on the Council of Scientific and Industrial Research (CSIR)-Central Institute of Mining and Fuel Research (CIMFR) determined in situ gas content and sorption capacities has been estimated to be around 4.6 TCM by Directorate of Hydrocarbons (DGH). Till now, 32 CBM blocks have been awarded in four rounds of international competitive bidding and on nomination basis. CIMFR has carried out detailed investigation to evaluate the coalbed methane reservoir parameters such as in situ gas content, molecular gas composition, sorption capacity, petrography, coal quality, thickness of coal seams, porosity, permeability and geo-mechanical properties. In situ gas content obtained through the direct method and initial recovery of methane from production wells encourages the large-scale future commercial production in coalfields such as Jharia, Bokaro, Raniganj, North Karanpura and Sohagpur. The CBM production may rise from the current 1.6 million metric standard cubic metres per day (mmscmd) to 10 mmscmd in 2022, reflecting a tremendous growth in CBM production.

India is endowed with bituminous coal of Palaeozoic and Tertiary ages within the CBM window at depths of nearly 200–1500 m. It is emphasized that Gondwana coal rank varies both laterally and vertically and changes from volatile sub-bituminous to bituminous coals (0.62–1.79% Ro). Coals are composed of 60–85% vitrinite, 15–40% inertinite, small amount of liptinite maceral and a trace amount of minerals. Methane adsorption isotherm determined as 13.91–29.54 m^3/t revealed that the maximum sorption capabilities of coals are affected by coal rank, high ash percentage, coal maceral, coal lithotype and especially to the high moisture content. Estimated gas contents range from 0.5 to 22 m^3/t. In combination with the geological information, the data indicated that the tectonic evolution of the basin had important influences on gas accumulation, preservation and escaping. The permeability is between 0.1 and 10 mD and the porosity ranges from 2 to 7%.

In Raniganj South, GEECL is the first commercial producer of CBM gas in India. It is engaged in exploration, development, production, distribution and sale of CBM gas. It currently owns two CBM gas blocks, one in Raniganj (South), West Bengal and other in Mannargudi, Tamil Nadu. The company started producing CBM gas commercially at the Raniganj (South) block in 2007. It has an estimated 2.4 trillion cubic feet (tcf) of original gas reserve in this block, spread over approximately 210 sq km, and produced 88.02 million metric standard cubic meter (mmscm) in 2013 from 157 wells. The company delivers CBM gas to more than 31 industrial customers through its own pipeline network in the Asansol-Durgapur industrial belt, which includes steel plants, steel rolling mills, glass, chemical and food industries. Compared with the other major U.S. CBM basins, GEECL's Raniganj (South) block displays remarkable similarities with the Black-Warrior basin of USA where multiple coal seams with significant gas content and favourable permeability account for high productivity. In Raniganj East, Essar Oil producing around 7,00,000 scm/d of gas. The total proven and probable reserves at Raniganj, evaluated as 113 billion cubic feet (bcf) gross. Nearly 150 wells have been placed on gas production; additional 155 wells have been drilled and are at various stages of the hydrofracking-completion-dewatering cycle for further gas production. In Sohagpur, Reliance Industries Limited (RIL) has done 12 core holes and two test wells in the block. Gas-In-Place of the order of 54.5 billion cubic metres (bcm) has been established. It is quoted that gas-in-place estimates are much more than the initial estimates done by DGH. Two test wells are producing incidental gas, from day one of dewatering, with rate more than 4000 m^3/day. The commercial quantities of CBM gas once produced from Sohagpur block can be consumed for captive power generation. Alternatively, it can be transported to nearby Hazira Bijapur Jagdishpur (HBJ) pipeline, which is at a distance of about 300 km, to reach wider markets through a dedicated pipeline. Usage through CNG is also possible in this area.

3 CO_2 Emissions in India

The top four emitting countries in the world, which together account for almost two-thirds (61%) of the total global CO_2 emissions are China (30%), the United States (15%), the European Union (EU-28) (10%) and India (6.5%). The present per capita annual CO_2 emission in India is estimated as 1.7 t as compared to 4.7 t world average and 17.0 t that of the US (World Bank 2015). By this level, even the planned combustion of coal by 2025 is likely to generate CO_2 just at par to the world average. India as such cannot be treated as the one responsible for emitting disproportionately high CO_2. Per capita CO_2 generation level in India is much below the world average and even with the planned power generation rate, expected to remain within the average numeral. This however does not give an excuse to forget ways and means to control the CO_2 emission in the interest of the global fraternity. Taking the benefits of latest technological innovation, the possible options to keep emission under control in near future are such as (i) use of Integrated Gasification Combined Cycle (IGCC) of Pressurized Fluidized Bed Combustion (PFBC) fuel efficient combustion technology to get more electricity from using less coal and reducing CO_2 emissions, (ii) capturing of methane from the coal beds and converting to CO_2 after using the heat energy and (iii) storage of CO_2 in unmineable coal beds while enhancing the methane recovery from the coal beds.

All the options are being adopted in leading countries and it is in the interest of India to follow suit. A part of CO_2 sequestration expenditure in all the trials is offset by additional methane recovery from the coal beds. India for one could take the advantage and help in minimizing CH_4 concentration in the environment and storage of CO_2 in deep coal beds keeping the financial burden to minimum.

4 Carbon Capture and Storage Activities in India

India is a major coal user and its demand is growing rapidly (IEA 2007). Approximately half of India's current annual CO_2 emissions of over 1300 Mt are from large point sources that are suitable for CO_2 capture. In fact, the 25 largest emitters contributed around 36% of total national CO_2 emissions in 2000; indicating important CCS opportunities (IEA GHG 2012). As a non-Annex I country to the United Nations Climate Change Convention, India has agreed to complete GHG emission inventories but is not required to meet an emissions reduction target. Further, because of the abundance of coal in India, combined with rapidly growing energy demand, the government of India is backing an initiative to develop up to nine Ultra-Mega Power Projects. This will add approximately 36 GW of installed coal-fired capacity in India. If the Clean Development Mechanism (CDM) Executive Board approves a CCS methodology, CCS projects could be certified for carbon trading under the Clean Development Mechanism, offering an important injection of funding that is needed. The Department of Science and Technology, Technology Bhawan in New Delhi launched the Indian CO_2 Sequestration Applied Research (ICOSAR) network in 2007 to facilitate dialogue with stakeholders and to develop a framework for activities and policies studies. CCS research in India includes CO_2-EOR scoping studies that are being carried out in mature oil fields; acid gas from the Hazira processing plant to be injected and reservoir properties (fluids, injection depth) indicate project feasibility. IGCC costs become 63% higher with capture than without capture (Goel 2007, 2008). India has joined a number of international efforts to advance the development and dissemination of CCS technologies. These include participation in the Carbon Sequestration Leadership Forum and the International Partnership for a Hydrogen Economy (IPHE), joining the US on the Government Steering Committee for the US Future Gen project, the US Big Sky CCS partnership, and the Asia Pacific Partnership for Clean Development and Climate. CCS workshops and knowledge sharing events have been organized, including the International Workshop on Carbon Capture and Storage (IWCCS) in 2007 in Hyderabad and the 2006 Carbon Sequestration Leadership Forum (CSLF) meeting in Delhi (Goel 2008). However, India's official position has not favoured the assessment of CO_2 storage potential in India or the implementation of a zero-emissions fossil-fuel power plant given the higher cost and technical uncertainties associated with CCS technologies.

5 Sorption of CO_2 and Methane

Methane adsorption capacity has been found useful for estimating CO_2 sorption capacity in the US coal fields and elsewhere. The required characteristics of the selected coal beds—vitrinite reflectance percentage and proximate analysis are found to be the relevant parameters affecting the gas recovery and subsequently CO_2 sequestration in coal beds. The coal mass has methane in micropores invariably less than the adsorption capacity of the coal. The adsorption capacity of the coal has been studied in the US, Canada, Australia, India and China. It is invariably found to be higher than the resource capacity indicating free surface area on coal molecule. Injection of CO_2 in such coal beds have the option of occupying the void and or occupy the total surface area by even displacing the methane molecules. The studies conducted so far support the later option because of stronger affinity of CO_2 to the coal molecule. It has been found that with the displacement of each methane molecule, 2–3 molecules of CO_2 are accommodated and thus its adsorption reaches closer to near complete (Mendhe et al. 2007).

The adsorption, storage and generation of methane are also known to depend upon the surface area of microporous system, thickness of coal seams/volume of coal and the confining pressure. A few of them have been explored for methane content under deep cover. Methane sorption capacity for Indian coals has been investigated by CIMFR. 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 (Greaves et al. 1993; Arri et al. 1992). The 2:1 ratio has been widely reported in the literature (Smith 1999, Byrer and Guthrie 2000; Gentzis 2000; Chikatmarla and Bustin 2003). However, recent studies indicate that this ratio can vary widely from more than 10 in low-rank coals to less than 2 in medium and low volatile bituminous coals (Stanton et al. 2001). Also some laboratory studies indicated that this ratio can be higher at pressures higher than 9.6 MPa (1450 psi), when gaseous CO_2 is changed into supercritical CO_2 (Hall et al. 1994). Understanding controls on CO_2 and CH_4 adsorption in coals is important for the modelling of both CO_2 sequestration and CBM production, yet the science on this subject is still in very early stages.

6 Estimation of in Situ Gas Content in Coal

The CBM recovery prospects in the absence of detailed exploration and study is estimated by empirical approaches like Langmuir adsorption Isotherm and Kim's equation (Kim 1977). The generation volume of thermogenic methane as per Meissner empirical equation is related to volatile matter (dry ash free basis) and rank of coal (Meissner 1984). The approach for estimation of gas in place is even more approximate depending upon the gas content and geometrical parameters like seam thickness, area and density of coal (Mukherjee et al. 1999). The equation of Kim empirical equation is based on adsorption isotherm and chemical composition of coal (Kim 1977). The volume of gas likely to be available is estimated by Direct and Indirect methods followed on coal samples in laboratory condition (Mukherjee et al. 1999).

Step in Direct Method

(a) Measurement of lost gas after the coal sample is cut by drilling bit and received in sealed container on the surface.
(b) Measurement of gas desorbed from the sample.
(c) Measurement of residual gas that remains in the sample after desorption ceases.
(d) Plot of the above quantity may be extrapolated to estimate gas likely to be available from a particular coal bed.

Step in Indirect Method

(e) Adsorption test for maximum quantity of gas a coal sample can hold by generating adsorption isotherm.
(f) Plot the adsorption quantity against pressure till equilibrium.
(g) Decrease the pressure and plot the gas volume against different pressures.
(h) Match the data with Langmuir's adsorption curve to estimate total gas content.

With the confirmed closer affinity of CO_2 to coal, faster rate of adsorption 2:1 and fixing of 2–3 mol in place of one mole of methane, the estimation of CO_2 storage may be treated by direct method of adsorption test for different coals. Given this opportunity, CO_2 adhere to the coal matrix with bond stronger than methane, amount stored is 8–9 times more by weight and volume is near total surface of the coal matrix. Based on methane sorption capacity, CO_2 sorption capacity of coal has been estimated for different Indian coals. The CO_2 sorption capacity, available coal reserve and CO_2 storage potential for different sites based on these assumptions are submitted below.

7 Screening Criteria for ECBM Using CO_2

The geologic factors determining the distribution and reducibility of coalbed methane resources are essentially the same as those determining carbon sequestration potential and include stratigraphy, structure, hydrogeology and sorption capacity. Technology and infrastructure must also be considered when screening areas for the demonstration and implementation of carbon sequestration technology. Emerging technologies to be considered include CO_2 separators for flue gas and enhanced gas recovery technology. A vital goal of sequestration is to deliver CO_2 at low enough cost so that coalbed methane remains economically viable on the open market. Once enhanced coalbed methane recovery is established, the groundwork can be laid for more intensive carbon sequestration efforts independent of the natural gas industry. Carbon sequestration further has potential to improve safety in underground coal mines and abandoned mines can play a role in the separation of CO_2 from flue gas. Infrastructure plays a critical role in the ways that carbon sequestration programs can proceed. Although a lack of infrastructure in many undeveloped basins may limit the applicability of carbon sequestration technology, a high degree of flexibility also exists. For example, flooding coal with CO_2 has potential for use as a primary production procedure that will eliminate concerns associated with water disposal and foster unprecedented recovery of the coalbed methane resource. Following are the major screening criteria for taking up of ECBM projects:

i. In situ gas content of coal seams
ii. Sorption capacity of methane and CO_2
iii. Porosity and permeability evolution due to shrinkage and swelling of coal
iv. Depth of reservoir and sequence stratigraphy
v. Thickness of reservoir
vi. Geological structure
vii. Hydrogeology
viii. Coal Quality
ix. Leakage and mineralization
x. A coal seam has sufficient reserve of CBM
xi. Minimum 1.35 m^3 of gas per tonne of coal is economical for ECBM
xii. Coal bed methane exists in areas where coal bed is buried deep and maintains sufficient water pressure.

Understanding controls on CO_2 and CH_4 adsorption in coals is important for the modelling of both CO_2 sequestration and ECBM production.

8 CO_2 Storage Potentiality in Coal Beds of India

Estimates for the geological storage potential in India are in the range of 400–500 Gt of CO_2, including on-shore and off-shore deep saline formations (300–400 Gt), basalt formation traps (200–400 Gt), unmineable coal seams (5 Gt) and depleted oil and gas reservoirs (5–10 Gt) (Singh et al. 2006). It should be noted that none of the fields that contribute to this value have the ability to store more than 100 Mt. CO_2 storage in deep coal seams is still in the demonstration phase (IEA GHG 2012). Indian coalbed are classified into grey concealed and unmineable based on its depth of occurrence and grade characteristics.

Coal resource distribution of Indian Territory is of Permo-Carboniferous Period in Lower Gondwana sediment's of Barakar and Raniganj formation of Damuda Group (Coal India 1994). Nearly, 14,000 sq km of the same is fairly well explored for coal resources while a large portion is buried deep under sediments of Jurassic to Pleistocene age and recent alluvium (Coal India 1994). The beds even in explored basins are thrown deep by major intra-basinal faults while the beds in some areas are concealed under basalt and inter-trapean formation or thick alluvium. The concealed beds are traced up to 3500 m depth cover. Any coal bed below 2000 m depth cover is not taken as a resource for any purpose including methane recovery and CO_2 sequestration.

8.1 Estimation of Unmineable Coal Beds

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 also 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. 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 (2015), and other agencies have been grouped as mineable and unmineable on the basis of the following factors:

(i) Exploration limit of coal has been to 1200 m depth cover.
(ii) Coking and superior grade non-coking up to the explored limit has been classed as mineable.
(iii) Inferior grade non-coking coal (Grade E-G) below 600 m depth cover in.
(iv) Damodar and Mahanadi Valleys have been taken as within mineable limit.
(v) Mineable limit for inferior grade non-coking coal of Godavari and Wardha Valleys have been taken as 800 m due to premium pricing structure.

The coal beds of Singrauli, Mand Raigarh, Talcher and Godavari valley come under the category where the coal reserve is available below the mining limit. With a view to capping injected CO_2 in the coal beds, minimum 100 m 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 40–60%, 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 1.

8.2 Estimation of Grey Area Coal Beds

The extension of coal beds below 1200 m 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

Table 1 Unmineable area 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

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 1200 m depth cover while in case of inferior grade non-coking the limit is 600 m for Son Mahanadi Valley and 800 m for Wardha Godavari Valley coal fields. The coal and CBM, recoverable CBM and CO_2 storage capacity for these areas is summarized in Table 2.

The methane reserve in these locations is within 3.15–11 Bm^3 in 76–450 sq km area. Cumulative seam thickness is very high within 15–120 m and average gas content; within 2.4–7.6 m^3/t of coal. Some of the seams of Damodar valley coal basins have gas concentration above 19 m3/t of coal. Total CO_2 sequestration even with 60% methane recovery is estimated over 114 BCM or Mt. approximately.

8.3 *Estimation of Concealed Coal Beds*

The coal beds not covered in resource estimation exercise because of the basalt trap or thick alluvium beds have been classed as concealed coal beds. Invariably such beds come under chance discovery during oil and natural gas exploration or drilling for some special missions. The bottom most coal bearing Barakar formation in such operations has been located within 300 m to 3 km depth cover over Nagaland to Cambay Basin Gujarat. For the CO_2 sequestration or even ECBM recovery, the beds below 2000 m have not been included in concealed potential sites. In case such sites are indicated roughly and the boundary and lithology is not defined, they 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 coal bed of the lineament or from different sources. These values are summarized in Table 3.

The potential CO_2 storage capacity for all the three classes is estimated in the light of general findings of laboratory and field trials of the USA, Canada, Australia and the latest of Poland. As each site is special with individual characteristic, the general findings of the previous studies have been supplemented by the information

Table 2 Grey area coal reserve and CO_2 storage capacity

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 average 24.5	73.0	76.0	0.75	18.35	36.33	21.80
East Bokaro	Range 22.3–33.5 average 28.1	100.0	113.0	1.53	42.90	84.94	76.45
Jharia	Range 22.0–56.0 average 34.5	40.0	193.0	1.04	35.96	71.20	64.08
Raniganj	Range 20.8–29.0 average 24.0	30.0	240.0	0.97	23.33	46.19	41.57
Sohagpur	Range 18.9–26.4 average 22.6	15.0	450.0	0.91	20.59	40.76	36.69
Talcher	Range 17.2–24.8 average 20.4	120.0	149.0	2.41	49.24	97.49	87.75

Table 3 Concealed area coal reserve and CO_2 storage capacity

Coalfield	Estimated adsorption capacity of CO_2 (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
West Bengal 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

available about the Indian sites for the methane recovery and storage potentials of CO_2. In the absence of definite information about the parameters like permeability and gas concentration, etc. lower side values have been accepted in empirical calculations.

9 CO_2 Storage Estimates for Indian Coal Seams Through ECBM

Stimulation of methane desorption from the coal beds is planned in a way that it remained stored safely forever. As per the studies conducted in the US, Australia and Canada, CO_2 injection enhances desorption of methane and in place of each methane molecule, three CO_2 molecules are adsorbed on the coal surface. The affinity of the CO_2 with the coal is stronger than the methane and unless the coal mass is disturbed physically it remains stored with a little chemical reaction and transformation. The coal beds subjected to CO_2 injection for enhanced methane recovery should be unmineable and a cap of impervious rock should be maintained to retain the CO_2 for years to come. The CO_2 storage capacity of the identified unmineable, grey area and concealed coal beds is summarized in Table 4.

Table 4 CO_2 storage capacity in candidate sites

Coalfield	CO_2 storage potential in Mt with 90% saturation level			Total (Mt)	Not considered
	Unmineable beds	Grey areas	Concealed areas		
East Bokaro	×	84.94	×	85	
South Karanpura	×	36.33	×	36	
Jharia	×	71.20	×	71	
Raniganj	×	41.57	×	42	
Singrauli	1.32	×	×	1	Insignificant
Sohagpur	×	36.70	×	37	
Mand Raigarh	2.67	×	×	3	Insignificant
Talcher	37.06	87.75	×	118	
Godavari-Ramgundam	67.75	×	?	68	
Cambay basin	×	×	1885.02	1885	
Barmer Sanchor basin	×	×	1667.95	1668	
W Bengal Gangetic basin	×	×	234.80	235	
Birbhum	×	×	151.61	152	
Domra Panagarh	×	×	29.20	29	
Wardha	×	×	11.80	12	Insignificant
Kamptee Coalfield	×	×	17.48	17	Insignificant
Total				4459	4426

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 lifetime of the bore wells, with recovery of methane as per best practice. The storage capacity of some of the candidates are very 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 very 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 a clear example of the latest finding of which has improved the CO_2 storage potential. The next target should be North Rajmahal Purnea basin with large point source of CO_2 generation in close vicinity.

10 Assessment of Priority Sites for CO_2 Storage

The identified sites are estimated to have 4459 Mt CO_2 storage potential, sufficient to store over 20% of total gas emission from the present power plants over their lifetime. The power station location of India is however distributed in each state, including the farthest in Punjab and Kerala. In fact prior to 1970, the location of the thermal power stations had nothing to do with the mine site. It is only after 1970, when the power grade coal was exclusively earmarked for the thermal power stations and restriction for transporting high ash coal to remote area was realized the power centre like Shakti nagar in Singrauli, Ralmahal, Talcher, Korba and Ramgundam came into existence. Even now, the power centres are being planned in close vicinity of basins with abundance of inferior grade non-coking coal. In other coalfields, the old designed thermal power units are distributed in Bokaro, Karanpura, Raniganj, Kamptee coalfield and Rewa coalfield.

The sites close to the operating thermal power units may be the most appropriate for CO_2 sequestration as the transportation cost of the gas will be minimum and the pollution level of CO_2 is alarming. The list of such sites and approximate CO_2 generation is summarized in Table 5.

The CO_2 generation in a well-designed thermal power plant of 2000 MW should be around 25,000 t per day but in most of the above units, the estimated emission level is comparatively high. The combustion of inferior grade coal in old-fashioned plants is the main reason for this abnormal pollution rate. This shows the need for advance combustion technology transfer, renovation and management of the existing units. The rate of CO_2 generation and total $CO_{2,}$ generated within the lifespan of a thermal power station; presuming 20 years or more from the date, the storage capacity compatibility for the nearest sites is summarized in Table 6. The sites with storage capacity below 12 Mt have been ignored because of their insignificant size.

The storage capacity of the nearby candidate, daily CO_2 generation and total gas likely to be generated during the lifetime of the power station with the present

Table 5 Power generation sources, and potential CO_2 storage sites

Nearest storage candidate	Power station	Installed capacity (MW/day)	Coal consumption (kg/KWH)	Million KWH per day	Coal combustion (t/day)	CO_2 generation (t/day)
Cambay	Gandhi nagar	330	0.60	?	2500	9200
Barmer Sanchor	Suratgarh	500	0.60	?	4000	14,600
Godavari	Kothagudam	1170	1.08	22.39	24,200	79,900
	Ramgundam	63	0.73	1.45	1060	3900
	Ramgundam STPS	2100	0.63	50.65	31,900	117,000
Total						200,800
East Bokaro	Bokaro A&B	805	0.80	5.70	4560	16,700
South Karanpura	Patratu	770	0.96	5.23	5000	18,300
	Tenughat	420	0.87	4.8	4200	15,400
Total						43,600
Raniganj	Mejia	630	0.70	9.9	6900	22,000
Sohagpur	Amarkantak	290	0.75		2175	8000
Birbhum	Bakareshwar	630	0.77	9.2	7100	26,000
Domra Panagarh	Durgapur-DVC	350	0.62	7.2	4500	16,500
	Durgapur-DPL	390	0.74	4.39	3250	11,900
Total						28,400
West Bengal basin	Kolaghat	1260	0.73	29.0	21,200	77,700
Jharia	Chandrapura	750	0.79	3.39	2700	9900
	Santaldih	480	0.60	3.6	2200	8000
Total						17,900
Rajmahal	Kahalgaon	840	0.84	17.7	14,900	51,000

(continued)

Table 5 (continued)

Nearest storage candidate	Power station	Installed capacity (MW/day)	Coal consumption (kg/KWH)	Million KWH per day	Coal combustion (t/day)	CO_2 generation (t/day)
	Farakka	1600	0.83	34.95	29,000	106,000
Total						157,000
Talcher	Talcher-NTPC	460	1.01	9.4	9500	34,800
	Talcher-STPS	1000	0.75	11.60	8700	31,900
Total						66,700

Table 6 CO_2 storage capacity and point source gas generation in close vicinity

Candidate	CO_2 storage capacity (Mt)	Nearest Point Source CO_2 generation		Mt in life time (20 years)
		t/day	Mt/year	
Cambay	1885	9200	3.36	67
Barmer Sanchor	1668	14,600	5.33	107
Godavari	68	200,800	73.29	1465
East Bokaro	85	16,700	6.10	122
S Karanpura	36	43,600	15.91	318
Birbhum	152	26,000	9.49	190
Domra Panagarh	29	28,400	10.36	207
West Bengal basin	235	103,700	37.85	757
Jharia	71	17,900	6.53	131
Talcher	118	66,700	24.35	487
Sohagpur	37	2175	0.79	16
Raniganj	42	6900	2.51	50

consumption rate of coal shows that the coal beds does not offer very promising sites for even the point emission sources like Shakti Nagar Singrauli, Rajmahal, Korba and Ramgundam. The storage potential howsoever small may help in minimizing the GHG pollution level and should be targeted along with ECBM recovery.

11 Impact Analysis of ECBM Over Regime

CO_2 can be injected into coal seams through ECBM process, the basic requirement for this are such seams with high porosity that can adsorb CO_2 overlaid by impervious fault free caprock that prevents migration of the stored CO_2 upwards or sideways. Coal seams contain methane which can be drilled for and pumped out, and CO_2 injected into the seam. CO_2 adheres to the surface of the coal twice as much as CH_4. This procedure increases production while locking the CO_2 into the coal bed. Several careful studies should, however be made before this option is implemented as follows:

i. Assessment of the efficacy of the injection process and ensuring the safe containment of CO_2. This requires the tracking of the CO_2 migration and to monitor the integrity of the reservoir.
ii. Impact of injection of fluids on the geophysical properties of the CBM reservoir and the change of geochemical properties over infinite time scales should be examined.

iii. Use of suitable geophysical strategies for depth and time frame for monitoring of migration, leakages and seepage issues.
iv. Laboratory studies on changes that take place in physical and hydro geological properties in response to varying saturation pressure, temperature and gas injection states under simulated conditions.
v. Monitoring/verification involving surface/well logging studies using seismic, electrical and electromagnetic techniques. The studies include fluid dynamic studies to monitor the plume location and migration.

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