

Potential for enhanced coalbed methane recovery

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Preface

This report has been produced by IEA Clean Coal Centre and is based on a survey and analysis of published literature, and on information gathered in discussions with interested organisations and individuals. Their assistance is gratefully acknowledged. It should be understood that the views expressed in this report are our own, and are not necessarily shared by those who supplied the information, nor by our member countries.

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IEA Clean Coal Centre began in 1975 and has contracting parties and sponsors from: Australia, Austria, China, the European Commission, Germany, India, Italy, Japan, Poland, Russia, South Africa, Thailand, the UK and the USA. The Service provides information and assessments on all aspects of coal from supply and transport, through markets and end-use technologies, to environmental issues and waste utilisation.

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Abstract

The recovery rate of methane is usually limited by the coal seam gas pressure and diffusion rate and, as a result, not all the available gas can be recovered. By injecting gas into the seam, further methane can be liberated. This gas can be CO_2 , N_2 , flue gas or a combination thereof. The injection of captured CO_2 to provide enhanced recovery of coalbed methane might serve to increase methane production whilst storing CO_2 , if the geography and economics are favourable. However, despite many pilot studies on ECBM, no projects have moved to the demonstration or commercial phase, due to both technical and economic issues.

Acronyms and abbreviations

APP	Asia Pacific Partnership
ARC	Alberta Research Council, Canada
BSCSP	Big Sky Carbon Sequestration Partnership, USA
CBM	coalbed methane
CCC	Clean Coal Centre
CDM	Clean Development Mechanism
COP	conference of the parties
CO ₂ -ECBM	CO ₂ enhanced coalbed methane
CSEMP	CO ₂ Storage and Enhanced Methane Recovery Project, USA
CSG	coal seam gas
CSIRO	Commonwealth Scientific and Industrial Research Organisation, Australia
CUCBM	China United CBM Corp
ECBM	enhanced coalbed methane
GHG	greenhouse gas
GIP	gas in place
GOIP	gas originally in place
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
MOST	Ministry of Science and Technology, China
MOVECBM	Monitoring and Verification of CO_2 storage and ECBM in Poland
NETL	National Energy Technology Laboratory, USA
NPV	net present value
PCOR	Plains CO ₂ Reduction Partnership, USA
PRB	Powder River Basin, USA
RECOPOL	Reduction of CO ₂ emissions by means of CO ₂ storage in Poland
ROI	return on investment
SECARB	Southeast regional Carbon Sequestration Partnership, USA
TNO-NITG	Netherlands Organisation for Applied Scientific Research Netherlands Geological Survey
UN FCCC	United Nations Framework Convention on Climate Change
US DOE	US Department of Energy
US EPA	US Environmental Protection Agency

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1 Introduction

Coalbed methane (CBM) is an important contributor to energy production, especially in North America where the majority of the country's natural gas comes from coal seams. Although methane (CH₄) can be obtained in a cost effective manner from suitable seams, towards the end of the lifetime of a CBM project, the pressure of the CH₄ present is insufficient to make extraction economically viable. Injecting gas down into the seam can help produce CH₄ that would otherwise have been inaccessible. This is known as enhanced CBM (ECBM). A CBM project will normally produce up to around 50% of the available CH₄ from a coal seam. With ECBM, this production rate can increase to 90%.

Using CO_2 as the injection gas is theoretically a win-win situation – more CH_4 can be produced whilst CO_2 is stored underground. This has been the driver behind the majority of ECBM pilot studies which have been carried out worldwide. CO_2 -ECBM has been covered extensively in several reports by our sister organisation, the IEA Greenhouse Gas R&D Programme and the interested reader is referred to their website <u>www.iea-GHG.org</u> for further information and numerous reports on the CO_2 capture side of the process. This report concentrates primarily on the methods used and the challenges encountered when using any gas to enhance CBM production rates.

Methods are being developed with focus on the use of microbial action to enhance methane production in coal seams (*see* for example NETL, 2015). However, this form of enhancing CBM production is not covered in this report.

Chapter 2 looks at the process of ECBM outlining the principle of gas injection and the chemical and physical processes of CH₄ liberation from coal seams. The tests and models used to predict gas production during ECBM are reviewed. Chapter 3 then summarises the economics of ECBM, looking at injection costs as well as relevant gas treatment requirements.

Despite enhanced ECBM being theoretically desirable, many proposed projects have stalled or been cancelled and the proof of concept is not yet fully achieved. Chapter 4 briefly reviews all the pilot projects which have taken place worldwide in an effort to understand why, as yet, none has proven the process commercially viable.

2 Principles of ECBM

In theory, ECBM is simple – a gas, commonly including CO_2 is injected into an unmineable coal seam to promote the release of CH_4 . Without gas injection, the CH_4 recovery rate from a CBM project is only a portion of the gas in place as the pressure of the seam decreases as water and CH_4 are recovered. Injection of gas down into the seam can result in the CH_4 production rate increasing towards 100%.

With the coal seam acting as both a source of saleable energy and a potential final storage site for flue gases or CO_2 , ECBM is a tempting technology. However, the gap between the technique in theory and in practice is emphasised by two decades of work with, to date, no full-scale demonstration projects.



Figure 1 Principle of ECBM (Zheng and Xu, 2014)

The basic premise of ECBM is shown in Figure 1. Gas is injected down into the seam via an injection well and the dispersion of this gas throughout the seam causes the release of CH_4 which is then captured as it appears at the production well.

The drilling and pumping technologies used in ECBM have been used and proven in other industries, such as oil and gas recovery. However, the addition of a gas injection and, in some cases, a CO₂ storage phase to the process increases the complexity of a project. The following sections summarise the major considerations and issues in establishing an ECBM project.

2.1 Site selection

CBM projects may be carried out prior to mining, sometimes as part of the safety requirements of the site, and other times as a means of harnessing this gas energy before moving in with traditional coal mining methods. Not only is the CH₄ a cheap energy source, it is also a potent greenhouse gas (GHG) and its release should therefore be avoided.

The US EPA (US Environmental Protection Agency, 2015) suggested that, 'if ECBM technology is 50% efficient, CH_4 emissions from mineable coal seams are cut in half, and total US emissions of methane could be reduced'. They acknowledged that the use of CO_2 in ECBM would 'cloud' the total GHG emission equation since, if the seam were mined, the CO_2 would be re-released into the atmosphere. However, due to the differences in global warming potentials (CH_4 has a global warming potential greater than 20 times that of CO_2), an overall reduction in greenhouse gas emissions is achieved along with improvement in mine safety.

Although CBM projects can be located at both active and inactive mines, the majority have been aimed at seams which are otherwise considered unmineable due to depth or inaccessibility. However, the definition of unmineable coal seams needs to be clarified. Continuing advancements in coal mining technologies make it difficult to provide a definitive categorisation of which seams are permanently unmineable and which may be unmineable now but mineable in future.

Li and Fang (2014) have summarised some different definitions of unmineable, as used in various ECBM projects (Table 1).

Table 1 Definitions of 'unmineable' (Li and Fang, 2014)				
Source	Definition			
'many literatures'	Seams at 800 or 1000 m in depth			
US DOE*, PCOR†	Under at least 305 m of overburden			
MGSC	Over 152 m deep and, between 152–305 m deep, seams of 0.5–1.1 m thickness			
China	1000–2000 m			
 * US Department of Energy (US DOE) Big Sky Carbon Sequestration Partnership (BSCSP) † PCOR (Plains CO₂ Reduction) Partnership, USA 				

In order to create a valid estimate of ECBM potential in coal seams in various countries and globally, there needs to be a standardised determination of appropriate (unmineable) seams. This would provide greater assurances to investors that the seams to be used for ECBM are being used for the most appropriate project.

2.2 Methane recovery

The primary aim of any CBM or ECBM project is CH₄ recovery. Previous reports by the CCC have looked at standard CBM methods, as well as alternative options for CBM use (Sloss, 2005, 2006).

CBM is a well-established source of gas for energy production. In San Juan basin, USA, BP has over 1500 CBM wells and ConocoPhillips has over 800 wells. There are more than 17,000 wells in the Powder River Basin alone and the estimate for the whole of the USA is around 90,000 wells (Palmer, 2010). The majority of US natural gas production comes from CBM and the San Juan Basin in Colorado and New Mexico produces up to 0.85 million m³ per day (Jamshidi, 2010).

Australia and Canada appear to have an emerging CBM market. China's coal seams are considered less suitable for CBM due to lower permeability and pressure. Despite this, several projects are underway in China. India has also started testing for potential CBM production sites (Palmer, 2010; *see* Chapter 4).

The principle of CBM is that CH₄ is in place in unmined coal seams and that it is there under pressure as it has been unable to escape since the coalification process began. By drilling vertically down into the coal seam, a path is created to allow CH₄ to be released from within the coal. This gas is forced, under its own pressure back up to the surface for collection. In most seams, water is present and dewatering assists in promoting the release of CH₄ from the coal.

The difference between CBM and conventional natural gas is that in CBM the CH₄ is stored within the molecular surface of the coal – actually adsorbed onto the coal surface. In natural gas wells, the gas is commonly already desorbed in underground spaces and pockets. Because of the large internal surface area of coal, in comparison to conventional gas reservoirs, coal seams can store six to seven times more gas on an equivalent reservoir volume basis. Figure 2 shows where CH₄ is present in a coal seam. The CH₄ is held both on the surface of the coal within the coal matrix and in the surrounding fractures, held in place by water (CSUG, 2010).

coalbed matrix illustrating gas surrounding the coal bound by water and rock



Figure 2 Methane within the coal seam (CSUG, 2010)

Much of the gas can be produced and captured by breaking through the cap rock and removing the water, thus releasing the pressure that is holding the CH_4 in place. The release of the CH_4 from the coal takes place in three main stages:

- desorption of the gas from the internal micro pores on the surface of the coal;
- diffusion of the gas through the matrix of the coal;
- fluid flow of the gas through the fracture network within the seam to the production well.

CH₄ will still be held deep within the coal particles further inside the seam, away from the drilling points and cleats, and so the release of some of the CH₄ from CBM is subject to additional factors such as seam permeability. Since permeability can be low in most coal seams, CBM usually comprises multiple wells in close spacing to achieve economic rates of gas flow. However, natural fractures within the seam are also important and so sites with natural fracture networks (due to localised faulting) are preferred. Lower rank coals are softer and most appropriate for vertical well drilling. However, the stronger, higher rank coal seams can cope with more invasive horizontal wells (Godec and others, 2014).

As mentioned earlier, most coal seams contain water and therefore pumping of the seam is a major part of the production process. However, there are a few sites, such as the Horseshoe Canyon formation in Alberta, Canada, which are dry. In these cases, CH₄ can be produced immediately upon drilling, with no drainage required (CSUG, 2010).

2.2.1 Gas in place estimates

Before a CBM project commences, the gas in place (GIP) will be determined by core sampling. Combined with information on the CH₄ adsorption isotherm of the coal (*see* Section 2.3.1), this will allow prediction of the reservoir pressure level. Projects with large volumes of gas in place and favourable gas pressure will merit significantly more investment than smaller reserves. However, those companies carrying out CBM projects are well aware that the GIP estimate is not an indication of how much of that gas is actually recoverable in an economic manner. The amount of CH₄ which is technically accessible is considered the recoverable resource. This latter value is more indicative of the volume of CH₄ which may be produced for cost estimates.

The GIP/resource estimates will also help determine the sealing efficiency of the cap rock – those sites which show CH_4 contents close to the theoretical maximum indicate sites with excellent cap rock. This means a site where little or no gas has escaped from the seam. Such a site will have relatively high GIP (since none has leaked) and higher gas pressure (faster and higher gas recovery rate). Sites with efficient cap rock will also be more suitable for CO_2 storage since they have demonstrated low levels of leakage over extended time periods. However, any potential damage which may be caused to the cap rock during the CBM drilling and production process which could lead to new leakage points (Mazzotti and others, 2009) must be considered.

The amount of CH₄ in a seam and its suitability for CBM will therefore depend on several factors (CSUG, 2010):

- fractures within the seam and cap rock: fractures in the seam aid the production of CH₄ by providing pathways for the CH₄ to travel; fractures in the cap rock may mean that the CH₄ has already escaped to the atmosphere;
- coal maturation: the higher the coal rank, the greater the natural gas content theoretically, but not always the case in practice;
- depth and location will affect the economics of production;
- hydrostatic pressure (only applies in coal seams with water in place).

The success of any CBM project is therefore determined very much on a case by case basis.

2.3 Enhancement of CBM with gas injection

The following sections look at how the recovery of CH₄ from coal seams can be enhanced by injecting alternative gases. This enhanced CH₄ production occurs due to the differences in the way different gases adsorb to and desorb from the surface of coal.

2.3.1 Adsorption isotherms

The principle of CH_4 release during ECBM is the preferential desorption of CH_4 from the coal as another gas is made available in the seam.

Some gases adsorb onto solid surfaces. However, different gases do so with different affinities and intensities. Further, different solid substrates have their own adsorption behaviours. Neither coal seams nor gases associated with coal seams are homogenous and so sorption behaviour will be variable. For simplicity, many gas sorption studies have focussed on the sorption of one gas while some have gone further and studied variable mixtures of CO₂ with air, N₂ or flue gas and at different pressures (Mazzotti and others, 2009).

The majority of papers relating to ECBM provide Langmuir isotherm figures for the coal. These figures relate the pressure inside the seam to the gas volume for the different gas species and give an indication of how easily each will adsorb or desorb from the seam. For example, Figure 3 shows the data for a coal seam in Airth, Scotland.





The Langmuir Isotherm is used to quantify the amount of a gas which is adsorbed on a surface as a function of partial pressure or concentration at a given temperature. It considers adsorption of an ideal gas onto an idealised surface – it assumes that all surfaces are flat, all adsorption sites are equal and that the gases present do not interact with each other.

Adsorption isotherms are best measured on dry samples as wet samples give less reliable results. Unfortunately, coal in coalbeds is often wet at the beginning and becomes dry during production and so determination of the adsorption isotherm is required for both states (Mazzotti and others, 2009). Problems with water in ECBM are discussed in more detail in Section 2.4.3.

The general conclusions from Langmuir isotherms on coal are:

- CO₂ adsorbs onto coal more readily than CH₄ (except in two studies on low rank coals);
- CH₄ adsorbs more readily than N₂.

These actual values of the coal specific isotherms for each coal give an indication of how easily the CH_4 will be released and how likely it is for the CO_2 to adsorb and remain in place in the seam being targeted. For example, the data in Figure 3 suggest that CO_2 injected into the coal seam can stimulate CH_4 desorption by displacement since CO_2 has a greater affinity to coal than CH_4 . The isotherm also suggests that the coal can adsorb around twice as much CO_2 as CH_4 . In some low rank coals, the ratio can be much higher with up to 10 times as much CO_2 replacing the CH_4 in the seam (Fang and others, 2013). Isotherm data are therefore used to help predict how easily CH_4 will be removed and how much CO_2 can be stored.

As will be discussed in more depth later, although CO_2 adsorbs more easily to coal than CH_4 , it also causes coal swelling which can have a negative feedback effect – the swelling coal causing the closure of spaces and gaps where CH_4 could be released and traps the remaining CH_4 in place. N_2 has a different effect – injection of N_2 can reduce any permeability reduction caused by CO_2 injection and can enhance well injectivity (Fang and others, 2013). Studies have shown that injection of N_2 reduces the partial pressure within the seam whilst maintaining the total pressure to drive gas production from the well. It is thought that the N_2 releases the CH_4 through gas stripping and sorption replacement. Between 25–50% of coal CH_4 storage capacity can be replaced with N_2 (US EPA, 2015).

And so to simplify the gas behaviour within the seam – as CO_2 is injected, the coal will start to swell as the CO_2 displaces the CH_4 and attaches to the coal in greater quantities. This swelling will reduce the permeability of CH_4 through the seam for production. Conversely, replacement of the injection gas with N_2 will result in some CH_4 being chased from the seam and the coal shrinking. A combination of the two gases could therefore result in a combination of swelling and shrinking which maintains some permeability through the coal. In the early 1990s, N_2 was used for early ECBM demonstrations (Gale and Freund, 2001). Figure 4 shows the initial use of N_2 to lower the partial pressure within the seam to promote CH_4 desorption. After a while, the N_2 will start to be produced along with CH_4 in the gas, which is undesirable. At this stage, switching to CO_2 injection can continue to stimulate CH_4 by replacement due to preferential adsorption of the CO_2 . This will continue to stimulate CH_4 production until there is eventual CO_2 breakthrough.





Some pilot studies (reviewed in Chapter 4) have confirmed that alternating CO_2 and N_2 may indeed be more effective.

2.3.2 Injection gases and processes

Figure 5 shows a typical CBM well (CSUG, 2010). A vertical hole is drilled down to the coal seam and the water in the seam is pumped up through tubing. This removes the water that is holding the CH₄ within the coal and so the CH₄ is released, under pressure, and driven up to the surface collection point.



Figure 5 Typical CBM well with water production (CSUG, 2010)

Figure 6 shows the use of a gas injection system to enhance CBM production (ECBM). Gas is injected down an injection well and allowed to permeate through the seam to release the CH₄ for collection in the production well.



Figure 6 ECBM diagram

Figure 7 shows a photograph of a CO_2 injection well emphasising the potential simplicity of the system and the small amount of equipment which appears above ground.



Figure 7 Gas injection at the ARC site in Canada (Lakeman, 2015)

Early projects in Canada and China were called 'huff and puff' projects since they used only one well. Gas was injected and removed via the same access point in a cyclical and sequential manner (Winthaegen,

2008). The Qinshui project in China used an injection-recovery cycle for the injection of industrial liquid CO_2 (*see* Section 4.2.1) Qin and others (2008) also mentioned huff and puff production as well as ' CO_2 foam fracturing'. However, nothing else on foam fracturing for ECBM has been found in the literature. Newer systems are all dual or multi-well, as was shown in Figure 1, where there is at least one injection well and at least one production well.

Some pilot ECBM projects have injected pure CO₂ whereas others have injected flue gases. Ideally, pure CO₂ would be injected in all projects to maximise the amount of CO₂ removed from the atmospheric burden. This is because coal, on average, has almost twice the adsorption capacity for CO₂ than it has for CH₄. However, as described earlier, a mix of CO₂ and N₂ and/or other gases will actually be more successful by increasing permeability. The majority of the projects discussed in Chapter 4 used a combination of gases, either CO₂ plus N₂ from industrial gas sources, or flue gases. In most, if not all, cases it was concluded that the best methods used a blend of both CO₂ and N₂, a mix naturally found in most combustion flue gases. Proposed projects in the USA and China even proceeded as far as locating potential sources of gases for injection, including coal-fired power plants and fertiliser plants.

According to Godec and others (2014), there are three main processes through which CH₄ is released during an ECBM project:

- reducing the pressure through dewatering (pumping, as in standard CBM projects);
- reducing the partial pressure further by injection of another inert gas into the formation;
- replacement of the CH₄ on the surface of the coal with another gas (commonly CO₂).

According to Mazzotti and others (2009), once injected, the gas used in ECBM is adsorbed and retained permanently if a sealing cap rock is present. Any CO₂ present is trapped as a dense gas in the coal cleats, being adsorbed both on and in the coal as well as being solubilised in the formation water. Deeper seams (>750 m) are optimal as the pressure is greater and the temperature higher, keeping CO₂ supercritical.

Whilst horizontal drilling and rock fracturing technologies can be used to enhance gas and oil recovery from shales, this is not appropriate for any ECBM project which includes gas storage since these disruptive approaches may damage the cap rock and reduce the storage efficiency for any trapped CO₂ (Godec and others, 2014). However, the RECOPOL project in Poland applied fracking and did not report any issues (*see* Chapter 4).

2.3.3 Gas storage capacity

As mentioned before, ECBM projects often aim to achieve permanent gas storage in the CH₄-depleted coal seam. This will either be flue gases or processed and purified CO₂. According to Mazzotti and others (2009), unmineable coal seams have a smaller potential for CO₂ storage than other geological formations but still have significant potential as a final repository. The success of CO₂ storage in coal seams is dependent on a number of physical and chemical factors which have been evaluated and reviewed by the Carbon Sequestration Leadership Forum (CSLF) (Saghafi, 2010).

The storage capacity for CO_2 in coal seams worldwide has been estimated at anywhere between zero and 1480 Gt. The Intergovernmental Panel on Climate Change (IPCC) give a more reserved estimate of up to 200 Gt. Estimates for potential reserves for individual countries have been collated by Li and Fang (2014) and the interested reader is referred to the original article for more detail.

To put these volumes in perspective, it has been estimated that the unmineable coal seams in the Powder River Basin of Wyoming and Montana, USA, could hold 14 $GtCO_2$ – equivalent to 47 years' worth of CO_2 output from all coal-fired plants in the USA (Robertson, 2009). Mazzotti and others (2009) cite a global storage range of CO_2 in unmineable coal seams at 3–200 Gt compared to total global emissions from human activities of around 30 Gt/y.

As will be discussed in Chapter 4, CO₂-ECBM pilot studies have been carried out for decades and in a 2001 review by Gale and Freund it was estimated that between 1996 and 2001, over 57 m³ of CO₂ had already been sequestered in coal seams (Gale and Freund, 2001).

2.4 Problems

Although ECBM makes sense in theory, there are several inherent problems and issues which mean that, in practice, these projects face significant challenges.

2.4.1 Swelling

As mentioned in Section 2.3.1, during CH₄ extraction in standard CBM projects, the physical and chemical nature of the coal seam can change significantly. As a coal seam becomes depleted of CH₄ during drilling, the reservoir will collapse – this will confine the reservoir and increase horizontal stress. This is offset, to some extent, by the coal matrix shrinking as gas desorbs (Godec and others, 2014). However, in ECBM a more dramatic effect is often seen due to the reaction of any CO₂ in the injected gas mix with the coal matrix.

One of the major problems with CO₂ injection into coal seams appears to be the variable permeability of the coal. A coal seam may start out with a high permeability for CO₂ but, as CO₂ is adsorbed, the coal swells and the permeability of the remaining coal is lowered. This is because the uptake of CO₂ is a combination of both surface adsorption and penetration (sorption) into the solid matrix, the latter causing the swelling. For the moment, the methods used to study adsorption of gases on coal account for both adsorption and sorption and the contributions cannot be separated. This means that it may not be possible to accurately predict swelling problems in advance (Mazzotti and others, 2009). Higher rank coals tend to have lower permeability, although permeability is sensitive to stress and pore pressure as well as temperature (Cai and others, 2014).

According to the review by Li and Fang (2014) many studies agree that adsorption of CO_2 can induce matrix swelling. Swelling of the coal will result in reduced permeability and injectivity for further CO_2 capture. Many studies have been carried out on coal swelling. Swelling in both block and powdered coal has been reported at around 7–8%, in terms of expansion, due to CO_2 adsorption. The Allison Unit,

Qinshui Basin and Yubari projects (*see* Chapter 4) have all reported problems with permeability and subsequent injectivity reduction (Li and Fang, 2014).

Godec and others (2014) also suggest that, in addition to the matrix swelling issue, the injectivity of CO₂-bearing gases may also be reduced due to the thermal effect of CO₂ injection, wellbore effects and precipitate formation. If the coal seam is appropriately configured, then horizontal drilling could reduce the swelling effect and create greater access to counteract the reduction in permeability. However, this will entail more complex equipment and drilling strategies.

A compromise must therefore be reached between injectivity and production. As mentioned in Section 2.3.1, high permeability coals will release CH₄ early on, reducing the impact of any CO₂ injection; whereas low permeability coals have low injectivity which delays CH₄ output and makes the economics of the project difficult (Fang and others, 2013). Godec and others (2014) suggest a CO₂-alternating-N₂ strategy but stress that the economics of this would depend on operational constraints, gas treatment costs and whether CO₂ capture was a primary goal of the project.

To clarify the swelling issue $-CO_2$ causes more coal swelling than CH_4 which, in turn, causes more swelling than N_2 . So under ECBM conditions, displacing CH_4 with CO_2 causes coal swelling whereas using N_2 causes a net shrinking. This coal swelling effect can be removed when the pressure in the seam is reduced. These volume and swelling changes will affect the coal permeability which will affect the injection pressure and gas production. All these effects must be considered when determining the gas production conditions. If injectivity decreases, then this can be compensated for by shut-in periods (as carried out in the Fenn-Big Valley project in Alberta) or through fracking (as in the RECOPOL Project). Both these projects are discussed in more detail in Chapter 4 (Mazzotti and others, 2009).

According to Connell and others (2013), 'a key challenge to the success of CO_2 -ECBM is the optimal management of coal swelling with CO_2 injection'.

2.4.2 Breakthrough of injected gases

Gas injection for CH₄ recovery will not be able to achieve full 100% CH₄ recovery as, towards the end of the project, the concentration of CH₄ will decline and the injected gases will start to reappear through the production well. ECBM projects will use Langmuir isotherms and production rates to estimate when gas breakthrough may occur but will also monitor gas composition as it is produced to ensure that quality is maintained. As mentioned in Section 2.4.4, breakthrough or leakage of CO₂ from a CO₂-ECBM project is one of the issues which raises most public concern. A proposed project in the Appalachian Basin (*see* Section 4.1.2) appears to have been halted partly due to breakthrough issues.

2.4.3 Water

In waterlogged coal seams, pumping up the water can release CH₄. Water is commonly produced during CBM recovery; however, this can interfere with ECBM. Thararoop and others (2012) state that neglecting the effect of water in the coal matrix will typically result in an overestimate of gas production. In a

modelling study by Jamshidi (2010; also Jamshidi and Jessen, 2012) it was shown that, over 11 years of CO_2 injection at a theoretical ECBM site, CH_4 production was doubled due to the CO_2 injection when no aquifer is considered. When an aquifer is present, CH_4 production can increase by 275%. However, this effect decreases as aquifer strength increases. The CO_2 injection increases the CH_4 production but also decreases the water production from moderate aquifer strengths.

Winthaegen (2008) summarised the results of the MOVECBM project in Poland (*see* Chapter 4). The project showed that, although it would appear that under gas pressure dry coal swells more than wet coal; the opposite effect was also noted for lower moisture coals. The report concluded that further research was needed on the effect of water on coal permeability in coal seams. As with all mining related industries, ECBM projects must ensure sound management of water storage and treatment ponds and ensure no damage to local groundwater, aquifers or ecosystems.

2.4.4 Safety and environmental concerns

ECBM projects have to undergo planning and impact assessment to ensure that there will be no damage to the local environment. In the review of the MOVECBM project (*see* Chapter 4) in Poland, Winthaegen (2008) summarised the tests carried out on emissions, seismology and soils to ensure that the project did not cause any environmental issues. It was concluded that, although leakage should not be an issue, monitors should be placed in regions exhibiting enhanced leakage risks. However, the location of monitors needs to take into account variations in natural fluxes of CO_2 , from sources such as organic activity, which could cause false concern. Water quality could be affected by acidification from dissolved CO_2 but it was suggested that, for pumped water, this would be a minor issue. Risk assessment of the equipment, such as potential explosion or leakage risks from gas storage tanks, would be carried out as per any similar industrial process.

Public acceptance of the project was also considered. It was reported that the greatest concerns related to the long-term effectiveness of CO_2 storage – a common concern for all CO_2 storage projects. As with any new industry, in addition to environmental issues, potential changes to the local transport infrastructure, or threat of noise or other nuisance problems to the local community must be taken into account. Winthaegen (2008) suggested that greater outreach to the public with information relating to these issues should lower concern.

2.5 Modelling and evaluation

Significant amounts of work have been carried out and continue in fields relating to gas behaviour in coal seams and how this will affect CH₄ recovery. Clarkson and others (2011) summarise the limitations in understanding of the permeability of gases in coal seams. Further study in this area would have a 'significant impact' on the ability to predict gas flow characteristics during ECBM.

There are numerous types of models used in ECBM (Li and Fang, 2014):

multicomponent adsorption theory;

- diffusion theory;
- flow theory.

Commercial systems are available for ECBM study, including GEM, ECLIPSE, SIMED II, COMET2 as well as non-commercial systems such as GCOMP. It is beyond the scope of this report to go into these in detail, but Li and Fang (2014) have provided a simple table summarising the main features of each (Table 2).

Table 2 Features of main ECBM simulators (Li and Fang, 2014)						
Features	GEM	ECLIPSE	COMET	SIMED II	GCOMP	
Multi component gas	Yes	Yes*	Yes	Yes	Yes	
Dual porosity	Yes	Yes	Yes	Yes	No	
Mixed gas diffusion	Yes	Yes*	Yes	Yes	Yes	
Dynamic permeability and porosity	Yes	Yes	Yes	Yes	Yes	
Coal swelling/shrinkage	Yes	Yes*	Yes	Yes	Yes	
* 'Yes' values changed from 'No' as per updated information from Skiba (2015)						

Pennsylvania State University has produced a reservoir simulator called PSU-COALCOMP based on a 2D coalbed with vertical homogeneity. This model has shown that CO₂ storage capacity of some sites may actually be only 50–70% of the theoretical capacity due to non-equilibrium of the coal system (Mazzotti and others, 2009). Imperial College, London, UK, have the METSIM2 ECBM simulator which has been used to match field data from the projects in Alberta and Japan (*see* Chapter 4). The model suggested that, at the Alberta site, mixtures of CO₂ and N₂ (75:25 respectively) could result in more CO₂ being stored than if CO₂ had been injected alone. However, breakthrough of the N₂ at the production well meant that this enhanced CO₂ storage had to be traded off against a reduction in the purity of the product (Mazzotti and others, 2009). The METSIM2 simulator has also been used to estimate ECBM potential in Airth, Scotland (*see* Chapter 4).

A 3D stoichiometric reservoir model of the Big George coal field in the Powder River Basin, Wyoming, USA, was run by Ross and others (2009) based on permeability and porosity data from the region. The simulation assumed CO₂ injection into the site over 13 years after a primary CH₄ production period of five years – a total of 18 years or 6720 days of projection. Matrix shrinkage and swelling were included. The model suggested that CO₂ injection would be fairly steady between around day 2000 and day 6720, reaching a cumulative storage total of almost 60 million m³. During this same period, CH₄ production would increase steadily to a total of over 11 million m³. Ross and others (2009) warned that trade-offs between acceptable injection and leakage rates would need to be considered on a site by site basis due to the lack of cap rock in the area and the variability in permeability of the overlying sands. The model results suggested that around 99% of the CO₂ injected would be stored and that the cumulative CH₄ production would be around 1.5–2 times greater with CO₂ than without. Models will be useful for any further development of ECBM but, as discussed in Sections 2.3 and 2.4, the information provided by standard measurements are limited in their practical applicability.

Principles of ECBM

2.6 Comments

CBM extraction is a proven technology and hugely profitable in North America. ECBM, in theory, could as much as double the CH₄ recovery from CBM projects while, at the same time, providing a disposal site for flue gases and CO₂. Although isotherm data suggest that CO₂ is highly suited for 'chasing' CH₄ out of coal seams, in practice, the situation is more complex. As the CO₂ adsorbs to the coal surface it causes localised swelling and reduced permeability–issues resulting in lower or even halted production rates. Although it is possible that these issues can be reduced by alternating CO₂ injection with N₂, by using flue gas, by allowing resting periods between injections, or by performing different drilling approaches, all these options add complexity and cost to a project which is already likely to be costing more than it is gaining in terms of commercial CH₄ sales. The economics of ECBM are discussed in Chapter 3 to follow.

3 Economics

The US EPA (2015) noted that there were three main barriers or limitations to ECBM – geologic, economic and policy. The geological challenges were discussed in Chapter 2 and so this Chapter concentrates on the economics of ECBM projects. Policies such as regulatory requirements or financial incentives could make the difference to the economics of a project. However, few, if any, policies are currently in place which could tip this balance.

The economics of ECBM depends on the balance of the profit obtained from the sale of gas for energy production against the costs of the transport and injection of the gases used, plus any associated site management, legal and operational costs. The economic success of an ECBM project is a combination of reservoir and operational conditions and is therefore site specific (Connell and others, 2013).

In simple terms, Wang and others (2009) reported that the revenue from CH₄ production could offset 'some 50%' of the costs associated with CO₂ capture and storage. Whilst this value is useful for giving an overall idea of the cost balance of a theoretical CO₂-ECBM project, individual project economics will vary significantly on a case by case basis.

Robertson (2009) stated that the injection of flue gas into CBM sites in the Powder River Basin in Wyoming to enhanced CH_4 recovery is 'marginally economic'. The cost of separation of CO_2 from flue gas prior to injection would make the combined CO_2 -ECBM uneconomic. However, the capacity for CO_2 storage in the region is high 212,870 t CO_2 /ha and therefore, should incentives be in place for CO_2 storage, the economics may become more favourable.

Many of the projects reviewed in Chapter 4 emphasise that the economics of the plant hinge upon the potential offset in costs from revenue for carbon abatement in the form of taxes or credits. However, at the moment, few if any credits exist for CO₂-ECBM. Although the Clean Development Mechanism (CDM) defined under the UN FCCC (United Nations Framework Convention on Climate Change) intended to facilitate the use of carbon credits and offsets to promote GHG reduction projects, carbon capture and storage projects were not included until the Durban COP (Conference of the Parties) in 2011 (UNFCCC, 2011). It would appear that there are, as yet, no ECBM projects proposed under the CDM, although the Qinshui Project in China planned to leverage these carbon credits in order to make the proposed project financially viable.

Figure 8 shows a diagram of considerations for a new CO₂-ECBM project (Saghafi, 2010).



Figure 8 Diagram of ECBM transition path (Saghafi, 2010)

Following the flow chart we see that the movement from one part of the project to the next, from CBM production to CO_2 -ECBM, is decided by economics. The CO_2 -ECBM is initiated and continued until there is CO_2 breakthrough, that is – until the maximum capacity for storage is reached.

3.1 Methane recovery

As mentioned earlier, CBM has been hugely profitable, especially in the USA. Because the technologies are established, CBM projects are almost guaranteed to be profitable and will cease operation as soon as gas production rates drop below the desired level. In order for ECBM to be a viable continuation of CBM, the economics of gas delivery and injection must be favourable.

3.2 Gas processing, transport and injection

In 2001, Gale and Freund suggested that CO_2 -ECBM may be profitable in the USA at prevailing well-head natural gas prices of 0.06–0.07 \$/m³ and that around 60 Gt of sequestration capacity could be available at moderate costs of under 50 \$/tCO₂. Outside the USA, the breakeven point was given as 0.11 \$/m³ or more, depending on the status of appropriate industry and infrastructure. Well-head natural gas prices rose from around 0.14 \$/m³ in 2001 to as much as \$0.38 in 2008 but they subsequently returned to the lower value of 0.14 \$/m³ in 2014 (data from http://www.eia.gov/dnav/ng/hist/n9190us3m.htm). Gale and Freund (2001) assumed a CO_2 supply cost of \$0.018 per thousand m³, assuming the CO_2 itself was free. The overall capture costs were estimated at <110 \$/tCO₂ and it was suggested that 60 Gt of CO_2 could be captured at a cost of under 50 \$/tCO₂. However, these cost estimates did not include the cost of CO_2 separation which was assumed to be 'significant'. It was suggested that some CO_2 -ECBM sites could be profitable, generating revenue at up to 20 \$/tCO₂ – assuming CO_2 could be obtained at no cost. However, it was acknowledged that, unless subsidies or taxes were extremely high, successful CO_2 storage would require favourable geologic and market conditions.

Robertson (2009) states that the cost of separating CO_2 from flue gas is the major cost driver associated with CO_2 sequestration in unmineable coal seams. Even with developments in separation technology,

sequestration of CO₂ in sites such as the Powder River Basin (PRB) will not become economically viable. Advancements in separation will bring costs down, but incentives will still be required to make CO₂-ECBM economically feasible.

Robertson (2009) studied the economic feasibility of processing CO_2 from the Wyodak 335 MW coal-fired (PRB coal) power plant in Wyoming and storing it in the unmineable Wyodak-Anderson coal zone 80 km away. The Wyodak plant is just one of the seven coal-fired plants in Wyoming, which together emit a total of 57 MtCO₂/y. The Wyodak plant was built in 1978, currently runs at a thermal efficiency of 29.3%, and CO_2 emissions amount to 9344 t/d. The Wyodak-Anderson subbituminous coal zone has unmineable coal below 305 m depth. The storage capacity in the zone is estimated at 5.34 MtCO₂ – 3000 years of CO_2 production from the Wyodak plant at current output levels. The economic feasibility of storing the CO_2 from the plant in the mine was evaluated based on two scenarios – separated gas (CO_2) versus unseparated flue gas (containing CO_2). Both scenarios included the costs of injection as well as the pipeline transport of the gas between the power plant and the mine. The cost of disposal of produced water was also taken into account. The costs are summarised in Table 3.

Table 3 Base values of input parameters used to compare economics of CO2 sequestration scenarios (Robertson, 2009)						
Input variable	Base	Minimum	Maximum	Units		
Length of transport pipeline	80.5	80.5	80.5	km		
Depth from surface to coal seam	457.2	304.8	609.6	m		
Capacity of N_2 separation facility	8,496	7,646	9,346	m³/d		
Capex – water disposal	36,400	35,000	40,000	\$/well		
Capex – N_2 separation facility	17.66	14.12	19.42	\$/m³/d		
Mineral rights and permitting	120,000	108,000	132,000	\$/129.5 ha		
Injected gas transportation tariff	2.01 ×10 ⁻⁴	1.8×10^{-4}	2.2×10^{-4}	\$/m³/km		
Cost of CO ₂ separation	46.30	22.04	55.11	\$/t		
Water disposal costs	0.629	0.566	0.692	\$/m ³		
$O\&M$ for N_2 separation	0.014	0.012	0.018	\$/m ³		
Natural gas price	0.282	0.212	0.424	\$/m ³		
Price differential for PRB wellhead	-0.035	-0.053	-0.018	\$/m ³		
Inflation rate	0.03	—	-	-		
Royalty rate	0.125	-	-	-		
Ad valorem and severance tax rate	0.12	-	-	-		
Federal income tax rate	0.35	-	-	-		
Discount rate	0.10	-	-	-		

The results of the study suggested that CH₄ production from the well would be slow for the first five or so years under both scenarios due to the large volume of water which would need to be driven from the mine. The results of the economic comparison are shown in Table 4.

Table 4 Economic results for scenario analysis (Robertson, 2009)						
Scenario	Project length, Y	NPV ₁₀ *, \$ million	ROI†, %	CH ₄ recovered, %GOIP‡	CO ₂ sequestered, Gt	
No gas injection (pressure depletion	26	1.55	24.3	71.7	0	
Flue gas injection	17	-0.81	5.4	70.2	133,358	
CO ₂ injection	19	-36.2	0	88.2	6,223,292	
* NPV ₁₀ – net present value at a discount rate of 10%; † ROI – return on investment; ‡ GOIP – gas originally in place						

The NPV (net present value) result indicates that the most economically tempting project would be one which did not involve any form of gas injection. Without injection, the project would take around 26 years to recover almost 72% of the CH_4 in place. The flue gas injection scenario would recover 70% of the gas in place within 17 years and would result in 133,358 Gt of CO_2 storage. The CO_2 injection approach would succeed in storing significantly more CO_2 (6,223,292 Gt) and would produce more CH_4 (88%) within 19 years. Although this may suggest that the flue gas injection approach is the most economic, the amount of CO_2 stored is actually relatively small – the project is more of a success in terms of enhanced CH_4 recovery than CO_2 storage. Conversely, the CO_2 injection option can be seen as a true CO_2 storage option but would not be economically viable without forced or voluntary subsidies.

Further analysis of the scenario data demonstrated that the input parameter with the greatest effect on the economic viability of the project is the cost of CO_2 separation from the flue gas. The estimate was known to be within a relatively wide range due to the uncertainty in the estimates for CO_2 separation costs. At the time the paper was written the cost of CO_2 processing was put at 42 \$/t based on site-specific retrofitting of 'currently' (2009) available technology. This value was expected to decrease to as low as 20 \$/t based on future technology improvements. Despite this, the model still suggests that, for this location at least, 'injecting CO_2 into an unmineable coal seam would most likely never be profitable without some additional economic driver being present'. However, since the gas pressures in the PRB seams are generally lower than elsewhere, the economic viability of CO_2 -ECBM in other basins with higher CH_4 contents could be more favourable (Robertson, 2009).

According to Robertson (2009), although the injection of flue gas for ECBM may be economic in itself, it 'will not significantly contribute to the need to sequester CO_2 in large quantities'.

3.3 Comments

It is important to note that the primary aim of both CBM and ECBM projects is economic profit through CH_4 recovery. The use and potential capture of flue gas or CO_2 in ECBM is currently not a source of economic advantage in any way and is unlikely to become such without a reduction in gas processing costs as well as tax incentives or carbon credits. For an ECBM project to be economically viable, several factors must be optimised:

• the gas to be injected must be low cost and readily available;

- the CH₄ produced must be profitable;
- the processing of injected gases must be affordable;
- any additional site costs must be low;
- additional gas and equipment transportation costs must be covered.

At the moment, other than the UNFCCC CDM, there are no legal or financial incentives which would make ECBM or CO_2 -ECBM tempting to a commercial investor and, until the technical issues discussed in Chapter 2 are dealt with, this situation is unlikely to change.

4 Case studies

In 1990, the IEA Greenhouse Gas R&D Programme studied potential sites for CO₂-ECBM worldwide, concluding that the most suitable countries for further development would be Australia, China, India and Poland (Winthaegen, 2008). Since then there have been a number of pilot and demonstration tests in various locations. Li and Fang (2014) have summarised the demonstration tests carried out between the onset of ECBM in the 1990s until now. These are summarised in Table 5.

Table 5 ECBM pilot and demonstration projects (Li and Fang, 2014)							
Project	Country	Location	Start date	Total CO₂ injected, t	Coal depth, m		
Allison unit	USA	New Mexico	1995	277,000	950		
Tanquary well	USA	SE Illinois	2008	91	273		
Lignite CCS	USA	North Dakota	2007	80	500		
Northern Appalachian Basin	USA	West Virginia	2003	20,000 (planned)	550		
Central Appalachian Basin	USA	Southwest Virginia	2009	907	490–670		
Black Warrior Basin	USA	Alabama	—	252	460–470		
Pump Canyon	USA	New Mexico	2009	16,700	910		
ARC	Canada	Alberta	—	200			
CSEMP	Canada	Alberta	_	10,000			
RECOPOL	Poland	Kaniow	2001	760	1050–1090		
Qinshui Basin	China	Qinshui Basin	2004	192	478		
Yubari	Japan	Ishikari coal basin	2004	884	890		
АРР	China	Liulin	2011	460	560		
Huaneng deep coal	China	Qinshui Basin	2014	1000 (planned)	>1000		

The most significant of these projects are discussed in more detail in the regional sections to follow.

4.1 North America

4.1.1 Canada

Canada has very few large scale CBM projects and relatively low permeability coals. In the early 2000s Alberta Research Council (ARC) established an ECBM project with over 20 participants including the US Department of Energy, the UK Department of Trade and Industry and the IEA GHG R&D Programme. The ARC project, sited at the Fenn Big Valley, involved a multi-phase project from proof-of concept through to micro-pilot tests with CO₂ and N₂ injection. Early results suggested that the combination of 13% CO₂ and 87% N₂ enhanced CH₄ production over injection with CO₂ alone. Over 200 tCO₂ were injected during this phase (Li and Fang, 2014).

According to Lakeman (2015), one of the latter phases of the ARC project went so far as to match sources of gases for injection (landfill gas, ethanol plants, coal-fired plants and acid gas plants) with coal zones in the Edmonton and Calgary regions which showed CBM potential. The project moved on to become CSEMP (CO_2 storage and enhanced methane production) with Suncor. During the two-cycle pilot test, around 10,000 tCO₂ were injected (Li and Fang, 2014).

In 2010, the ARC became Alberta Innovates – Technology Futures and, according to the <u>www.albertatechfutures.ca</u> website, current CO₂ sequestration work is concentrating on oil sands and no further ECBM work is being undertaken at the moment.

4.1.2 USA

The Southeast Regional Carbon Sequestration Partnership (SECARB) has a Central Appalachian Coal Seam Sequestration Group which characterises the ECBM potential for the region. There are six other similar regional groups established and supported by the National Energy Technology Centre (NETL) of the US Department of Energy. Coal seams in the Central Appalachian Basin are estimated to be able to hold more than 1.3 billion tCO₂ whilst increasing CH₄ reserves by 70.1 billion m³. Many of the CBM fields in the region are reaching maturity and therefore ECBM has potential to boost production.

SECARB tested in the Pocahontas and Lee formations in the central Appalachian basin in Virginia at an existing CBM well. Around 1000 tCO_2 were injected at a rate of 41.6 t/d (SECARB, 2015a; Li and Fang, 2014). Surface and near surface monitoring was carried out pre-, during and post-injection at various locations around the site. This first SECARB ECBM project was completed in 2009. More SECARB studies in the Pocahontas and Lee basins concentrated on modelling the optimal depth for ECBM (greater than 183 m) along with recommendations on sites away from sources of drinking water, faults, active mining areas and so on (Grimm and others, 2012).

SECARB also tested in the Black Warrior Basin in the southern Appalachians. Three seams – Black Creek, Mary Lee and Pratt were selected for injection tests and a total of 252 tCO₂ were injected (Li and Fang, 2014). The project, which cost almost \$2.4 million, ended in 2010 (SECARB, 2014, 2015b).

The Allison Project was the first large scale ECBM pilot project in the world, incorporating four CO_2 injection wells and nine CH_4 production wells. The production wells had previously been extracting CBM by standard methods. Injection of CO_2 continued for five years and the production ratio for CH_4 was enhanced by 150% allowing 95% CH_4 recovery from the site (Li and Fang, 2014). Perhaps the most interesting conclusion of the Allison projects was confirmation that the use of CO_2 alone results in a reduction in permeability and injectivity whilst N_2 injection results in more rapid breakthrough and reduced product purity (Mazzotti and others, 2009).

The significantly smaller Tanquary project was designed to determine CO_2 storage capacities and injection rates to evaluate the ECBM potential for Illinois Basin coal. Injection was carried out 'continuously' for around six months at the end of 2008 but was interrupted by problems with equipment failures. Around 91 tCO₂ was injected overall and the monitoring results indicated no leakage of CO_2 to groundwater nor any escape to the surface (Li and Fang, 2014).

Around 90 tCO₂ were injected during a two week field test in Burke County, North Dakota in 2007. The project, initiated by the Plains CO₂ Reduction (PCOR) Partnership, used one injection well and four monitoring wells to study the movement of CO₂ through the coal in the 3.7 x 3.7 m, 335 m deep seam. The

test was hailed a success and was expected to lead to further studies (Li and Fang, 2014), however no further activity has been reported on this project.

The Pump Canyon site in the San Juan coal basin in New Mexico hosted a test well in 2008. A tracer was used to compare the actual gas flow to the predicted gas flow. The comparison was regarded as 'good'. The study indicated that swelling in the coal matrix tended to be localised around the injection well and the early drop in permeability following the initiation of injection was also localised in this area with other areas further away not showing this problem. This suggested that this localised pressure could be reduced by hydraulic fracturing as long as the cap rock was not disturbed during this process (Siriwardane and others, 2012). The Pump Canyon project injected a total of 167,000 tCO₂ in a 12-month period between July 2008 and August 2009 and remains the largest-scale (in terms of total volume) demonstration project to date (Li and Fang, 2014).

Consol have carried out an injection field test in the northern Appalachian Basin in two separate coalbeds, into both Pittsburgh and Upper Freeport coals. The seven year project ran from 2003 to 2010 to demonstrate the feasibility of horizontal drilling for ECBM (Li and Fang, 2014). Although the project in Marshall County was intended to continue beyond the initial injection trials into further long-term considerations (CO_2 in water and gas phases once trapped) and environmental monitoring, the project appears to have stalled following issues with a CO_2 breakthrough episode and pump failure (Locke and Winschel, 2014).

Whilst some of these US studies showed potential, none has been taken further and the only 'existing' (Consol) project does not seem sufficiently successful to merit further investment.

4.2 Asia

With still-growing populations and increasing electrification requirements, many regions in Asia are considering all options for energy sustainability. It is for this reason that Asia may be the most likely region to continue investment in ECBM development.

4.2.1 China

Chinese coal reserves generally have low permeability. The use of gas injection to enhance CBM recovery has been investigated in China since the late 1990s. However, the uptake of the technology has been relatively slow due to the lack of practical demonstration of its economic and technical feasibility (Qin, 2008).

According to Fang and Li (2014) there is 9,881 Mt CO₂ storage capacity in unmineable coalbeds between 1000 and 2000 m deep in China. The same seams could release 4.26 trillion m³ of CH₄. The capacity for ECBM varies from coal field to coal field; the greatest potential is in the following basins: Ordas, Junggar, Qinshui and Tuha. This volume of gas could significantly offset the country's dependence on coal, providing a cleaner burning fuel.

The APP project was established between the China United Coalbed Methane Corp (CUCBM), CSIRO (Commonwealth Scientific and Industrial Research Organisation, Australia) and JCoal (Japan) in the Liulin gas block in the Shanxi Province. Over 460 tCO₂ were injected into an existing horizontal CBM well between September 2011 and March 2012 (Li and Fang, 2014). This particular trial was unique in its use of multi-lateral horizontal wells for gas injection. The injected CO₂ gas was obtained from a commercial gas supplier. Sulphur hexafluoride (SF₆) was injected as a tracer gas. The study demonstrated a gradual breakthrough of CO₂ into the CH₄ in the reservoir, which increased to around 15% by the end of the injection period. The breakthrough of the CO₂ was shown to be relatively slow and progressive over time. The tracer gas demonstrated that, although there was CO₂ breakthrough towards the end of the study, this only occurred in the target reservoir and not in neighbouring formations, confirming that the storage was effective.

A bilateral project between Canada and China established an ECBM test site in south Qinshui. The project began in 2004 with injection of liquid CO₂. The CO₂ was injected in a batch manner – individual truck loads at a time followed by an overnight soaking period. After 192 t had been injected, the site was left for a 40-day extended soak period to allow the CO_2 to reach equilibrium with the coal. The well then went into production for 30 days to determine the gas quality and production rate (Li and Fang, 2014). The project was completed in 2007 and the results from the initial pilot phase were entered into the GEM model. It was then estimated that, should the project be expanded into a multi-well system (100 wells -45 injectors and 55 producers) and operated for five years, around 30 billion m³ of CO₂ would be stored. The requirement for the site would be $1575 \text{ tCO}_2/\text{d}$ or 520 kt/annually. It was suggested that the CO₂ would be shipped via pipelines in a supercritical phase over a distance of around 120 km. The main source of CO₂ was proposed as the Tian'ji chemical fertiliser plant at Lucheng, around 115 km from the ECBM site. However, the current CO_2 output from the plant is only 800 t/d so additional sources of injection gas would need to be found. There are coal gasification facilities in the region which could be used. It was suggested that any small amount of H₂S associated with the CO₂ from coal gasification would have little effect on the ECBM with no desulphurisation being required. In order to consider the full CO₂ budget of the project, Wong and others (2010) considered the CO₂ injection rate but also looked at the CO₂ generated from the coal-fired power plants which would supply the power for the project, via the grid, for plant operation such as gas compression. They concluded that the net CO₂ stored would be around 79–80% of the CO₂ injected under the project.

Wong and others (2010) made an estimate of the cost of such an ECBM plant in China, admitting that the calculations had to rely on numerous assumptions on equipment and operating costs since the technology is new to the region. It would appear that the plant would not start making a net positive cash flow, after covering costs and so on, until year 9 of operation, with a real internal rate of return (defined as the discount rate that yields zero net present value over a 20-year project life) of 11.9%. Credits for CO₂ storage would make a large difference; a \$20/credit (per tCO₂ stored) would mean the project would pay out after 20 years with a real internal rate of return of 20%. The Qinshui project was hailed as 'successful' by Wong and others (2010). As a result of these initial positive results, MOST (Ministry of

Science and Technology, China) announced funding for an ECBM project led by the Huaneng Clean Energy Research Institute in the Qinshui Basin. The project plans to inject 1000 tCO_2 and become the largest ECBM project in China (Li and Fang, 2014). No update has been found to confirm whether or not the project is proceeding.

4.2.2 Japan

Japan's first ECBM project was the Yubari project on Hokkaido Island. Initial tests between 2004 and 2007, totalling 884 tCO₂, suggested problems with swelling in the coal and reduced permeability. N_2 flooding did increase the CO₂ injection rate but only temporarily (Li and Fang, 2014). No further work in this area has been found.

4.2.3 India

99% of the coal reserves in India are found in the Gondwana basin. CBM production is already underway in the Barakar formation (Vishal and others, 2015). Most of the CBM reservoirs in India are water saturated and so dewatering is part of the pre-degasification process. In some cases, dewatering could delay CH₄ production for up to a year (Vishal and others, 2013a). Vishal and others (2013b) note that limited research is available for Indian coals and so they have begun to carry out the types of coal analysis which are standard for evaluating ECBM potential.

Chatterjee and Paul (2013) have also carried out coal analyses in India for evaluating ECBM. The Jharia coalfield has seams at over 600 m depth and with minimum faults and high homogeneity, making it theoretically suitable for ECBM. However, Chatterjee and Paul (2013) suggest that 'much more' research is needed on the capacity, technology, commercial feasibility and overall economics before any move towards pilot-scale testing.

4.3 Europe

4.3.1 Poland

The RECOPOL (Reduction of CO₂ Emissions by means of CO₂ storage in the Silesian Coal basin of Poland) project was the first European study on ECBM, initiated in the early 2000s. The study was funded by the European Commission (5th Framework Programme) and carried out by and international partners' consortium coordinated by TNO-NITG (Netherlands Organisation for Applied Scientific Research – Netherlands Geological Survey). The project was operated locally by GIG (Central Mining Institute of Katowice, Poland). The Silesian basin was selected as this region had already produced CBM and had favourable coal seams. In the early stages of the study it became evident that continuous injection of gas was not possible until the coal seams were fractured to improve permeability and gas flow. Once operational the project achieved 12–15 tCO₂ injection per day for over a month. The project stopped on the target date following exhaustion of the test CO₂ supply. Gas production rates at the site were increased from around 40 m³/d (with high CH₄ content) to over 700 m³/d (with low CH₄ content). During standard CBM production, the site had achieved only around 100 m³/d. The RECOPOL project succeeded

in demonstrating that CO_2 -ECBM is feasible but also highlighted technical challenges which would need to be tackled.

Following on from RECOPO (after 760 tCO₂ injection), a new project was initiated called MOVECBM (Monitoring and verification of CO₂ storage and ECBM in Poland) in 2006 and ran for two years. During this time 760 tCO₂ were injected of which 682 t (around 90%) remained in the reservoir after releases during the injection and back-production phases. Poland has between 20 and 415 billion m³ in CBM resources with the potential for 470 tCO₂ storage in the Upper Silesian Coal Basin. Two further possible sites for CO₂-ECBM have been identified (Winthaegen, 2008). Figure 9 shows the possible economics for the MOVECBM project.



Figure 9 Calculated revenues of the MOVECBM project (Winthaegen, 2008)

The large variation between economics of the worst case and best case scenarios show just how much more information is required before the project could be deemed worth scaling up. The best case scenario relies on funding or economic incentives for CO₂ storage, allowing the site to make a profit from taking the CO₂. At the same time, natural gas prices would also need to be high to ensure sales. The data in the figure give an idea of overall cost but unfortunately the original document does not give more details on the units of volume being sold, probably tonnes.

Since CBM projects are not currently active in Poland, and none are planned, the project is not expected to continue (Winthaegen, 2008). However, the results from the MOVECBM project have been shared with partners in China (PetroChina, State Key Laboratory of Coal Conversion and others) in order to disseminate information and encourage project work in Asia.

4.3.2 Turkey

The Bartin-Amasra District in the Zonguldak coal basin, Turkey's only hard coal region, has seams which may be suitable for CBM. Sinayuç and Gumrah (2009) used a simulation programme to predict that the area contains possible reserves of 2.07 billion m³ with proven reserves of 0.86 billion m³. The CO₂ storage potential was estimated using the GEM model, the results indicating that, over 100 years of site operation, this could enhance CH₄ recovery by 23% to 91.5 million m³ from 74.5 million m³. However, the CO₂ injection rate of 5192 t/y would only represent 0.3% of the annual CO₂ emission from the Zonguldak

Catalagzi Power Plant nearby. The narrow seam thickness (1.9 m) and low permeability of the coal were contributing factors to the limited CO₂ storage capacity of this project. No further work has been published.

4.3.3 UK

CBM recovery is already underway within several projects in the Airth Valley, Clackmannanshire, in Scotland. Imperial College have used the METSIM2 simulator and site data to indicate the CO₂.ECBM for several seams in the area. The CO₂ storage capacity for the area was estimated at 2163 Mt. However, if flue gas were used, then the capacity for CO₂ is reduced to 427 Mt due to the presence of other gases. If the CO₂ were enriched (50% CO₂:50%N₂), the storage capacity could be 1345 Mt. In a standard CBM system, using seven horizontal wells, the site could recover around 34% of the recoverable gas in place within 10 years. This would be increased to 52% with a 14 well-pattern. The recovery of CH₄ would increase to 72% with gas (pure CO₂) injection, providing storage for 176 MtCO₂. Flue gas injection for an extended period of 40 years could release almost 90% of the CH₄ and achieve 357 MtCO₂ storage. Mixed gas injection (50%CO₂:50%N₂) would release 'slightly less' methane (value not given) but could triple the volume of CO₂ stored over the 40 years (Sinayuç and others, 2011). There does not seem to be any pilot scale or development programme planned.

4.3.4 Other Europe

There have been a few minor pilot projects elsewhere in Europe. For example, in the Achterhoek area of the Netherlands (Mazzotti and others, 2009), the Sulcis Coal Province in Italy (Mazzotti and others, 2009), and the Warndt Colliery, Saar, Germany (Mazzotti and others, 2009). The Münster Basin in North Rhine-Westphalia, Germany, has a potential storage area of 820 km² and so has been evaluated for potential CO₂-ECBM. A modelling study based on measured coal analysis suggested that, assuming a 40% accessibility of the coal and a CH₄ recovery efficiency of 80%, up to 160 MtCO₂ could be stored in seams down to 3000 m in depth. However, the actual storage capacity may be lower (16–55 Mt) due to low permeability and depth of some of the coal seams in the region. Kronimus and others (2008) who reported on the estimates, also suggested that, since the basin is situated in a densely populated area, there may be concerns such as risks to health, safety and the environment in the region.

4.4 Australia

Australia has become a major producer of CBM with some of the most productive fields in the world and gas production expected to continue to increase. Production of CBM in Queensland has increased from virtually zero in 1998 to reach 125 PJ (10¹² m³) in 2007-08 (Saghafi, 2010). Most of the CBM fields in Australia are close to populated areas and to power plants and therefore ECBM is being considered in the region.

Whilst most coal seams contain mainly CH_4 gas or a mix of CH_4 and CO_2 with CH_4 as the dominant gas, Australian coal seams often contain as much if not more CO_2 than CH_4 . The concentrations of CH_4 and CO_2 can vary from almost 100% of one to almost 100% of the other with the concentration varying widely even within a single seam. Saghafi (2010) explains the possible reasons for the gas variations and presents results from analysis of gases in various Australian coal seams. The results indicated that the gas contents for both CO_2 and CH_4 could be up to 25 m³/t for coal seams up to 750 m.

The APP (Asia Pacific Partnership) are planning a CO_2 -ECBM project for Australia with a plan to inject 1000 t CO_2 into a seam. Those planning the project were reported to be using the results of the Yubari project in Japan for guidance on how to proceed (Saghafi, 2010). However, as with most of the other projects discussed in this report, the work seems to have stalled.

4.5 Other countries

Weniger and others (2010) studied the sorption characteristics of coals in the Parana Basin, Brazil, with the aim of determining the feasibility of CBM and ECBM projects in the region. It was estimated that the Santa Terezinha coal field could hold a total of 15.4 GtCO_2 in a 20 x 40 km area. At the moment, there are no CBM projects in Brazil, although a test well was drilled in the Santa Terezhina field in 2007. The total gas in place for CH₄ was estimated at 5.5 million m³. At this stage it would seem that no steps have been taken to propose any pilot projects in the region.

4.6 Comments

There have been a number of ECBM projects initiated around the world in the last three decades, with the majority of these in the USA where CBM is an established industry. Various projects have demonstrated that enhanced CH₄ recovery is possible, especially when flue gases or a mix of CO₂ and N₂ are used, since this reduces swelling and injectivity problems. However, for the moment it would seem that there are no significant further projects underway. Exploration and academic studies are still underway in China and China's high demand for energy production and potentially suitable coal seams may make it the most suitable location for any future developments in the ECBM industry. There is still theoretically potential for a Chinese project in the Qinshui basin, the economics of which appear to hinge on the use of CDM credits.

Conclusions

5 Conclusions

For the moment it would seem that the concept of ECBM is appealing but that, in practical terms, the process is more challenging than first expected.

The two main drivers for ECBM are natural gas prices and potential carbon storage. Most, if not all, of the ECBM projects reviewed focussed more on CO_2 storage than on CH_4 – the enhanced CH_4 production revenue being seen as a means to recover CO_2 storage costs rather than the use of CO_2 to enhance CH_4 production revenue. However, CO_2 alone has been shown to cause swelling and injectivity issues and so a combination of CO_2 and N_2 or even unprocessed combustion flue gases may be more suitable injection mixtures. Flue gases from a coal-fired power plant have been shown to be suitable as injection gases but only feasibility studies and small scale projects have taken place so far. Results suggest that capturing, processing and transporting the gas from the site of production to the CBM site is simply not economic without additional financial incentives. At the moment, the only potential financial incentives for flue gas capture for ECBM would be based on the CO_2 fraction and related carbon credits. CO_2 -ECBM projects could be relevant under the UNFCCC Clean Development Mechanism, and China has considered this as a means of making a proposed project in the Qinshui basin economically viable.

More information is required on the long-term stability and fate of stored gases, including the effect of impurities such as SO_2 and NOx and the potential breakthrough of CO_2 from storage sites. Although significant research work has been carried out and continues in China, more proof is needed of the applicability of lab results to actual results in the field, including the reliability of predicted permeability and gas recovery rates.

The remaining barriers to ECBM are therefore:

- demonstration of the technology at a commercial level;
- more practical experience with counteracting problems with swelling and reductions in injectivity;
- best practice guidance to educate potential new investors, share experience, and help reduce the variations in success which occur on a site by site basis;
- higher natural gas prices;
- financial incentives for flue gas and CO₂ storage.

Currently it would seem that only China is continuing with work to develop ECBM potential. The growing population and energy demand coupled with the desire to move away from coal, makes ECBM more attractive in China than it may be elsewhere. However, even if the Chinese are successful in demonstrating a project at commercial scale, the nature and economics of ECBM are so site specific that success will be achieved only on a case by case basis.

6 References

Busch A, Gensterblum Y (2011) CBM and CO₂-ECBM related sorption processes in coal: A review. *International Journal of Coal Geology*; 87 (2); 49-71 (2011)

Cai Y, Pan Z, Liu D, Zheng G, Tang S, Connell I, Yao Y, Zhou Y (2014) Effects of pressure and temperature on gas diffusion and flow for primary and enhanced coal bed methane recovery. *Energy Exploration and Exploitation*; 32 (4); 601-619 (2014)

Chatterjee R, Paul S (2013) Classification of coal seams for coal bed methane exploitation in central part of Jharia coalfield, India - A statistical approach. *Fuel*; 111; 20-29 (2013)

Chen R (2013) Interaction between supercritical CO₂ and coal petrography. *Advanced Materials Research*; 616-618; 306-309 (2013)

Clarkson C R, Rahmanian M, Kantzas A, Morad K (2011) Relative permeability of CBM reservoirs: Controls on curve shape. *International Journal of Coal Geology*; 88 (4); 204-217 (2011)

Cliff D, Brady D, Watkinson M (2014) Developments in the management of spontaneous combustion in Australian underground coal mines. In: *14th Coal Operator's Conference.* Australia, University of Wollongong, Australian Institute of Metallurgy and Mine managers Association of Australia, 330-338. http://ro.uow.edu.au/cgi/viewcontent.cgi?article=2189&context=coal (2014)

Connell L D, Pan Z, Shangzhi M, Camilleri M, Down D, Carras J, Wenzhong Z, Xiaokang F, Benguang G, Briggs C, Lupton N (2013) Description of a CO₂ enhanced coal bed methane field trial using a multilateral horizontal well. *Energy Procedia*; 37; 6760-6768 (2013)

CSUG, Canadian Society for Unconventional Resources (2010) Understanding natural gas from coal in Alberta. <u>http://www.csug.ca/images/CSUG_presentations/2010/NGC_Alberta_web.pdf</u> 21pp (2010)

Fang Z, Li X, Wang G G X (2013) A gas mixture enhanced coalbed methane recovery technology applied to underground coal mines. *Journal of Mining Science;* 49 (1); 106-117 (2013)

Fang Z, Li X (2014) A preliminary evaluation of carbon dioxide storage capacity in unmineable coalbeds in China. *Acta Geotechnica*; 9 (1); 109-114 (2014)

Gale J, Freund P (2001) Coalbed methane enhancement with CO₂ sequestration worldwide potential. *Environmental Geosciences;* 8 (3): 210-217 (2001)

Grimm R P, Eriksson K A, Ripepi N, Eble C, Greb S F (2012) Seal evaluation and confinement screening criteria for beneficial carbon dioxide storage with enhanced coal bed methane recovery in the Pocahontas Basin, Virginia. *International Journal of Coal Geology*; 90-9; 110-125 (2012)

Godec M, Koperna G, Gale J (2014) CO₂-ECBM: a review of its status and global potential. *Energy Procedia*; 63; 5858-5869 (2014)

IEA GHG, IEA Greenhouse Gas (2013) *Potential implications on gas production from shales and coals for geological storage of CO*₂. Report 2013/10. Cheltenham, UK, IEA GHG. http://ieaghg.org/docs/General_Docs/Reports/2013-10.pdf 159 pp (2013)

IEA GHG, IEA Greenhouse Gas (2015) *The RECOPOL project.* Overview paper. Downloaded from: <u>http://www.ieaghg.org/docs/overviews/2006-10.pdf</u> 3 pp (2015)

Jamshidi M (2010) Effect of various injected gases on methane recovery and water production in enhanced coalbed methane operations. In: *Proceedings - SPE Annual Technical Conference and Exhibition*, 7, pp. 5875-5884 (2011)

Jamshidi M, Jessen K (2012) Water production in enhanced coalbed methane operations. *Journal of Petroleum Science and Engineering*; 92-93; 56-64 (2012)

Karmis M, Ripepi N S, Miskovic I, Conrad J M, Miller MJ, Shea C (2008) CO₂ sequestration in unminable coal seams: Characterization, modelling, assessment and testing of sinks in central Appalachia. In: *25th Annual International Pittsburgh Coal Conference, PCC - Proceedings*, 43 p (2008)

Kronimus A, Busch A, Alles S, Juch D, Jurisch A, Littke R (2008) A preliminary evaluation of the CO₂ storage potential in unminable coal seams of the Münster Cretaceous Basin, Germany. International Journal of Greenhouse Gas Control; 2 (3); 329-341 (2008)

Kumar H, Elsworth D, Liu J, Pone D, Mathews J P (2012) Optimizing enhanced coalbed methane recovery for unhindered production and CO₂ injectivity. *International Journal of Greenhouse Gas Control;* 11; 86-97 (2012)

Lakeman B (2015) Alberta Research Council enhanced coalbed methane recovery project in Alberta, Canada. <u>http://www.cslforum.org/publications/documents/Alberta_Research_Council_Enhanced.pdf</u> 26 pp (2015)

Li Xiaochun, Fang Zhi-ming (2014) Current status and technical challenges of CO2 storage in coal seams and enhanced coalbed methane recovery – an overview (2014) *International Journal of Coal Science Technology;* 1 (1); 93-102 (2014)

Liu A, Fu X, Wang K, An H, Wang G (2013) Investigation of coalbed methane potential in low-rank coal reservoirs - Free and soluble gas contents. *Fuel;* 112; 14-22 (2013)

Locke J E, Winschel R A (2014) *CO*₂ sequestration in unmineable coal with enhanced coal bed methane recovery. DE-FC26-01NT41148. Paper presented at: Carbon Storage R&D Project Review Meeting. http://www.netl.doe.gov/File%20Library/Events/2014/carbon_storage/1--James-Locke.pdf 25 pp (Aug 2014)

Ma Q, Harpalani S, Liu S (2011) A simplified permeability model for coalbed methane reservoirs based on matchstick strain and constant volume theory. *International Journal of Coal Geology*; 85 (1); 43-48 (2011)

Mazzotti M, Pini R, Storti G, Burlini (2009) Carbon dioxide (CO₂) sequestration in unmineable coal seams and use for enhanced coalbed methane recovery (ECBM). *Developments and Innovation in Carbon Dioxide (CO₂) Capture and Storage Technology*; 2; 127-165 (2010)

NETL (2015) Increasing the Rate and Extent of Microbial Coal to Methane Conversion through Optimization of Microbial Activity, Thermodynamics, and Reactive Transport. Pittsburgh, USA, NET (National Energy Technology Centre), US Department of Energy. http://www.netl.doe.gov/research/coal/project-information/proj?k=FE0024068. 1pp (2015)

Palmer I (2010) Coalbed methane completions: A world view. *International Journal of Coal Geology*; 82 (3-4); 184-195 (2010)

QIN Y (2008) Mechanism of CO₂ enhanced CBM recovery in China: a review. *Journal of China University of Mining and Technology*; 18 (3); 406-412 (2008)

Ripepi N (2011) *CO*₂ storage in unconventional gas formations with enhanced gas recover potential. <u>http://www.secarbon.org/wp-content/uploads/2011/05/13-Ripepi.pdf</u> 31 pp (2011)

Robertson E P (2009) Economic analysis of carbon dioxide sequestration in Powder River basin coal. *International Journal of Coal Geology*; 77 (1-2); 234-241 (2009)

Ross H E, Hagin P, Zoback M D (2009) CO₂ storage and enhanced coalbed methane recovery: Reservoir characterization and fluid flow simulations of the Big George coal, Powder River Basin, Wyoming, USA. *International Journal of Greenhouse Gas Control*; 3 (6); 773-786 (2009)

Saghafi A (2010) Potential for ECBM and CO₂ storage in mixed gas Australian coals. *International Journal of Coal Geology*; 82 (3-4); 240-251 (2010)

SECARB (2014) Southeast Regional Carbon Sequestration Partnership: A Southern States Energy Board carbon management program. <u>http://www.secarbon.org/files/secarb-fact-sheet.pdf</u> 15 pp (2014)

SECARB (2015a) Southeast Regional Carbon Sequestration Partnership: Central Appalachian coal seam project. <u>http://www.secarbon.org/files/central-appalachian-basin.pdf</u> 7 pp (2015a)

SECARB (2015b) Southeast Regional Carbon Sequestration Partnership: Black Warrior Basin coal seam project. <u>http://www.secarbon.org/files/black-warrior-basin.pdf</u> 5 pp (2015b)

SECARB (2015c) *Southeast Regional Carbon Sequestration Partnership:* Phase III Early CO₂ injection field test at Cranfield. <u>http://www.secarbon.org/files/black-warrior-basin.pdf</u> 7 pp (2015c)

Sinayuç Ç, Gümrah F (2009) Modelling of ECBM recovery from Amasra coalbed in Zonguldak Basin, Turkey. *International Journal of Coal Geology;* 77 (1-2); 162-174 (2009)

Sinayuç C, Shi J-Q, Imrie C E. Syed S, Korre A, Durucan S (2011) Implementation of horizontal well CBM/ECBM technology and the assessment of effective CO₂ storage capacity in a Scottish coalfield. **Energy Procedia;** 4; 2150-2156 (2011)

Siriwardane H J, Bowes B D, Bromhal GS, Gondle R K, Wells A W, Strazisar B R (2012) Modelling of CBM production, CO₂ injection, and tracer movement at a field CO₂ sequestration site. *International Journal of Coal Geology*; 96-97; 120-136 (2012)

Skiba J (2015) Central Mining Institute, Poland, Experimental Mine "Barbara" (April 2015) *Personal communication*

Sloss L L (2005) *Coalbed methane emissions – capture and utilisation*. CCC/104, London, UK, IEA Clean Coal Centre, 56 pp (Nov 2005)

Sloss L L (2006) *Power projects using methane from coal mines.* CCC/112, London, UK, IEA Clean Coal Centre, 46 pp (2006)

Thararoop P, Karpyn Z T, Ertekin T (2012) Numerical studies on the effects of water presence in the coal matrix and coal shrinkage and swelling phenomena on CO₂-enhanced coalbed methane recovery process. *International Journal of Oil, Gas and Coal Technology*; 5 (1); 47-65 (2012)

Tu Y, Xie C, Li R, Xie S (2013) The contrast experimental study of displacing coalbed methane by injecting carbon dioxide or nitrogen. *Advanced Materials Research*; 616-618; 778-785 (2013)

UN FCCC, UN Framework Convention on Climate Change (2011) *Carbon dioxide capture and storage in geological formations as CDM project activities.* <u>http://unfccc.int/resource/docs/2011/cmp7/eng/10a02.pdf#page=13</u> vp (2011)

US EPA, US Environmental Protection Agency (2015) *Enhanced CBM/CMM recovery.* NC, USA, US EPA, <u>http://www.epa.gov/cmop/docs/cmm recovery.pdf</u> 9 pp (2015)

Varade A M, Meshram T (2010) Coal bed methane exploration: A journey from alternative energy option to the environment polluting agent. *Nature Environment and Pollution Technology*; 9 (3); 575-580 (2010)

Vishal V, Singh L, Pradhan S P, Singh T N, Ranjith PG (2013a) Numerical modelling of Gondwana coal seams in India as coalbed methane reservoirs substituted for carbon dioxide sequestration. *Energy*; 49 (1); 384-394 (2013)

Vishal V, Ranjith P G, Pradhan S P, Singh T N (2013b) Permeability of sub-critical carbon dioxide in naturally fractured Indian bituminous coal at a range of down-hole stress conditions. *Engineering Geology*; 167; 148-156 (2013)

Vishal V, Singh T N, Ranjith PG (2015) Influence of sorption time in CO₂-ECBM process in Indian coals using coupled numerical simulation. *Fuel*; 139; 51-58 (Jan 2015)

Wang G X, Massarotto P, Rudolph V (2009) An improved permeability model of coal for coalbed methane recovery and CO₂ geosequestration. *International Journal of Coal Geology;* 77 (1-2); 127-136 (2009)

Wei Z, Zhang D (2013) A fully coupled multiphase multicomponent flow and geomechanics model for enhanced coalbed-methane recovery and CO₂ storage. *SPE Journal*; 18 (3); 448-467 (2013)

Weniger P, Kalkreuth W, Busch A, Krooss B M (2010) High-pressure methane and carbon dioxide sorption on coal and shale samples from the Paraná Basin, Brazil. *International Journal of Coal Geology*; 84 (3-4); 190-205 (2010)

Winthaegen P (2008) *MOVECBM Monitoring and verification of CO₂ storage and ECBM in Poland.* FP6-2005-Energy-4. Amsterdam, The Netherlands, Netherlands Organisation for Applied Scientific Research TNO, 53 pp (2008)

Wong S, Macdonald D., Andrei S, Gunter W D, Deng X, Law D, Ye J, Feng S, Fan Z, Ho P (2010) Conceptual economics of full scale enhanced coalbed methane production and CO₂ storage in anthracitic coals at South Qinshui basin, Shanxi, China. *International Journal of Coal Geology*; 82 (3-4); 280-286 (201)

Yang X-L, Zhang Y-L, Ren C.Z (2012) The numerical simulation for seepage rule of coal-bed methane with hydraulic cutting seam mining based on Matlab. *Advanced Materials Research*; 524-527; 485-488 (2012)

Yu H, Yuan J, Guo W, Cheng J, Hu Q (2008) A preliminary laboratory experiment on coalbed methane displacement with carbon dioxide injection. *International Journal of Coal Geology*; 73 (2); 156-166 (2008)

Zheng G, Pan Z, Chen Z, Tang S, Connell L, Zhang S, Wang B (2012) Laboratory study of gas permeability and cleat compressibility for CBM/ECBM in Chinese coals. *Energy Exploration and Exploitation;* 30 (3); 451-476 (2012)

Zheng B, Xu J (2014) Carbon capture and storage development trends from a techno-paradigm perspective. *Energies;* 7(8); 5221-5250 (2014) http://www.mdpi.com/1996-1073/7/8/5221/htm