COAL SEAM GAS RECOVERY IN AUSTRALIA AND TRANSITION TO CO\textsubscript{2}-ECBM

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ABSTRACT

In the last decade eastern Australian states have been the scenes for great advances in coal seam methane (CSM) exploration and production. In the mid 1990’s CSM was almost absent from the Australian gas market, but by the end of 2006 it was estimated that 60-70 PJ of commercial CSM was being produced in the states of Queensland and New South Wales (NSW). In 2006, ~45% of the natural gas consumed in Queensland was sourced from CSM and by 2010 it is expected that the share of CSM should reach 70% of the state’s gas consumption. Simultaneously the increase in greenhouse gas emissions from electricity generation and other stationary sources is becoming a great concern. In active CSM fields where gas production is diminishing, the injection of CO\textsubscript{2} could enhance the release of methane while CO\textsubscript{2} can be stored in these seams. This investigation aims at evaluating the feasibility of CO\textsubscript{2} enhanced coal seam gas recovery (CO\textsubscript{2}-ECBM) operations in Australian coal seams. The investigation focuses on the coal seam gas reservoir properties, measured by CSIRO over the last two decades, to devise a model for the CO\textsubscript{2} storage potential of coal seams as a function of coal seam depth. Results from CO\textsubscript{2} natural analogue studies undertaken by CSIRO show that the coal seams are generally undersaturated with respect to CO\textsubscript{2} and this observation is taken into account in the development of the model. Some results of analyses of the cost of CO\textsubscript{2} sequestration and methane recovery in respect to the main component of the cost, i.e. CO\textsubscript{2} capture are also presented.

INTRODUCTION

Australia is currently one of the largest commercial producers of CSM in the world with some 70 PJ of commercial gas being produced across the eastern states of Australia (with more than 90% of the production from Queensland’s coal seam gas fields). Some CSM fields in the Bowen and Surat Basins in Queensland including Fairview, Dawson Valley and Peat Scotia, have been producing CSG for almost one decade and are amongst the best gas producers in the world. Thick and continuous coal seams, with high gas content (averaging 5-15 m\textsuperscript{3}/t) and permeability (tens to hundreds of mD), lead to high gas production rates (~20,000-30,000 m\textsuperscript{3}/day per well). Reserve estimations for the high output areas are in the order of 10,000 PJ. This compares favourably with Queensland’s gas consumption of ~200 PJ per year and ~45% of this gas is currently sourced from coal seam gas. The most prospective locations for enhanced coal seam gas recovery (ECBM) would probably be the current thriving CSM producer fields after they become largely depleted, where the extra gas would not be recovered if a stimulation method such as CO\textsubscript{2} stimulated ECBM (CO\textsubscript{2}-ECBM) is not applied. Furthermore, they are attractive locations because of favourable geological and reservoir conditions such as high permeability, lack of cleat mineralization and
presence of good quality seal cap rocks; otherwise the coal seam gas would have escaped from these seams over geological time.

Concurrently with increase in CSM production the greenhouse gas emissions (GHGE) from fossil-based energy production is also increasing. In 2004 Australia’s net GHGE were ~565 Mt CO$_2$-e with almost 50% of emissions from stationary energy sources (mostly coal-fired power plants). Though the increase in total GHG emissions relative to 1990 is only 2.3%, the emissions from stationary energy sources has increased significantly by 43% in comparison to 1990 levels. While other sources of energy (such as wind and solar) are being considered to meet the future energy demands, the reliance on fossil fuels, and in particular on coal, will remain strong into the foreseeable future. Further increases in CO$_2$ emissions from stationary energy sources can therefore be expected to occur unless some action is taken to mitigate these emissions.

One option that is being considered in Australia is the capture and storage (CCS) of CO$_2$ in geological formations such as saline aquifers, disused oil and gas wells, and unmineable coal seams. The black coal-fired power plants of eastern Australia are situated in close proximity to or in the vicinity of major coal basins (Bowen and Surat Basins in Queensland; Gunnedah, Clarence-Moreton and Sydney Basins in New South Wales). Transport of CO$_2$ captured from the flue gases of such power stations to nearby coalfields would be relatively cheap in terms of both capital and operating costs compared to instances where potential storage areas are located at considerable distances from power stations. However, in the absence of regulatory intervention and a price signal from the Australian Government to stimulate action by the industry, it is unlikely that CCS will occur at any significant level in the very near future (the next 5-10 years). A short to mid term (~ 50 years) option for Australia to mitigate its fossil fuel related CO$_2$ emissions at lower cost and/or with added benefit would be to sequester CO$_2$ in coal seams which are not targeted for mining at the moment and contain methane. Many of the CSM producing seams at great depth (>700 m) or at shallow depth (300 to 700 m) which are not suitable for mining but contain sufficient volumes of methane can be used for CO$_2$ disposal and enhanced gas recovery (CO$_2$-ECBM).

So far the limited pilot CO$_2$-ECBM operations around the world and in particular in USA [1, 2] have shown that combined coal seam gas recovery and CO$_2$ storage can lead to some extra volumes of methane being recovered. The economic analyses of CO$_2$-ECBM pilot operations [2, 3] also suggest that this practice could become profitable with some increases in the price of produced gas and reduction in the cost of CO$_2$. In addition to the price of gas the viability of CO$_2$-ECBM operations is also affected by the efficiency of gas drainage and CO$_2$ injection processes. By using advanced and efficient new directional drilling technology including surface to in-seam to surface drilling, and multiple lateral technology the drilling mileage reduces and profitability is enhanced by the increase in the volume of gas that is drained as a result of gas injection. With new drilling and gas drainage techniques the zone of influence of the borehole is significantly increased through larger contact with the seam and the fact that the borehole acts as an efficient in-seam fracture. In-seam drilling in Australia is possible to a distance of ~1500 m [4]. Currently more than ~500 km/yr of directional in-seam gas drilling is undertaken in underground mines in Australia with ~100 km/yr for CSM exploration and production [5]. Also with this technique the gas recovery operations for thin and low permeability coal seams would become more attractive. In the last two decades surface to in-seam directional technology, which initially was used for gas drainage in underground coal mines, has developed rapidly and is used for coal seam gas production largely in Queensland but also to lesser extent in NSW.

With increasing public and government interest in the development of options for reducing GHG emissions in the future, it is timely to develop strategies and technologies to meet a potential upsurge in interest in CO2-ECBM.
EVOLUTION OF COAL SEAM GAS IN AUSTRALIA

Australia has some of the world’s largest black coal resources, in excess of 73 billion tonnes [6], and is the largest exporter of coal in the world. Australian coal seams are ‘gassy’ particularly at great depth. Coal seam gas consists predominantly of methane (CH$_4$), carbon dioxide (CO$_2$) and to a lesser extent of nitrogen (N$_2$). Methane contents of up to 25 m$^3$ per tonne of coal occur in coal seams of NSW and Queensland. Also mixed gas conditions exist in many coal seams and high CO$_2$ content similar to CH$_4$ levels can be encountered. For many decades the driving force for research on coal seam gas has been safe mining in gassy coals and extensive research has been undertaken to develop efficient gas drainage technologies to reduce high gas emissions and outburst risks. By the early 1990’s there were some 670 gas outbursts events registered in coal mines in NSW [7]. In Queensland, though in smaller numbers, gas outbursts have also occurred, leading in some cases to mine closure [6].

Since the early 1980’s, mine drained gas or coal mine methane (CMM) has been used in Australia. For instance, in the early 1980’s Westcliff mine was operating a 14 MW electricity plant at the mine site using mine drained gas [7]. Mine gas utilization has grown considerably in the last decade. In 1996 a mine gas utilization project started at Appin and Tower collieries in NSW where drained gas and ventilation gas were used to produce power to a nominal capacity of 94 MW using modular 1 MW reciprocating engines. With the closure of Tower colliery the project is running at a lower capacity of ~54 MW. Other mine gas utilisation projects followed this project in NSW and in Queensland, with the latest project being the 16 modular generators used to produce 32 MW of electricity on site at German Creek mine in Queensland. There are also ongoing investigations into the use of very lean gas from mine ventilation systems. For example, in Westcliff colliery in NSW a specialized combustion unit is being installed to burn methane in mine ventilation air. The generated steam is used to drive a steam turbine generator (6MW electricity). This is the first commercially installed plant in the world to generate electricity using mine ventilation air (MVA) as the main fuel. In the mid 1990’s studies conducted by CSIRO showed that an estimated one billion cubic meters of CH$_4$ (~38 Mt CO$_2$-e) were emitted from coal seams during mining in Australian coal mines [8, 9]. At that time only a dozen mines in Australia had gas drainage systems installed. The authors estimate that currently one quarter of this gas is utilised.

Coal seam methane (CSM) recovery in Australia was also of interest to oil and gas companies and exploration started in the early to mid 1980’s. By the early 1990’s exploration flourished which led to the first Australian CSM production in Queensland from the Dawson Valley gas wells and Moura Mine highwall boreholes. Gas from coal seams in this area is being supplied to the Wallumbilla-Gladstone pipeline. Since 1995 CSM production in Australia has increased with more than 90% of CSM production in Queensland where currently some 45% of the state’s gas consumption is drawn from coal seam methane. The published data obtained by the authors from various sources indicate a commercial CSM production trend for Queensland as shown in Figure 1. It is estimated that Queensland (Qld) alone has CSM resources of 150 to 500 kPJ (~250 TCF) and reserves of up to 12000 PJ (12 TCF).

In NSW the State government sponsored a project (managed by Sydney Gas Limited) to explore and optimise the production of CSM from the Sydney Basin with the hope of reducing the reliance on petroleum gas. The project started in the late 1990’s and targeted the CSM fields of the southern (Camden region), Newcastle and Hunter coalfields of the Sydney Basin. The Gunnedah Basin Permian coal measures in north-eastern New South Wales are also being explored for CSM and the results of exploration are promising. Currently Camden gas field produces ~4-5 PJ/y from gas wells to depths >900 m. Flowrates of 20,000 to 30,000 m$^3$/day per well are achieved in this area. Permian coal measures of the Gunnedah Basin in north-eastern New South Wales are also being explored for CSM and commercial production is expected in the near future.

The Queensland Government’s ‘13% Gas Scheme’ has provided the ideal climate for the developing coal seam gas industry. Under this scheme, which was announced in 2000 and became effective in 2005, the electricity retailers are required to source at least 13 percent of the electricity they sell in Queensland from gas-fired generation. When the scheme was announced coal seam gas constituted around 2 PJ per
year - less than 5% of Queensland's gas requirements. By 2007, it is expected that coal seam gas will make up ~65-70% of Queensland's gas consumption.

The NSW government has no set target for natural gas use. However, a greenhouse gas mitigation scheme has been drafted which would encourage lower GHG intensive power suppliers. The NSW Greenhouse Gas Abatement Scheme (GGAS) commenced on 1 January 2003 and remains in force until 2012. The Electricity Supply Amendment (Greenhouse Gas Emission Reduction) Act of 2002 sets a state greenhouse gas benchmark expressed in terms of emissions per capita (tonnes of CO$_2$-e per capita). The initial level was set to 8.65 t/capita at the commencement of GGAS in 2003. The benchmark progressively drops to 7.27 tonnes in 2007 which represents a reduction of 5% below the Kyoto Protocol baseline year of 1989-1990. The per capita amount continues at this level until 2012. Recently (November 2006), the GGAS was extended to a further nine years until 2020 with the aim of reducing CO$_2$ emissions in the atmosphere by a further 86 Mt.

**CO$_2$ SEQUESTRATION AND ENHANCED COAL SEAM GAS RECOVERY (CO$_2$-ECBM) FOR AUSTRALIA**

Though Australia has a small share (<1.4%) of the total world greenhouse gas emissions, it is one of the largest emitters on a per capita basis (>25 tonne per year per head). In Table 1, the data from the Australian Greenhouse Gas Office (AGO) for 2004 are reported. A total of 560 Mt CO$_2$-e was emitted in 2004 with more than 68% of emissions from the energy sector of which 72% were emitted from stationary energy plants making the share of the stationary energy almost 50% of the total emissions.

Nearly 80% of Australia’s electricity is generated from coal- and gas-fired power plants and as a result ~180 Mt CO$_2$-e is produced annually. NSW and Qld secure nearly all of their electricity from coal-fired, and to a lesser extent from gas–fired, power plants. In order to mitigate the GHGE the Australian Government has committed to a Mandatory Renewable Energy Target (MRET) scheme which some states (NSW and SA) have adhered to and set different targets. For example, in NSW ~10% of the electricity must be generated from the renewable resources by 2010 and 20% by 2020. However, even with the MRET established in Qld and NSW, the increase in the renewable share could not reduce the dependence on fossil fuel significantly in the near future. Based on current data and prediction of energy demand there would be no realistic prospects in the near future that the dependence of Australian electricity sector on fossil fuels (coal and gas) would decrease significantly. Meanwhile, demand for electricity is predicted to rise steadily, up to 50% by 2020, meaning that the overall emissions of CO$_2$ are set to rise substantially. In this context CO$_2$ capture from flue gas and its sequestration (CCS) is increasingly seen as a means whereby we can continue our dependence upon coal and gas to generate electricity without consequential increases in atmospheric CO$_2$ levels.

Simultaneous CO$_2$ storage and CH$_4$ capture is an appealing option because of combined GHGE mitigation and energy recovery benefits. In the eastern states of Australia where there are few geological structures suitable for carbon sequestration, such as depleted oil and gas reservoirs close to the source of CO$_2$ production (power plants), sequestration of CO$_2$ in coal seams has rightly attracted attention of the energy sector and research organisations. Suitable coal formations do exist close to current and future power plants in eastern Australia. The deep unmineable coal seams are excellent candidates to store CO$_2$ captured from flue gas of power plants in the region.

Coal seams can trap significant amounts of gas in their micro pore system in the adsorbed phase. The quantity of gas that can be adsorbed increases with pore gas pressure (also related to depth) and decreases with temperature. In Figure 2 an example of CH$_4$ adsorption isotherms of a Bowen Basin coal at three different temperatures of 24, 33 and 42 °C is shown.

Based on naturally stored CO$_2$ in Australian coal seams, an adsorption capacity of 20 m$^3$/t or higher can be achieved in these seams. Laterally continuous and thick seams (5-10 m thickness) often occur in Australian sedimentary basins some of which, at certain depths and ash yields, would not be suitable for
mining. These seams would be located at 500 to 1000 m depths. Coals at greater depths are more suitable for sequestration as the thickness of strata would not allow the leakage of CO₂ to the surface over short periods of time (<1000 years). However, the permeability of these coals is likely to be low and would require more sophisticated stimulation technologies to enhance the permeability.

**CO₂ STORAGE POTENTIAL OF AUSTRALIAN COALS AND NATURAL ANALOGUES**

Geological reservoirs where CO₂ has been naturally trapped over time are valuable analogues for assessing of the feasibility of the disposal of anthropogenic CO₂ in such structures. In the last few years extensive research work has concentrated on evaluating geo-reservoirs such as sandstone and limestone formations to evaluate their storage, flow and gas trapping properties. In comparison with rock reservoirs, coal seam reservoirs of equal size can retain significantly larger volumes of gas than sandstone or limestone gas reservoirs. The storage of gas in coal occurs mainly via gas adsorption onto micropore surfaces, while in sandstone reservoirs the gas is in a free phase and stored by compression. In Australia, and in particular in the Sydney Basin, numerous coal seams contain large amounts of CO₂ which in some cases constitute 100% of the seam gas. In these instances, CO₂ is believed to be derived mainly from magmatic sources [11]. Carbon isotope analysis of CO₂ in coal seam of the Sydney Basin show that δ¹³C values mostly ranges from -5 to -10‰ indicating a magmatic origin for most of the CO₂. Most of the CO₂ present in these coals was derived from Tertiary magmatic activity and has been stored more than 50 million years. This juvenile CO₂ has replaced the original CH₄ generated during the coalification in the Jurassic and Early Cretaceous periods [13].

The natural sequestration of magmatic CO₂ in coal seams over geological time indicates that this gas can be stored and retained in coal for a very long time. In the last few years Faiz et al. [12] undertook a detailed study of coal seams of the Sydney Basin in NSW to investigate the geological and reservoir factors influencing the storage and entrapment of naturally occurring CO₂ in these coal seams. Some of the findings of these studies have been published previously [13, 14, 15]. Natural analogue studies were undertaken to gain insights into the theoretical and actual CO₂ storage capacity of various Sydney Basin coal seams under various geological conditions. This provides a direct method of estimating the CO₂ sequestration potential rather than the commonly used method of estimation of CO₂ storage from the in-situ methane content of coal seams multiplied by the ratio of CO₂ to CH₄ adsorption capacity. The latter method would not give the 'true' potential of CO₂ storage since, firstly, the coal seams are generally undersaturated, and secondly, the degree of saturation could depend on gas type as well.

In order to evaluate the capacity of Sydney Basin coals for CO₂ sequestration and as part of the natural analogue study, gas adsorption, gas content and gas composition data from numerous coals were analysed. About 40 coal samples from 17 coal seams in the Sydney Basin were measured for their adsorption and flow properties. Some of the data and the methodology have been presented previously [15]. The sample locations span across the Southern, Newcastle and Hunter coalfields. Samples were obtained from the coal face in mines and from boreholes from <30 m to >700 m. The volatile matter content of these samples varies from 13.5 to 42.6%, ash content from 3.3 to 40.2% and moisture from 0.4 to 7.9%. Three contact metamorphosed coals with volatile matter contents of <20% were also measured. The maximum mean vitrinite reflectance (Rₒ max) for measured coals varies from 0.66 to 1.50% and for the contact metamorphosed coals up to 11.2%. In the next section the results of adsorption measurements on these coals are used to give an estimation of CO₂ storage potential of Sydney Basin coals.

**A MODEL OF CO₂ STORAGE POTENTIAL FOR SYDNEY BASIN COALS**

Based on the results of adsorption measurements of coals from the Sydney Basin, a model describing the storage capacity for Sydney Basin coals can be formulated. In this study, a model and preliminary estimations of the storage capacities were produced according to coal seam depths and measured isotherm data, assuming that the hydrostatic pressure equals the gas pressure at a given depth. In Figure 3 the results of estimation of CO₂ storage capacity with depth based on the assumptions described above
are shown. The analysis of data shows that the storage capacity in the adsorbed phase on coal can be expressed in terms of depth by a power function [15]:

\[ c = C_0 \left( \frac{h}{H_0} \right)^\alpha \tag{1} \]

where \( c \) is the maximum saturated CO\(_2\) adsorption capacity of coal at depth \( h \), and, \( C_0 \) and \( H_0 \) are the reference depth and its corresponding storage value, respectively. \( \alpha \) is the exponent of the power equation. The values for the parameters in Eq (1) for the Sydney Basin coals are: \( C_0 = 31.72 \pm 6.75 \text{ m}^3/\text{t}, H_0 = 400 \text{ m} \) and \( \alpha = 0.625 \).

The graph shows that at about 700 m seam depth the predicted saturated capacity for Sydney Basin coals would be 45.0 ±9.6 m\(^3\)/t.

In practice the saturated limit of storage capacity cannot be achieved if the injected gas cannot reach all the adsorption sites and in cases where coal has a low diffusivity or in the presence of water in the pore system. For this reason a saturation coefficient, \( k \), is defined (0<\( k <1 \)) which encompasses the factors which affect the saturation of coal. Using the saturation concept, and depending on the target depth of the sequestration project, the mass of CO\(_2\) which can be stored in Sydney Basin coals can be estimated as follows:

\[ Q = k \cdot \rho \cdot P \cdot C_0 \left( \frac{h}{H_0} \right)^\alpha \tag{2} \]

where \( Q \) is the mass of CO\(_2\) which can be sequestered (tonne), \( P \) is the tonnage of coal available for sequestration, \( \rho \) is the CO\(_2\) density (tonne/m\(^3\)) at normal conditions (20°C and 1 atm.) and \( k \) is the saturation factor (\( k <1 \)).

**COMPARISON OF PREDICTED CO\(_2\) STORAGE AND MEASURED CO\(_2\) CONTENT IN SYDNEY BASIN COALS**

Natural occurrence of CO\(_2\) in large quantities provides an important opportunity to study the in-situ behavior of CO\(_2\) in geological systems and its interactions with coal. Coals in the Sydney Basin are largely CO\(_2\) undersaturated [13] compared to their laboratory saturated values. Though this phenomenon also occurs for CH\(_4\), the level of undersaturation is generally much smaller. Measurements of CO\(_2\) and CH\(_4\) storage capacities of Sydney Basin coals [15, 16] show that up to twice as much CO\(_2\) can be stored relative to CH\(_4\). Measurements of the gas contents of these coals, however, show that CH\(_4\) and CO\(_2\) have similar upper storage limits and the seams are largely undersaturated with respect to predicted CO\(_2\) contents on the basis of adsorption isotherms that were measured in the laboratory (Figure 4).

The saturation factor \( k \) in Eq (2) encompasses a number of factors including flow properties of the coal seam and the coal seam roof (seal). As seen in Figure 4, the CO\(_2\) contents of Sydney coals are generally less than 20 m\(^3\)/t and the highest contents are restricted to depths of 300 to 650 m. In general, the in-situ CO\(_2\) contents are 40–60% of the predicted capacity. The higher values correspond to areas where the intruded CO\(_2\) has replaced over 95% of the pre-existing CH\(_4\). These observations suggest that the \( k \)-values in Eq (2) would be at least less than 0.6 and as small as 0.4.

The reasons for such large undersaturation in Sydney Basin coals are currently being assessed. Some causes of CO\(_2\) undersaturation compared to CH\(_4\) saturation levels may be:

- High solubility of CO\(_2\) in water and its hydro-migration
- High diffusivity of CO\(_2\) and its preferential escape through cap-rocks
- Effect of initial CH\(_4\) content of coal on subsequent adsorption of magmatic CO\(_2\)
An initial ECBM study [16] on the effects of initial methane content on the storage capacity of a Bowen Basin coal showed that considerably less CO\textsubscript{2} may be stored if small amounts of methane are present as shown in Figure 5. This may have implications for CO\textsubscript{2} storage in coal seams which generally contain other adsorbed gases. Additional laboratory evaluations of CO\textsubscript{2} interactions with coal, coupled with observations of naturally occurring CO\textsubscript{2} in coal seams should allow a more accurate quantification of the potential for CO\textsubscript{2} storage in coal seams.

**FEASIBILITY AND ECONOMICS OF CO\textsubscript{2}-ECBM**

One important property for the success of CO\textsubscript{2}-ECBM would be a high permeability in the coal seams. The coal seams in the southern region of NSW have low permeability and might not be favorable for CO\textsubscript{2}-ECBM at this stage. However, the northern region and Hunter coalfield have higher permeability and may be better prospects for a trial. In Queensland the most favourable sites for CO\textsubscript{2}-ECBM would be the currently well-performing CSM coal seam gas fields such as Fairview and Dawson Valley in the Bowen Basin (bituminous coals). However, the lower rank coals of the Walloon coal measures in the Surat Basin should also be considered as the CO\textsubscript{2}/CH\textsubscript{4} storage ratios of these coals could be high.

In Australia one important factor for CO\textsubscript{2} sequestration would be the depth of the coal seam. If a CO\textsubscript{2}-ECBM operation for enhancing methane recovery from coal seam is undertaken, then the expectation is that the sequestered CO\textsubscript{2} will be contained for a significantly long period of time. Hence, coal mining could not take place so that the coal seam would need to be one that is essentially unmineable. However what criteria should be used to assess the mineability of coal? Economic considerations look into the cost of mining and price of the product. While price is a function of coal quality and depends to some extent on the volume of supply, the cost is a function of the capital and operational requirements which are generally dependent on the mining depth. In Figure 6 this process is shown schematically. The location of breakeven point B could move back and forth depending on the market and coal price. However, due to the high slope of the cost-depth curve the movement of the breakeven point would not change the corresponding depth significantly. Therefore, an economically unmineable coal seam might stay unmineable for quite a long time. This would allow for the evaluation of an ‘unmineable’ coal depth in a coalfield with greater certainty that this would remain the case for a long period of time.

If the depth factor is such that the coal seam can be defined as unmineable and the site is geologically suitable with regard to reservoir properties, then CO\textsubscript{2} – ECBM can be economic if the sale of the methane can cover the cost of producing the gas. In relation to the total cost of sequestration, the main cost is the capture of CO\textsubscript{2}, particularly if it is to be sourced from flue gas. Furthermore, the total cost would need to include the cost of transport and compression of the CO\textsubscript{2} as well as the removal of non-adsorbed CO\textsubscript{2} that finds its way to the producer well. The cost of storage is reduced if the existing CSM wells are used and some are converted to injector wells. In Australia, the largest CO\textsubscript{2} emissions after agriculture are from stationary power plants (Table 1) and therefore significant reduction in GHGE could be achieved if the flue gas CO\textsubscript{2} is captured and stored. Therefore an attractive option for mitigating greenhouse gases would be to use the flue gas CO\textsubscript{2} for a CO\textsubscript{2}-ECBM project. However, the concentration of CO\textsubscript{2} in flue gases from power stations is relatively low (<14% for conventional coal-fired power stations) and capture is a costly operation. Wong et al. [17] undertook a study on CO\textsubscript{2} delivered cost particularly in relation to delivery to the San Juan Basin. Their results show a cost of US$10 to US$36 per tonne of CO\textsubscript{2} with the smallest cost for CO\textsubscript{2} sourced from a natural deposit and the highest sourced from Econoamine FG processed flue gas. These costs do not consider incentives or carbon credits and it can be deduced that any possible carbon credit or other incentives to reduce emissions, which seems highly probable in the longer term in Australia, can significantly enhance the accounting.

A preliminary in-house study was undertaken by CSIRO in 2002 to evaluate a CO\textsubscript{2}-ECBM project. The study investigated the use of coal seam gas (CSM) to generate electricity. The flue gas was to be used as a source of CO\textsubscript{2} to be injected back into coal seams to enhance CSM recovery. The technical and economic analyses laid emphasis on the capture and separation of CO\textsubscript{2} in the flue gas from a gas engine.
The engine was designed to combust some 30,000 m$^3$/day (1 MMcfd) of coal seam gas. It was assumed that if coal seam gas is used, then the concentration of CO$_2$ in the exhaust gas would be 8% by volume. Given that the exhaust gas is at atmospheric pressure and its concentration of CO$_2$ is low, only a chemical solvent (amine) was considered to capture the CO$_2$. A CO$_2$ removal and recovery method such as the Econamine FG process was considered to separate CO$_2$ from the engine exhaust. The method requires a large quantity of low-pressure steam (at 350 kPa absolute) to separate the captured CO$_2$ from the solvent and regenerate the solvent; hence co-generation of steam using waste heat from the engine is an essential component of the system. The total capital cost of the installation amounted to AUS $53 million for the system including CO$_2$ drying and final compression to ~10,000 kPa. The operating cost for such a plant was found to be ~AUS $65/tonne of CO$_2$ captured. This cost was found to be uneconomic in an Australian context. One can argue that the high cost is partly related to the small scale of the operation and the low concentration of CO$_2$ in the flue gas from the gas engine. However, even at this scale the plant would have a relatively large footprint and would involve columns around 25 m high, making it difficult to move from one location to another as the CSM project developed into new areas. Because of the high cost of capture some workers [18] suggest the use of untreated flue gas for CO$_2$-ECBM in Australian coal seams, however the large volumes of flue gas to be compressed and transported (note that the ratio of N$_2$:CO$_2$ in the flue gas is about 10) would increase the cost significantly. Besides the high cost of compression and transport, the underground space required for such storage would be beyond the space available in ‘unmineable’ coal deposits.

If CO$_2$ reduction becomes an option for the fossil fuel dependent power industry in Australia, then the inclusion of post-combustion CO$_2$ capture and storage using the best available technologies would have to be considered for both new and existing power plants. The energy required for capturing, compressing and transporting the CO$_2$ would result in a significant reduction in the net power output of the plant. The impact of capture, compression and transportation can be expressed in terms of the reduction in net plant efficiency. For instance, a study of power plants in Europe [19] shows that should CO$_2$ reduction be implemented then the estimated efficiency reduction would be in the order of 13-25% depending on the type of power plant and the capture method used.

**CO$_2$-ECBM DEMONSTRATION PROJECTS IN AUSTRALIA**

To date no ECBM plant is operating in Australia; however, CO$_2$ sequestration is now considered as a strong option to mitigate the GHG emissions. Early studies on the size of CO$_2$ storage space in geological structures were performed in late 1990’s. In early 2000 a demonstration pilot was being considered whereby CO$_2$ would be injected into a coalfield of the Dawson Valley in Queensland [20]. This coalfield, where CSM production is still operating successfully, had been ranked the most suitable world reservoir for an ECBM demonstration plant. The assessment was based on a geological scoring method [21, 22]. The suitable sites were ranked according to the market potential, production potential, CSM resource/CO$_2$ storage potential, CO$_2$ supply potential and financeability of the project. Other suitable world basins listed at that time were the southern Qinshui Basin in China in Shanxi province (which is now the site for a CO$_2$-ECBM trial), the upper Silesian Basin in Poland (EU funded Recopol project) and the Cambay Basin in India [21, 22].

Recently, a CO$_2$-ECBM trial site in Fairview fairway in southern Queensland in the Bowen Basin is being considered [23]. Fairview is a high performance CSM field and has been producing large volumes of gas over the last decade. The Fairview Power Project is to start in April 2007 and involves the extraction of methane from unmineable (deep) coal seams to feed a 100 MW power plant. The CO$_2$ in the flue gas will be captured and injected back into the coal seams. The power plant is to be constructed near the town of Roma in southern Queensland. This project is to be funded through the Australian Government’s Low Emissions Technology Demonstration Fund (LETDF).

Overall the authors suggest that in Australia trial be undertaken in a currently active or depleted CSM gas field. If a reservoir has exhibited an acceptable level of methane flow, it could be expected that CO$_2$ injectivity will also be in an acceptable range. The first trials and the pilot plant should provide sufficient
data for characterizing the in-situ behaviour of coal gas interaction and enable calibration of the parameters of the local ECBM model. If the pilot plant is successful then a model of CSM to ECBM transition in Australia could look somewhat like the diagram presented in Figure 7.

CONCLUSIONS

Australia’s CSM industry has rapidly developed from being almost zero PJ per annum a decade ago to 70 PJ currently. Simultaneously, increasing pressure is experienced by the fossil fuel dependent power generation industry to reduce their GHGE. In this context and in view of the large coal resources of Australia CO₂-ECBM be regarded as a valid option to reduce emissions and to produce natural gas for the developing gas market in eastern Australia. The cost of CO₂-ECBM could be significantly lower compared to CO₂ sequestration alone. In addition to the income from extra methane produced a project undertaken in a depleted CSM field would benefit from the previously drilled and completed CSM producer wells. Some producer wells could be converted to injector wells. Also installed pipelines and infrastructure for gas cleaning and water disposal can be utilized to further reduce operational costs.

We suggest that the CO₂-ECBM trial operations could be established in almost depleted CBM gas fields. The established infrastructure can be used, and since these locations are relatively close to population centers and power plants, major costs such as gas pipelines, drilling and completion of the gas producer wells would be significantly reduced. Also the fact that the CSM wells were producing indicates that the reservoir properties of the coal seam are favourable. The most favourable sites would appear to be Fairview and Dawson Valley in Bowen Basin (bituminous coals). A lower rank coal of the Walloon coal measures in the Surat Basin may also be suitable as the CO₂ storage potential is very high.

ACKNOWLEDGEMENT

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REFERENCES


Figure 3. Estimated CO$_2$ storage of Sydney Basin coal at in-situ ash and moisture conditions (modified after Saghafi et al. [15])

Figure 4. Estimated and measured CO$_2$ content of Sydney Basin coal. Predicted storage corresponds to saturated CO$_2$ storage of coal at a given seam depth (modified after Faiz et al. [13]).
### Figure 5. Effect of initial methane content of coal on its subsequent CO₂ storage capacity

<table>
<thead>
<tr>
<th>CO₂ adsorbed (m³/t)</th>
<th>CO₂ adsorption, coal with initial methane content of 6.3 m³/t</th>
<th>Deficit in CO₂ storage capacity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Coal with zero initial methane content</td>
<td></td>
</tr>
</tbody>
</table>

- CO₂ capacity deficit due to initial methane in coal

Figure 6. Cost of mining depends strongly on coal seam depth; except for very large coal price changes, this factor would not significantly modify the depth limit for coal mining.

![Cost of mining diagram](image)

**Figure 6.** Cost of mining depends strongly on coal seam depth; except for very large coal price changes, this factor would not significantly modify the depth limit for coal mining.

<table>
<thead>
<tr>
<th>Mining cost ($/tonne)</th>
<th>Coal price ($/tonne)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cost</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Coal price</strong></td>
<td></td>
</tr>
</tbody>
</table>

**Limit depth of mining**

**ECBM depth**
Table 1 – Australia’s anthropogenic greenhouse gas emissions (modified from AGO, 2004)

<table>
<thead>
<tr>
<th>Sector</th>
<th>Emissions, Mt CO\textsubscript{2}-e</th>
<th>Percent change in emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1990</td>
<td>2004</td>
</tr>
<tr>
<td>Energy</td>
<td>287.5</td>
<td>387.2</td>
</tr>
<tr>
<td>Stationary Energy</td>
<td>195.7</td>
<td>279.9</td>
</tr>
<tr>
<td>Transport</td>
<td>61.7</td>
<td>76.2</td>
</tr>
<tr>
<td>Fugitive missions</td>
<td>30.0</td>
<td>31.0</td>
</tr>
<tr>
<td>Industrial processes</td>
<td>25.3</td>
<td>29.8</td>
</tr>
<tr>
<td>Agriculture</td>
<td>91.1</td>
<td>93.1</td>
</tr>
<tr>
<td>Land use and forestry</td>
<td>128.9</td>
<td>35.5</td>
</tr>
<tr>
<td>Waste</td>
<td>19.2</td>
<td>19.1</td>
</tr>
<tr>
<td><strong>Australia’s Net Emissions</strong></td>
<td><strong>551.9</strong></td>
<td><strong>564.7</strong></td>
</tr>
</tbody>
</table>

Figure 7. Suggested path for CSM to ECBM transition

CSM production economical?

CSM reservoir depleted?

ECBM reservoir depleted?

Inject flue gas CO\textsubscript{2}/N\textsubscript{2}

Produce CH\textsubscript{4}

Produce Extra CH\textsubscript{4}

Feasibility study

Stop