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ORIGINAL RESEARCH PAPER

An Overview of Enhanced Coalbed Methane Recovery

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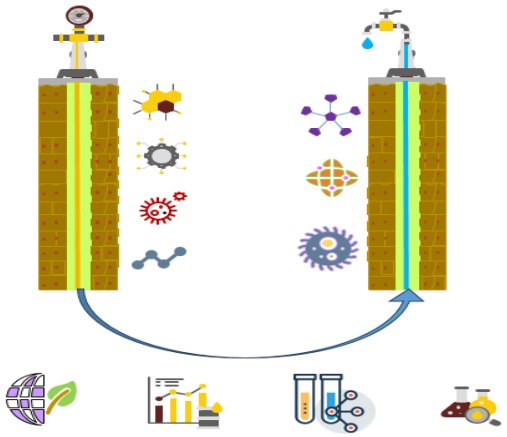
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A B S T R A C T

The development of green energy technologies to reduce greenhouse gas emissions has accelerated interest in enhanced coalbed methane recovery (ECBM). Conventional coalbed methane production causes significant environmental issues due to saline water extraction. ECBM offers a safer alternative by injecting gases such as carbon dioxide (CO_2) or nitrogen (N_2) into coal seams to improve methane recovery. CO_2 injection enhances methane displacement and enables carbon sequestration but causes coal swelling, reducing permeability and methane production rates. In contrast, N_2 injection improves injectivity and methane recovery through coal shrinkage, though it leads to faster nitrogen breakthrough and higher gas treatment costs. Studies show that injecting a CO_2–N_2 mixture provides a synergistic effect, combining improved methane recovery, enhanced injectivity, reduced swelling, and substantial CO_2 sequestration. Globally, several ECBM projects, particularly in the USA, demonstrate the feasibility of using flue gas mixtures. Although CO_2 separation costs remain a major economic challenge, suitable incentives for carbon storage could significantly improve the viability of CO_2-enhanced ECBM processes.



1. Introduction

Given the now widely acknowledged threat global warming poses to humanity, urgent mitigation measures in this regard have become a global necessity. Finding appropriate means to realize the emission reduction targets within a short time frame presents a major challenge. As is common knowledge, the burning of fossil fuels (coal and oil) represents the main method of energy production globally; however, this releases excessive amounts of carbon dioxide into the atmosphere. New green energy solutions that mitigate the levels of harmful gasses released into the atmosphere offer the most promising solution. The advancement of new fossil-fuel resources to substitute coal dependency would greatly reduce global carbon dioxide emissions. Power generation from natural gas, which offers greater energy security given that conventional fossil fuels are running out, represents a potential solution; hence, the development of new unconventional gas resources, such as enhanced coalbed methane recovery, has been greatly accelerated [1].

Coalbed methane contributes greatly to energy production, particularly in North America where coal seams provide the bulk of the country's natural gas [2]. Although methane may be acquired from coal seams in a cost-efficient manner in the initial phase of a coalbed methane project, towards the end of the project lifetime the methane pressure in the coal seam is inadequate for economically feasible extraction. It has been found that the injection of gas into the seam aids in producing methane that would be inaccessible otherwise and is known as enhanced coalbed methane recovery. Normally, a coalbed methane project produces approx. 50% of the methane is available in a coal seam; however, production rates of up to 90% can result from the use of enhanced coalbed methane projects [2].

This study aims to provide an overview of the enhanced coalbed methane recovery process. Firstly, the basic principles of the process were discussed, and a comparison was made between conventional gas resources and coal seams which speaks to the advantages associated with coal seams as a gas

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resource, and prospective coal deposits for enhanced coalbed methane recovery both in South Africa and globally were explored in detail. A *literature review* then discussed the carbon dioxide and nitrogen-enhanced coalbed methane process mechanisms in detail, and an overview of adsorption isotherms and the effects of swelling on methane production is provided. The *discussion* first looked at the issue of water production posed by conventional coalbed methane recovery and thereafter compared the carbon dioxide and nitrogen-enhanced processes in terms of productivity, risk environmental impact, and economics. Lastly, the economics of the process were discussed, particularly concerning pilot and demonstration projects that have been undertaken to date.

1.1. Principles of Enhanced Coalbed Methane Recovery

Methane is under pressure in unmined coal seams as it has been unable to escape since the beginning of the coalification process. During the coalbed methane operation, a vertical hole is drilled into the coal seam and a path is formed to allow for the release of methane from within the coal mass. As a result of its pressure, the gas is pushed up to the surface and collected. As is the case in most coal seams, dewatering is necessary to remove the water that is present and aids in promoting the release of methane from the coal mass [2].

Enhanced coalbed methane recovery, on the other hand, makes use of a gas (usually CO_2 or N_2) which is injected into an unmineable coal seam in an attempt to stimulate the release of methane [3]. Without the use of gas injection, the methane recovery from a coalbed methane project will form only a fraction of the gas in place due to the decrease in pressure of the seam as methane and water are recovered. As the coal seam acts as both a final storage point for flue gases or carbon dioxide (which are harmful greenhouse gases), as well as a source of energy, enhanced coalbed methane recovery represents a promising technology [3]. However, a large gap remains between theory and practice as no full-scale projects have commenced to date [2].

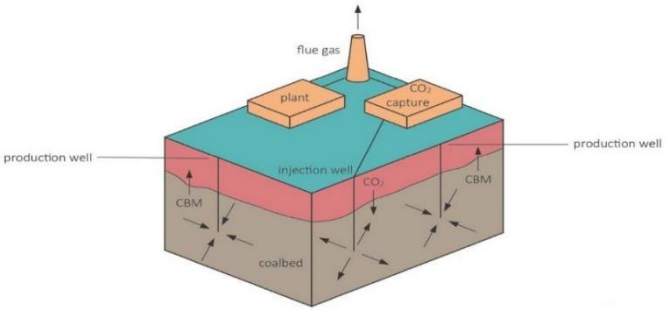


Figure 1. Principle of enhanced coalbed methane recovery [3].

Referring to Figure 1, which depicts the basic principle of enhanced coalbed methane recovery, the injection of gas into the coal seam is administered via the injection well. As the gas disperses throughout the seam, methane is released and is collected as it appears at the production well [3]. It should be noted that the pumping and drilling technologies used in this process have been successfully applied in other industries, such as oil and gas recovery. Additional complexity is added to the project with the inclusion of a gas injection and carbon dioxide storage phase, which requires additional considerations.

1.2. Coal Seams as Unconventional Gas Resources

Over millions of years, the biodegradation of plant material under high pressure and high-temperature conditions results in the formation of coal [4]. According to the degree of transformation, or *coalification*, different coal ranks are formed which are classified according to their carbon content. In general, an increase in coal rank is associated with an increase in carbon content. Coal is sub-divided into low and high-rank coal, with lignite and sub-bituminous making up the low rank, and bituminous and anthracite making up the high rank, as depicted in Figure 2.

As the composition of coal (volatile matter, water, carbon dioxide and ash content) varies with coal rank (refer to Table 1), so do physical properties such as porosity, strength and permeability.

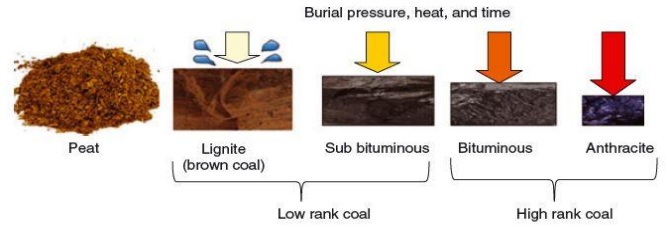


Figure 2. Progressive Formation of Different Coal Ranks [4].

Table 1. Variation of coal composition with rank [5].

Coal Property	Lignite	Sub-bituminous	Bituminous	Anthracite
Moisture Content (wt%)	50-70	25-30	5-10	2-5
Carbon Content (wt%)	60-75	75-80	80-90	90-95
Volatile Matter Content (wt%)	45-55	40-45	20-40	5-7

For example, bituminous and anthracite coals (high rank) possess high strength, low porosity, low permeability and high adsorption capacity [5]. Perera & Ranjith [1] define permeability as a measure of the ability of a fluid to flow through a coal seam and further state that it depends on the "degree of pore space available for fluid movement".

1.3. Comparison Between Conventional Reservoirs and Coal Seams

A major distinction between coal seams and conventional natural gas reservoirs is that in coal seams, the methane is stored in the molecular surface of the coal as it is adsorbed onto the coal surface. In conventional natural gas reservoirs, however, the gas has already desorbed into the pockets and spaces underground [2]. As a result of the excessive internal surface area that coal possesses, coal seams can store a much greater amount of gas compared to conventional natural gas reservoirs. Regarding conventional reservoirs, the relative permeability does not form a critical factor for gas production because a small amount of mobile water is available and permeability remains relatively constant with a reduction in pressure [1]. For coals, a large amount of available mobile water exists; hence, permeability varies greatly with a reduction in pressure, and the maximum production point (which is available at a condition of extremely low pressure) can be attained by dewatering [1].

A dual-porosity system exists in coal bed reservoirs, consisting of both micro and macropores [1].

Due to the micropores being much smaller, it is difficult for water molecules to enter these pores; therefore, micropores act as a storage house for gases, yielding 7 times greater storage capacity in coal seams in comparison to conventional reservoirs [6].

Referring to Figure 3, coal has a well-built natural cleat system, made up of orthogonal face cleats and butt cleats. As face cleats are continuous and create paths of higher permeability when compared to discontinuous butt cleats, they offer a greater contribution to the coal permeability. Of course, increased permeability favours the coalbed methane process. As a result of the dual-porosity and natural cleat system of coal seams, coal behaves as naturally fractured reservoirs for gas movement [1].

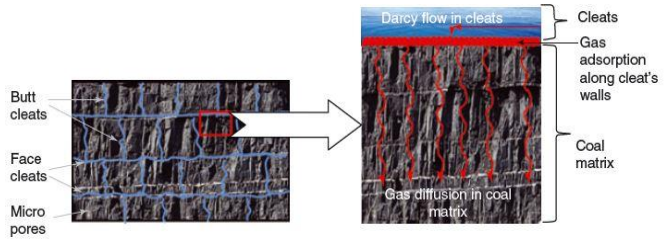


Figure 3. Gas transport process through coal [1].

1.4. Methane Gas Contained in Coal Seams

All coal seams contain various quantities of natural gases which are formed during the coalification process. Most commonly, these gases contain 90% methane and small quantities of wet compounds, such as ethane and butane. As a result of the continuous increase in pressure that occurs during the coalification process, the naturally formed methane is trapped within the coal seam [1]. Eventually, the methane gas adsorbs into the cleats (refer to Figure 3). Vishal, et al. [7]. state that the hydrostatic pressure applied due to the surrounding saturated rock additionally contributes to containing the methane gas inside the coal seam. Coal bed methane is extremely pure in comparison to conventional petroleum gas and requires little/no treatment for commercial use [8]. A coal seam appropriate for coal bed methane development requires good permeability-preferably above 1mD [9], a high gas content of 15-30 m^3/ton of methane [10] adequate lateral continuity and thickness for ready movement of gas into wells and a location 250m-1000 m below the earth's surface [1].

By referring to Figure 4, it can be seen that methane is held within the coalbed matrix on the surface of the coal, as well as within the surrounding fractures while being held in place by high-pressure water [11]. Gas is mainly captured by the breaking of the cap rock together with the removal of the water, which releases the pressure holding the methane in place. The release of methane from the coal seam occurs in 3 stages (refer to Figures 3 and 4) [11]:

- Gas desorption from internal micropores on the coal surface
- Gas diffusion through the coal matrix

- Gas fluid flows through the fracture network in the seam to the production well

As previously mentioned, most coal seams require dewatering; therefore, pumping of the seam forms a major aspect of the production process. In certain cases, however, there are sites which are dry and allow for the immediate production of methane upon drilling, with no drainage necessary [11]. An example of this is the Horseshoe Canyon formation in Canada.

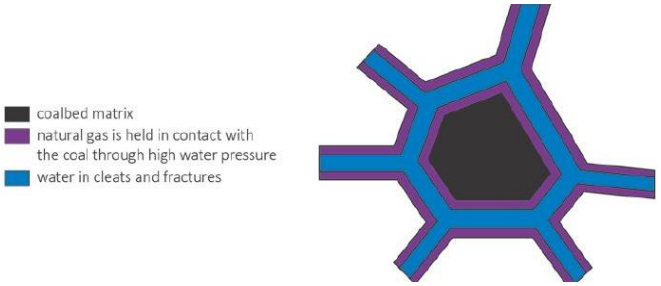


Figure 4. Methane gas contained within the coalbed matrix [11].

The quantity of gas contained in a coal seam essentially depends on the coal rank as coal bed methane is formed during the coalification process. Low-rank coals (such as lignite) possess a small amount of coal bed methane, while high-rank coals possess the greatest amount, such as anthracite. Although this is true, anthracite is a hard coal with low desorption capability; therefore, it is challenging to produce coal bed methane using this coal type [8]. For this reason, medium-rank coals (such as bituminous) are most commonly used to extract coal bed methane [8]. Due to the soft nature of lower coal ranks these coals are suitable for vertical well drilling, while the stronger coal seams of higher rank can handle more intrusive horizontal wells [12].

1.5. Location of Potential Enhanced Coalbed Methane Recovery Operations

The IEA Greenhouse Gas R&D Programme [13] undertook an assessment of 20 of the world's major coal deposits regarding their potential to undertake considerably enhanced coalbed methane recovery operations. Specific screening criteria were implemented in selecting these coal deposits. Due to the voluminous nature of the list, this report will focus on the top 5 most prospective coal deposits, as well as those located in South Africa.

The potential of a coal deposit to undertake an enhanced coalbed methane recovery operation which is economically viable relies on a combination of 4 factors [13]:

1. **Coalbed Methane Producibility:** With the in-place coal bed methane resource and coal seam permeability in mind, the per-well recovery rate, as well as the size of the recoverable coalbed methane reserve is crucial.
2. **CO_2 Availability**: The concentration, supply rate and nature of the carbon dioxide source, and how convenient its location is relative to the coalbed methane resource should be noted.
3. **Development Cost:** The effect of carbon dioxide systems, location and other factors on the capital and operating costs is important.
4. **Markets:** Given the minimum gas price required for profitable operation, the existence of current or potential markets is another critical factor.

Based on the aforementioned factors, including others, each coalbed methane resource area was given a score from 1-5. Appendix A lists the overall ranking of the most prospective deposits globally. From this table, it can be seen that Canada and Australia have an evolving coalbed methane market and India has potential coalbed methane production sites. The top 5 basins include San Juan-United States (29/30), Uinta-United States (24/30), Bowen-Australia (24/30), Raton-United States (23/30) and Cambay-India (23/30). In South Africa particularly, the coal basin in the Main Karoo was ranked 20th with an overall score of 14/30 and the Waterberg coal basin was ranked 17th with an overall score of 17/30. Table 2 depicts the production indicators of the top 5 global potential enhanced coalbed recovery locations, while Table 3 depicts the same with specific regard to South Africa.

Contrary to popular belief, the gas-in-place indicator is not a measure of the gas recoverable in an economical manner; this value is rather referred to as the recoverable ECBM (enhanced coalbed methane) [2]. Aside from the gas-in-place indicating the amount of gas contained in the coal seam, this indicator aids in determining the cap rock sealing efficiency. Sites with a methane content close to the theoretical maximum are representative of sites with good cap rock as little to no gas has managed to escape from the seam. In addition to a relatively high gas-in-place, this site will have higher gas pressure which leads to a higher gas recovery rate. Sites exhibiting good cap rock are more appropriate for carbon dioxide storage due to the low leakage levels over long periods [14]. Concerning Tables 2 and 3, the CO_2 sequestration potential refers to the removal and storage of carbon dioxide gas from the atmosphere [14].

Table 2. Production indicators of top 5 global potential enhanced coalbed recovery locations [13].

		San Juan	Uinta	Bowen	Raton	Cambay
Resource Potential	Gas-In-Place (Gm^3)	1 700	280	2 940	285	1 000
	Recoverable ECBM(Gm^3)	380	63	240	23	20
	CO_2 Sequestration Potential (Mt)	1 400	230	870	85	74
Commercial Potential	Gas Market	Excellent	Excellent	Developed	Good	Good
	CO_2 Availability	Excellent	Good	Moderate	Excellent	Good
CBM Activity	Leasing/Testing	Fully leased, fully developed	Mostly leased, partly developed	Active	Partly leased, partly developed	Active
	Commercial Production (Mm^3/year)	25 800	672	41	310	None
	World Ranking	1	2	3	4	5

Gm^3-cubic gigametre, Mm^3/year-cubic megametre per year

1.5.1. San Juan Basin

Regarding the San Juan basin, the average coal depth is approximately 1,000 m with an estimated methane composition of 90%. The gas content varies from 7-20 m^3/ton and averages at ±16 m^3/ton. The coal mass is exceptionally well cleated and excellent lateral communication and reservoir continuity exist. The coal rank in this area increases from sub-bituminous in the southern San Juan region to medium-volatile bituminous in the northern region. In addition, the permeability varies from 1-100 mD, while averaging at around 20 mD [13]. Referring to the aforementioned property ranges suggested for coal seams appropriate for coal bed methane development, it can be seen why the San Juan basin is the most promising coal seam for enhanced coalbed methane development.

In this basin, the recoverable enhanced coalbed methane is 380 Gm^3, the amount of carbon dioxide that could be sequestered in this basin with the full application of enhanced coalbed methane recovery is 1400 Mt and the prospective gas-in-place resource is 1 700 Gm^3 which represents a major resource with an extremely favourable gas concentration [13]. Similar details of the remaining top 5 prospective coal basins are presented in Table 2.

Currently, approximately 1,500 coalbed methane wells are located in the San Juan basin [2]. In the United States, the bulk of the natural gas production originates from coalbed methane recovery, of which the San Juan basin produces ~0.85 million m^3/day [15].

Table 3. Production Indicators of South African Potential Enhanced Coalbed Recovery in Main Karoo and Waterberg [13].

		Waterberg	Main Karoo
Resource Potential	Gas-In-Place (Gm^3)	315	125
	Recoverable ECBM(Gm^3)	25	2.6
	CO_2 Sequestration Potential (Mt)	93	9.6
Commercial Potential	Gas Market	Moderate-local industry	Good industrial, commercial and residential in Johannesburg Region
	CO_2 Availability	Fair-limited coal fired power plant emissions	Good-coal-fired power plants and other industrial emissions
CBM Activity	Leasing/Testing	None	None
	Commercial Production (Mm^3/year)	None	None
	World Ranking	17	20

1.5.2. South African Coal Basins

The main Karoo basin, which is located in Mpumalanga and extends to the northern parts of Free State and KwaZulu-Natal, possesses an average coal depth of 250 m to 400 m. Apart from the production indicators presented in Table 3, it should be noted that the coal rank consists of mostly high-volatile bituminous coal which is suitable for coalbed methane development. The average gas content varies from 7 to 10 m^3/ton, while the methane content averages at around 95% [13]. Although the seams are somewhat well fractured, cleating is only moderately well developed. Permeability measurements are not

available; however, an average of 1 mD was estimated based on the coal characteristics [13]. Regarding the Waterberg basin, the coal depth ranges from 400-500 m, while a similar coal rank and methane content to that of the main Karoo basin exists. Furthermore, cleating is only moderately well-developed, and permeability of 1-5 mD is estimated [13]. Once again, comparing this to the suggested aforementioned property ranges for appropriate coal seams it can be seen why the South African basins are ranked towards the bottom of the top 20 prospective coal deposits, especially regarding the low gas content, lack of lateral continuity for the ready movement of gas and low permeability.

2. Enhanced Coalbed Methane Recovery Methods

As the enhanced coalbed methane recovery process is based on the conventional coalbed methane production process, it is necessary to review the latter in detail.

2.1. Coalbed Methane Production Process

Expanding on Section 1.1., which explored the basic principles of coalbed methane recovery, at increased pore fluid pressure, a larger amount of methane may be deposited in coal seams through the adsorption process. Hence, a decrease in the pore pressure allows for the desorption of methane and subsequent production of methane [16]. A reduction in pore pressure is attained by pumping out the existing pore fluid, which is usually water, through both horizontal bore-holes and vertical wells. Initially, this well system will function to remove water; thereafter, methane gas will be desorbed and released [1]. The gas produced is subsequently collected, separated, and harvested to serve as a fuel source.

Rice & Nuccio [17] separates the coalbed methane recovery process into three distinct stages, depicted in Figure 5. The initial stage is dewatering, during which an excessive amount of water is removed from the reservoir to decrease the pore pressure. An important characteristic of this stage is a much greater production rate of water compared to methane. Over time, however, the methane production increases while the water production decreases. During the second stage, which is termed stable production, the production of methane reaches a maximum and stabilizes, and the production of water decreases continuously. During the final stage, the production of water becomes negligible and the production of methane reduces until it becomes uneconomical to produce.

Coalbed methane production results in shrinkage, hardening, and strengthening of the coal seam which therefore affects the permeability and reduces the production of methane [1]. This occurs due to the effect of the external lithostatic pressure which acts on the coal seam due to an increase in mass of the surrounding rock with a reduction in pore pressure reducing the porosity of the coal seam [18]. For this reason, normal pressure depletion techniques are not efficient for producing commercially viable quantities of methane, even with the use of many wells. Gale & Freund [19] describe a scenario where pressure depletion techniques were not able to recover even 50% of the gas-in-place as it required around 70%-80% pressure depletion which is both uneconomical and impractical, resulting in a significant amount of methane remaining in the seam.

In light of this, it has become necessary to search for advanced technologies for coalbed methane production to ensure safer and more economical production.

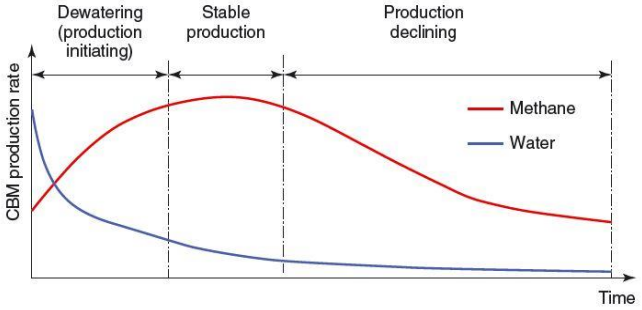


Figure 5. Production stages in a typical coalbed methane recovery process [17].

2.1.1. CO_2-Enhanced Coalbed Methane Recovery

Enhanced coalbed methane recovery entails injecting a gas, or gas mixture, into the coal seam to enhance the production of methane. Up to now, the testing of two main recovery methods has been undertaken, viz. CO_2-enhanced coalbed methane recovery and N_2-enhanced coalbed methane recovery [1].

A more reactive (adsorptive) gas may be introduced into the coal seam to promote the release of adsorbed methane. The methane gas will eventually desorb due to the preferred adsorption of the more reactive gas into the coal matrix. As described by Ranjith, et al. [20], the gaseous state equilibrium ratio of methane to carbon dioxide is 3:1, while the sorbed phase equilibrium ratio is 1:1. Therefore, when carbon dioxide is injected into the coal seam, sorbed methane is not forced into the gaseous state; hence, the only possible method for methane production enhancement is the replacement of adsorbed methane by the increasingly reactive adsorbing carbon dioxide. The preferential adsorption of carbon dioxide over methane occurs on the basis that approx. 2 to 3 mol of carbon dioxide is retained on the coal surface per mole of methane released [21]. This ratio is much greater when carbon dioxide is in the supercritical state. For this reason, the preferred coal seams for carbon dioxide coalbed methane recovery processes are situated deeper underground, approx. 800 m to 1,000 m below the surface, which allows for the effective trapping of the injected carbon dioxide within the seam and avoids leakage into the atmosphere and contamination of groundwater resources. As a result of the high pressures and temperatures that exist at such depths, carbon dioxide exists in its supercritical state at ~7.38 MPa and ~31.8°C (Perera & Ranjith, 2015). As per Curtis [22], carbon dioxide in the supercritical condition exhibits behaviour very similar to water due to its high density and viscosity. Moreover, methane behaves similarly to an ideal gas with a density approaching zero. The viscose nature of carbon dioxide at these conditions aids the release of coalbed methane from the matrix.

From the above, it can be deduced that the injection of carbon dioxide in the supercritical state possesses a superior ability to promote methane production from coal seams and will also lead to the sequestration of carbon dioxide over an extended period if performed appropriately [1]. However, research suggests that a strain is induced between the gas molecules and the adsorbing coal layer when gas of any kind adsorbs within the coal mass and is referred to as swelling. This reduces the coal mass pore space and ultimately the gas movement and flow ability of the gas [1]. Swelling is discussed in depth in section 2.3. Given the higher potential carbon dioxide has to adsorb into the coal mass in comparison with other gases such as methane and nitrogen, this gas creates a greater swelling effect in coal which is up to two times greater under supercritical conditions [23].

2.1.2. N_2-Enhanced Coalbed Methane Recovery

Upon injection, nitrogen remains as a free gas in the fracture pore space due to its relatively non-adsorptive nature [1]. Ranjith, et al. [20] state that the gaseous state ratio of methane to nitrogen is approx. 1:3, while the adsorbed phase equilibrium ratio is approx. 2:1. This means that when nitrogen is injected into the coal seam, it replaces all the gaseous state methane from the coal mass, creating a zero partial pressure of methane in the gaseous phase without altering the total pressure. This results in a disequilibrium in the system which causes the extraction of the adsorbed phase methane from the coal mass in the gaseous phase to attain partial pressure equilibrium, which promotes the coalbed methane production [24]. The concept by which nitrogen injection accelerates coalbed methane production is termed inert gas stripping. It has been found that for each volume of nitrogen injected, two volumes of methane may be produced [25]. Due to nitrogen's smaller adsorptive capacity compared to the existing methane in the coal matrix, desorption of methane with the injecting nitrogen causes shrinkage in the swelled regions of the coal matrix [24]. This contributes favourably to enhanced coalbed methane recovery as a result of increased seam permeability [24].

2.1.3. CO_2 + N_2-Enhanced Coalbed Methane Recovery

Owing to the belief that a mixed nitrogen and carbon dioxide injection creates better production mechanisms, this approach has since become increasingly popular. Parakh [27] undertook a study to investigate the carbon dioxide + nitrogen method with the use of a 45% nitrogen and 55% carbon dioxide gas mixture. The study revealed that the carbon dioxide + nitrogen process consists of three major stages of production. During the initial stage there is a high production rate controlled by nitrogen, thereafter, a slower production rate controlled by carbon dioxide and lastly, the third stage of production occurs purely due to convection during which the production rate equals the injection rate. This study further suggests that an increase in the carbon dioxide concentration in the injecting gas leads to a decrease in the production rate due to its more adsorptive nature. Figure 6 illustrates the comparative performance of a mixture injection in comparison to pure carbon dioxide or nitrogen injection on the methane recovery performance. Referring to this figure, it can be seen that the addition of carbon dioxide delays the nitrogen breakthrough visible in the pure nitrogen-enhanced process, from ~0.7 PVI (Figure 6b) to ~1 PVI (Figure 6c). In terms of the gas production process, this decreases the purification costs. Moreover, enhanced methane production results in comparison to the pure carbon dioxide enhanced process (Figure 6d).

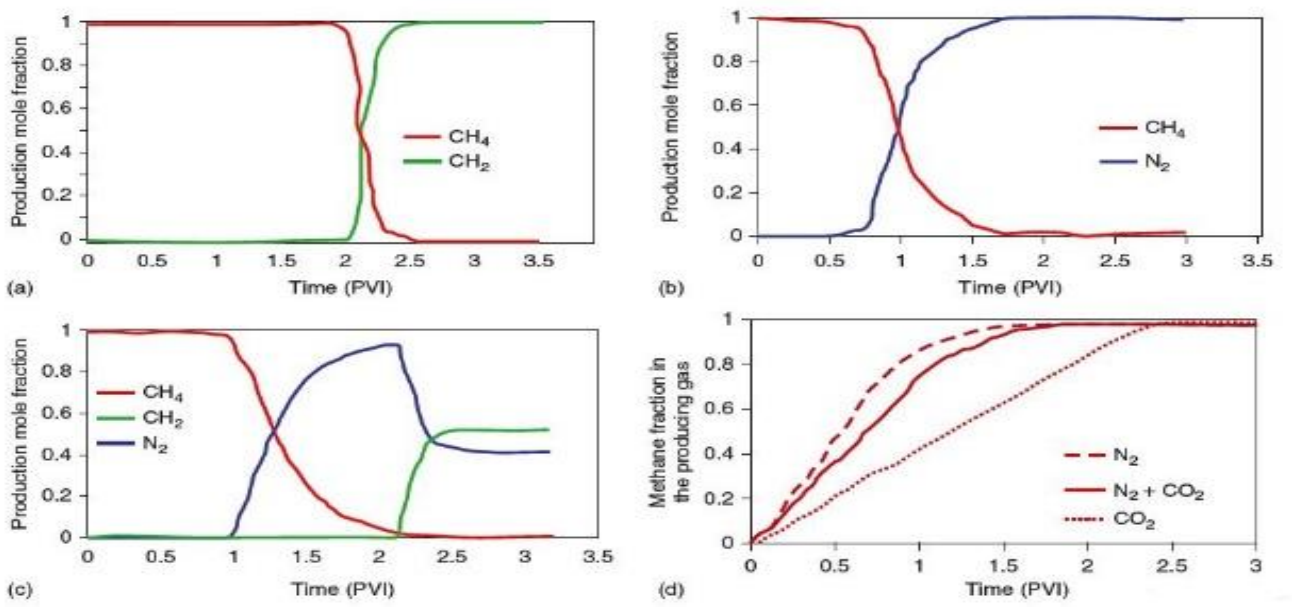


Figure 6. Breakthrough of gases under a) pure carbon dioxide injection b) pure nitrogen injection c) nitrogen + carbon dioxide injection and d) methane production under the three ECBM methods (Parakh, 2007).

2.2. Adsorption Isotherms

Following the basic principles of enhanced coalbed methane recovery (Section 1.1), once carbon dioxide (or another suitable gas) has been injected underground, it remains as a dense gas trapped in the coal cleats, adsorbed both on and in the coal and solubilised in the formation water [27]. Suitable storage conditions exist at high density, where the pressure and temperature yield supercritical carbon dioxide. Enhanced coalbed methane recovery is therefore an adsorption/desorption process that occurs at supercritical conditions, and proceeds by the injection of carbon dioxide in one or more injection wells, and the collection of methane from one or more production wells [27].

Given that enhanced coalbed methane recovery is controlled by the adsorption of carbon dioxide and desorption of methane, it is necessary to review the competitive adsorption equilibria concerning these gases as well as nitrogen [27]. Nitrogen is relevant as it has been successfully implemented for enhanced coalbed methane recovery [28]. Pure carbon dioxide adsorption isotherms offer an approximation of the coalbed capacity for carbon dioxide storage, while pure methane adsorption isotherms offer the maximum theoretical amount of coalbed methane, i.e. the maximum gas-in-place.

Concerning coal, the carbon dioxide, methane, and nitrogen uptake involves both adsorption on the surface, as well as penetration (sorption) into the solid matrix [27]. Different gases do so with varying intensities and affinities. Furthermore, different adsorption behaviour is exhibited by different solid substrates [2]. As the coal seams and gases associated with the coal seams are non-homogenous, varying sorption behaviour is expected. However, the combined contributions of both sorption and adsorption is the only quantity that can be measured while the individual contributions cannot be obtained. Although literature reveals many studies centred on the sorption of one gas, studies detailing variable mixtures of carbon dioxide with air, flue gas or nitrogen have been undertaken at varying pressures. Various semi-empirical isotherm models have been adopted in describing the experimental adsorption data, the most popular being the Langmuir model for single gas adsorption [2, 29] and the extended Langmuir equation for multicomponent gas adsorption [30]. Figure 7 illustrates the Langmuir isotherm figures for carbon dioxide, methane, and nitrogen for a coal seam in Airth, Scotland.

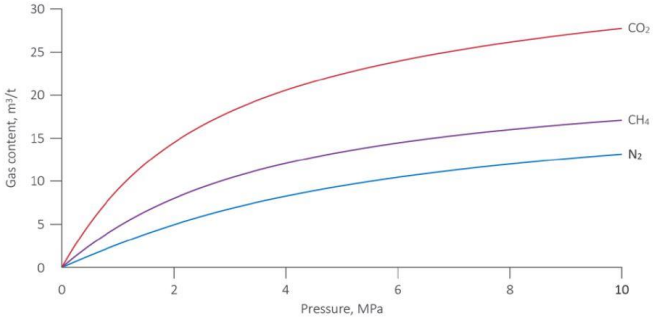


Figure 7. Langmuir Isotherms (CO_2, CH_4 and N_2) for coal seam in Airth, Scotland [31].

From such figures, the relationship between the pressure within the seam and the gas volume of each gas species may be deduced and indicates the ease with which the gas will adsorb or desorb from the seam [31]. Concerning Figure 7, it can be seen that carbon dioxide adsorbs onto coal more readily than methane, and methane adsorbs more readily than nitrogen, which conforms to the results obtained from numerous other studies [29, 32]. Mazzotti, et al. [27] state that two cases have been noted in which preferential adsorption of methane over carbon dioxide was observed with low-rank coals.

The Langmuir isotherm quantifies the quantity of gas adsorbed on the surface as a function of concentration or partial pressure, at a specific temperature. This particular model considers an ideal gas being adsorbed onto an idealised surface while assuming equal adsorption sites, flat surfaces and no interaction between the gases present [2]. Unfortunately, adsorption isotherms constructed using wet samples yield less reliable results. As coal seams are usually wet at the beginning of production and proceed to dry out during production, construction of the adsorption isotherm is required for both cases [27]. It was further stated that less carbon dioxide adsorbs onto wet coal compared to dry coal as a result of competitive water adsorption.

The actual values of the isotherms specific to each coal indicate the ease with which methane will be released and the likelihood for carbon dioxide to adsorb and remain stored in place in the targeted seam [33]. Referring to Figure 7, it can be seen that injecting carbon dioxide into the coal seam promotes methane desorption by displacement due to carbon dioxide's higher affinity to coal compared to methane. This isotherm also infers that coal can adsorb about twice as much carbon dioxide as methane. This ratio increases greatly in low-rank coals, with methane being replaced with up to ten times as much carbon dioxide [33].

2.3. Swelling

Although it is known that carbon dioxide adsorbs more readily to coal compared to methane, it also leads to coal swelling which greatly decreases the flowability through the coal mass by closing the pore space [2]. This causes the tortuosity for carbon dioxide to increase due to a reduction in the coal mass permeability. Therefore, swelling leads to decreased permeability and hence injectivity for additional carbon dioxide capture. It should be noted that the onset of the swelling process may occur as quickly as within one hour of the carbon dioxide injection [1].

The variable permeability of the coal caused by the injection of carbon dioxide into the coal seam represents a major problem. Although a coal seam may initially have a high permeability for carbon dioxide, as carbon dioxide adsorbs and swelling occurs, the permeability of the remaining coal is reduced. This is because the uptake of carbon dioxide is associated with both surface adsorption and penetration (sorption) into the solid matrix, the latter of which causes swelling. As previously mentioned, academics are presently incapable of distinguishing between the adsorption and sorption contributions when investigating the adsorption of gases on coal. As such, it is presently impossible to anticipate swelling problems in advance [27]. Most often, coals of higher rank possess lower permeability; however, it should be noted that permeability

is also a function of stress, pore pressure, and temperature [34]. Changes in the coal permeability will affect the injection pressure as well as gas production. The Yubari, Allison Unit, and Qinshui Basin projects have noted permeability, and therefore injectivity reduction problems associated with swelling [35].

Nitrogen, however, has a different effect as the injection of nitrogen causes a net shrinkage and diminishes the permeability reduction associated with the carbon dioxide injection; hence enhancing well injectivity [33]. As previously mentioned, the US Environmental Protection Agency states that the injection of nitrogen reduces the partial pressure in the coal seam while maintaining an adequate total pressure to facilitate production from the well. It is further stated that nitrogen releases methane as a consequence of sorption replacement and gas stripping. It has been estimated that 25% to 50% of the coal methane storage capacity may be substituted with nitrogen [25].

Consequently, as carbon dioxide is injected into the coal seam, the coal begins to swell as the carbon dioxide dislodges the methane and instead attaches to the coal in larger amounts. The swelling has the effect of decreasing the permeability of methane through the seam for production. On the other hand, replacing the injection gas with nitrogen results in some methane being chased from the seam and shrinkage of the coal. Combining the two gases could yield a combination of shrinking and swelling that preserves some permeability within the coal [2].

Figure 8 depicts the initial use of nitrogen which decreases the partial pressure in the seam and stimulates methane desorption. Over time, nitrogen will begin to be produced with methane, which is undesirable. If a switch to carbon dioxide injection is made at this stage, methane production will still be promoted by replacement as a result of preferential adsorption of the carbon dioxide. This will lead to continually stimulated methane production which terminates when there is a carbon dioxide breakthrough [2]. Carbon dioxide breakthrough occurs towards the end of a project when the concentration of methane declines and the injected gases begin to reappear at the production well. The nitrogen-enhanced coalbed methane project, however, involves quicker nitrogen breakthrough which can be attributed to its freely existing nature within the coal seam [1]. Enhanced coalbed methane recovery projects make use of adsorption isotherms and production rates to predict the onset of gas breakthrough while monitoring the gas composition during production to make certain that the correct quality is achieved.

Coals with increased permeability will release methane in the initial stages, reducing the impact of any carbon dioxide injection; however, coals with decreased permeability have low injectivity which causes a delay in methane output and unfavourably affects the economics of the projects. It should be noted that the competitive adsorption equilibria of gases involved in enhanced coalbed methane recovery are complex, and require sophisticated models to simulate and accurately predict gas behaviour [2].

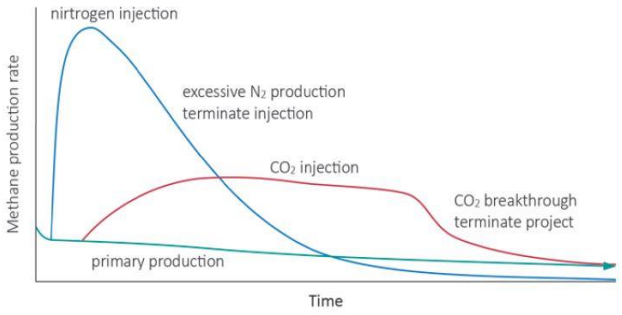


Figure 8. Methane production profiles with N_2 and CO_2 injection [19].

2.4. Gas Storage Capacity

One of the aims of enhanced coalbed methane recovery projects is to achieve final gas storage in the methane-depleted coal seam to aid in mitigating global warming. This gas may be processed and purified carbon dioxide or flue gases. Although the potential for carbon dioxide storage in unmineable coal seams possesses a small potential compared to other geological formations, they still possess considerable potential as a permanent gas storage repository [27].

Considering coal seams globally, the storage capacity for carbon dioxide has been estimated to be between 0 and 1480 Gt [2]. The IPCC proposed a more conservative estimate of 200 Gt [27].

To gain perspective of these volumes, the Powder River Basin in the U.S.A. has been estimated to hold 15 Gt of carbon dioxide in unmineable coal seams, which is equivalent to 47 years' worth of the carbon dioxide emitted from all coal-fired plants in the U.S.A. [36]. In addition, Mazzotti, et al. [27] suggest a global carbon dioxide storage range of 3 to 200 Gt in unmineable coal seams, compared to global emissions of 30 Gt/y from human activities.

3. Discussion

3.1. The Issue of Water Production

Although the conventional coalbed methane production method may appear deceivingly simple, it involves a major water production issue.

Most often, deep coal seams are under saturated conditions, hence requiring thousands of gallons of contaminated water to be pumped out every day to deplete the pressure within the coal seam to achieve the methane desorption pressure [37]. Thomas & Beatie [18] suggest that a coalbed methane production well in the Powder River Basin (U.S.A.) produces around 17,000 to 22,000 gallons of water per day during the first few years of production. Removing such a significant amount of underground water is associated with a large number of environmental issues, the main concern being the depletion of the water table. This has the effect of reducing the agricultural productivity of the soil, which has a direct impact on farmers.

The Santos GLNG project predicted that the presence of four bore wells which are located in and around the Arcadia Valley coalbed methane field (in the Bowen Basin) will result in a 7 to 25 m groundwater level drawdown before the end of 2028 [38]. In addition, releasing this water onto the ground leads to scouring of the stream channels, creating considerable sedimentation and erosion, which negatively impacts the aquatic habitat. Due to the highly saline nature of coalbed methane water, the mixing of this water with the groundwater pollutes the groundwater in the area [1]. This affects the drinking water, water used for farming activities, washing activities, etc.

3.2. Comparison of N_2-ECBM and CO_2-ECBM Methods

By comparing the advantages and disadvantages of carbon dioxide-enhanced coalbed methane recovery and nitrogen-enhanced coalbed methane recovery methods in terms of productivity, risk and environmental aspects, and economic aspects, the optimum method may be deduced.

3.2.1. Productivity

Although the nitrogen enhanced coalbed methane recovery process allows for a more rapid and greater coalbed methane production enhancement compared to the carbon dioxide enhanced coalbed methane recovery process, it also causes quicker nitrogen breakthrough which pollutes the methane produced and leads to increased gas treatment cost [1]. This occurs during the nitrogen injection process due to the creation of a high-pressure gap between the injection point and the rest of the coal mass. This high-pressure gap causes the flushing of the nitrogen, which behaves as a free gas in the fracture system, out of the coal mass and eventually mixes with the methane produced [39].

The consideration of carbon dioxide injection, however, is associated with less rapid and smaller coalbed methane production enhancement as well as greater delays in carbon dioxide breakthrough. As the carbon dioxide molecules are in the stable adsorbed phase within the coal matrix, the carbon dioxide molecules that are injected have a smaller chance of being released from the coal mass compared to nitrogen. Another benefit of the carbon dioxide-enhanced coalbed methane process is a great reduction in the carbon dioxide emissions released into the atmosphere [4].

As previously mentioned, swelling occurs by shrinkage of the fracture network available for movement of the gas due to the adsorption of injected carbon dioxide. This greatly hinders the permeability of the coal seam and ultimately, coalbed methane production [1]. Reeves [24] undertook a study comparing coalbed methane production enhancement with the use of carbon dioxide-enhanced coalbed methane production and nitrogen-enhanced coalbed methane production by developing a numerical model for a typical coal seam, the results of which are depicted in Figure 9. By referring to the same, it can be seen that nitrogen injection results in considerably greater coal seam gas production over fifteen years compared to carbon dioxide injection. Describing this quantitatively, a nitrogen injection of 10 Mcfd (thousand cubic feet per day)/ft increases coal seam gas productivity by ~21%, compared to the same injection using carbon dioxide which yields a ~4% increase in coal seam gas productivity. A further observation relates to the increased sensitivity of the injection rate variation to nitrogen compared to carbon dioxide, as coal seam gas production is significantly greater at excessive injection pressures for nitrogen than carbon dioxide. To explain this quantitatively, at an injection rate of 50 Mcfd/ft, nitrogen enhances coal seam gas production by ~57%, whereas a ~29% increase is achieved with carbon dioxide. From this, it can be deduced that nitrogen injection at excessive injection pressures represents the optimum method for coalbed methane production. However, the respective breakthroughs of carbon dioxide and nitrogen require consideration as the purity of the gas produced is a critical factor due to its effect on the gas treatment cost. Figure 10 illustrates the observations made when comparing the carbon dioxide and nitrogen breakthroughs during the production of coal seam gas.

Referring to Figure 10, no observable carbon dioxide breakthroughs were noted in the gas produced over fifteen years. With regards to nitrogen injection, however, rapid nitrogen breakthroughs were identified in the gas produced and increased considerably with an increase in nitrogen injection rates. As previously mentioned, this is associated with significant post-treatment costs to separate nitrogen from methane. As a method of delaying breakthroughs and obtaining optimum productivity, both enhanced coalbed methane production methods need to be combined, i.e. the injection of a mixture of both nitrogen and carbon dioxide is required as depicted in Figure 11.

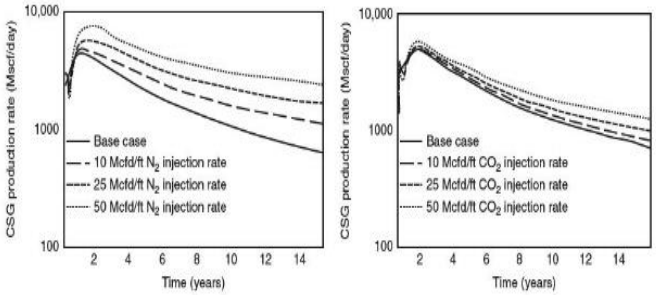


Figure 9. Comparison of CO_2-ECBM (right) and N_2-ECBM (left) production processes [24].

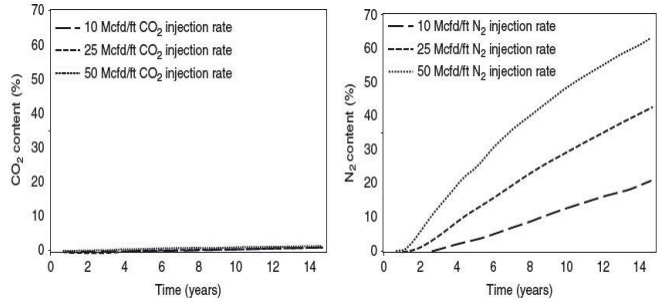


Figure 10. Comparison of carbon dioxide (left) and nitrogen (right) breakthroughs [24].

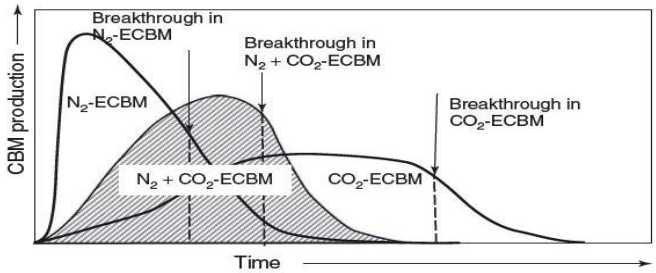


Figure 11. Optimisation of enhanced coalbed methane recovery through a combination of CO_2-ECBM and N_2-ECBM [24].

3.2.2. Risk and Environmental Impact

The aim of any enhancement method should be to minimise the associated risk and environmental impact. With regards to the carbon dioxide-enhanced coalbed methane process, the leakage of carbon dioxide from the coal seam poses the main risk. Metz, et al. [40] divides this into two categories: global and local. The global risk includes the contribution to critical climate change as carbon dioxide is released from coal seams and migrates into the atmosphere. Further to this, carbon dioxide leakage negatively affects groundwater, ecosystems, and humans- such hazards are referred to as local risks [1]. Existing research suggests that a coal seam that is well-maintained can securely retain more than ninety-nine percent of injected carbon dioxide underground for over one thousand years [1]. Should carbon dioxide leakage occur due to injection well failure, a rapid release of carbon dioxide will result, posing a hazard to workers and other people in close vicinity to the site. It should be noted that a carbon dioxide composition of greater than ten percent in the air may be fatal [1]. For this reason, the installation of detecting devices in wells as well as in areas away from wells is necessary to rapidly identify such leakages. The location of such detectors needs to account for natural fluxes of carbon dioxide that could arise from organic activity to avoid creating false concerns. Regular checks are also conducted to reduce the possibility of leaks. The slow and gradual leakage of carbon dioxide may affect drinking-water aquifers as carbon dioxide accumulates in the sub-surface. Further leakage of carbon dioxide into the soil may lead to soil acidification and replacement of its oxygen, both of which lead to an unfavourable environment for crop growth and soil ecosystems [1].

Given the comparatively inert nature of nitrogen, the leakage of this gas into the atmosphere using any of the aforementioned methods does not contribute critically to the damage of the environment in the same way carbon dioxide does as almost eighty percent of the environment is made up of nitrogen. Hence, there is no global risk associated with the nitrogen enhanced coalbed methane recovery process. In addition, no major hazard is created with the mixing of nitrogen into the atmosphere or soil as nitrogen molecules are held together by strong triple bonds and are difficult to transform into nitrate or any other hazardous nitrogen form [41]. However, in certain cases, high temperature and high-pressure conditions together with biological reactions deep underground may cause the formation of NO_3^- (nitrate). Although the solubility of nitrogen in water may be negligible, nitrate is easily soluble in water [41]. The mixing of the latter in groundwater leads to the contamination of drinking water resulting in detrimental biological effects. An excessively high concentration of nitrates in drinking water can cause colon and gastric cancers [1]. Therefore, although a risk exists with underground nitrogen leakage, this risk is low in comparison to carbon dioxide. Considering all factors, increased environmental risk is associated with the carbon dioxide-enhanced coalbed methane process compared to the nitrogen-enhanced coalbed methane process.

Although the carbon dioxide-enhanced process is associated with a greater environmental risk, this process aids in the protection of the environment through its contribution to mitigating the atmospheric carbon dioxide level by the sequestration of significant quantities of carbon dioxide deep underground [1]. As previously mentioned, the preferential adsorption of carbon dioxide over methane occurs on the basis that approx. 2 to 3 mol of carbon dioxide is retained on the coal surface per mole of methane released [42]. Therefore, in addition to enhancing methane production, this process will result in the sequestration of carbon dioxide over an extended period, aiding the mitigation of climate change which has become a global imperative [43]. The global potential of this has been explored in section 2.4 (gas storage potential). However, the future mining of coal seams would be limited by the sequestration of carbon dioxide in these seams.

The carbon dioxide sequestration potential associated with the carbon dioxide-enhanced coalbed methane process represents a unique advantage compared to the nitrogen-enhanced coalbed methane process. Therefore, although the carbon dioxide-enhanced process possesses a greater environmental pollution risk through leakage, it assists in environmental protection by storing a significant amount of carbon dioxide. The development of this process would allow for the establishment of an extensive market for carbon dioxide, whether released from power plants or other industrial sources, thereby uplifting the economy [1]. On the other hand, the nitrogen-enhanced process possesses a smaller environmental pollution risk through leakage but does not aid in carbon dioxide sequestration or environmental protection.

Concerning both the carbon dioxide-enhanced and nitrogen-enhanced processes, public acceptance of the project is a critical factor. Sloss [2] reported that common concerns included possible changes to the local transport infrastructure, the noise hazard as well as other nuisance problems that must be considered.

3.2.3. Economic Aspect

In general, the profit from the enhanced coalbed methane production process depends on the following factors [1]:

- Value of gas produced
- Cost of gas transportation
- Cost of production
- Cost of taxes/CO_2 credits

Of the abovementioned, the cost of production is the most substantial expense. This cost depends largely on the total cost of producing the gas, which includes [1]: availability and cost of carbon dioxide or nitrogen, implementation cost (including cost of drilling and maintaining the horizontal boreholes and wells), water disposal, processing costs (including cost of water treatment and gas purification). In production, the largest cost is related to the gas injection of carbon dioxide or nitrogen [44]. A study by Duane, et al. [44] states that carbon dioxide needs to be allocated a gas price of at least \$2/1000 ft^3 of methane if carbon dioxide is available at \$1/1000 ft^3 in the carbon dioxide enhanced process because at least 2 ft^3 of carbon dioxide is necessary to displace one cubic foot of methane. Therefore, should the coal seam lie in close vicinity to local power plants, the carbon dioxide enhanced process is suitable as the efficient and low-cost supply of adequate carbon dioxide will be ensured. Given the amount of nitrogen required for the nitrogen-enhanced process, which is 0.5 ft^3 of nitrogen to displace one cubic foot of methane [24], this process appears to be more economically feasible.

Reeves [24] further compared the economics of both processes by estimating the resulting net profit from producing 1 Mft^3 of gas by employing four

injection wells in a typical coal seam. It was assumed that both processes produce the same quantity of gas (refer to Table 4). From Table 4, it can be seen that larger profits are associated with the nitrogen-enhanced process compared to the carbon dioxide-enhanced process. This is mainly attributed to the amount of gas (carbon dioxide or nitrogen) that is required to recover methane. Therefore, although the nitrogen enhanced process has a greater processing cost, this process is more profitable given the much smaller amount of nitrogen required for the production of gas from the seam. As previously mentioned, studies suggest a higher production potential for nitrogen enhanced processes compared to carbon dioxide-enhanced processes (refer to Figure 9), this infers that the profit depicted for the nitrogen-enhanced process in Table 4 should be much higher as the assumption of similar production amounts was made.

Table 4. Comparison of economics of carbon dioxide-enhanced and nitrogen-enhanced coalbed methane processes [24].

Component	**Carbon dioxide** enhanced coalbed methane production	**Nitrogen** enhanced coalbed methane production
Gas price	$3,00	$3,00
Basin differential	$0,30	$0,30
BTU adjustment (5%)	$0,15	$0,15
Production taxes (20%)	$0,51	$0,51
Gas Processing[1]	$0,50	$1,00
Capital costs[2]	$0,25	$0,25
Gas costs (CO_2:CH_4 ratio 3:1, N_2:CH_4 ratio of 1:2)[3]	$0,90	$0,30
Net profit	$0,39	$0,49

1. Nitrogen gas processing cost is double that of carbon dioxide given the comparatively earlier breakthrough
2. Capital costs=$500 000×4 (injection wells) =$0.25 per Mcf
3. Gas costs: CO_2=$0.30/Mcf×3.0=$0.90/Mcf, N_2=$0.60/Mcf×0.5=$0.30/Mcf

3.3. CO_2 + N_2-Enhanced Coalbed Methane Method

Given the advantages associated with mixed injection of carbon dioxide and nitrogen, this method has become increasingly popular in enhanced coalbed methane recovery processes.

The injection of flue gas, which is made up of ~87% nitrogen and ~13% carbon dioxide, represents a more commercially feasible coalbed methane recovery method as a result of its greater availability compared to pure nitrogen or carbon dioxide and its greater ability to enhance the coalbed methane recovery process compared to carbon dioxide enhanced processes [1]. Therefore, a higher production rate is achieved with an earlier response compared to the carbon dioxide-enhanced process, while sequestrating similar amounts of carbon dioxide and attaining an increased injection rate [1]. This is possible because adding nitrogen into the injecting carbon dioxide greatly promotes gas injectivity compared to pure carbon dioxide injection, allowing the attainment of higher injection rates. In addition, the presence of nitrogen gas shows the potential to recover the carbon dioxide injection-induced swelling to some extent, which may also encourage the higher injection ability of the nitrogen + carbon dioxide mixture compared to pure carbon dioxide (refer to Figure 12). However, it should be noted that the recovery rate of the swelled areas differs with various injection gas properties such as pressure and composition, as well as seam properties such as moisture content, depth, and rank [1].

Although the injection of a carbon dioxide and nitrogen mixture involves additional preparation costs as a specific predetermined ratio of carbon dioxide and nitrogen is required, a much lower production cost is expected compared to the injection of pure carbon dioxide as the amount of carbon dioxide required is reduced considerably [1]. This also contributes more to the reduction in carbon dioxide atmospheric levels compared to the nitrogen-enhanced process.

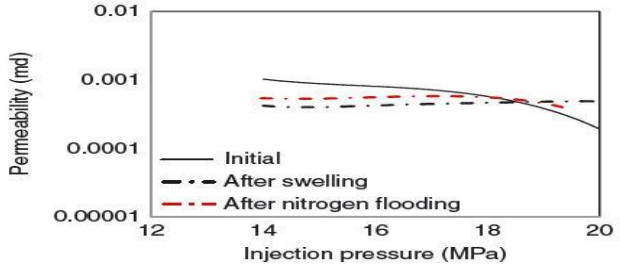


Figure 12. Effect of nitrogen flood on carbon dioxide permeability for 25 Mpa confining pressure condition [1].

3.4. An Overview of the Economics of the Enhanced Coalbed Methane Process

Building on section 3.2.3, the economics of the enhanced coalbed methane process relies on the difference between the sale of gas for energy production and the cost of transport and injection of the gas used, in addition to operational, legal, and management costs. Individual project economics vary greatly with each case as costs are site-specific [2]. Coalbed methane production has been extremely profitable due to the establishment of suitable technologies, enhanced coalbed methane production on the other hand requires favourable economics of gas delivery and injection, which largely relies on advancements made in separation technologies. Having existing infrastructure in place that can be used as well as a stable demand for natural gas aids in improving the economics of this process.

With enhanced coalbed methane recovery, the large costs associated with separating carbon dioxide from flue gas before the injection is one of the main cost drivers deeming the carbon dioxide-enhanced process uneconomic. However, in many cases, a large capacity for carbon dioxide storage exists; therefore, should suitable incentives be introduced for carbon dioxide-enhanced coalbed methane recovery, in the form of taxes or credits, the economics of this process will improve greatly [2]. Referring to Figure 13, it can be seen that the transition from coalbed methane production to carbon dioxide-enhanced coalbed methane production is driven by economic feasibility. For this to be possible, the following factors must be optimised [2]:

- the gas that is injected must be low-cost and readily available
- the methane produced must be profitable
- the processing of the injected gases must be affordable
- additional site costs must be low
- additional gas and equipment transportation costs must be considered

3.5. Pilot and Demonstration Projects

Since the identification of prospective coal deposits for enhanced coalbed methane recovery potential (detailed in Appendix A and Section 1.5), several pilot and demonstration projects have commenced, as detailed in Table 5.

Although there have been numerous projects conducted globally in the last 30 years, most of these are located in the U.S.A. where coalbed methane production is already a well-established industry [35]. Overall, several projects have demonstrated the possibility of enhanced methane recovery, more especially with the use of flue gas or a mixture of carbon dioxide and nitrogen due to the reduction in swelling and injectivity problems that are observed [35]. Further academic studies and exploration are being conducted in China, fuelled by the country's high demand for energy production and suitable coal seams. This combination may make China the most promising location for future enhanced coalbed methane recovery developments. Many of these projects, such as in the Qinshui basin, show theoretical potential, the economics of which hinge on the introduction of coalbed methane recovery credits [35].

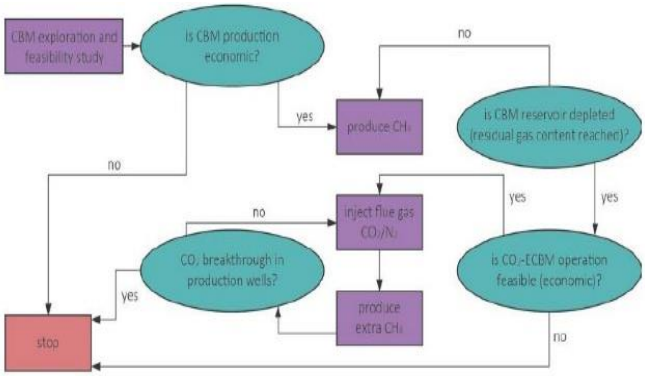


Figure 13. Enhanced Coalbed Methane transition path [2].

Table 5. Enhanced Coalbed Methane pilot and demonstration project [35].

Project	Country	Location	Start Date	Total carbon dioxide injected (tons)	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
APP	China	Liulin	2011	460	560
Huaneng deep coal	China	Qinshui Basin	2014	1000 (planned)	>1 000

4. Conclusions

- Various amounts of naturally formed gases, which are formed during the coalification process, are contained in every coal seam. Ninety percent of this gas is coalbed methane, which is trapped within the coal mass as a result of the high pressures applied during the coalification process.
- Coal seams have a significantly greater storage capacity (approximately seven times greater) in comparison to conventional gas reservoirs.
- A coal seam appropriate for coal bed methane development requires good permeability-preferably above 1mD, a high gas content of 15-30 m^3/ton of methane, adequate lateral continuity and thickness for ready movement of the gas into wells, and a location 250m-1000 m below the earth's surface. Medium rank coals are preferable for coalbed methane production.
- Reducing the pore pressure within the coal mass causes the coalbed methane to be released, which may be used to produce energy given its purity.
- Conventional coalbed methane production entails pumping out the existing pore fluid (water), which results in the release of thousands of gallons of saline water over an extensive period, causing pollution of the groundwater, depletion of the water table, and scouring of the stream channels.
- In the process of enhanced coalbed methane recovery, a gas or mixture of gases is injected into a coal seam to enhance the methane recovery rate. Carbon dioxide-enhanced coalbed methane recovery and nitrogen-enhanced coalbed methane recovery represent the main methods.
- Enhanced coalbed methane recovery is an adsorption/desorption process. It has been seen that carbon dioxide adsorbs onto coal more readily than methane, and methane adsorbs more readily than nitrogen.
- During the carbon dioxide-enhanced process, methane desorbs from the coal seam by injecting more reactive carbon dioxide into the seam. The preferential adsorption of carbon dioxide over methane occurs on the basis that approx. 2 to 3 mol of carbon dioxide are adsorbed per mole of methane produced, this ratio is much greater when carbon dioxide is in the supercritical state deep underground.
- In addition, the carbon dioxide-enhanced coalbed methane process allows for long-term sequestration of carbon dioxide. The global storage capacity for carbon dioxide has been conservatively estimated to be around 200 Gt.
- Swelling of the coal matrix occurs with carbon dioxide adsorption, which diminishes the flow ability and hence permeability through the seam. Eventually, this results in a considerable decrease in the production rate of methane.
- During the nitrogen-enhanced process, all the gaseous state methane from the coal mass is replaced by nitrogen, which desorbs methane.
- The injection of nitrogen causes a net shrinkage and diminishes the permeability reduction associated with the carbon dioxide injection; hence enhancing well injectivity.
- A major problem with the nitrogen-enhanced process is that of rapid nitrogen breakthrough which incurs large gas treatment costs.
- Although a more rapid and greater enhancement of coalbed methane recovery is attained with the nitrogen enhanced coalbed methane process, a much quicker breakthrough is observed compared to the carbon dioxide enhanced process. As expected, the carbon dioxide-enhanced processes are associated with larger local and global risks, which are minimal with the nitrogen enhanced process given the inert nature of nitrogen. However, the carbon dioxide-enhanced process also aids in environmental protection through carbon dioxide sequestration, which is not the case in the nitrogen-enhanced process. Although the nitrogen enhanced process incurs increased processing costs, it appears more economically feasible given the reduced gas quantity required for the process, as ~ 0.5 ft^3 of nitrogen is required to displace one cubic foot of methane compared to ~2 to 3 ft^3 of carbon dioxide in the carbon dioxide enhanced process.
- An injection containing a mixture of carbon dioxide and nitrogen creates a collaborative production mechanism that yields an increased production rate with rapid response in comparison to the carbon dioxide-enhanced process and therefore presents the most viable solution. Moreover, this approach allows for the sequestration of a similar amount of carbon dioxide to the carbon dioxide-enhanced process, while attaining an increased injection rate similar to the nitrogen-enhanced process.
- The large costs associated with separating carbon dioxide from flue gas before injection is one of the main cost drivers deeming the carbon dioxide enhanced process uneconomic. However, a large capacity for carbon dioxide storage exists; therefore, should suitable incentives be introduced for carbon dioxide-enhanced coalbed methane recovery, the economics of this process will improve greatly. However, individual project economics vary greatly with each case as costs are site-specific.
- Numerous prospective coal deposits have been identified globally for enhanced coalbed methane recovery, most of which are located in the U.S.A. Several projects have demonstrated the possibility of enhanced methane recovery, more especially with the use of flue gas or a mixture of carbon dioxide and nitrogen due to the reduction in swelling and injectivity problems that are observed.

Credit authorship Contribution Statement

Trenelle Moodley: Conceptualization, Investigation, Resources, Writing - Original Draft. Amir H. Mohammadi: Conceptualization, Supervision, Project administration, and Writing - Review & Editing.

Conflicts of Interest

The authors declare that they do not have any personal or financial conflicts of interest.

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