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# $CO_2$ STORAGE IN ABANDONED COAL MINES

**Paria Jalili, Serkan Saydam, Yildiray Cinar**

*ABSTRACT*: Emissions $CO_2$ into the atmosphere have become a serious concern worldwide. Despite efforts to reduce the $CO_2$ concentration, global $CO_2$ emissions are increasing, and are estimated to be almost twice the current emissions by 2040 unless mitigating techniques are adopted. Many methods have been introduced to mitigate $CO_2$ emissions to the atmosphere. One of them is to capture $CO_2$ from stationary sources and transport, and store it in abandoned coal mines. $CO_2$ can be stored in abandoned coal mines in three states: free in empty spaces, adsorbed on the remaining coal or dissolved in mine water. The amount of storage could be significant depending on geological characteristics of mines and engineering design parameters. It would also be possible to recover some $CH_4$ which could offset the cost of the project. A review of the previous studies completed on $CO_2$ sequestration in abandoned coal mines around the world and preliminary assessments of the potential in Australia are presented.

## INTRODUCTION

The concentration of $CO_2$ and other greenhouse gases, as a result of anthropogenic activities, is on the rise. The concentration of $CO_2$ had not changed in the past 650,000 years, varying between 180-300 ppm. However, in the last two centuries, because of using fossil fuels as a source for cheap and available energy, the amount of $CO_2$ in the atmosphere has increased significantly (389 ppm in 2010). Given the fact that fossil fuels will dominate the energy generation for the foreseeable future, the combustion of fossil fuels will continue to output significant amount of greenhouse gases.

Australia ranks first, among developed countries, with $CO_2$ emissions of 20.6 t per year, before the United States, which is producing 19.8 t per year (Maplecroft, 2009 and International Energy Agency - IEA, 2005). The power generation industry has the highest share for $CO_2$ emissions. Australia uses coal heavily for power generation which causes around 37% of the country's total emissions (Department of Climate Change, 2007).

Initiatives such as the Kyoto Protocol have been put into the place in an attempt to technically and socially evolve society for less dependency on fossil fuels. The Kyoto Protocol between 39 industrialised countries and European Community (called Annex I countries) planned to reduce the greenhouse gases by 5.2% from the 1991 level over the five year period (2008-2012) (Kyoto Protocol, 1997).

Carbon Capture and Storage (CCS) is one of the proposed options for minimising global greenhouse gas emissions in the long-term. It involves capturing, compressing and injecting $CO_2$ deep underground. For deep underground storage sites, the options for $CO_2$ storage include unmineable coal seams, deep saline aquifers, depleted oil and gas reservoirs and abandoned coal mines.

## THE CONCEPTS OF STORAGE

$CO_2$ can be stored in an abandoned coal mine through three physical mechanisms: by adsorption on the remaining coal, by solution in the mine water and by compression in the empty space of the mine. The adsorption of $CO_2$ on coal is the result of the wan der Waals forces between the adsorbate ($CH_4$ or $CO_2$) and adsorbent (coal) (Piessens and Dusar, 2003b). It depends on the type of coal and also the amount of coal available for adsorption. Calculating the amount of coal available for adsorption is very important as most of the $CO_2$ would be adsorbed through this mechanism.

$CO_2$ is also expected to dissolve in ground water which has the less contribution amount compared to the other modes of storage (in most cases, less than 10% of the total sequestration amount). Residual space is the mined-out volume that remains after collapse and subsidence. The mined-out volume can easily be estimated from the amount of exploited coal and its density, augmented with the volume of extracted host rock. The volume lost due to collapse and subsidence is too difficult to estimate. It can be calculated from the total subsidence, if accurate data are available, or with a site-specific ratio between mined-out volume and residual space, depending of geology, mining and back-filling techniques. The latter approach

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requires data from drill cores or other *in situ* measurements (Piessens and Dusar, 2003b). The sum of these three amounts (adsorption on the remaining coal, dissolution in the mine water and free space storage) should represent the total sequestration capacity for an abandoned coal mine. The amount of storage for each mechanism varies from mine to mine depending on coal properties and the mine pressure.

$CO_2$ adsorbs on coal more than $CH_4$ (almost twice). By injecting $CO_2$ into the abandoned coal mine $CH_4$ may be released which can offset some of the cost of $CO_2$ sequestration.

Houtrelle (1999) introduced some basic conditions for gas storage in abandoned mines:

- There should be no lateral communication with other mines. This would allow the gas to migrate to places where it becomes difficult to retrieve.
- There should be no communication between the mine reservoir and the surface. This would allow the gas to leak to the atmosphere.
- The amount of the influx of water into the mine should preferably be low. The mine has to be kept dry by pumping for storage of $CO_2$ to prevent gas pressures which may cause leakage of the gas.

Piessens and Dusar (2003a) also suggested two criteria for $CO_2$ sequestration in abandoned coal mines:

- The top of the mine workings should be at least 500 m underground.
- The reservoir pressure should be 30% more than hydrostatic pressure to prevent water influx.

## PROJECTS FOR $CH_4$ STORAGE IN ABANDONED MINES

Abandoned coal mines had been used to store natural gas since 1961. Three examples around the world have been reported. Two of these are located in Belgium (Peronnes and Anderlus Abandoned Coal Mines) and the other one is in the USA (Leyden Abandoned Coal Mine). These projects have been set up for meeting peak demands and avoiding the peak pricing of natural gas. All of these pilot projects faced some unforeseen problems like sealing of the shafts and production wells, flooding, compositional and pressure changes due to adsorption and desorption. However, the Leyden Coal Mine was positively evaluated, leading to an expansion of its capacity. The Peronnes and Anderlus Coal Mines were terminated due to an increase in local taxes and unforeseen costs (Piessens and Dusar, 2004).

### Leyden coal mine (USA)

The Leyden gas storage operation was commenced in 1961 and is still in operation. The Leyden Mine was near Denver, Colorado, USA and was in operation from 1903 till 1950. During its operation, 6 Mt of sub-bituminous coal were produced. The mine consisted of four shafts providing the access to two horizontal seams from 240 to 260 m below the surface, in the upper cretaceous Laramie formation. The public Service Company of Colorado (PSCo) began storing gas at Leyden in the late 1950's as a means of optimizing natural gas supplies. The original purpose of the Leyden storage facility was to ensure that PSCo could provide gas to the Denver area during peak demand times. It has still been used for this purpose; moreover they have used this as a key role in optimizing PSCo's year-round gas buying and selling strategy.

The cap rock consists of 20 m claystone in the Leyden Mine. The leak off test shows that the Leyden Mine's cap rock can only withstand 75% of the hydrostatic pressure which would be 1.8 MPa. During the initial development of the storage system, water was pumped from the mine as gas was being injected. Two active water wells are currently used to continuously remove approximately 50,000 $m^3$ of water from the mine each year. It was a room and pillar operation and PSCo reports that the extraction efficiency was about 35%. This means still 65% of the original coal remained in place after the mining ended, primarily in the pillars. The EPA (Environmental Protection Agency - USA) estimates that the sorption capacity of the coal within the mine ranges from 85 to 127 $Mm^3$ at the Leyden Mine facility's, average operating pressure of 1.1 MPa and from 100 to 140 $Mm^3$ at the facility's maximum operating pressure of 1.8 MPa (Schultz, 1998).

### Anderlus and Peronnes Mines (Belgium)

The Anderlus and Peronnes Mines, located in the gassy Hainaut Coalfield in Southern Belgium (between Mons and Charleroi) have been used for seasonal storage of natural gas. Figure 1 shows the locations of mines in Belgium. Anderlus mine operated between 1857 and 1969. 25 Mt of sub bituminous coal were produced during its operation. Storage operation began in 1980 at depths from 600 to 1100 m. The overburden is almost 50 m thickness, but varies from South to North. A thrust fault acts as a primary hydrogeological barrier (Piessens and Dusar, 2004a). The reservoir volume assumed to be 6 to 10 $Mm^3$ which could be considered to store 180 $Mm^3$ of $CH_4$. Peronnes Mine is also located at the same area and it was in operation from 1860 until 1969. This mine could store 120 $Mm^3$ of $CH_4$.

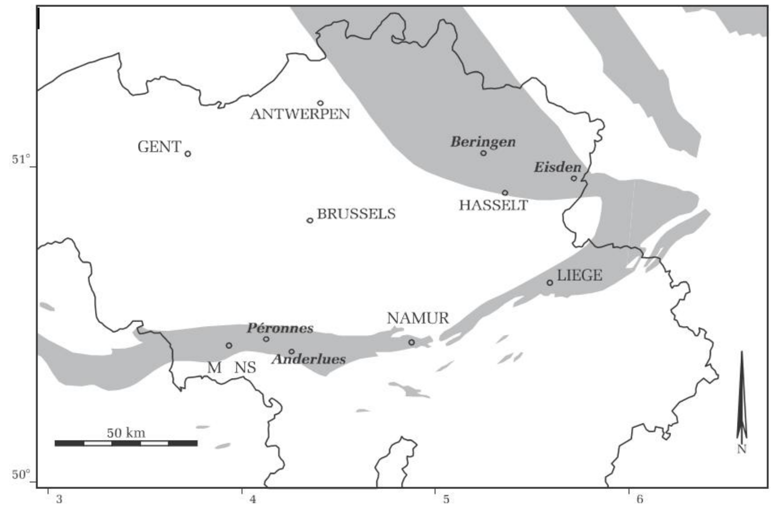


**Figure 1 - The location of the mines in Belgium (After Renier, 1954)**

The storage operation for both Peronnes and Anderlus Mines were stopped in 1996 and 2000, respectively as an unforseen cost for sealing the shafts was required.

## PLANNING FOR STORAGE

An abandoned coal mine differs from other reservoirs in shape, height, permeability, initial pressure state and modes of storage. Hence it requires a specific tool to predict the reservoir performance. Piessens and Dusar (2003a) introduced a software package, named $CO_2$-VR, for calculating the storage capacity in abandoned coal mines. $CO_2$-VR is a reservoir simulator which is the combination of Micro-Excel and Visual Basic. It calculates the reservoir pressure and density of $CO_2$ at each depth. $CO_2$-VR is the only available software used for the simulation of $CO_2$ sequestration in abandoned coal mines. Below are the examples of the mines, for which $CO_2$-VR was used for their simulation for $CO_2$ storage.

### Campine basin

The Campine Basin is located in the north of Belgium. The depth of the Campine Basin is reported to vary from 350 to 1090 m. The Basin contains seven mines, which had been operated between 1917 and 1992. The average temperature gradient for the Campine Basin is assumed to be 0.0035 °C/m with an average ambient temperature of about 9.8 °C. The water temperature at the deepest level of the mine was assumed to be 48 °C. All the shafts were filled with the reinforced concrete from 560 m to the surface. The cap rock is assumed to consist of cretaceous chalks and marls.

The Beringen is a typical colliery among these seven collieries for the Campine Basin. Almost 80 Mt of medium to high volatile A type bituminous coal was extracted. 85 $Mm^3$ is assumed as the mined-out volume by the 7% residual volume fraction (Van Tongeren and Laenen, 2001). This gives a residual volume space of 5.95 $Mm^3$. The maximum surface recovery is assumed to be 3-5 % of the original subsidence which is around 25-30 cm.

The ascertained sequestration capacity for a reservoir pressure being equal to 130% and the hydrostatic pressure is around 2.7 Mt $CO_2$ with the potential to sequestrate a total 5 Mt. When combined with the neighbouring and probably interconnected collieries, the combined ascertained capacity would be about

7 Mt $CO_2$, extendable to 13 Mt. This is sufficient to sequester between 0.3 to 0.5 Mtpa for 25 years (Piessens and Dusar, 2003a). The total ascertained capacity for all the Campine collieries including Zolder and Houthalen is 1 Mtpa for more than 15 years, with a potential to sequester for over 30 years at this rate (Piessens and Dusar, 2004a).

The case study for the Belgian collieries shows that sequestration is a viable option, even for the ascertained capacity alone.

**Table 1 - Estimated residual volume and sequestration capacity for the abandoned Campine coal mines (Piessens and Dusar, 2004a)**

| | Residual Volume ($m^3$) | Ascertained Sequestration Capacity (Mt) | Potential Sequestration Capacity (Mt) | Total Sequestration Capacity (Mt) |
|---|---|---|---|---|
| Beringen | (5.9 106+/- 2.3 106) | 3.0 | 2.5 | 5.5 |
| Zolder | (6.2 106+/-2.4 106) | 3.2 | 2.6 | 5.8 |
| Houthalen | (1.8 106+/-600 000) | 0.9 | 0.8 | 1.7 |
| **Subtotal** | **13.9 $10^6$** | **7.1** | **5.9** | **13.0** |
| Eisden | (5.5 106+/-2.1 106) | 2.8 | 2.3 | 5.1 |
| Waterschei | (5.1 106+/-2.0 106) | 2.6 | 2.2 | 4.8 |
| Winterslag | (4.8 106+/-1.9 106) | 2.4 | 2.0 | 4.5 |
| Zwartberg | (3.0 106+/-1.1 106) | 1.5 | 1.3 | 2.8 |
| **Subtotal** | **18.4 $10^6$** | **9.4** | **7.8** | **17.2** |
| ***Total*** | ***32.3 $10^6$*** | ***16.4*** | ***13.7*** | ***30.1*** |

### A typical mine from Upper Silesian Coal Basin, Poland

For the purpose of study, one of the active Polish coal mines located in the Upper Silesian Coal Basin was selected and its storage capacity has been estimated (Lutyński, 2010). The shafts had been sealed from 440 m upward and the reservoir pressure at that depth was assumed to be around 5.85 MPa (not exceeding 30% more that hydrostatic pressure).

The results show that, at a reservoir pressure of 5.43 MPa, 3.5 Mt of $CO_2$ can be stored in the empty space as compressed gas and in mine water as dissolved. Almost a similar amount (3.53 Mt) of $CO_2$ can be stored in the remaining coal as adsorbed at the given pressure. In the calculations, the "worst case" scenario was taken into account deliberately. Moreover, there is a huge possibility of connections to remaining proven reserves. Both facts suggest this amount should be increased by 30% to determine the ascertained potential. This yields a storage capacity of 8.09 Mt of $CO_2$ for this coal mine at 5.43 MPa.

## POTENTIAL FOR $CO_2$ SEQUESTRATION IN AUSTRALIAN ABANDONED COAL MINES

Australia has a huge source of coal and abundant coal mines, which can make the sequestration viable and bring the opportunities for $CO_2$ sequestration. With collaboration between the Schools of Mining Engineering and Petroleum Engineering at the University of New South Wales, a study has recently been initiated to assess the potential for $CO_2$ sequestration in abandoned coal mines located in New South Wales and Queensland.

Many factors have to be considered in a simulation of $CO_2$ sequestration in abandoned coal mines. These include depth, coal reserve, sealing, mine condition, mine water, and existent faults. The most important ones are assumed to be depth and total coal reserves. The deeper abandoned coal mines have higher reservoir pressures resulting in high capacity for $CO_2$ storage. The total coal reserve is important as almost half of the $CO_2$ would be adsorbed on the remaining coal compared to solution storage and compression storage.

Figure 2 shows the total coal reserve versus depth for the abandoned coal mines in New South Wales and Queensland. The results indicate that, although Queensland's abandoned coal mines have higher coal reserves compared to the New South Wales's coal mines, they do not have sufficient depth for $CO_2$ sequestration. Similarly, a few mines in New South Wales are deep enough but their reserves are not as large as Queensland's coal mines. It is clear that more investigation needs to be done as the depth and coal reserve are not the only parameters given that many other factors like sealing, mine condition, mine water, existent faults may potentially affect the capacity. Investigation regarding these issues is ongoing and will be published soon.

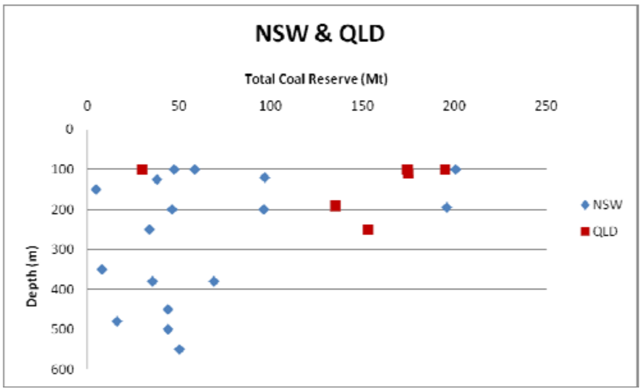


**Figure 2 - Total coal reserve versus depth data for the abandoned coal mines in New South Wales and Queensland (International Longwall News, 2010; Geoscience Australia, 2010)**

## CONCLUSIONS

According to Maplecroft (2009) and IEA (2005), Australia ranks first in per capita $CO_2$ emissions in the world just before the United States and Canada. Given the concerns that are rising about greenhouse gas emissions, the emissions need to be mitigated. $CO_2$ sequestration in abandoned coal mines can be one of the new methods as Australia has significant coal mines. Examples around the world have shown that this technique can be a viable option to reduce the amount of green house gases liberated. The reasons for this include low initial investment cost as no transport is needed from the power plants and the possibility of incremental methane recovery which can offset some of the cost of $CO_2$ sequestration.

Like other methods, sequestering $CO_2$ in abandoned coal mines has several difficulties. Sealing of the shafts and faults is one of the first issues and has to be fully studied. Water influx is also very important as it could pressurize the $CO_2$ and may cause $CO_2$ leakage through the seals to the surface. In order to prevent water influx into the mine, the reservoir pressure should be more than the hydrostatic pressure (normally 30% more than hydrostatic pressure but may vary from mine to mine). This will cause an overpressure in the mine and may cause the leakage of $CO_2$ through the seal as well. The other issue is the lack of the data for abandoned coal mines. In most of the abandoned coal mines the leeway of water influx is not monitored after the closure. Most of the data using for simulations are not available as a certain value which may result in under or overestimation of the storage capacity. As a result, care must be taken in the screening studies.

The screening studies for $CO_2$ sequestration in abandoned coal mines in New South Wales and Queensland are currently ongoing at the University of New South Wales with the aim of determining the storage capacity and evaluating the possible methane recovery.

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## REFERENCES

Department of Climate Change, 2007. [online]. Available from <http://www.climatechange.gov.au/inventory/index.html> [Accessed on: 17/04/2010].

Geoscience Australia, 2010. The Australian atlas of mineral resources, mines, and processing centres [online]. Available from: < http://www.australianminesatlas.gov.au/> [Accessed on: 22/07/2010]

Houtrelle, S, 1999. Stockage de gaz naturel en mine de charbon abandonnée. Approche géologique du site d'Anderlues. Faculté Polytechnique de Mons, Master thesis, 50 p.

International Longwall News, 2010. Australian longwall mines 2009-2010 review [online]. Available from: <http://www.longwalls.com/storyview.asp?_storyid=1139886&sectionsource=s50> [Accessed on: 12/07/2010].
International Energy Agency 2005, Investment in coal supply and use - An Industry Perspective on the IEA World Energy Investment Outlook *CIAB Collection.* Available from: http://www.iea.org/textbase/nppdf/free/2005/ciab_invest.pdf.
Kyoto Protocol. 1997. The Kyoto Protocol to the United Nations Framework Convention on Climate Change. Kyoto: *UNEP/WMO*.
Lutyński, M, 2010. A concept of enhanced methane recovery by high pressure $CO_2$ storage in abandoned coal mine. *Gospodarka surowcami mineralnymi*, vol, 26(1), pp 93-104.
Maplecroft, 2009. Maplecroft Climate Change Risk Report 2009/2010. [online]. Available from: http://maplecroft.com/Climate-Change_clientrelease2.pdf.
Piessens, K and Dusar, M, 2003a. $CO_2$ geothermics in abandoned coal mines. *Proceedings of the 2003 International Coalbed Methane Symposium*, Tuscaloosa, paper 0345, 10p.
Piessens, K and Dusar, M, 2003b. $CO_2$ sequestration in abandoned coal mines. *Proceedings of the 2003 International Coalbed Methane Symposium,* Tuscaloosa, paper 0346, 11p.
Piessens, K and Dusar, M, 2003c. The Vertical Reservoir Simulator $CO_2$-VR. *Proceedings of the 2003 International Coalbed Methane Symposium,* Tuscaloosa, paper 0347, 14p.
Piessens, K and Dusar, M, 2004a. Feasibility of $CO_2$ sequestration in abandoned coal mines in Belgium. *Geologica Belgica*, 7(3-4), pp 165-180.
Schultz, K 1998. Gas storage at the abandoned Leyden coal mine near Denver, Colorado. *EPA report, contract 68-W5-oo18*, prepared by Raven Ridge Resources Inc., 12p.
Van Tongeren, P C and Laenen, B, 2001. Residual space volumes in abandoned subsurface coalmines of the Campine Basin (northern Belgium); *Vito-report* ordered by NITG-TNO, GESTCO 3, 38p.
Van Tongeren P, R Dreesen, J Patyn and A Daneels, 2000. Residual space volumes in abandoned subsurface coal mines and possibilities for re-use, in Dutch; *Vito-report 2000/ETE/R/069* ordered by ANRE, 51p.