LOw Carbon After Life: sustainable use of flooded coal mine voids as a thermal energy source - a baseline activity for minimising post-closure enviromental risks

Research Fund for Coal & Steel

LoCAL Deliverable 1.8

Feasibility of CO_2 storage in flooded mine workings

WP number	WP 1
Partner responsible	UoG

University of Glasgow

Deliverable 1.8

Feasibility of CO_2 storage in flooded mine workings

Planned active pilot projects on mine water as a heat source are themselves aimed at obtaining a low-carbon energy source from the remains of the high-carbon past, but also in terms of the CO_2 capture agenda they could, if deep enough, be considered as potential CO_2 storage zones. The following sections will discuss carbon dioxide capture and storage (CCS) in the context of standard sequestration in a geological formation, such as a sandstones, and then reflect on the implications for repurposing and storing within flooded mine workings. Before discussing some of the technical aspects of carbon sequestration we must first look at the legislation and policy of CCS in the EU, as this will lay out the requirements for successful implementation and provide the framework for the suitability of flooded mine workings as carbon storage repositories.

Legislation

The successful implementation of CCS, in any form, depends on the regulatory framework established to govern its deployment. Companies wishing to proceed with geological storage of CO_2 need policy and regulatory certainty in order to assess the financial risk, raise the capital and proceed with investments (Bachu 2008). An effective framework must also ensure that CCS is both safe and effective. The model that CCS is likely to follow involves a pattern of permit application, project approval, active injection, site closure, post-closure and long-term stewardship. Any framework needs to take into account the technical barriers and issues that occur during this pattern including; site selection, classification of CO_2, intellectual property rights (IPR), risk characterisation, monitoring and verification requirements, regional impacts and liability. The definitions of long term and short term must also be clearly defined for these processes in any binding legislation.

The European Union is currently at the forefront of developing CCS policy and regulation through the European Commission (EC) Directive on the Geological Storage of Carbon Dioxide (2009/31/EC), which sets out the foundations of an absolute regulatory frame work for environmentally safe CCS within Europe. The EC directive and its accompanying guidance documents form a pretty conclusive set of regulations for the geological storage of CO_2.

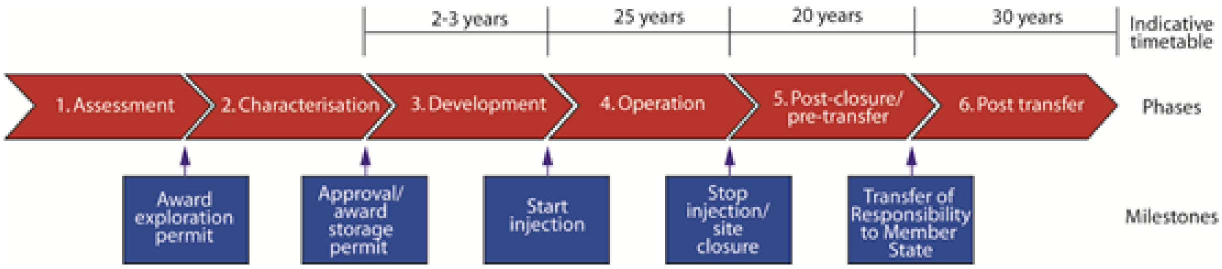

Figure 1. Phases and milestones of the EC Directive with indicative timetable.

The EC currently envisages the lifecycle geological storage project as consisting of six main phases separated by five major project or regulatory milestones (Figure 1). This framework is based on the 'stage gate' approach commonly used for major energy project frameworks in industry project management systems. It separates out major phases and milestones into project development, operation and closure stages as well as highlight where permits and regulatory approvals are required (EC GD1 2010). Not all activities are sequential and depending on the nature of the option and the availability of data some of the earlier phases may not be required for some projects. Two significant issues facing the implementation of CCS are the long-term stewardship (i.e. liability and responsibility) of storage sites and the financial mechanisms available to guarantee security of a site in case any unintended migration should occur. These factors are dealt with by Articles 18 and 19 of the EC Directive.

European Commission Article 18: Transfer of Responsibility

States that when a storage site has been closed [Article 17(1) (a) or (b)] the responsibility for the site can be transferred to the Competent Authority (CA) of the Member State (MS) subject to the following conditions:

- All available evidence indicates that the stored CO_2 will be completely and permanently contained.
- A minimum period after closure, to be determined by the Competent Authority (CA) has elapsed. This minimum period shall be no shorter than 20 years, unless the CA is convinced that the first condition is fulfilled.
    - If the above condition is met then this time frame can be adjusted downwards.

    - It may also be adjusted upwards if the criteria outlined are not met.
- The financial obligations under Article. 20 (Financial Mechanism) have been fulfilled. This requires the State to ensure that the operator of a storage site makes a FS available to the competent authority that shall cover at least the cost of monitoring for a period of 30 years.
- The site has been sealed and the injection facilities have been removed.

The operator is also expected to prepare and submit a transfer report which demonstrates all possible evidence for complete and 'permanent' containment. The EC Directive suggests that this can be achieved by meeting three conditions [Article 18(2)]:

- The conformity of the actual behaviour of the injected CO_2 with the modelled behaviour.
- The absence of any detectable leakage.
- Demonstration that the storage site is evolving towards a situation of long-term stability.

Beyond the transfer, the CA may not recover any costs from the operator unless there are leakages or significant irregularities as a result of operator's negligence, concealment of data, wilful deceit or failure to exercise due diligence. Obligations which become the responsibility of the CA upon transfer of responsibility include (GD4): monitoring, corrective measures, surrender of emission allowances, update of the provisional post-closure plan, and operation of the site.

European Commission Article 19: Financial Security

Article 19(1) requires that 'Member States shall ensure proof that adequate provisions can be established, by way of financial security or any other equivalent, on the basis of arrangements to be decided by the Member States, is presented by the potential operator as part of the application for a storage permit'. The meanings of 'financial security' and 'any other equivalent' are not provided by Article 19 though both are defined within Guidance Document 4 (EC GD4 2010). GD4 suggests that MS and CA's use one or both of the following methods for 'financial security' (FS):

- List specific types of allowable FS mechanisms that might be derived from existing laws and regulations about FS instruments; e.g. trust funds, surety bonds, financial institution guarantees, bank guarantees, first-party and related party guarantees, and insurance.

- List the necessary characteristics of an acceptable FS mechanism which may address the certainty, amount, liquidity, flexibility and duration of the instrument.

GD4 also states that the following approaches may be used to define 'any other equivalent':

- List specific types of allowable mechanisms that may not qualify as financial security mechanisms but that can accomplish the required security, such as self-guarantees and related-party guarantees.
- List the necessary characteristics of “other equivalent” mechanisms: The characteristics may address certainty, amount, liquidity, flexibility and duration of an instrument.

Article 19 (2) requires that the FS should be periodically adjusted to take account of changes to the assessed risk of leakage and the estimated costs of the obligations to be addressed [permit issued pursuant to the CCS Directive as well as obligations arising from the Emissions Trading Scheme (ETS) Directive (2003/87/EC)].

Article 19(3) states that the FS shall remain valid and effective until the transfer of responsibility to the competent authority (CA) following closure. In line with Article 18, FS must cover all obligations involved within the permit for CCS, including those which may become the responsibility of the CA following post-closure hand-over. These include: monitoring, corrective measures, surrender of emission allowances, update of the post closure plan and operation of the site (GD4). In preparing, reviewing, or approving cost estimates, several principles are suggested by GD4 to constitute best practice. Where more than one scenario can be costed for monitoring FS, options for determining the required amount of FS should include a three point estimate.

- Amounts should be sufficient for the CA to perform the obligation (often termed “third-party costs”) and should include necessary costs of CA overhead, oversight, and support services.
- Amounts should not be adjusted by multiplying with an estimated probability to calculate an expected value
- No credit should be allowed for presumed salvage value (e.g. at site closure).

- A bottom-line contingency of at least 25% should be required. Though there is scope for this to be set higher by the MS. In the UK, the Environmental Agency adds a contingency of 40-50% for transfrontier movements of hazardous waste and 50% to the estimated costs of decommissioning offshore installations (GD4).
- Assumptions regarding general inflation and any non-inflation cost escalation should be clarified.

In addition the draft directive also requires financial guarantee arrangements to cover contingent liabilities that arise under the EU Emission Trading Scheme (ETS) (2003/87/EC). This will only arise in the event of a leak of CO_2 to the biosphere. Initial FS surrenders of allowances should be based on the potential for leakage during: the operators anticipated period of injection, expected duration of closure of activities and minimum period of years for post-closure determined by the CA. The actual amount of FS for this obligation can be based on the potential total tons of emissions multiplied by the market cost of purchasing an equivalent amount of allowances. This calculation will require (1) estimates for the total tons of emissions that may be released (including due to leakage), (2) the timing of emissions and (3) costs of allowances when releases occur. Estimates for the total potential leakage can be based on a conservative estimate of the worst-case scenario of CO_2 that can be released from storage (based on borehole failure which implies a leakage of CO_2 at the rate of injection) and a best case assumption that only a small portion of the CO_2 is released (suggested as ~1% by GD4).

Gaps in the current set up

There are several unclear matters which emerge from the EC Directive. Some of the more important subjects that need to be clarified are predicted costs, definition of CO_2, definition of the storage complex and leakage, viable financial security mechanisms and intellectual property rights.

Definition of CO_2

Classification of CO_2 is important as it will determine its legality and treatment under international treaties and national laws and regulations. This definition can range from pollutant to commodity. Table 1 highlights how CO_2 has been classified in some current and planned geological storage projects (IEA 2007).

Country	Site	Definition	Legislation
Poland	RECOPOL	industrial	Polish Mining Law
Norway	Sleipner	industrial commodity	Norwegian Petroleum Directorate
Algeria	In Salah	Industrial product	Algerian Hydrocarbon Law
Australia	Gorgon	By-product	*Barrow Island Act 2003*

Table 1: Definitions of CO_2 for selected storage projects.

For Sleipner extracted CO_2 is considered to be the result of industrial activities. Though this is deemed acceptable under the international marine pollution treaties (Solomon et al. 2007) there has been some dispute because of the projects design for long term storage (IEA 2007).

Definition of Storage Complex and 'leakage'

In order to create appropriate legal framework it is necessary to define the boundaries for a storage site, termed the 'storage complex', and to constrain what constitutes leakage of injected CO_2 (which will largely depend on a clear definition for the former). There is no referral to boundaries or 'storage complex' in the EC Directive. There are currently no published works on the definition of a 'storage complex', though there are some relevant publications which deal with 'leakage' that can possibly be fed into a definition of the 'storage complex'.

A basic 'storage complex' model, comprising of three main zones is shown in Figure 2. These zones would be defined during the site appraisal and transparently revised using any new information obtained during the baseline screening. The baseline screening could also be utilised to test the geological model devised in the appraisal.

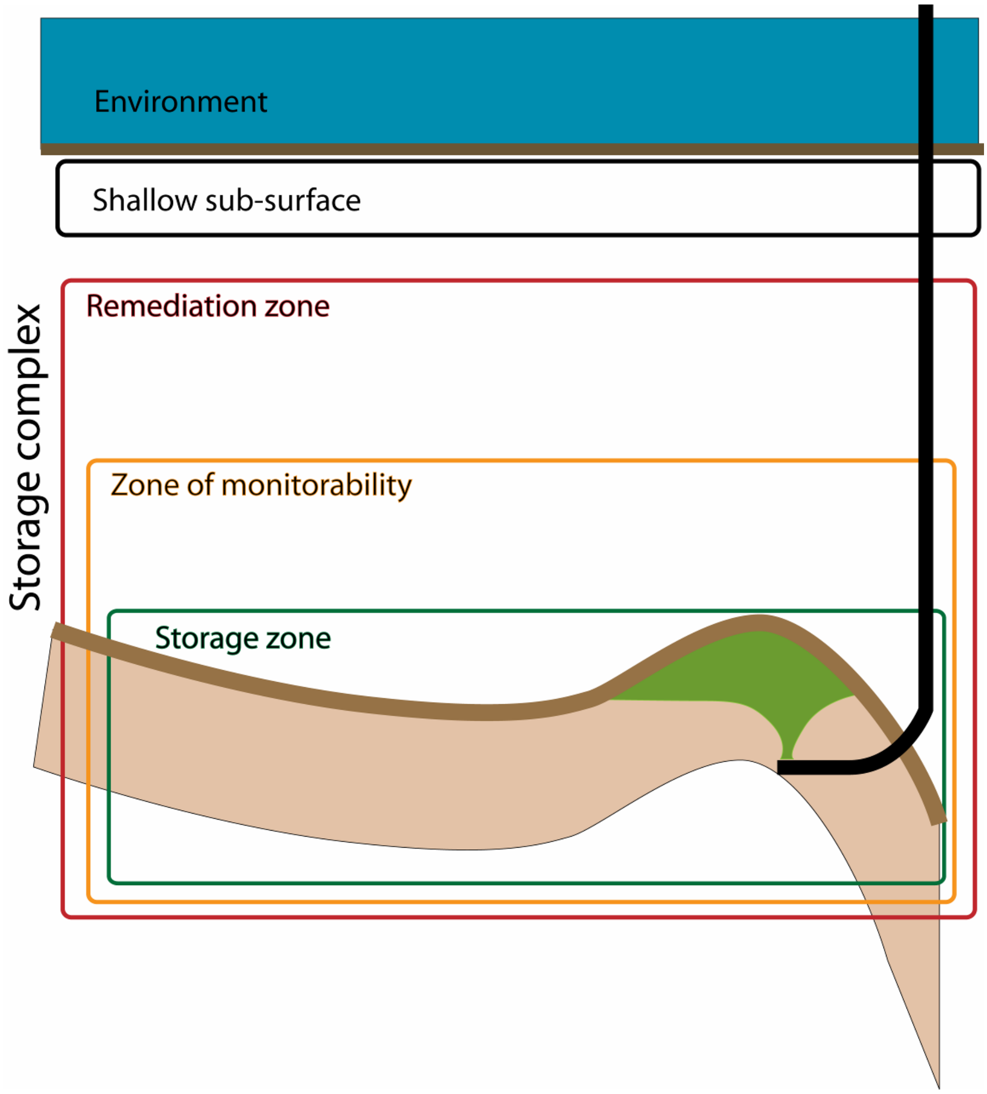

Figure 2: Model for 'storage complex'

1. The storage zone: where the CO_2 is intended to remain.
2. The monitoring zone: reflects our ability to measure CO_2 outwith the storage zone and is a function of monitoring strategy sensitivity. It resolves the volume of CO_2 that will have to migrate outwith the storage zone if it is to be detectable within geophysical uncertainty and reflects the distances CO_2 might be expected to travel between successive survey periods. The spatial geometry and temporal resolution of this zone will be specific to the monitoring tools applied. Different sensitivities will be required depending upon the spatial

distribution of risks (e.g. near the wellbore). A cost benefit analysis can be used to determine the resolvable volume of CO_2 that can be observed.

3. The zone of remediation: reflects the spatial extent that CO_2, which is identified outwith the storage zone, will travel from the point of detection, through remediation.

Within their definition migration of CO_2 outside of the storage complex into the shallow subsurface (where some negative impact may be expected to occur) would be considered a project fail. This model could be furthered by taking scale into consideration as this will be important for defining the storage complex and any inherent zones within the regulatory framework for CCS. Simulations have shown that the aerial extent of a CO_2 plume can reach from $10km^2$ to $100km^2$ and may grow after completion of injection (Juanes et al. 2010). Approach to this scale of migration could vary depending on the allowable extent of the storage permit and the legal ownership of the pore space.

Most researchers believe that the risk of leakage from well chosen, well operated sites is extremely low (IPCC 2005), however few studies have been carried out into leakage rates and it is likely that these will vary from site to site (Burnside et al. 2013). Leakage is defined by the Clean Development Mechanism (CDM) as ‘emissions caused by a project that occur outside the project boundaries’ (UNFCCC 2006). Wilson et al. (2009) use the alternative term ‘seepage’ to define CO_2 that migrates from the intended geological storage reservoir to another subsurface zone or back into the atmosphere. The CDM definition would fit well with a clear definition of the ‘storage complex’. In the example of a storage complex above this would count as any migration of injected CO_2 outwith the ‘zone of monitorability’ and into the ‘zone of remediation’. The second definition provided by Wilson et al. (2009) perhaps isn’t conclusive enough for UK storage operations. This is because of the partial licensing of saline formations by TCE which provides an important implication for definitions of ‘leakage’. As saline formations are widespread and contain enormous quantities of water, plus in many cases are not as well characterised as oil and gas fields, it is not outwith the realms of possibility that migration of CO_2 may occur laterally along an saline formation outwith the licensed portion of the formation (depending on how large the zone is set).

Liability and responsibility

Regulatory framework must clearly define who is responsible for any mishaps that may occur during injection and storage of CO_2. Issues can be divided into long and short term liability, with the most important issues related to long term given long sequestration time requirements and the comparatively short life spans of companies. Short term is mainly concerned with operational liability- this has been successfully managed for decades in the oil and gas industries. The main issue with short term will be who is responsible for the injected CO_2 in the event of a leakage event- the CO_2 source, the injector/operator or the land owner.

For long-term liability, a clear definition for the timescale of 'long-term' and a handle on the timescales involved with hand-over of responsibility to the CA need to be established. The EC Directive recommends a minimum time scale of 20 years post closure. This is a similar stance to the approach adopted by Australia and the USA. In the USA state legislators in Texas and Illinois offered state indemnity for long term liabilities for the recently cancelled FutureGen project. In Australia long term liability is guaranteed to be assumed by the Australian and Western Australian Governments. In the face of some public opposition Resources and Energy Minister Martin Ferguson stated that the project's importance in creating wealth, jobs and investment justified government acceptance of liability.

Financial Security mechanisms

The EU Directive requires a non-discretionary financial security to be in place prior to the commencement of injection- this would mean that an operator would only have to face up to significant financial penalty in the event of project failure. GD4 of the Directive suggests a list of FS mechanisms that can possibly be implemented for GS but doesn't provide recommendations on which, if any, are the most suitable. Pricing low probability risks that could incur large liabilities in GS is difficult due to the lack of track record and experience.

Examples of FS utilised in similar industries and independent research on varieties of FS which could be tailored for GS both provide potential sources of FS which are potentially realistic for use in GS. Financial precedents exist in the mining and petroleum industries in relation to site rehabilitation and decommissioning. These include the establishment of trust funds, environmental performance bonds, or bank guarantees to cover the estimated costs (IEA 2007). However, the timeframes involved with the long term geological storage of CO_2

do not match up with the viable lifespan of a company (i.e. 10's of years). As rules and boundaries to manage GS over the long term must be developed by regulatory body's research into different FS mechanisms that can cater for long term storage will need to be considered when deciding on appropriate FS mechanisms. Hungary, for example has used its 1993 Mining Act to set a minimum FS amount of HUF 200 million (ca. EUR 650,000) (EC 2014).

CCS progress in the EU

Since the formulation of the Directive on the Geological Storage of Carbon Dioxide in 2009, little progress has been made in terms of demonstration and commercialisation of CCS (EC 2017). Research activities to improve our understanding of geological CO_2 storage in typical storage scenarios are still in progress across a number of EU countries, such as Belgium, the Czech Republic, Germany, France, Hungary, Malta, Lithuania, the Netherlands, Slovakia, Spain and the UK. However, a number of member states and territories have decided to restrict CCS (the Czech Republic, Germany), ruled it out due to unsuitable geology (Finland, Luxembourg and the Brussels Capital Region of Belgium), or flat out decided to completely dismiss it as a CO_2 emission mitigation strategy (Austria, Estonia, Ireland, Latvia, Slovenia, Sweden) (EC 2014). This lack of progress in typical geological storage situations, where there is a general scientific consensus over the secure and safe sequestration of CO_2, showcases the challenges faced if CO_2 in open, flooded mine void systems was ever to be taken into proper consideration as a method for anthropogenic CO_2 storage.

Geological storage of CO_2

The safest way to geologically store CO_2 is in the supercritical, dense phase. The critical point, or saturation line, for supercritical CO_2 is 31.1°C and 73.8 bar, storage temperatures and pressures must be beyond these values to maintain dense phase behaviour. Vertical pressure is equal to the product of substance density, depth and acceleration. Utilising typical density values for water (ca. 1g/cm^3) and an acceleration equal to gravity (ca. 10m/s^2), hydrostatic pressure gradient is typically 100 bar /km. This means a depth of greater than 740 m is required for supercritical CO_2 in most cases.

Geothermal gradients are more variable and are there for highly site specific. In the case of the Markham Colliery the geothermal gradient is 28°C/km and the mean surface temperature is 10°C (Burnside et al. 2016b), so a depth of at least 820 m would be required for storage of supercritical CO_2. For practicality a greater depth would be required to keep clear of the phase transition boundary.

Geological Trapping Mechanisms

In order to determine the potential liability of CO_2 injection it is important to quantify what proportion of CO_2 will become trapped within a target storage formation. Trapping processes include any chemical or physical mechanism through which CO_2 can be stored in a geological environment (Sifuentes et al. 2009). There are currently five recognised methods of CO_2 trapping in porous media, and the efficiency of long term storage is directly related to the efficiency of each of these geological trapping mechanisms. Each will store differing fractions of the injected CO_2 depending on the influence of the different physical properties in the ambient and engineering induced environment of the storage formation (Burnside and Naylor 2013).

Hydrodynamic trapping

Hydrodynamic trapping entails structural or stratigraphic trapping via a confining cap rock formation or low permeability layers within a heterogeneous storage formation. This method does not guarantee permanent trapping; however it does define the volume of rock available for storage as it limits the ability of free CO_2 to escape the target formation. In this style of trapping the confining unit prevents ascent of buoyant CO_2. The distribution, capacity, integrity and orientation of the confining unit have a huge bearing on the fraction of injected CO_2 that can be contained in this manner. However, this mechanism cannot be used to quantify the volume of CO_2 that is available for escape.

Residual trapping

Residual trapping is controlled by permeability effects within the storage formation. Relative gas permeability, maximum CO_2 saturation, trapped CO_2 saturation, wettability and capillary effects are all important properties for residual trapping (Juanes et al. 2006; Ngheim et al. 2009). Once injected CO_2 is trapped in this manner it is permanently contained as an immobile phase.

Capillary trapping

Though often included under the residual trapping method capillary trapping is fast becoming recognised as a trapping mechanism in its own right (Juanes et al. 2010; Szulczewski et al.

2009; Saadatpoor et al. 2009). Local capillary trapping can take effect during vertical migration of injected CO_2 when a region is encountered within a heterogeneous storage formation where capillary entry pressure is locally higher than in the surrounding rock (typically in regions 10^{-2} to 10^{+1} m in scale- Saadatpoor et al. 2009). This trapping mechanism differs from structural trapping in that much of the accumulated CO_2 will not escape should the integrity of the seal above the storage formation be compromised. Capillary trapping also has the potential to trap a far greater volume of CO_2 than residual saturation for the same volume of rock (Saadatpoor et al. 2010). Capillary trapping is advantageous for storage security as it can retard buoyant CO_2 plume migration and create longer CO_2 migration pathways which will increase interaction between the CO_2, rock and formation brine and increase the chance of other trapping mechanisms taking place.

Solubility trapping

Solubility trapping occurs when the injected CO_2 dissolves into the brine and becomes an aqueous phase. The fraction of CO_2 that will dissolve into the formation brine is dependent on the degree of interaction between the two substances and the fluid properties of the brine. This method of trapping is not necessarily permanent as drops in pressure (either due to migration of the brine or within the reservoir) may lead to release of the CO_2 fraction. As ground water flow is minimal in offshore settings there is a greater chance of permanent storage in comparison onshore storage formations.

Mineral trapping

Mineral trapping involves the precipitation of carbonate from chemical reactions between the minerals in the storage formation and CO_2 which has dissolved into the formation brine (Xu et al. 2004; Druckenmiller et al. 2006). Like residual trapping this method permanently stores CO_2, though it takes part over much longer timescales, typically in the range of 100’s to 1,000’s of years (IPCC 2005; Figure 3). Mineral trapping is very much dependant on the composition of the storage formation and the amount of CO_2 dissolved in the formation brine.

Residual and mineral trapping are the most secure methods of containment as they permanently immobilise CO_2. Mineral trapping can be a lengthy process (100’s to 1,000’s of years) as it requires carbonic acid (the result of CO_2 dissolution into brine) to dissolve the necessary minerals from the storage formation in order to get all the required constituents for carbonate precipitation. Residual trapping, on the other hand, has been recognised as one of the most rapid CO_2 trapping mechanism with time scales on the order of years to decades (Juanes et al. 2010).

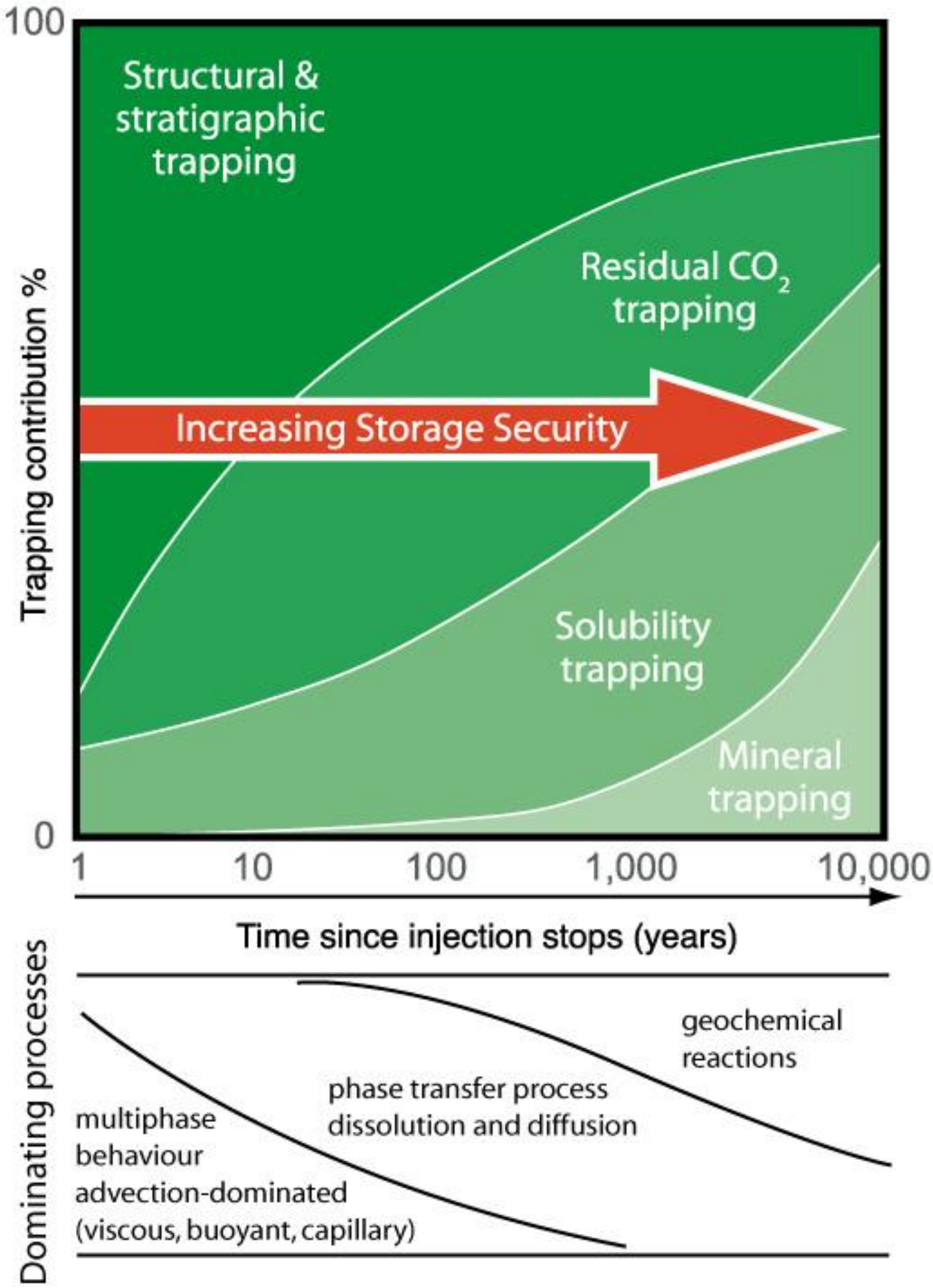

Figure 3: CO_2 storage security with time (IPCC, 2005) with dominating processes (Darcis et al. 2009).

Out of the five main methods for trapping of CO_2 residual saturation is the only one that takes immediate effect post-injection that guarantees long term storage security. Injected CO_2 is permanently stored via this method as CO_2 is trapped as an immobile phase due to a combination of capillary and wettability effects (Burnside and Naylor 2013). When published core scale experimental results for residual saturation into account Figure 3 can be redrawn as Figure 4.

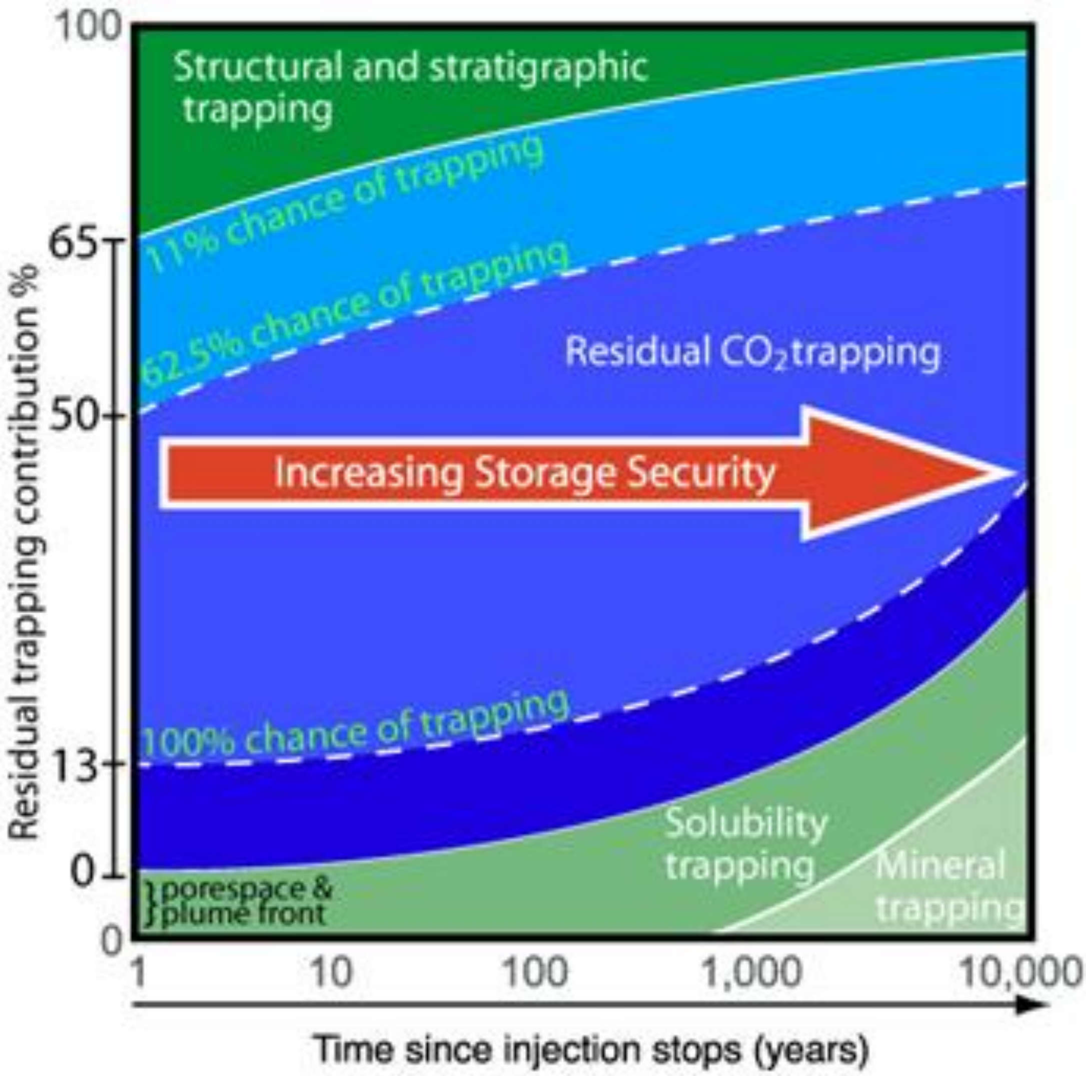

Figure 4: CO_2 storage security with time in porous media with better appreciation for residual trapping effects.

As can be seen for typical sandstone storage reservoirs, residual trapping provides most storage security (up to 65%), and diminishes the absolute importance of hydrodynamic and solubility trapping. CO_2 storage in mine water systems, thanks to the large void spaces, would largely remove residual and result in very low storage security.

Solubility and hydrodynamic trapping would be the only methods available for secure storage. Geological storage requires a sufficiently impermeable confining unit in order to contain vertical migration of injected supercritical CO_2. The mine void system provides ready-made, extensive hydrological pathways through coal-bearing sedimentary successions. Even if suitably impermeable strata (such as shale or siltstone) where available it would have to meet numerous requirements to be of any use in secure storage of CO_2. Issues with the geometry, extent and integrity of caprocks are therefore important facets to acknowledge. When considering potential movement of injected CO_2 the magnitude of structural dip of the caprock contact is a significant factor. On looking at sandstone storage reservoirs, Leetaru et al. (2009) suggest that a dip of 5° may lead to an additional ~1.5 km of lateral plume migration. Information such as this is important as CO_2 migration over this kind of distance may represent a compromise to storage security depending on the boundaries set for the storage complex. If there is any form of undulation in the contact between the storage reservoir and caprock additional stratigraphic trapping may result in extra security (Juanes et al. 2010).

The most secure mechanism in flooded mine workings would be solubility trapping. CO_2 dissolution decreases with increasing salinity of storage waters. Analytical experiments by Sifuentes et al. (2009) show that for the same injection rate and period that 12% of CO_2 dissolves in pure water in comparison to 3% in high salinity (260,000 ppm) brine. Numerical simulations have demonstrated that dissolved CO_2 will travel with the velocity of formation waters (1 to 10 cm/year) whilst free-phase CO_2 will be driven by both natural hydro-dynamic flow and its buoyancy with respect to the formation water (Gunter et al. 1996). Dissolved CO_2 is up to 10 kg/m3 denser than free phase CO_2 (Audigane et al. 2006), so its vertical buoyancy will be significantly retarded.

As CO_2 dissolves in brine it decomposes into H^+ and HCO_3^- via carbonic acid (Nghiem et al. 2009).

CO_2 (aq) + $H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- + H^+$ (1)

This would have a direct effect on the geochemical environment within a flooded coal mine system, which is already undergoing dramatic changes in response to post-abandonment flooding (Burnside et al. 2016a). This is particularly true of pyrite-bearing coals, such as those of British Carboniferous Coal Measures, which oxidise in the unsaturated zone given good supplies of atmospheric oxygen and water to release acid, sulphate and dissolved iron (Banks et al., 1997a, b):

$2FeS_2 + 7O_2 + 2H_2O = 2Fe^{2+} + 4SO_4^{2-} + 4H^+_{(aq)}$ (2)

Much of the acid generated by this reaction will often be neutralised by reactions with carbonate minerals, such as calcite, to release alkalinity and base cations. This would be further exacerbated by the dissolution of CO_2 in Equation 1.

$4H^+_{(aq)} + 4CaCO_3 = 4Ca^{2+} + 4HCO_3^-$ (3)

The Carboniferous Coal Measures also contain iron-bearing carbonates, such as siderite and ankerite, which neutralise acid, but release even more dissolved iron in the process. Again, exacerbated by the dissolution of CO_2 in Equation 1

$4H^+_{(aq)} + 4FeCO_3 = 4Fe^{2+} + 4HCO_3^-$ (4)

On contact with oxygen, the ferrous iron (Fe^{2+}) oxidises to ferric iron (Fe^{3+}) and hydrolyses to produce an insoluble ochre precipitate.

$4Fe^{2+} + O_2 + 4H^+_{(aq)} + 10H_2O = 4Fe^{3+} + 12H_2O = 4Fe(OH)_{3\downarrow} + 12H^+_{(aq)}$ (5)

The addition of large volumes of CO_2 for storage could potentially lead to far greater quantities of dissolved iron in solution and impede natural acid mine recovery (Younger 1998). In turn this would pose problems for any future use of the flooded mine system as a geothermal resource, as there would be a high risk of ochre precipitation during pumped extraction.

Summary

The current lack of policy and regulation regarding geological CO_2 storage constitutes a barrier to the meaningful deployment of CCS. If an appropriate initial legal framework could be put in place to aid the administration of pilot projects this would be the first step on the way to creating a clear set of rules and regulations for CCS and allow for proper assessment of flooded coal mines as a storage reservoir. Due to a lack of real world experience and track record an initial framework must be flexible for pilot projects. This is important as it is undesirable to create regulations that lock in inappropriate features or ignore key issues. A clear and transparent liability regime will also help public acceptance of CCS, which may become a stumbling block, especially for any form of terrestrial storage, as it will increase general understanding and create confidence that risks to human health and the environment can be successfully managed in the event of an accident.

It will be important to take into account geological, geophysical and geochemical observations during formation of a complete regulatory framework as these will form the basis for GS site selection as well as monitoring and verification protocols. The long-term fate of injected CO_2 is influenced by many variables, including reservoir and seal structure, stratigraphic architecture, reservoir heterogeneity, pressure and temperature conditions, mineral compositions of the rock framework, and hydrodynamics and geochemistry of reservoir waters. The extent of the effect of the main migration and trapping mechanisms depend on the local conditions formed by these variables in the storage water reservoir and its surroundings. The conditions within storage reservoir waters are also likely to change through time due to a combination of natural processes and engineered induced interactions due to both injection of CO_2 and the introduction of a substantial volume of fluid to the storage location.

To gain a real understanding of these processes and to confidently predict the behaviour of injected CO_2 in flooded coal mine systems requires detailed water reservoir and seal characterisation, and accurate modelling and simulation of the fate of injected CO_2. Subsurface CO_2 storage in coal mine systems will likely preclude the most secure type of geological trapping mechanism, residual saturation, and place a large emphasis on solubility trapping. This could have major geochemical ramifications for the geochemistry of the mine water reservoir and would rule it out as a resource for future geothermal application.

References

Audigane, P., I. Gaus, I. Czernichowski-Lauriol, K. Pruess and T. Xu, 2006. A long term 2D vertical modelling of the CO_2 storage at Sleipner (North Sea) using TOUGHREACT: *Proceedings in TOUGH Symposium* San Francisco, USA, 12-22 May.

Bachu, S., 2008. Legal and regulatory challenges in the implementation of CO_2 geological storage: An Alberta and Canadian perspective: International Journal of Greenhouse Gas Control, v. 2, p. 259-273.

Banks, D., Burke, S.P., and Gray, C.G., 1997a. Hydrogeochemistry of coal mine drainage and other ferruginous waters in north Derbyshire and south Yorkshire, UK. Quarterly Journal of Engineering Geology 30: 257-280. DOI: 10.1144/GSL.QJEG.1997.030.P3.07

Banks, D., Younger, P.L., Arnesen, R.T., Iversen, E.R., Banks, S.B., 1997b. Mine water chemistry: the good, the bad and the ugly. Environmental Geology 32: 157-174. DOI: 10.1007/s002540050204

Burnside, N. M., Shipton, Z., Dockrill, B., and Ellam, R.M., 2013. Man-made versus natural CO2 leakage: a 400 k.y. history of an analogue for engineered geological storage of CO2. Geology, 41(4), pp. 471-474. (doi:10.1130/G33738.1)

Burnside, N. M., and Naylor, M., 2014. Review and implications of relative permeability of CO2/brine systems and residual trapping of CO2. International Journal of Greenhouse Gas Control, 23, pp. 1-11. (doi:10.1016/j.ijggc.2014.01.013)

Burnside, N., Banks, D., and Boyce, A., 2016a. Sustainability of thermal energy production at the flooded mine workings of the former Caphouse Colliery, Yorkshire, United Kingdom. International Journal of Coal Geology, 164, pp. 85-91. (doi:10.1016/j.coal.2016.03.006)

Burnside, N.M., Banks, D., Boyce, A.J., and Athresh, A., 2016b. Hydrochemistry and stable isotopes as tools for understanding the sustainability of minewater geothermal energy production from a 'standing column' heat pump system: Markham Colliery, Bolsover, Derbyshire, UK. International Journal of Coal Geology, 165, pp. 223-230. (doi:10.1016/j.coal.2016.08.021)

Darcis, M., Class, H., and Flemisch, B., 2009. Coupling Models of Different Complexity for the Simulation of CO2 Storage in Saline Aquifers: Energy Procedia, v. 1, p. 1767-1774.

Druckenmiller, M.L., Maroto-Valer, M.M., and Hill, M., 2006. Investigation of Carbon Sequestration via Induced Calcite Formation in Natural Gas Well Brine: Energy & Fuels, v. 20, p. 172-179.

European Commission, 2009. Directive 2009/31/EC of the European Parliament and of the Council on the geological storage of carbon dioxide: Official Journal of the European Union.

European Commission, 2009. European Commission Emission Trading Scheme Directive Annexe 1 update: Official Journal of the European Union.

European Commission, 2010. Guidance Document 1: CO_2 storage life cycle risk management framework: Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide.

European Commission, 2010. Guidance Document 2: Site Characterisation, CO_2 Stream Composition, Monitoring and Corrective Measures: Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide.

European Commission, 2010. Guidance Document 3: Criteria for transfer of responsibility to the competent authority: Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide.

European Commission, 2010. Guidance Document 4: Article 19 Financial Security and Article 20 Financial Contribution: Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide.

European Commission, 2014. Report on the implementation of Directive 2009/31/EC on the geological storage of carbon dioxide. COM(2014) 99.

European Commission, 2017. Report on the implementation of Directive 2009/31/EC on the geological storage of carbon dioxide. COM(2017) 37.

Gunter, W.D., Bachu, S., Law, D.H.S., Marwaha, V., Drysdale, D.L., Macdonald, D.E., and McCann, T.J., 1996. Technical and economic feasibility of CO_2 disposal in aquifers within the Alberta sedimentary basin, Canada: Energy Conversion and Management, v. 37, p. 1135-1142.

International Energy Agency, 2007. Legal Aspects of Storing CO_2: Update and Recommendations: Paris.

IPCC, 2005. IPCC Special Report on Carbon Dioxide Capture and Storage: Cambridge, Cambridge University Press.

Juanes, R., MacMinn, C., and Szulczewski, M., 2010. The Footprint of the CO_2 Plume during Carbon Dioxide Storage in Saline Aquifers: Storage Efficiency for Capillary Trapping at the Basin Scale: Transport in Porous Media, v. 82, p. 19-30.

Leetaru, H.E., Frailey, S.M., Damico, J., Mehnert, E., Birkholzer, J., Zhou, Q., and Jordan, P.D., 2009. Understanding CO_2 Plume Behaviour and Basin-Scale Pressure Changes during Sequestration Projects through the use of Reservoir Fluid Modeling: Energy Procedia, v. 1, p. 1799-1806.

Nghiem, L., Shrivastava, V., Kohse, B., Hassam, M., and Yang, C., 2009. Simulation of Trapping Processes for CO_2 Storage in Saline Aquifers, Canadian International Petroleum Conference: Calgary, Alberta, Petroleum Society of Canada.

Saadatpoor, E., Bryant, S., and Sepehrnoori, K., 2010. New Trapping Mechanism in Carbon Sequestration: Transport in Porous Media, v. 82, p. 3-17.

Saadatpoor, E., Bryant, S.L., and Sepehrnoori, K., 2009. Effect of capillary heterogeneity on buoyant plumes: A new local trapping mechanism: Energy Procedia, v. 1, p. 3299-3306.

Sifuentes, W.F., Giddins, M.A., and Blunt, M.J., 2009. Modeling CO_2 Storage in Aquifers: Assessing the key contributors to uncertainty, Offshore Europe: Aberdeen, UK, Society of Petroleum Engineers.

Solomon, S., Kristiansen, B., Stangeland, A., Torp, T.A., and Kårstad, O., 2007. A proposal of regulatory framework for carbon dioxide storage in geological formations, *International risk governance council workshop,* Washington, DC.

Szulczewski, M.L., Cueto-Felgueroso, L., and Juanes, R., 2009. Scaling of capillary trapping in unstable two-phase flow: Application to CO_2 sequestration in deep saline aquifers: Energy Procedia, v. 1, p. 3421-3428.

UNFCCC, 2006. Glossary of CDM Terms: Version 2, United Nations Framework Convention on Climate Change.

Wilson, E.J., Klass, A.B., and Bergan, S., 2009. Assessing a Liability Regime for Carbon Capture and Storage: Energy Procedia, v. 1, p. 4575-4582.

Xu, T., Apps, J.A., and Pruess, K., 2004. Numerical simulation of CO_2 disposal by mineral trapping in deep aquifers: Applied Geochemistry, v. 19, p. 917-936.

Younger, P.L., 1998. Coalfield abandonment: geochemical processes and hydrochemical products in Energy and the Environment: Geochemistry of Fossil, Nuclear & Renewable Resources. Nicholson, K. (Ed.) Environmental Geochemistry Series Vol. 1, MacGregor Science, pp. 1-29.