Project Ramsay: Potential for Underground Coal Gasification with Carbon Capture and Storage (UCG-CCS) in North East England, UK.

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Abstract

North East England is historically an energy intensive region due to its proud industrial heritage and leading position in manufacturing, engineering and chemical processing industries. In the coming years, our world will continue to face economic, environmental and energy related challenges. In the short and medium term, increases in global demand for energy are unlikely to be satisfied in full by the emergence of renewable energy technologies, which presently supply only a small fraction of our energy budget. This paper makes a case for clean use of coal in response to the needs of our society and the world to meet energy security needs in the new global low-carbon economy.

Although, a transformation from fossil fuels to renewable energy sources should be the long-term goal, fossil fuels still form the backbone of our energy infrastructure, their use is inevitable, and they will still be supplying the major part of the global energy needs for most of the 21st century. The emerging Underground Coal Gasification (UCG) technologies provide exciting opportunities to unlock the energy stored in coal seams in a sustainable and environmentally friendly manner when they are linked to carbon capture and storage (CCS). The syngas (or synthesis gas) produced from UCG is a flexible fuel which can be cleaned for use in industrial heating, power generation or further chemical conversion into energy carriers like hydrogen, methanol and substitute natural gas.

Project Ramsay is seeking to create the world's first commercial scale underground coal gasification and carbon capture storage (UCG-CCS) operation. This paper presents our feasibility study and the initial findings on assessing the suitability of coal seams in North East England for UCG linked to Carbon Capture and Storage.

The broad conclusions from the feasibility study are that: previous estimates for UCG-compatible coal had been conservative; there are coal seams that appear to be usable for CO_2 storage following UCG; and some of the end uses for syngas are potentially attractive. The most attractive options in financial terms are (1) to sell syngas, take back captured CO_2 and store it for a fee, and (2) to sell decarbonised hydrogen and methane. It was concluded that a project could be done in phases, ramping up the scale over time in order to minimise technical risk and investor exposure. Such a project could deliver a positive return on investment, albeit on a longer timescale than more conventional energy projects.

1. Introduction

There is growing international interest in UCG technology as a means of accessing the energy locked within inaccessible coal reserves (Green, 2008). The main motivations for moving towards UCG as a future coal utilisation technique are the environmental and other advantages over the conventional mining process. Of particular interest in the application of UCG is in the utilisation of unmineable coal deposits and deeper seams which are not included in the 'proved reserves' figures (Couch, 2009). Studies (e.g. World Energy Council, 2007, IEA, 2009) have suggested that UCG technology could potentially increase the world's coal reserves and increase the energy reserve base of coal by as much as 600 Gt, which represents a 70% increase. The worldwide inferred 'proven' mineable coal resources to reserves ratio is about 6:1, indicating that the potential increase in recoverable resources using UCG is enormous, with a total gas volume estimate on the order of 6,900 Tcf (EC, 2008). As of the end of 2005, the world's coal 'proved reserves' (which is the amount of coal assessed as being economically recoverable using current technology) were independently estimated to be 850 Gt (World Energy Council, 2007) and 900 Gt (BP, 2007) respectively. In terms of energy content, the world's coal resources are vast and are almost certainly much greater than those of other fossil fuels- oil and gas combined. However, only a fraction of the energy can be recovered by conventional mining. Some are recoverable in the form of coal bed methane (CBM) extraction and considerably more would become recoverable if UCG is fully developed into commercial-scale. Although previous experience (e.g., Gregg et al., 1976; Green 1999 & 2008; Friedmann, 2008) suggests that coal with a wide range of properties can be utilised for UCG, there are a number of site-specific technical factors which are important to the process including but not limited to the geology of the coal seam, coal thickness, permeability of the overlaying strata etc (Walker, 1999; Green, 1999; Friendmann, 2008).

Fossil fuels currently underpin most aspects of modern life and most projections show that fossil fuels will continue to dominate energy supply well into the next century, to 2050 at least (APGTF, 2009). In the UK and other industrialised nations, coal was the primary source of energy for industrial development for some 200 years (CRF report, 1996). In recent years, increasing attention to environmental concerns, and fierce competition from oil, natural gas and nuclear energy have resulted in a marked decline in worldwide coal production and consumption (DTI, 2000). Nevertheless, coal is still by far the largest fossil fuel resource in the world and is geographically well spread across the continents (DOE, 1995, IEA, 2006). Worldwide coal reserves are vast and estimated as over 10 trillion tonnes (IEA, 2007). However, unless cleaner and cheaper ways can be found to convert coal to gas or liquid fuels, coal is unlikely to become an acceptable replacement for dwindling and uncertain supplies of oil and natural gas, for which there is a growing consensus among energy experts that global supplies will only meet demand until global oil production peaks sometime between 2017 and 2020 (IEA, 2000, BP, 2001, Salameh, 2002).

UCG has a long history of technical development involving over 100 experiments, 50 field tests and trials and more than 20 feasibility studies since the 1930s (Burton, 2007). International activity in the development in UCG can realistically be focussed on work undertaken in the Former Soviet Union (FSU) since the First World War (Gregg et al., 1976; Kreinen, 1992; Green, 2009). The historical UCG work in the FSU undoubtedly provided the necessary catalyst for the growing commercial interest in the technology in the Western countries (Western Europe & the US) in the 1970s (Walker, 2007). The development work on UCG undertaken in the West over the past four decades has focussed on technology improvements undertaken within the R & D frameworks (NCC, 1999; Green, 1999; DTI, 2004).

The international development and activity in UCG development is dominated by the work undertaken in the past 80 years in the Former Soviet Union (FSU), in Western Europe and in the US (Australian Coal Review, 1999). By far the largest UCG activity has been in the FSU with field experiments being performed in the 1930s. The magnitude of these efforts have been summarised by Gregg et al. (1976) and Kreinen (1992). A huge financial value of ten million 1976 dollars was placed on the Soviet UCG efforts by Gregg et al (1976) which shows its significance. However, the major effort in Western countries to develop UCG took place in the USA (led by the Lawrence Livermore National Laboratory-LLNL), where several hundred million dollars of research and development funding (by the US Department of Energy-DOE) were expended over the period from the mid-1970s to the late 1980s (DOE, 2000).

Recent independent research in a report by AEA Group on "Future Value of Coal Carbon Abatement Technologies to UK Industry" suggests that clean coal technology could bring between £2-4 billion a year to the UK economy by 2030, and support between 30,000-60,000 in jobs such as engineering, manufacturing and procurement.

This paper presents the case for a commercial-scale underground coal gasification project with carbon capture and storage (UCG-CCS) to be developed in North East England. The project is named "Project Ramsay" to acknowledge the contributions of Sir William Ramsay (the UCG pioneer) who conducted the first UCG experiments in the Durham coalfield in 1912.

2. Project Description

2.1. Project Rationale

There is international consensus among the experts that the global peak in oil and gas production will occur between 2017 and 2021 (e.g., Strahan, 2007) with global production of oil and gas expected to be substantially depleted by 2050 and 2070 respectively. In addition, within the world's proven fossil fuel reserves, oil accounts for 19%, gas is 17% and coal is a massive 64% with up to ten trillion tonnes widely distributed around the world. Adding total reserves to total resources, coal accounts for 95% of the fossil fuel content of the planet giving potentially hundreds of years of energy. The UK still has the most extensive coal reserves in the EU and although coal has been mined at industrial scale in North East England longer than anywhere else in the world, we have still only managed to extract about 25% of the total coal resources. The North East retains considerable knowledge of coal mining in general and of the nature of North East coal workings in particular. This knowledge is of particular relevance to Project Ramsay.

North East England is classed as a socially and economically disadvantaged region and the coal industry plays an important role in providing quality, well-paid manual jobs for the populace. So, significantly, the local population understand the economic role of coal exploration and exploitation in the region both historically and potentially in the future. However, due to stringent environmental measures and climate change issues, low investment in the coal industry in the last decades is threatening the future viability of the industry in the region and putting thousands of jobs at risk. In the EU, energy technology is expected to be a key element of Europe's plans to reduce greenhouse gas emissions and for its move towards a sustainable, low carbon future (DECC 2009). Given the central role assigned to CCS technology in the UK energy projections, the aim of "Project Ramsay (UCG-CCS)" is to be able to use the technologies to access proven coal resources in the region economically and make the use of coal more environmentally friendly while addressing the twin problems of energy security and climate change and to also safeguard jobs in the region's coal industry. In addition, North East England consumes a total of 83, 617.6 kWh of energy (or 7.7%) of the total UK energy consumption and emits 33 million tonnes of CO_2 (or 6.3%) of the UK CO_2 emissions from energy annually. Reduction of CO_2 emissions from fossil fuels (particularly coal) has been identified as key to meeting the UK short-term and long-term climate targets (DECC 2009).

Clean coal is expected to continue to play a crucial role in the UK energy mix for the foreseeable future and it is expected that 40% of North East England and indeed UK electricity will be derived from low-carbon sources including nuclear and coal by 2020 (DECC 2009). Currently, North East England mines over 1.5 million tonnes of coal a year which represents about 7% of the UK total coal production of 21 million tonnes (CA, 2009). UK coal imports are significantly higher. For example, in 2007 the UK total coal demand was 62.9 million tonnes with 43.9 million tonnes being imported from countries such as Russia, South Africa, Australia, Columbia, USA and Indonesia. The potential energy of North East coal reserves exceeds that of the UK oil and gas reserves (put together). North East England, however, actually generates only a quarter of its coal-fired electricity using its own coal.

Globally, issues such as availability, affordability, security of supply and technological simplicity make it inevitable that coal will be utilised as a bridging technology until energy provided by renewable resources provides a technologically and economically viable alternative on the large scale required. However, that is still decades in the future, making the development of clean coal technologies an immediate imperative. There is an emerging consensus among experts that under the most optimistic growth projections for renewable energy technologies and for new nuclear build, and notwithstanding the remaining natural gas resources around the world, coal will remain a large-scale supplier of energy to the world's economy for many decades to come. When fully developed, it is hoped that the outcome of this research work will be applicable to key developing and coal-based economies such as China and India. In the North East and indeed the UK as a whole, it is envisaged that UCG technology could enable deep coal resources that are uneconomic to mine conventionally to be exploited. Security of supply considerations alone suggest the time is right to re-evaluate the case for coal in the UK and international future energy-mix.

2.2. Project Phases

The project was divided into seven different Work Streams.

Work Stream 1: (April 2008-July 2008)

- Feasibility study, including analysis of UCG current state of science and technology and determination of site selection criteria.
- Analysis of North East England coal resources and determination of suitable UCG locations (onshore, near shore & offshore)
- Characterisation of the most promising locations for potential UCG operations in North East England.

Responsibility: Newcastle University.

Work Stream 2: (July 2008-September 2008)

- Independent assessment of existing North East England coal data and proposed licensed areas.
- Review of proposed licensed areas and associated geology, hydrogeology and further exploration specification.

Responsibility: IMC Geophysics International Ltd.

Work Stream 3: (April 2008-April 2009)

- Licensing advice and negotiations which cover exploration licenses, offshore oil and gas exploration licenses, production licenses and liabilities

Responsibility: PB Power Ltd., Newcastle University and HPM Group Ltd.

Work Stream 4: (April 2008-April 2009)

- Determination of how existing UCG technologies would be used in long reach drilling applications from shore
- Specification and outline engineering design and costing for demonstration

Responsibility: UCG Engineering Ltd. & PB Power Ltd.

Work Stream 5: (April 2008-April 2009)

- Commercial assessment of utilisation and sales potential of syngas for power and chemical production in North East England
- Advice on above the ground engineering
- Planning and application for shore installations and the shore exploration rig - identifying the requirements
- Economic feasibility and financial modelling of proposed operations

Responsibility: PB Power Ltd.

Work Stream 6: (April 2008-April 2009)

- Project proposal and prospectus drafting for funding (technical, legal, financial and commercial)

Responsibility: Northern Corporate Services (NCS) Ltd.

Work Stream 7: (April 2008-April 2009)

- Development of a PR social and political plan and the holding of preliminary discussions with local and central Government

Responsibility: HPM Group Ltd.

3. Analysis of North East England's Coal reserves and resources

The UK has 17 billion tonnes of gasifiable coal which can sustain the UK energy needs for centuries compared with only 160 million tonnes of mineable coal left and 400 million tonnes in total proven coal reserves, which can only last for another 10 years if continued to be mined at the current rate of 16 million tonnes per annum (Fergusson 2009). Despite the long history of coal mining in North East England, huge resources of coal remain. The majority of these reserves lie at locations and depths beyond the capability of conventional mining. The availability of new emerging technologies in underground coal gasification (UCG) using directional drilling opens up the prospect of accessing these coals affordably.

North East England has the longest history of conventional coal mining at industrial scale anywhere in the world dating back to 1511 (Coal Authority, 1975). Despite extensive exploitation, more than 75% of the coal reserves in the North East are still untouched at depths below 1000m (Younger, 2009).

Based on the analysis of the coal records carried out as part of this feasibility study, it was conluded that North East England alone has untapped coal resource (onshore, near-shore and offshore) of 2 billion tonnes that is unlikely ever to be mined. This offers the prospect of using indigenous coal to meet the most ambitious plans for CCS deployment in the UK. The IEA has recently estimated that the total coal resource on the planet is 18 trillion tonnes – very different to the published figures for mineable coal reserves. The large reserves of indigenous coal deposits, both offshore and onshore in the southern North Sea has the potential to supply the UK's future energy needs for several decades (if not centuries), long after the oil and natural gas are exhausted (DTI, 2004 & 2007). However, traditional mining methods are not suitable for offshore reserves, whilst spiralling development and infrastructural costs have rendered exploitation of onshore coal deposits uneconomical and make the extraction of these coal reserves highly problematic.

4. A brief history of UCG in the UK

Although Underground Coal Gasification was apparently first suggested by two engineers, brothers Werner and Wilhelm Siemens, as early as 1868, independently of them the Russian scientist Dmitry I. Mendeleev had been developing a detailed design for the operational concepts of UCG as early as 1880. The first UCG experimental work was led by William Ramsay in County Durham, UK in 1912. Despite the fact that the knowledge of the UCG process has existed for more than 100 years, however, its progress towards development internationally has been anything but smooth. Most of the national programmes of research work undertaken in the last 50 years have taken place in the FSU, Western Europe, the US and to a limited extent in China, Australia, New Zealand and South Africa. With the UK's premier position of having one of the largest industrial scale conventional coal mining histories in the world (Younger et al., 2009) and being home to about 15% of the world's coal reserve (DTI, 1999), its long standing interest in the development of UCG technology is not surprising.

In the UK, the concept of UCG was first conceived and postulated by Lord Kelvin in the 19th century (Younger et al., 2009). However, the first UCG patent issued and recorded in the UK was in 1909 to an American, A.G.Betts (Crouch, 2009). The discoverer of noble gases, Sir William Ramsay, actively promoted and expanded upon Brett's ideas over the next several years and his strong advocacy for the development of this technology culminated in the first ever UCG experiments being carried out in County Durham, North East England in 1912 (Roddy & Gonzalez, 2009; Younger et al., 2009). Ramsay's death and the outbreak of First World War (FWW) halted further progress of further experiments (Ergo Exergy, 2005). Notable UCG milestones and timelines in the UK are:

- 1912-Sir William Ramsay carried out the first UCG experiments in County Durham;
- 1949-50: Bore hole trials in Newman Spinney;

- 1958-59: National Coal Board (NCB) trials conclude at Newman Spinney;
- 1992-96: UK participated in the EU trial in Spain;
- April 1999: Energy White Paper 67 supports UCG;
- June 1999: DTI grant Coal Authority £15m for UCG study;
- Jan. 2000-07: Series of public speaking engagements to promote and support UCG notably: the London conference by CA (2000), 50th Robens Lecture (Oct. 2001), UCG conference by DTI (Oct. 2003);
- Oct. 2004: Publication of DTI report on UCG in the UK;
- Dec. 2005: Formation of UCG Partnership and the 1st UCGP international conference;
- Feb. ’07, ’08, ’09 (2nd, 3rd & 4th) UCGP international conference on UCG.

5. Recent developments in North East England

5.1. Characteristics of North East England coal resource

A reconnaissance study and assessment of potential coal seam targets for an underground coal gasification development and carbon capture and storage (UCG-CCS) project in onshore, near shore and offshore locations in the North East has been carried out. Existing data and records from the Coal Authority (CA), British Geological Survey (BSG) and the department for Business Enterprise and Regulatory Reform (BERR) were used in this study. Log processing and analysis of the geophysical logs from sites of interest were carried out to determine porosity and strength of the roof and floor measures. Seismic reprocessing of the potential target areas were carried out to determine the improvement in resolution of seismic data achievable from existing 2D data using modern processing software.

The geology of the area is largely Productive Coal Measures overlain by Permian and Triassic measures offshore. Namurian and Dinantian measures outcrop to the north and are below the Productive Coal Measures in the bulk of the study area. Permian cover extends westwards to within 5km of the coast in the south of the study area. The Westphalian Coal Measures have a high proportion of arenaceous measures with the proportion of mudstones increasing to the south of the study area. Sandstones, mudstones and coals are cyclic through the sequence but individual coal is not generally thick, although in local areas individual seams unite to form thick complexes. Typically coal seams in the study area are around 1m ± 0.5m in thickness but coal sections in excess of 2m do occur locally in the Main and Brass Till seams particularly and where seams unite. However, significant areas of the thicker, higher seams have already been mined or are in virgin areas too close to the seabed for UCG/CCS development based on the 100m cover criterion. The majority of the thickest potential target seams are in the Middle Coal Measures.

5.2. Criteria for UCG-CCS site selection

The broad criteria used for identifying potential UCG target seams was a seam thickness greater than 1m (although this may be reduced to 0.8m), depth cover from Ground Level, seabed or base of permain to be 100m or greater and a minimum stand-off distance vertically or laterally from old mineworkings of 250m, although this could be reduced to 100m. Additional secondary criteria such as the preference for a coal seam target to have a mudstone roof and to have dip were also taken into account. Investigation of the available data in the study area indicates there are three potential offshore areas of UCG development in the Productive Coal Measures after applying the defined criteria for UCG potential.

There are extensive mineworkings onshore and in the near onshore in most of these areas. Mineworking in coal seams in the studied area has taken place for more than 200 years but there are no significant underground coal mines currently operating in the area. The identified area with the greatest UCG/CCS potential is affected by faults and igneous dykes which may be water migration routes due to adjacent fracturing. Coal Measures Sandstones in this area are known to have low porosity and intergranular permeabilities. The primary difference in approach to UCG activity between near onshore areas and further offshore is in the ability to reach the coal reserves from a wholly shore-based enterprise using directional drilling versus the need to utilise offshore rigs. Cost analysis has shown that there is no significant cost advantage in one approach over the other for the coal reserves under consideration. The initial high cost of offshore rigs are broadly offset by the more expensive long reach drilling costs associated with a near shore based project.

Particular attention was paid to coal seams at depths of 800 metres and below since these offer the prospect of storing captured CO_2 in its supercritical state in UCG-created voids as described later in the paper.

5.3. Identification and characterisation of the most promising locations for potential UCG-CCS operations in North East England

The project considered both nearshore coal seams (<2km) and offshore coal seams (up to 10 km) at several locations. Some very interesting coal seams were found consistent with the criteria described above.

However, generating syngas from coal is only part of Project Ramsay: the region also provides ready energy and chemicals markets for syngas and its derivatives, and therefore offers a genuine prospect for a commercial UCG-CCS operation. Geography is important: these markets need to be sufficiently close to the chosen UCG base to be serviceable economically. The siting of a UCG production operation in North East England allows ready access to the process industry markets on Teesside for syngas and for derived gas products of methane and hydrogen. Equally, there are a number of existing power users and potential new investments in power generation plant at a scale that could make syngas a viable fuel. These options were all reviewed as part of the feasibility study.

From its inception, Project Ramsay has always considered CCS as being an essential element of a successful UCG project. Consequently, detailed consideration has been given to those coal targets that are at sufficient depth to provide the option for CO_2 storage and where significant revenues can be generated by providing a long term storage site for CO_2. Note, however, that CO_2 is also generated in large quantities by the same process and power industries that provide a potential market for the syngas and its derivatives. Increasingly there is a business opportunity in CO_2 collection, transmission and storage. There is therefore the option of extending the envelope to take in CO_2 from other industrial sources and offer additional storage capacity. The voids created through the UCG process in deep coal seams provide a storage option for CO_2 whether that CO_2 was produced through use of UCG syngas or from other industrial activities.

In assessing the suitability of specific locations the study therefore looked at a range of factors such as: the location of the most suitable coal seams relative to existing power plants and potential new power plants; the existence of pipeline corridors; the location of the most suitable coal seams relative to large industrial users of syngas and hydrogen; the potential for linking into other sources of CO_2 and CO_2 collection systems; the potential for connecting the UCG facility to the proposed new CO_2 pipeline linking the Eston Grange IGCC/CCS plant to storage locations under the North Sea, and so on.

6. Prospects for CO_2 storage in the UCG voids

During coal gasification, the UCG process creates voids deep underground. These voids will ultimately lead to the creation of high permeability zones of artificial breccias when they collapse. Storage of CO_2 in these artificial high-permeability zones is a very attractive proposition particularly where UCG has taken place at depths in excess of about 700-800m (Younger at al., 2009). Furthermore, as most UCG processes are oxygen-blown, carbon dioxide, hydrogen, methane and water vapour are the only gases produced, thus making separation and capture of carbon dioxide simpler and cheaper than in other processes. The process is therefore exceptionally compatible with CCS. In most UCG scenarios, the captured carbon dioxide can be consigned to storage within the UCG voids and surrounding strata via the same boreholes used for injection and extraction. This combined UCG-CCS project therefore offers an integrated energy recovery from coal and a highly integrated carbon management plan which could achieve a reduction in CO_2 emissions of as much as 85% compared with conventional coal-fired power station (Roddy, 2008).

For nearly a century, the practice involving the storage of natural gas in salt caverns has been well documented. This practice allows supply flexibility against a fluctuating demand and in Canada, acid gas has been injected underground since the 1990s as wastes (e.g. Younger et al., 2009). Furthermore, subsurface injection of gases is being successfully accomplished worldwide for different purposes and in different scenarios. This includes oil and gas operations, temporary storage and permanent disposal (e.g. Exergy, 2008, Green, 2009). For example, Enhanced Oil Recovery (EOR) by the oil industry has been in practice since the 1970s. This involves the injection of CO_2 into the oil reservoir, and more recently, Enhanced Gas Recovery (ERG) for gas recovery.

The prospects for carbon sequestration in a UCG operation arise from a serendipitous association of a source of CO_2 and a viable long-term storage site. As with the other major CCS options, UCG-CCS takes place in a sedimentary basin with particular geological features that are particularly appropriate for geological storage. The general requirements of a site for carbon geological storage are (IPCC 2005):

- Proximity to a source of carbon dioxide, to guarantee the supply of CO_2 and improve the economics of the operation by avoiding long transportation routes.
- Injectivity: the formation needs a high enough permeability to allow the injection of the fluid.
- Storage capacity: sufficient to store the CO_2 produced during the plant lifetime.
- Containment: some trapping mechanism has to guarantee the permanence of the CO_2 store for a considerable amount of time, circa 1,000 years

In addition to the generic site requirements, it is important to note the effect of the characteristics of the CO_2 stream in the constraints set on the storage site.

The first of the four requirements is fully achieved by the UCG-CCS configuration. The plant and CO_2 injection infrastructures, geological and geophysical studies will have already been developed for the UCG operation when the time comes for CCS. Though capture is the main component of the cost of CCS (70-80%), the cost reduction in the remaining 20-30% is very significant. Details of how the other three requirements can be met are provided in a separate paper (Roddy et al., 2009).

Another critical aspect which influences the mechanisms and requirements for the CO_2 storage site is the characteristic of the CO_2 stream to be injected. Anthropogenic CO_2 contains impurities which depend on the combustion process and the capture method. Some of these impurities are H_2O, SO_2, NO, H_2S, O_2, CH_4, HCN, Ar, N_2, H_2

and particulates (Anheden *et al.* 2005) and they will affect the thermodynamics (density, viscosity, critical point) compared with pure CO_2 (Li *et al.* 2009). In general, the presence of impurities decreases the critical temperature and increases the critical pressure (Seevam *et al.* 2008) at which CO_2 enters its supercritical state – which is essential for geological storage without further reaction. In the case of a pre-combustion process, the supercritical pressure can reach 83 bar while the critical temperature decreases to 29º C (Seevam *et al.* 2008). For typical northern Europe conditions, this would imply minimum depths on the order of 800 m for CCS to work.

The thesis behind UCG-CCS method is based on the assumption that the sort of geological formations that are found in saline aquifers, unmineable coal seams, which are suitable for CO_2 storage would be found in the UCG coal seams (Friedmann et al., 2008). UCG-CCS provides unique new strategies for carbon capture and sequestration with minimal energy penalty for CO_2 removal (estimated at 6%-Friedmann et al., 2007a). Though the mechanisms of CO_2 storage in coal cavity are reasonably well understood (e.g. Friedmann et al., 2008), however, unresolved key issues against UCG sequestration include, sequestration resources, site criteria (injectivity, capacity and effectiveness), monitoring and verification, hazards and risks (leakage) and scale-up (Friedmann, et al., 2008). Competitive carbon-capture economics and coincidence of storage targets make UCG with CCS an attractive carbon management package. UCG-CCS represents ideal prospects for permanent sequestration of a large proportion of carbon dioxide with the stored CO_2 being kept in place by cap rocks higher in the sequence (Younger et al., 2009).

Hitherto, there are no examples of integrated UCG-CCS projects anywhere in the world. This is because storage of CO_2 as a supercritical fluid (i.e. a fluid with the density of a liquid but the compressibility, viscosity and diffusity of a gas) requires depth of at least 700m (and probably more than 800 for impure CO_2 recovery from flue gas), whereas UCG projects around the world to-date have targeted coal seams which are shallower than this (typically ≤600m). Rough estimate suggests that the storage capacity of UCG created coal cavity for which CO_2 could be stored is between 20-60% depending on a number of factors mainly site geology (Personal Communication, 2009).

Although there has been a considerable amount of discussion about the possibilities of storing CO_2 in the cavities formed during UCG operations (e.g., Roddy, 2008), and some people have claimed that UCG provides some inherent synergies to facilitate CO_2 separation and its long-term geological storage (e.g., Roddy, 2009), however, experts have always been careful to say that storage in UCG cavities has yet to be established as a practical and commercial possibility (e.g., Friedmann et al., 2007a; 2008a). But as with CCS from coal-fired power plants, the technology is at early stage of development and commercial-scale demonstrations would be needed before CO_2 storage in the cavity can be commercially ready.

7. Overview of economic viability of UCG with CCS (UCG-CCS) in North East England

As with all commercial activities, the economic case for UCG-CCS amounts to a balance of credits and debits. On the credit side, UCG-CCS offers a low-cost route to emissions reduction; the cost is lower than for surface gasification plants because there is no need to mine, store or transport coal, there are no solid residues to dispose of, and there is no need to purchase a gasifier; it converts an abundant natural resource into a secure, economic supply of gas; it enables stranded coal resources (e.g. deep or offshore) to be converted into commercial reserves; there is a range of potential end users and markets e.g. power generation, heating, synthetic fuels, chemicals and hydrogen; it is largely immune to crude oil price swings (unlike conventional coal mining which relies on diesel fuelled equipment and transportation);it is cheaper than natural gas for power generation; and finally, as explained in greater detail in the section above, UCG creates conditions for deep geological storage of CO_2 which are orders of magnitude more favourable than in natural saline aquifers or depleted hydrocarbon reservoirs.

On the debit side of the balance sheet for UCG-CCS are: technical and commercial uncertainties (e.g. lack of economies of scale) since the technology has not yet been widely deployed; syngas production rates and composition are variable compared with pipeline-delivered natural gas; open-cast coal mining (where acceptable) is cheaper; ground subsidence must be managed, and there is some risk of aquifer contamination; trials and prospective site evaluation are expensive; there can be significant costs in transporting the syngas to the point of use; carbon capture technology for high-temperature pre-combustion applications is not yet a commercial reality (though capture post-combustion is); and planning approval processes (not only for UCG but also for CCS) are still under development in the majority of countries.

Wide-scale proliferation of commercial UCG projects has thus far been inhibited by the availability of comparatively cheap supplies of crude oil and natural gas. Looking at 2008 data, against a natural gas price (in the USA) of $9 per million Btu, raw syngas can be produced via UCG in the USA for $1.8 per million Btu based on air gasification (Green, 2008). Using oxygen-blown UCG in Europe the cost of syngas becomes $3.8 per million Btu. These figures are now sufficiently low for UCG to look commercially attractive whenever oil and gas prices are reasonably high.

The economic case for UCG syngas displacing natural gas or coal for power generation is relatively straightforward. Alternative uses such as conversion of syngas into liquid fuels, chemical intermediates or hydrogen are more difficult because whilst the added value is well known (and much higher than for power generation) there is a tighter requirement for syngas cleanup. Technologies for cleaning up UCG syngas to chemical feedstock standard are still under development and so the costs are less well known. There are several such projects underway at present, which should help elucidate the figures in due course.

Having reviewed the range of opportunities available in North East England, it was concluded that, in broad terms, the most financially attractive options are (1) to sell syngas, take back captured CO_2 and store it for a fee, and (2) to sell decarbonised hydrogen and methane.

Project Ramsay aims to provide an option for CO_2 storage within the UCG cavities that are created. The environmental imperative for CCS has previously been described, however, there are also sound commercial reasons for including CCS as an integral part of the project since the creation of a long term storage site for CO_2 provides another opportunity for revenue generation. The commercial rationale for

CCS has been created by the emergence of greenhouse gas emissions trading schemes (ETS) - so called ‘cap-and-trade’ schemes – which have created a market for carbon credits trading. The Kyoto Protocol established carbon credits as a key component of national and international ETS implemented to mitigate global warming. ETS provide a way to reduce greenhouse gas emissions on an industrial scale by capping total annual emissions and allowing the market to assign a monetary value to any shortfall through trading. Credits can be exchanged between businesses or bought and sold in international markets at the prevailing market price.

In July 2003 the European Council formally adopted the Emissions Trading Directive. This Directive laid out the framework for the European Emissions Trading Scheme (EU ETS). The scheme started on 1 January 2005 and from this date, emissions from companies in sectors covered by the scheme were capped across (the then) 25 European countries. The EU ETS gives carbon a price.

8. Regulatory Frameworks for UCG-CCS in North East England

A UK Regulatory framework for UCG has been extensively reported in the IEA-Underground Coal Gasification publication (Cough, 2009). The relevant requirements for North east England are summarised below.

UCG is covered by land use, planning and environmental regulation provisions for all onshore operations. There is currently no spatial system for offshore operations, thus, each proposal would be considered on its merits. However, any gas recovered offshore would be taken to an onshore storage and power generation or liquids production facility and this would fall within the ambit of planning provisions. A project that spans the areas of coal exploitation, gas production and an offshore environment will be subject to a wide range of environmental and operational permits.

Under Town and Country planning provisions, there is a presumption in favour of permitting planning applications, if environmentally acceptable, subject to suitable mitigation measures, where these are in conformity with policies in the mineral development plan. Development of a trial site for UCG-CCS or of a full production facility would be considered as a mining operation in any planning application.

However, any associated electricity generation or liquids production facilities would be regarded as an industrial facility. Therefore, policies concerning both mining and industrial operations would need to be taken into account by the relevant local planning authority. Since UCG is a recent issue in the UK, there is a policy vacuum concerning the extraction element of any proposal in any development plans, and applications would be considered on their merits. However, there will be policies relevant to industrial facilities that are relevant to processing and generation facilities. If the local planning authority refuses an application, it may be the subject of an appeal to the Secretary of State.

Project Ramsay will require a number of consents and permits. Some of these will require associated studies such as an environmental impact assessment in order to obtain the necessary permissions, whilst others will be more easily acquired. Onshore development may be subject to the following:

- The Town and Country Planning Act 1990
- The Environment Agency (EA) Environmental Permitting (England and Wales) Regulations 2007 (replacing the PPC Regulations)
- Waste Water Discharge (Authorisation) Regulations 2007
- Water Resources Act, 1991
- Pipelines Act 1962; Section 36 of the Electricity Act 1989; Section 37 of the Electricity Act 1989
- Greenhouse gas emissions under the Emissions Trading Scheme
- Control Of Major Accident Hazards (COMAH), if sufficient CO_2 is stored on site
- Waste Management Licence if sufficient waste is produced
- Generation Licence if substantial quantities of electricity are produced

In addition to the above there will also be various requirements placed on the project by legislation such as the Environmental Impact Assessment (EIA) Regulations, the oil storage regulations, UK air quality objectives and other such regulations and guidelines that will not require permits but will inform the project design. Thus UCG processes, for both trial and semi-commercial operations, would be covered by the

Pollution Prevention and Control Regulations (IPPC 2000). Like all gasification, UCG will need an IPPC permit from the Environment Agency. IPPC requires the application and use of Best Available Technology (BAT) for all emissions. Groundwater Regulations 1998 is also covered in the IPPC permit process.

8.1. UCG-CCS Licensing Requirements in the UK

The undertaking of any UCG-CCS project will require formal consents of various forms. Planning and other ‘legislative’ consents are listed above. In addition, specific consent will be required to access and make use of the coal. Until very recently, there was some debate and a lack of clarity over which authority would be the consenting authority for a UCG-CCS project, i.e. the UK Coal Authority (CA) or the Oil and Gas Directorate of BERR. It has recently been confirmed that Petroleum Licensing will not be required for UCG thus the appropriate licensing is the CA and the licensing route is described below.

8.2. UCG-CCS Licensing Procedure in the UK

Under the Coal Industry Act 1994, certain coal mining operations require a licence and these include UCG. Those operations are, broadly:-

- the winning, working or getting of coal;
- the treatment of coal in the strata for the purpose of winning any product of coal; and
- the winning, working or getting of any product of coal resulting from such treatment;

in any part of the UK, under the territorial sea adjacent to the UK, or on the UK Continental Shelf. In addition to such a licence anyone wishing to carry on such coal extraction operations will require a property interest in the coal which will almost always be owned by the CA, therefore, a lease of coal from the CA is most often required.

The licence application procedure for development of a coal resource is relatively straightforward. An application is made containing all of the required information and after due consideration, the CA either denies or grants a licence. The CA may be prepared to grant a conditional licence and an option for lease of coal in its ownership. A conditional licence defers the coming into effect of the authorisation to exploit coal until specified requirements have been satisfied, e.g. that planning consent has been obtained, and will lapse if these requirements are not fulfilled within a specified and agreed period.

9. Public perception of UCG-CCS in North East England

The international interest in the technology of Underground Coal Gasification (UCG) as a means of accessing the energy contained within inaccessible coal reserves has been growing astronomically in the last decade. However, one of the potential uncertainties/obstacles to the deployment of UCG worldwide is the adverse public perceptions and reactions, leading to either stopping or delaying applications for UCG operations. Public, local community and non-governmental organisations (NGOs) perceptions have, for many years, been important in planning decisions on energy projects in many countries, most famously in relation to nuclear power (Bradford, 1992, Owens & Cowell, 2002, Pickett, 2002, Surrey & Huggett, 1976, Wynne, 1982).

For CCS however, the first wake-up call came in March (2009) when a Dutch council objected to Shell's plans to store CO_2 in depleted gas fields under the town of Barendrecht, near Rotterdam despite a successful environmental impact assessment and the enthusiastic backing of the Dutch government. In addition, recently, July (2009), opposition from local people (who are sceptical about the safety of the project) led to the termination of the world's first demonstration CCS project (Schwarze Pumpe project) from a coal-fired power station proposed by the Swedish energy company Vattenfall in Spremberg, northern Germany. The spread of localised resistance is now a force that some fear could sink Europe's attempts to build 10 to 12 demonstration projects for carbon capture and storage (CCS) by 2015. Aiming to pre-empt such opposition, the French oil giant Total is making great efforts to engage the local community when launching its CCS project in Lacq, southern France.

UCG remains a relatively unknown technology with some characteristics which might influence how it is more widely perceived by stakeholders, members of local communities and the wider public. There may be concerns about possible risks and how readily the processes involved can be effectively controlled. Studies have shown that public trust plays a crucial role in shaping public opinion and local people form their opinions about supporting or objecting to a particular development based on the information available to them. Public perception of UCG has had inadequate attention during the development phases of UCG. Few studies have been done and part of the poor image that UCG has amongst some sections of the public is that the technology has been poorly explained; perceived exaggerated claims about the technology and the risks involved have either been ignored or seemed to have been glossed over.

A failed proposal for a UCG drill site at Silverdale (Staffordshire) provides an opportunity to understand the influence of local social, cultural and institutional factors on the manner in which the risks and benefits associated with UCG are perceived in the UK. This real-life example of public reactions to UCG emerged in the late 1990s at Silverdale, when an application for a proposed trial project was made in 2000 by the Coal Authority (CA). It elicited negative public reactions and was subsequently abandoned due to the public outcry and a legal challenge as to whether UCG research and development was permitted under the remit of the organisation (DTI, 2004; Shackley *et al.*, 2004). Public opposition to UCG may arise for a number of reasons, including fears and concerns about: the safety of UCG, the long-term security of UCG sites, visual intrusion on the landscape, lack of perceived ‘need’ for UCG, and other Not in My Back Yard (NIMBY) type of reactions (DTI, 2004; Shackley *et al*., 2006). Many governments now accept that some better understanding of potential public perceptions in advance of the implementation of a new energy technology is desirable to inform technology implementation. In the UK, the government has accepted that the public might play a constructive role in the actual development of a new energy technology by allowing the public to debate and scrutinize the science behind the technologies.

Thought no formal research has been done in the North East England on this subject, however, a pilot study by the UK Department for Trade and Industry (DTI) in 2003 at Silverdale on the public perception of UCG suggests that the familiarity of local people with the consequences and legacies of conventional coal mining amplified the perceptions of the risk of affected people (Shackley et al., 2004). However, people welcomed the idea of using UCG in remote locations (offshore & near shore) to master the technology before applying it in coal seams close to populated areas. They were strongly in favour of UCG in combination with carbon capture and storage (UCG-CCS) (Shackley et al., 2004).

In the North East, however, opposition is expected to be relatively low. Coal is the story of North East England and coal mining was once one of the most important economic activities in the region which ultimately led to Britain emerging as the vanguard of the industrial revolution in the 18th and 19th centuries. The region has one of the longest mining histories in the world which began in 1585 and led the entire world into the era of 'carboniferous capitalism' beginning with the industrial-scale coal mines beneath Lobly Hill, Gateshead. The era brought considerable prosperity to the region and to the whole of Britain. The mining industry has changed dramatically in the region in the last decade or so and since the late 1970s, mine operations in the region as in other part of the UK have become uneconomic (due to stringent environmental regulations) and as a consequence of this economic instability, over 75% of the region's mines have been decommissioned.

To improve the public perception of UCG operations, there is thus scope for a considerable amount of work, particularly in places where developments are being considered, to provide good explanations and information. For a trial or commercial application to proceed, UCG would have to be part of, and integrated with, wider local development initiatives aimed at creating new employment opportunities or improving quality of life and be beneficial to the local economy and environment as a consequence.

10. Summary/Conclusions

Estimates of the total global coal resources are of the order of thousands of billions of tonnes, whereas figures usually quoted for accessible coal reserves are typically tens of billions of tonnes. There is thus a huge gap between reserves and resources. UCG offers the tantalising prospect of closing that gap quite considerably. If the UCG opportunity can be linked successfully to emerging CCS technology, then the implications for addressing the twin challenges of climate change and finite fossil fuel reserves is truly game-changing. There are particular attractions in developing a "selfcontained" solution whereby clean use of coal and carbon dioxide sequestration are combined in the same location without a need for material transfer. From a different perspective, there is an attraction in extending the envelope to include syngas export and CO_2 import/export. The former opens up the prospect of linking into lucrative opportunities beyond the power generation sector: the latter offers contingency plans on a number of fronts.

Project Ramsay is seeking to create a commercial scale underground coal gasification and carbon capture and storage (UCG-CCS) operation in North East England. The UK government has emphasised that renewable, nuclear and clean fossil fuels will form the trinity of low-carbon and the future of energy in Britain. Under these plans, 40% of the UK electricity will come from clean coal (low-carbon energy) by 2020 and more in the years after. The UK has set a legally binding of 34% for CO_2 emission reduction by 2020 and 80% by 2050, compared to 1990 levels. Half of this reduction is expected to come from industrial power generation (mostly coal-fired power station), 15% from improved domestic energy efficiency and 10% from changes in the work place.

UCG-CCS is an essential technology for reducing global emissions and needs to be developed rapidly if the UK is to play its part in the fight against climate change. North East England has the highest *per capita* energy demand in the UK due to the high level of manufacturing industries and we expect this to continue, particularly as we look to the electrification of transport, so the development of a proposal like this represents a truly world-leading opportunity for the region and the country as a whole.

The broad conclusions from the feasibility study are that: previous estimates for UCG-compatible coal had been conservative; there are coal seams that appear to be usable for CO_2 storage following UCG; and some of the end uses for syngas are potentially attractive. The most attractive options in financial terms are (1) to sell syngas, take back captured CO_2 and store it for a fee, and (2) to sell decarbonised hydrogen and methane. It was concluded that a project could be done in phases, ramping up the scale over time in order to minimise technical risk and investor exposure. Such a project could deliver a positive return on investment, albeit on a longer timescale than more conventional energy projects.

Our vision is for North East England to act as the gateway to UCG-CCS development and therefore to the decarbonisation of energy, through the creation of a “North East Cluster” that could see power stations and industrial sites in the region hooking up to a single CO_2 pipeline. A cluster approach would effectively “future-proof” the development of CCS by allowing new facilities to connect quickly to the energy network that would work much like the existing national grids for gas supplies and electricity transmission. Initial feasibility study suggests that there is great potential for a viable UCG-CCS project located off the coast of North East England assuming that the various technical challenges can be overcome. Such a project would need to be financed as a strategic investment in energy and CCS as the returns available and timescales involved are not sufficiently attractive to venture or capital equity investors compared with more conventional alternatives.

North East England has recently been designated as the UK’s first Low Carbon Economic Area and the first specialist region specialising in ultra-low carbon vehicles as part of the UK Low Carbon Industrial Strategy. Project Ramsay will complement this initiative and take forward the UK’s response to the challenge of climate change from fossil-fuel power plants at a time when it has significant need to replace its ageing fleet of power generation assets. The project thus provides the North East and the UK with an ideal opportunity to provide modern, leading technology necessary to maintain a balance between security of supply and achieve the necessary reduction in CO_2 emissions in our power plants. The benefits of this technology to the UK economy can not be over-emphasised: apart from helping the UK to minimise its dependence on imported oil and gas, the market size for commercial exportation of this technology to countries like China and India is immense.

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