Underground coal gasification with CCS: a pathway to decarbonising industry

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Underground coal gasification (UCG) opens up the prospect of accessing trillions of tonnes of otherwise unmineable coal. When combined with carbon capture and storage (CCS), UCG offers some attractive new low-carbon solutions on a vast scale. This paper has several aims: to review key developments in technologies for UCG, CCS and CO_2 storage in coal seam voids; to quantify the scale of the opportunity that these technologies open up; to examine the scope for linking these developments to other more familiar plans for decarbonising the fossil fuel power generation industry and other carbon-intensive industries; to identify the main hurdles to be overcome in taking forward any large-scale UCG–CCS proposition; and to propose a basis on which UCG-CCS can sit at the heart of plans to decarbonise present day industry in a way that dove-tails with longer-term ambitions for an economy based on renewable energy.

1. Introduction

World coal "reserves" are usually stated in tens of billions of tonnes based on an assessment of those coal resources which are judged to be mineable economically.[1,2] With world population forecast to rise from just over 6 billion people today to 9 billion people in 2050, and with developing countries starting to move towards the levels of *per capita* energy consumption currently seen in the developed world, the demand for energy in all its forms is set to rise markedly, with some sources predicting a doubling or even a trebling in total primary energy demand by 2050 relative to today.

The world's oil and gas reserves are being rapidly consumed, starting with the most economically attractive. Various estimates have been made to ascertain when annual production rates of oil and gas will reach their peak.[3] In some areas the peak has already been passed *e.g.* North Sea oil. On a worldwide basis the figures usually quoted are 2017 for peak oil and 2040 for peak gas production, with oil resources being substantially exhausted by 2050 and gas resources by 2070. There are those who predict a plateau rather than a peak, usually based on bringing additional resources into play *e.g.* converting coal into liquid fuels or converting biomass into liquid fuels. However, whether you believe in a peak or a plateau, there is little sign in the demand forecasts of a drop in demand for oil or gas. As demand begins to outstrip ability to supply, conventional economics tells us that prices will rise dramatically, triggering more ambitious technology development in a bid to convert more of the Earth's finite fossil fuel resources into usable reserves.

Returning to coal, estimates of total world coal resource (including unmineable coal) are usually stated in trillions of tonnes rather than billions. An obvious question to ask is: can we harness the energy contained within coal without having to mine the coal? The first experimental work on this question was carried out in 1912 by Sir William Ramsay in County Durham, North East England. Although successful, the work was interrupted by the First World War. The work was not resumed afterwards largely due to the ready availability of relatively cheap conventionally mined coal in Western Europe. Cheap coal was followed by cheap oil and then cheap gas. Climate change, although predicted by Arrhenius in 1896, was not a widely appreciated problem at that time. Perhaps with hindsight some of the wealth resulting from this rapid use of finite fossil fuel

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Broader context

Coal reserves significantly exceed those of oil and gas. When total coal *resource* is considered (including coal which it is uneconomic to mine), it dominates the fossil fuel picture. Unfortunately, it is also the most intensive source of CO_2 when used for conventional power generation. If coal is gasified *in situ* underground, the resulting synthesis gas can be used for power generation and also for chemical synthesis. Applying carbon capture and storage technology to a power generation facility allows the greenhouse gas impact to be minimised. Increasingly the petrochemicals industry is also looking at options for affordable CO_2 capture. Much work has been done on suitable storage solutions for CO_2. This paper explores a different CO_2 storage solution, using the voids created in underground strata through underground gasification of coal. Taken as a whole, this proposition significantly extends the feedstock slate for both power generation and "petrochemical" products, adds an extra degree of freedom for handling CO_2 storage, and thereby offers an environmentally credible bridge to the longer-term renewables-dominated future that many of us aspire to – especially if part of the revenue windfall is earmarked for rapid expansion of renewable energy research and development.

reserves should have been set aside to fund accelerated research and development of the technologies so badly needed today? Europe opted instead for rapid economic expansion based on the cheapest possible fossil fuels, and alternatives were sidelined.

One of those alternatives was the gasification of coal *in situ*, now referred to as underground coal gasification (UCG), in order to produce a versatile gaseous fuel – synthesis gas (or syngas). Syngas is a mixture of hydrogen, carbon monoxide and carbon dioxide which can be used as a fuel in a gas turbine or for chemical synthesis. Syngas produced in other ways is, of course, a widely used feedstock in the chemical industry with widespread use in the production of ammonia for fertiliser, methanol as a chemical intermediate, ethanol and synthetic fuels.

UCG technology was first taken up at industrial scale in the Former Soviet Union (FSU) with significant development programmes beginning in the 1930s, leading to industrial scale operations.[4] Commercial scale operations have also been conducted in China. Feasibility studies or trial operations have been conducted in Australia, the USA, Spain,[5] South Africa, India and the UK.[6]† The Underground Coal Gasification Partnership (UCGP) has estimated that around 20 billion cubic metres of syngas has been produced to-date from UCG activities across the world, equivalent to about 15 million tonnes of coal.[7] To date, the largest power generation plant based on UCG is a 100 MW steam turbine plant at Angren in Uzbekistan.

In summary, the deployment of UCG technology has therefore proceeded at different rates around the world, with most interest arising in countries that lacked (or were then thought to lack) significant hydrocarbon deposits. Some of the leading developments today are in Australia and the USA. The Chinchilla project in Australia aims to generate 30–40 MW of electricity and then move on to produce 17 000 barrels per day of liquid fuels.[8] The plant has run several successful campaigns. Much of the underpinning science for UCG is being developed in the USA at the Lawrence Livermore National Laboratory.[9] In fifteen countries around the world there are now people working to find the most effective way of securing licences for UCG deployment within specific jurisdictions.

There is a clear attraction in a world of finite fossil fuel reserves to finding ever cheaper ways of converting underground coal into a usable syngas. However, if we stop at that point then we have created a huge problem in respect of climate change since coal is the most carbon-intensive of the fossil fuels. All fossil fuels produce CO_2 when burned conventionally, but some liberate more energy than others in the process. Although calorific values vary by source, typical figures would be 50 GJ t^{-1} for natural gas, 45 GJ t^{-1} for crude oil and 30 GJ t^{-1} for coal – which means that coal has the highest CO_2 emissions per unit of energy produced. If we are going to see a major swing towards the use of coal, technologies for capturing the downstream CO_2 emissions become increasingly important.

Much has been reported on carbon capture and storage (CCS), the name given to a family of technologies for extracting CO_2 from a mixed gas stream, transporting it to a suitable long-term storage repository (*e.g.* depleted oil and gas fields or saline aquifers), and storing it there.[10,11] The main variants are pre-combustion capture (in which CO_2 is removed before the syngas reaches the gas turbine), post-combustion capture (in which CO_2 is removed from the power station flue gases) and the oxy-fuel process (which eliminates nitrogen from the flue gas by combusting the fuel in a mixture of oxygen and recycled flue gases). Typically a CCS scheme sets out to capture and store 85–90% of the CO_2 that would otherwise be emitted. The most salient features of the technology are summarised later in this paper. If UCG can be successfully linked to CCS, then the combined UCG–CCS offering provides a way of harnessing the energy contained within huge untapped coal resource whilst remaining within the ever-tightening targets for reducing CO_2 emissions. The requirements for achieving long-term storage of CO_2 and the CO_2 trapping mechanisms for deep saline aquifers and depleted hydrocarbon fields are well documented.[12,13]

Finally, there is the intriguing possibility of storing the CO_2 arising from UCG back in the voids created in the coal seam during gasification. This alternative to storing CO_2 in a depleted hydrocarbon field or in a saline aquifer has received relatively little attention, but it holds out the prospect of a largely self-contained solution. The technical basis for this storage option is outlined later in the paper.

This paper has several aims: to review key developments in technologies for UCG, CCS and CO_2 storage in coal seam voids; to quantify the scale of the opportunity that these technologies open up; to examine the scope for linking these developments to other more familiar plans for decarbonising the fossil fuel power generation industry and other carbon-intensive industries; to identify the main hurdles to be overcome in taking forward any large-scale UCG–CCS proposition; and to propose a basis on which UCG–CCS can sit at the heart of plans to decarbonise present day industry in a way that dove-tails with longer-term ambitions for an economy based on renewable energy.

The alternative, it is suggested, is an inexorable drive to include more conventional coal in the energy mix over the next few decades. However, there is an additional factor to consider – and one that is difficult to place a value on in economic terms. More than 5000 deaths a year occur in the coal mines of China: 4 deaths for every million tonnes of coal mined. In Ukraine, the death rate is even worse: 7 deaths per million tonnes. To put these figures into perspective, the last time death rates in UK coal mines were as high as they currently are in China was back in the 1920s; in the case of Ukraine the parallel figures occur way back in the 1880s. Much of this mining is linked to energy provision in support of the manufacturing of goods for export to Western countries. UCG could provide an ethically acceptable way of enabling this economically driven low-cost manufacturing activity to continue.

2. Technology basics

2.1. UCG technology

The basic idea is that energy can be recovered from deeply buried coal seams by gasification of the coal *in situ.* This is readily achieved by introducing hot steam and oxygen or air to the coal *via* injection boreholes. In a sense, the uncontrolled combustion

† For further details on the history of UCG see: D. J. Roddy and G. Gonzalez in *Carbon Capture, Sequestration and Storage (Issues in Environmental Science and Technology)*: **29**, ed. R. E. Hester and R Harrison, 2009.

of coal underground is well known as a result of the many coal fires that have occurred around the world. However, the controlled gasification of underground coal is a different matter.

UCG has been approached in many different ways. One approach (still favoured by the Chinese today) involves using mined tunnels or roadways to connect the injection wells to the production well. This is known as the "long and large (cross-section) tunnel gasification method" (LLT).[14] Another approach involves sinking a series of vertical wells (the "linked vertical well method", LVW) and moving the injection point along to a new well whenever the current stretch of coal seam has been exhausted. The LVW method is used in South Africa.

A popular approach, especially in Europe and the USA, is the use of controlled retractable injection point (CRIP) technology.[15] The CRIP system involves a burner attached to retractable coiled tubing which is used to ignite the coal. It operates by moving the injection system to a location within the target coal seam close to the production well and igniting the coal to start the gasification reaction. The injection point is then gradually retracted away from the production well as the rate of gas production begins to fall off.

The target coal seam can be on-shore, near-shore or off-shore. In all three cases, a fundamental requirement is the ability to accurately and remotely direct drilling equipment to create the network of gasification channels, injection wells and production wells for a UCG operation. Directional drilling is a proven technology in the oil and gas industry. The in-seam drilling of coal seams has been part of coal exploitation since at least the 1950s. Underground steering of boreholes made its commercial entrance in the oil and gas industry around 1990, when operators established the benefits of lateral drilling for extending the life of wells and fixed drilling platforms and for reaching inaccessible locations. Now that directional drilling has become common for coal bed methane (CBM) and enhanced CBM applications, there are specialist drilling companies around who supply services to CBM operators. The focus to-date has been on reducing costs. UCG has a tighter requirement on accuracy. The ability of directional drilling to meet these requirements at an affordable cost is still under review.‡

2.2. Carbon capture technology

The broad technology options available for capturing CO_2 are physical absorption, chemical absorption, membrane separation and cryogenic separation.[16] In the physical absorption process, CO_2 is dissolved in a solvent such as liquid methanol or a glycol solvent.[17,18] With chemical absorption the CO_2 is removed by reacting it with a chemical solvent such as methyl diethanolamine.[19] These processes typically absorb 85–90% of the CO_2 in a pre-combustion capture process where the CO_2 partial pressure is relatively high.

‡ For further details on UCG technology see: D. J. Roddy and G. Gonzalez in *Carbon Capture, Sequestration and Storage* (*Issues in Environmental Science and Technology*): **29**, ed. R. E. Hester and R Harrison, 2009; M. Green, Proceedings of the International Coal Conference, Pittsburgh, 2008; E. Burton, J. Friedmann and R. Upadhye, *Best Practices in Underground Coal Gasification*, Lawrence Livermore National Laboratory, California, USA, 2006.

Membrane separation is less well developed than physical and chemical absorption, and it is not yet ready for use in CCS on a commercial scale.[20,21] An example of a membrane that is permeable to CO_2 is polyvinylamine.[22] Polymeric membranes are commercially available but suffer from problems with temperature stability, permeability performance and selectivity performance.[23] Inorganic membranes offer some advantages in pre-combustion capture plants because of their flexibility and low energy penalty, but they are very expensive. Development work on membranes continues.[24]

Cryogenic separation is based on liquefying CO_2 in order to separate it from the other gases. Energy requirements for the refrigeration step are high.[25]

2.3. CO_2 storage in UCG voids

Returning to the storage mechanism, the UCG process creates voids deep underground following gasification of the coal. These voids will inevitably collapse, just as voids produced by longwall coal mining do, leaving high permeability zones of artificial breccias – known as 'goaf' (from the Welsh word *ogof*, meaning a cave) – which are almost invariably isolated from surface by low permeability superincumbent strata.[26] Where UCG has taken place at depths in excess of about 700–800 m, storage of CO_2 in these artificial high-permeability zones is a very attractive proposition. A combined UCG–CCS project can then offer integrated energy recovery from coal and storage of CO_2 at the same site.

In a longwall panel, all of the coal is progressively removed from a rectangular area, and the roof is allowed to collapse forming goaf. Typical longwall panels are usually about 1 km long, 150 to 250m wide and 1–3 m high.[27] Though there are different possible lay-outs for a UCG operation, one configuration is a chamber with a length of 500–600 m, 30–40 m wide and with the height equal to the thickness of the coal seam. A longitudinal pillar would separate the gasification chambers. A gasification chamber of the above dimensions corresponds to the 'shortwall' variant of collapse-based coal mining, a configuration which is well understood, as it is widely used in conventional mining to achieve rapid face movement with minimal disturbance of overlying aquifers.

Direct measurements of goaf permeability are rather rare, but reported values are in the range of 1–20 darcy[28] compared with figures of 0.01–1 darcy for natural, deep saline aquifers. (A medium with a permeability of 1 darcy permits a flow of 1 $cm^3 s^{-1}$ of a fluid with viscosity 1 cP under a pressure gradient of 1 atm cm^{-1} acting across an area of 1 cm^2.) It could therefore be up to 2000 times easier to inject CO_2 into UCG goaf than into natural, deep saline aquifers.

A rough estimation shows that the volume needed at 800 metres depth to store the CO_2 produced from the syngas can be 4 or 5 times the volume occupied by the extracted coal. The actual storage volume available is larger than the volume occupied by the extracted coal as a result of the increased permeability of partially collapsed overlying strata. As with depleted hydrocarbon fields and deep saline aquifers, the actual storage capacity will depend on the compressibility of the strata without exceeding the fracturing limit of the rock, and would need to be determined experimentally or through more detailed modelling.

Regulations for subsurface injection of waste gases in Alberta set the injection pressure limit at 90% of the rock fracturing pressure.[29] §

3. The scale of the opportunity

One of the main attractions of UCG is the sheer scale of the opportunity whether measured in terms of coal availability or CO_2 storage potential. The prospect of being able to move rapidly to decarbonise mainstream electricity supplies is also very appealing.

3.1. Coal resource

Recent estimates of the total remaining coal resource in the world quote a figure of 18 trillion tonnes.[30] Compared with the figures usually quoted for accessible coal reserves (typically tens of billions of tonnes), there is a huge gap between reserves and resource. UCG offers the tantalising prospect of closing that gap quite considerably. It has been estimated by the UCGP that around 4 trillion tonnes of otherwise unusable coal could be suitable for UCG.[31] It should also be noted that the geographic disposition of coal resources is quite different to the picture for oil and gas, which means that the whole balance of power in the energy supply arena is set to change quite considerably if UCG technology unlocks significant new levels of usable coal.

3.2. Storage potential

For the reasons given in Section 2.3 above there is still a question over the precise volume of CO_2 that can be stored in the UCG coal void. Suppose, for the sake of argument, that 50% of the CO_2 arising can be stored back in the void space. If the aspiration is to target (say) 4 trillion tonnes of coal for UCG operations, that would translate into 12 trillion tonnes of CO_2 arisings, with (say) 10 trillion tonnes of CO_2 being captured (if CCS is deployed universally), and 5 trillion tonnes being stored in UCG void space. Compared with current levels of CO_2 emissions world-wide of around 27 billion tonnes per year, we are therefore looking at around 200 years of CO_2 storage capacity at current emission levels, which is getting close to the figures usually quoted for CO_2 storage capacity in saline aquifers. From a global perspective, therefore, the UCG–CCS concept deserves more serious consideration alongside some of the other more prominent carbon management proposals.

3.3. Links to other carbon-intensive industry

The power generation sector is now looking seriously at the prospect of large-scale deployment of CCS technology. The APGTF report[32] points to the need for at least 80 new CCS plants per year from 2020. The aim is to substantially decarbonise the fossil fuel power generation industry. Such projections tend to be based on a mix of pre-combustion capture, post-combustion capture and oxy-fuel CCS processes[33] and take no account of the UCG–CCS potential. If the syngas from UCG is passed through a water gas shift process (to convert carbon monoxide and hydrogen into CO_2 plus additional hydrogen) followed by a carbon capture step prior to feeding the hydrogen-rich gas into a power plant, then it becomes a variant on pre-combustion capture technology. If instead the UCG syngas is supplied direct to a power plant for combustion and the CO_2 is then captured from the flue gases, then it becomes a variant on post-combustion capture technology.

Either power plant type can be dedicated to syngas from UCG only. However, subject to suitable syngas cleaning and conditioning, UCG syngas could be fed to power plants (with pre- and/or post- combustion capture) alongside other gaseous feedstocks. It is therefore credible to propose that the carbon management plan for a UCG facility (based on CO_2 storage in the coal seam void) can be integrated with other carbon management plans (based on CO_2 storage in depleted hydrocarbon fields and saline aquifers.[34]

There are attractions in interlinking the various CO_2 storage routes. CO_2 storage in a depleted hydrocarbon field is sometimes the most attractive option financially, particularly if the CO_2 can be sold for enhanced oil recovery or enhanced gas recovery (where CO_2 is injected in order to mobilise otherwise unrecoverable oil or gas). However, it is useful to have an alternative so that it is never seen as a distressed sale, or to provide a contingency plan against operating problems in the oil or gas field. Saline aquifer storage is attractive because the capacity available world-wide is very much larger than for depleted hydrocarbon fields.[35] Proximity of the storage location to the power plant operation then becomes an influencing factor (in terms of pipeline length, CO_2 pumping capacity requirement *etc.*). Against this background, which is relatively well known, CO_2 storage in UCG voids provides an additional degree of freedom.

Plans are already being developed in various parts of the world for creating networks of CO_2 transport pipelines. Such networks, over the long term, will be more cost effective than point-to-point solutions developed by individual projects in complete isolation. The question of how best to incentivise the creation of such networks has yet to be resolved.[35]

In anticipation of such CO_2 collection and transportation networks being created, work has begun in a number of places to explore the possibility of linking other sources of CO_2 into such a network. Some of the more obvious sources are cement manufacture, fermentation processes, steel-making and other metal-processing installations, as well as some petrochemical facilities that produce relatively pure CO_2 streams. There are economies of scale in linking such facilities into a CO_2 network. The Yorkshire and Humber area of England has developed tentative plans for collecting and transporting CO_2 by investing £2bn in a network that in time is expected to be worth £1.2bn per year to the region's economy. They concentrate on a limited area which contains 12 large point sources of CO_2 and accounts for 92% of the region's CO_2 emissions (80% from power stations; 20% from other large point sources).[36] Similar work is underway elsewhere in the UK and overseas.

The whole issue of using coal (with some kind of carbon management plan) as a feedstock for multiple industrial processes is receiving more attention as countries become concerned about security of oil and gas supplies. Looking at 2008 data, against a natural gas price (in the USA) of $9 per million

§ For further details on the storage mechanism see: P. L. Younger, D. J. Roddy and G. Gonzalez, *Proceedings of the 7th International Petroleum Geology conference*, London, 2009

Btu (1 British thermal unit = 1.055 kJ) raw syngas can be produced *via* UCG in the USA for $1.8 per million Btu based on air gasification.[37] Using oxygen-blown UCG in Europe the cost of syngas becomes $3.8 per million Btu. These figures are sufficiently low for UCG to look commercially attractive when oil and gas prices are reasonably high. Some studies have shown that the most financially attractive propositions for coal use lie outside of the power generation sector, but the most "bankable" projects continue to lie in power generation because forward pricing structures are more clearly defined.

UCG can therefore provide syngas as a feedstock into many of the above processes (not just power generation) whilst UCG–CCS can link into the same CO_2 networks to provide an additional degree of freedom in carbon management plans as described above.

3.4. Case study

North East England is often seen as the "birthplace of carboniferous capitalism" with its long history of industrial coal mining stretching back to 1585. One of the exciting clean coal development projects in North East England aims to gasify 2 million tonnes per year of imported coal and petroleum coke to produce syngas, apply pre-combustion carbon capture technology[38] and generate 800 MW of electricity whilst storing 5 million tonnes per year of CO_2. This project at Eston Grange, which has been under development for a number of years, has identified a wide range of opportunities for adding value to the investment proposition by taking advantage of the surrounding petrochemicals infrastructure.[39]

Project Ramsay (named after Sir William Ramsay) was established to assess the opportunity for UCG–CCS in North East England. As part of the project, specialists were commissioned to undertake a thorough review of all available data to determine the quantity and accessibility of coal suitable for UCG and for UCG–CCS. The study examined available data from a number of sources, including the Coal Authority, the British Geological Survey and BERR as well as data held by others, including Newcastle University.

Suitability of the area was considered for UCG and UCG–CCS taking into account coal seam thickness, depth of cover between the top of target coal seams and the sea bed where relevant, permeability of the relevant strata and, where relevant, stand-off distances from old mine workings. For UCG a depth of 100 metres or greater was used, and for UCG–CCS the minimum depth was increased to 800 metres to achieve the storage pressures necessary for CO_2 in its supercritical state.

The project considered both near-shore coal seams (<2 km) and off-shore coal seams (10 km or more) at a few locations. The study took account of specific local 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 power plant to saline aquifers under the North Sea, and so on.

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. A range of options have been considered.[40,41] The simplest case is when the UCG syngas is supplied as a feedstock into an existing power station or a planned new one. In this case the carbon management plan would be based on post-combustion capture of CO_2. Another broad option is to convert the UCG syngas into hydrogen and CO_2. The hydrogen can then be used locally as a feedstock or fuel, supplied to the planned Eston Grange power station as a fuel, or used locally in a dedicated new IGCC plant. In all these cases the carbon management plan would be based on pre-combustion capture of CO_2. If the UCG syngas is transported to nearby Teesside (where much of the UK's petrochemicals activity is based), the various integration options described in section 3.3 become available, each of which implies a carbon management plan.

There are other large CO_2 emitters in the region such as steelmaking and aluminium production, which extends still further the range of options for building a large network for distributing and storing anthropogenic CO_2. The respective roles of saline aquifer storage and coal seam void storage, and the balance between them, remain to be determined. The factors that impact most on the decision are cost, level of technology confidence, and relative geographic disposition of facilities. Out of the wide range of options for taking forward a UCG–CCS project in North East England, the most promising are now being studied in more detail.

4. Challenges along the way

The main challenges to be addressed are: professional management of environmental risk; developing an appropriate approach to licensing operations; cultivating public acceptance of the technology; and securing funding for the first few large demonstration projects.

4.1. Environmental risk management

The main risks to be considered in UCG are groundwater depletion, groundwater contamination, gas leakage and subsidence. Set against these, its outstanding environmental advantages are the elimination of coal stock piles and coal transport and much of the disturbance at surface, low dust and noise levels, the absence of health and safety concerns relating to underground workers, the avoidance of ash handling at power stations, and the elimination of SO_2 and NO_x emissions. Most of the contaminants produced in coal gasification are included in the List I of the Water Framework Directive (2000/60/EC), which forbids release into a water body. Consequently, for a UCG operation to be permitted in the EU, any potential water contamination would almost certainly have to be restricted to water which had been previously classified as permanently unusable (PU).

For CO_2 storage, the main risks identified are divided into three groups:[42] leakage, dissolution in formation water and displacement. At a local scale, leakage into the atmosphere or the shallow subsurface can cause asphyxiation to animals or humans, or affect plants and underground ecosystems. If the leakage is offshore, it can affect the living organisms in the water column and the seabed and interfere with other legitimate uses of the sea. It is also important to make a distinction between sudden large releases and continuous small ones.

The coupling of UCG–CCS alters the hazards and the risks inherent in UCG or CCS on its own.[43] On the one hand, the operation takes place at a much greater depth than conventional UCG (so that the conditions for CO_2 in its supercritical state are met). This certainly decreases the risk of potable aquifer contamination and of subsidence effects on the surface. On the other hand, the pressurization of the cavity with the injection of the CO_2 can increase the risk of fracture propagation.¶

4.2. Licensing

As of October 2009, there were approximately 15 licences for UCG in operations in 8 countries around the world, at varying stages of development. The licensing requirements vary from country to country and tend to be particularly onerous in developed countries. Taking the UK as an example, 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 remit 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. 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 impact on project design. Thus UCG processes, for both trial and semi-commercial operations, would be covered by the Pollution Prevention and Control Regulations. Like all gasification, UCG needs an IPPC permit from the Environment Agency. IPPC requires the application and use of Best Available Technology (BAT) for all emissions. Compliance with the Groundwater Regulations 1998 is also covered in the IPPC permit process.

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 or the Oil and Gas Directorate of BERR. The latest advice is that the licensing body should be the Coal Authority, but that before operations actually begin there should also be a "methane drainage" type of Petroleum Licence in place (as at existing coal mines) to cover the operator in case any native methane emerges from the coal seam.

¶ The environmental risks outlined above are explored in more detail in: D. J. Roddy and G. Gonzalez in *Carbon Capture, Sequestration and Storage (Issues in Environmental Science and Technology)*: **29**, ed. R. E. Hester and R Harrison, 2009; W S Atkins Consultants, Review of Environmental Issues of Underground Coal Gasification - *Best Practice Guide. DTI Cleaner Coal Technology Transfer Programme*. DTI. Birmingham, DTI: 82 pp, 2004

A case could be made for adding an additional requirement into the licensing process whereby a small proportion of the revenue from future UCG operations is taken in the form of a levy and used to fund an accelerated research and development programme for renewable energy technologies. It is perhaps unfortunate that such an approach was not taken when North Sea oil and gas were discovered. Such an arrangement would position UCG–CCS as more than a stop-gap solution and underpin the claim that it is in fact a genuine bridge to a renewable energy future.

4.3. Public acceptance

Public, local community and non-governmental organisation (NGO) perceptions have, for many years, been important in planning decisions on energy projects in many countries. For CCS, 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, in July 2009 opposition from local people led to the termination of the world's first CCS demonstration project (the Schwarze Pumpe project) – a coal-fired power station proposed by Vattenfall in Spremberg, northern Germany.

A failed proposal for a UCG drill site at Silverdale (Staffordshire, UK) 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. An application for a proposed trial project made in 2000 by the Coal Authority 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.[44,45] 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 might 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.‖

4.4. Cost of demonstrating at scale

Whilst the underlying science can be developed through modelling work backed up by laboratory-scale experimental work, most countries active in the field have found the need to move to pilot-scale trials in order to explore UCG performance at depth in coal seams. The cost of these trials tends to be dominated by drilling costs and usually amount to millions of pounds. Extended trials to explore the consistency of operation over a period of time are particularly expensive. The trials reported to-date are at relatively shallow depths (100–200 metres) whereas the seams of particular interest for CO_2 storage in its supercritical state lie at depths of more than 800 metres.

‖ For a fuller treatment of this topic see: L. K. Mudashiru and D. J. Roddy, *Proceedings of the 26th Annual International Coal Conference*, Pittsburgh, USA, 2009

5. Conclusions

The Earth possesses huge levels of untapped coal resource, much of which will be become accessible with the advent of UCG technology. At current rates of coal consumption this coal resource runs to several hundred years' worth. The chances of countries around the world choosing not to use this coal resource are very low indeed. The extent to which it will be done in conjunction with CCS depends on future economics of carbon capture technology, future economics of CO_2 storage technology (including CO_2 storage in UCG voids), achievable levels of environmental control, and societal attitudes to all of the above in the context of climate change. Approached in the right way and at the right scale, UCG–CCS stands to offer a cost-effective, self-contained, near-zero-carbon solution to energy provision in areas rich in coal resource. Energy provision can take a number of forms such as electricity generation, synthetic fuel manufacture *etc.* When linked to other sources of CO_2 production, CO_2 transmission networks and CO_2 storage locations, UCG–CCS offers an extra degree of freedom or an added level of flexibility in reducing the overall carbon footprint of a cluster of carbon-intensive industries.

The basic economics, on a first-pass assessment, appear to work. Much remains to be done, however, in order to confirm the feasibility of producing syngas of an adequate purity at an affordable cost from deeper coal seams, to determine the extent to which it is cost-effective to expand the envelope of use of syngas beyond power generation, to develop the most cost-effective borehole configurations for accessing long, deep coal sequences, and to demonstrate all of this at sufficient scale to attract the level of investment required. These challenges draw upon a range of disciplines that are rarely combined, including chemistry, chemical engineering, power engineering, reservoir engineering and hydrogeology.

Described in the above terms, UCG–CCS can be seen as a clever way of using finite fossil fuel resources as a bridge to a very different future world in which large-scale renewable energy technologies have come of age. At that level, UCG–CCS buys us time. However, it can do much more than that if pursued aggressively and with a licensing/taxation regime that recovers a revenue stream for investment in a vastly accelerated programme of renewable energy technology development. In that way, carbon-intensive industries can radically reduce their carbon footprint and at the same time accelerate the movement towards large-scale renewable energy technology deployment, with UCG–CCS at the heart of the development programme to serve as a driver and a beacon.

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