Can new technologies be used to exploit the coal resources in the Yorkshire–Nottinghamshire Coalfield?

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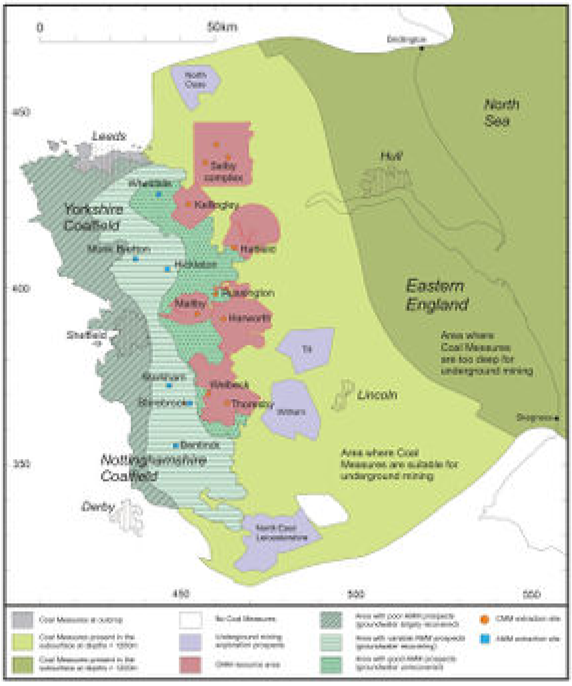

Figure 1 Location of conventional coal, AMM and CMM resources in eastern England.

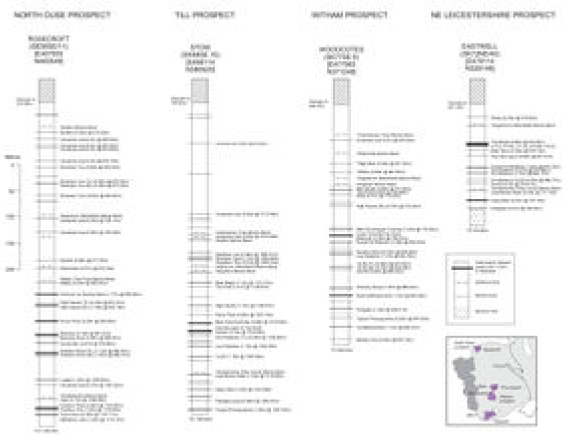
Figure 2 Borehole log correlation to show the main seams present in eastern England and their typical thickness.

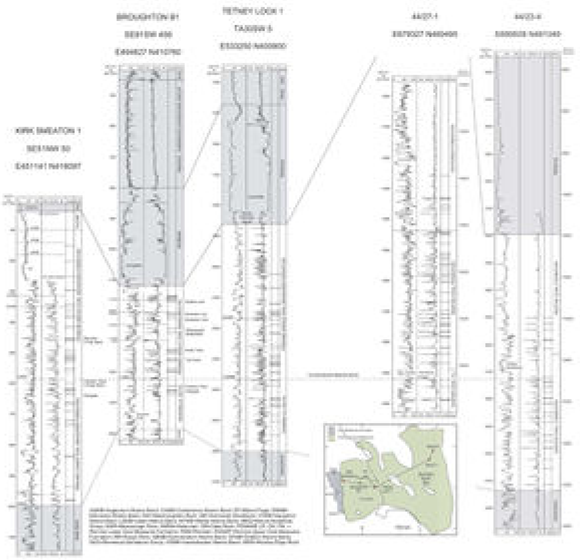

Figure 3 Generalized correlation of well geophysical logs of Westphalian coal-bearing sequences from eastern England eastwards into the southern North Sea (SNS). Note the increasing depth of the geophysical logs, with Coal Measures present at depths of up to about 5 km in the SNS.

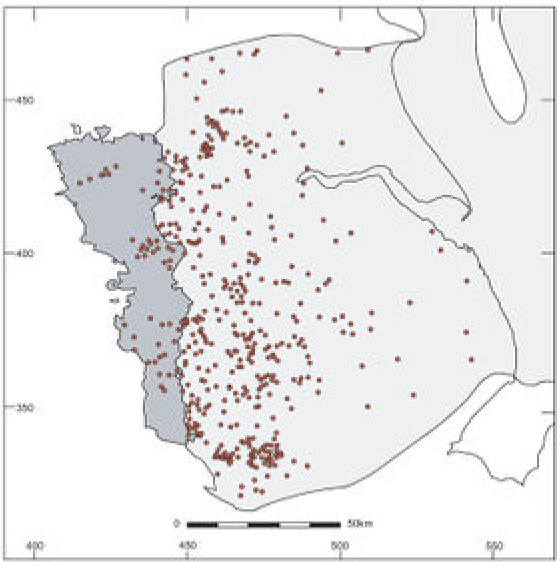

Figure 4 Location of principle deep boreholes proving rocks of the Pennine Coal Measures Group in eastern England.

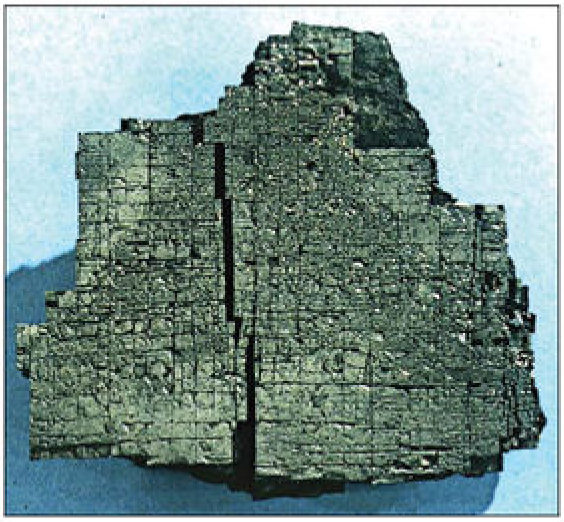

Figure 5 Cleat in coal. The surface facing the viewer is the face cleat. The horizontal fractures are bedding planes. The vertical fractures are the butt cleat.

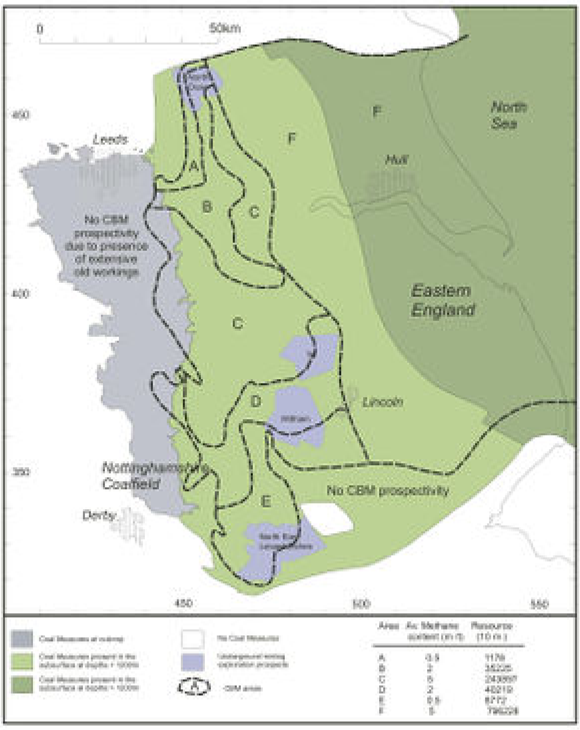

Figure 6 Location of CBM resource areas in eastern England.

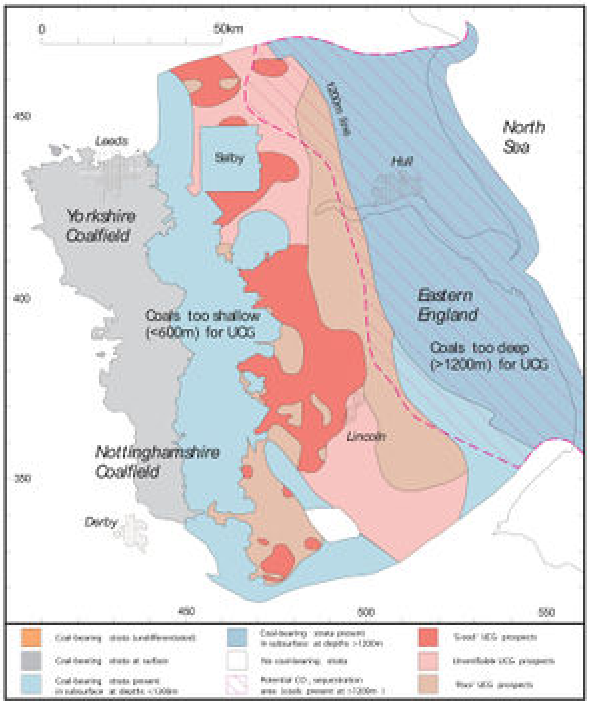

Figure 7 Location of underground coal gasification resources in eastern England.

Mine	Methane capture/utilization plant
Harworth	Surface drainage plant – gas used for 14 MW(e) electrical power generation
Kellingley	Surface drainage plant – gas used for 2.8 MW(e) electrical power generation
Maltby	Surface drainage plant – gas used for 4.2 MW(e) electrical power generation
Riccall-Whitemoor	Surface drainage plant – some gas used in boilers
Rossington	Surface drainage plant
Stillingfleet–N Selby	Surface drainage plant
Thoresby	Surface drainage plant – gas used for 2 MW(e) electrical power generation
Welbeck	Surface drainage plant – gas used in boilers and for 2.8 MW(e) electrical power generation
Wistow	Gas drained and discharged underground
Hatfield	Gas drained and discharged underground

Table 1 Current CMM capture and utilization in the Yorkshire–Nottinghamshire coalfield.

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By S. Holloway, N. S. Jones, D. P. Creedy, K. Garner

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Summary

Coal mining in the Yorkshire–Nottinghamshire coalfield has been one of the region's most important industries over the past 150 years. The number of working mines peaked at over 400 in the late nineteenth and early part of the twentieth century. However, many have closed over the past few years and now there are only ten large working mines still open. Three of these in the Selby complex (Ricall–Whitemoor, Stillingfleet and Wistow) are scheduled to close in April 2004. Although there are significant untouched coal resources east of the current deep mines, the prospects for opening new mines in the Yorkshire–Nottinghamshire coalfield appear to be very poor. Consequently, there has been a revival of interest in the potential for releasing some of the energy value of the remaining coal resources via alternative technologies such as coal-bed methane production and underground coal gasification. Methane is already being drained from the few remaining deep mines and, in some cases, utilized as fuel for boilers or for electricity generation. The production of methane from abandoned mines is also taking place, but recent low electricity and gas prices have adversely affected its economics. There has not been any exploratory drilling for coal-bed methane in the Yorkshire–Nottinghamshire coalfield, perhaps because the average seam methane content is somewhat lower than in some of the major coalfields on the west side of the country. However, the major barrier to the development of the region's vast coal-bed methane resources is perceived to be low seam permeability. The potential for underground coal gasification is very large but the scope for production is likely to be constrained by environmental considerations.

Introduction

There are vast coal resources beneath parts of Yorkshire, Nottinghamshire, Lincolnshire and northeast Leicestershire (henceforth referred to as the Yorkshire–Nottinghamshire coalfield). This coalfield has been extensively and intensively exploited for hundreds of years, particularly since the industrial revolution. Over 400 collieries were open at its peak in the late nineteenth and early part of the twentieth century. Over the centuries, mining has gradually advanced to the east, exploiting progressively deeper seams. Nottinghamshire's pits were some of the deepest in the country. For example, Bevercotes (opened in the 1960s but now closed) and Harworth have shafts more than 1000m deep.

Underground and surface coal production in the UK reached a maximum of about 27010^{3} tonnes per annum in the late nineteenth and early part of the twentieth century, and has now declined to about 28.9×10^{3} tonnes in 2002 (DTI 2003). Although mining has declined from its peak, ten major deep mines are still (March 2004) in production in this area. Of the total UK deep mine production of

15.8Mt in 2002 (DTI 2003), approximately 80 per cent was from mines in the Yorkshire–Nottinghamshire coalfield, with the Selby complex producing 25 per cent of the total.

Coals in this area are mainly restricted to the Pennine Coal Measures Group, of Westphalian age. These are present at outcrop in an area trending north-northwest–south-southeast between Derby and Leeds, including Sheffield. From its outcrop, the Coal Measures dip eastwards beneath younger rocks, forming a thick continuous sheet of concealed strata that extends to the coast between Bridlington in the north and Skegness in the south (Figure 1). From there it continues eastwards beneath the southern North Sea.

The stratigraphy of the Coal Measures is well known in the west along the outcrop and in the shallow subsurface, where extensive exploitation and exploration for coal has taken place. The best coal seams occur in the Pennine Lower and Middle Coal Measures formations. The most valuable and widely extracted seam is the Top Hard (= Barnsley) Coal, which is up to 3m thick around Selby. Cumulative coal thickness of seams >0.4m is generally 19–29m, and there are commonly several seams >2m in thickness in most areas away from the coalfield margins.

Farther east, the stratigraphy is not so well known, although there is detailed information on coal-seam thickness and distribution in the former deep-coal mining prospects of North Ouse, Witham, Till and northeast Leicestershire (Figure 2). East of these areas, little detailed information is available, because there are no continuously cored boreholes. However, information from deep boreholes, most of which are oil and gas exploration wells, suggests that the vast coal resources formerly present in the mined areas, and found in the mining prospects, continue in the subsurface all the way to the coast and beneath the southern North Sea (Figure 3). The Westphalian succession in these wells in general can only be inferred from a combination of geophysical logs, drill cuttings and rare short cores (Figure 3). There is statistical evidence that thin seams are under-represented on oilwell geophysical logs (Knight et al. 1996) and the thickness of detected seams is probably exaggerated, because dirt adjacent to or within the seams is commonly not separable from the coal itself. Nonetheless, the density of borehole information is high (Figure 4), and it can be inferred with a fair degree of confidence that the typical coal resources proven in the mined areas extend to the coast and then under the southern North Sea.

The decline of deep underground mining, together with the search for cleaner, environmentally acceptable sources of energy, has sparked interest in the possibility of exploiting methane that has become accessible as a result of the mining process. Further research has been focused on the potential to release some of the energy value of coal via alternative, non-mining technologies such as coal-bed methane production and underground coal gasification. If successful, these could supplement declining conventional UK natural gas production. This paper aims to review some of the recent advances in the utilization of methane from coal in eastern England.

1. Coal-bed methane

1.1 Composition, origin, occurrence and recovery of coal-bed methane

Coal-bed methane is the methane-rich gas, known as firedamp in the mining industry, that occurs naturally in coal seams. It originates from the coalification of organic matter during its burial (Davidson et al. 1995). Typically, it is 80–95 per cent methane, 0–8 per cent ethane, 0–4 per cent propane and higher hydrocarbons, 2–8 per cent nitrogen and 0.2–6 per cent carbon dioxide, with traces of argon, helium and hydrogen (Creedy 1991).

The porosity of coal (the volume percentage occupied by pores) is commonly between 1 and 3 per cent (Davidson et al. 1995) and it consists mainly of micropores (pores <2nm in size). However, the total internal surface area of the micropores is very large (about $90 m^2 g^{-1}$ coal). Coal-bed methane occurs as a monomolecular layer adsorbed onto the surfaces of these micro-pores in the carbonaceous macerals that make up the bulk of the solid coal. It also occurs as free gas molecules in the cleat (see below) and any other cracks and fissures present in the coal seam. Therefore, the retention of large amounts of gas molecules in a small volume of coal is possible and coal seams may contain up to $25 m^3$ methane per tonne of coal (Creedy 1991).

The proportion of the free gas in the total gas content of coal of a coal seam is *c*. 5–10 per cent. Normally, the free gas and the adsorbed gas phases are in equilibrium in a coal pore and there is a constant and equal exchange of molecules between them. The adsorbed gas is held in place by electrostatic forces. These forces can be overcome by reducing the pressure on the coal or increasing its temperature.

Coal also contains a natural network of vertical or subvertical fractures known as the cleat. Typically this network consists of two orthogonal fracture sets. The dominant set of fractures (the face cleat) crosscuts the subordinate set (the butt or back cleat). When combined with the natural bedding planes in coal, they divide the coal seam in three planes and, where well developed, allow it to break up into small “bricks” (Figure 5). The cleat generally imparts some permeability to the coal (in bituminous coals this is commonly 1mD or less, but may locally be *c*. <30mD). Because the face cleat is longer than butt cleat, permeability is commonly anisotropic and is greater in the face cleat direction. Cleat intensity, defined as the number of fractures per unit distance perpendicular to the cleat, is an important factor in determining coal permeability (MacCarthy et al. 1996). However, coal-seam permeability is also a function of confining stress, which acts to close the cleat, and it is reasonable to expect that the permeability will decrease with depth as the overburden pressure increases (Durucan & Edwards 1986, Davidson et al. 1995). Furthermore, in some localities, the cleat may be filled with any of a variety of mineral cements that can almost totally occlude the permeability.

Table 1 Current CMM capture and utilization in the Yorkshire– Nottinghamshire coalfield.

Mine	Methane capture/utilization plant
Harworth	Surface drainage plant – gas used for 14MW(e) electrical power generation
Kellingley	Surface drainage plant – gas used for 2.8MW(e) electrical power generation
Maltby	Surface drainage plant – gas used for 4.2MW(e) electrical power generation
Riccall-Whitemoor	Surface drainage plant – some gas used in boilers
Rossington	Surface drainage plant
Stillingfleet–N Selby	Surface drainage plant
Thoresby	Surface drainage plant – gas used for 2MW(e) electrical power generation
Welbeck	Surface drainage plant – gas used in boilers and for 2.8MW(e) electrical power generation
Wistow	Gas drained and discharged underground
Hatfield	Gas drained and discharged underground

The exchange of gases between the cleat system and the microporosity in the solid coal is thought to occur by diffusion (Davidson et al. 1995).

Coal-bed methane can be recovered from coal seams by:* drainage in working coal mines (coalmine methane, CMM)

- extraction from abandoned coal mines (abandoned mine methane, AMM)
- production from unmined (virgin) coal using surface bore-holes (virgin coal-bed methane, VCBM).

The characteristics of each of these coal-bed methane sources are different in terms of reservoir characteristics, production technology and gas composition.

1.2 Coalmine methane (CMM)

Methane trapped in coal and surrounding strata can be released as a result of mining; this gas is known as coalmine methane (CMM). The gas is released not only from the mined seam but also from seams in the collapsed and fractured, and thus stress-modified, strata surrounding the mined seam. Methane is an underground safety hazard, so its control, by dilution with air or drainage (or both), has been carried out for hundreds of years. The first recorded utilization of this methane was for heating and lighting at Haig colliery (West Cumbria) in 1733 (Bromilow & Jones 1955).

The US Environmental Protection Agency (US EPA 1998) recognizes three types of CMM:* Fumigant or ventilation air methane (VAM), which represents a dilute mixture of methane (typically <1% of volume) in air vented to the surface as part of the mine ventilation system.

- High-grade CMM obtained by draining in advance of mining (known as pre-drainage, not practised or feasible in the UK), which may be suitable for injection into natural gas pipelines after treatment to remove water and excess carbon dioxide.
- Goaf gas, which represents the mixture of methane and air in the goaf. This is usually less than 85 per cent methane (typically 35–75% in the UK), so is not suitable for direct pipeline injection.

The last two types of CMM can be used as a fuel source. Even ventilation air methane CMM can make a contribution; for example, the CMM power station at Appin Colliery in New South Wales, Australia, incorporates a proportion of the methane-bearing vented mine air into the gas-engine intakes (Bibler et al. 1998, Creedy et al. 2001a).

All the active mines in the Yorkshire–Nottinghamshire coalfield drain and utilize methane (Table 1). Current practice involves capturing methane released from unmined coal seams within the strata above and below a longwall face. Longwall mining may reduce the stress regime in strata from 160–200m above, and 40–70m below, the worked seam (Creedy et al. 2001a). Hence, boreholes are drilled into the strata that have been stress-modified by mining and connected to pipelines, to which suction is applied to draw out the gas (ibid.). The primary reason for CMM drainage is to prevent the percentage of methane in the mine ventilation air rising above safe levels for working (identified in mining legislation). The capture of gas from the surrounding strata before it enters the mine air enables mining to proceed faster than would otherwise be possible. Utilization reduces greenhouse gas emissions by converting methane to less harmful carbon dioxide.

Using this methane capture technique, high flow rates may be achievable, but gas purity can be variable; methane concentration is commonly in the range 35–75 per cent. For example, nearly 130000m^3 CH_4 per day at about 50 per cent purity have been produced at Harworth colliery, Nottinghamshire (Goode 1994). Gas drainage and supply to a surface utilization scheme may be subject to interruptions in supply as gas capture is linked to the mining operation. This can be buffered to a limited extent using gas holders, although none are in use at present. In addition, there is no turndown capability and an external fuel supply may be necessary to sustain a utilization process. Past utilization in Yorkshire and Nottinghamshire (Young et al. 1994) included sales of mine gas to Manvers coking plant in Yorkshire (Kelly & Quick 1965), from Harworth colliery to a local glass works (Smith 1982) and from Kellingley colliery to a nearby chemical works (Simpson 1985). Current methane drainage and utilization in the Yorkshire–Nottinghamshire coalfield is shown in Table 1.

1.3 Abandoned mine methane (AMM)

When a mine closes, the residual gas contained in the stress-modified strata forms an abandoned mine methane resource. Abandoned mine methane (AMM) consists of the fuel gas (mainly methane) fraction of the free gas trapped within abandoned coal mines, plus any methane that can be desorbed from the coal seams in the strata surrounding the mined seam by applying suction to the mine workings (Creedy et al. 2001a).

The principle of AMM production is that total extraction methods of coal mining (e.g. longwall mining) lead to the collapse of overlying and underlying strata into the void from which the coal seam was extracted. This reduces the stress regime in the seams in a zone up to about 150–200m above and 40–70m below the mined seam, fractures the intervening strata and increases the permeability of the coal. Although the reduction in pressure associated with mining results in some of the methane desorbing from these seams and mixing with the mine air, some is retained in the *in situ* coal. A further reduction in pressure, caused by applying suction to the workings, causes more methane to des-orb from the surrounding seams into the workings, where the former mine roadways act as a pathway for the gas to migrate to the surface extraction point.

Not all abandoned mines will be suitable; negative factors include:* the many surface connections, hence a high risk of air ingress

- shallow workings connected to the surface
- flooded workings
- low initial gas-seam content
- low residual gas content
- limited volume of de-stressed coal.

A detailed understanding of the underground network of mine workings, particularly any connections with adjacent mines, is essential, as this will influence the reservoir size. An adequately sealed shaft or drift is also required to prevent air being drawn in to dilute the extracted gas. Also fundamental to the exploitation of this resource is information on the level and rate of groundwater recovery, which, with time, will act to reduce the accessible volume of connected mine workings. Gas cannot be extracted from workings that have been flooded by recovering minewater levels, so the state of minewater recovery is critical to the success of projects.

In order to gain a greater appreciation of the problems associated with rising minewaters, minewater recovery studies have been commissioned by the Coal Authority in recent years. A study of these reports has allowed the delineation of areas in the Yorkshire–Nottinghamshire coalfield with varying suitability for AMM exploitation (Figure 1). Along the western flank of the coalfield, in a belt trending north-northwest–south-southeast approximately 12km in width, AMM prospects are thought to be poor (Figure 1). In this area, mine workings are mostly old and shallow, and minewater is likely to have recovered. In the east, where the workings are more modern and groundwater is being controlled by pumping, prospects for AMM are likely to be good. In the combined Yorkshire–Nottinghamshire coalfield, this good AMM region covers an area of approximately 666 km^2. In between these two areas the AMM prospects are considered to be variable. Potential may exist, but further exploratory work will be required on a site-specific basis. In the Yorkshire–Nottinghamshire coalfield, this variable zone covers an approximate area of 1500 km^2.

In Nottinghamshire, many of the mines are connected underground and minewater recovery is controlled to some extent by pumping to protect the remaining working mines in north Nottinghamshire. Minewater recovery has started to the south of the working mines of Thoresby and Welbeck, and recovery is probably complete in the older, shallower workings along the western side of the coalfield. However, the former Bevercotes colliery, the most southerly pits in Nottinghamshire (Cotgrave, Clifton and Gedling) and Asfordby in the Vale of Belvoir, are not connected to the main area of mining in Nottinghamshire and their minewater recovery status is unknown, although predictions could be made using water inflow data gathered during mining.

In the UK, AMM has been utilized from as early as 1954 onwards, when the National Coal Board collected methane for electricity generation from the closed Old Boston Colliery (Sage 2001). Between 1957 and 1967, gas was recovered at a rate of $52Ls^{-1}$ initially and later at up to $300Ls^{-1}$ (ibid.). There are hundreds of abandoned coal mines in the Yorkshire–Nottinghamshire coalfield that could potentially be exploited for AMM, and recently several companies have launched projects, with varying long-term success. Octagon Energy developed a 5.4MW electricity production plant using AMM from Hickleton Colliery, near Barnsley in South Yorkshire. This scheme is now operated by GreenPark Energy. Gas is extracted from the shaft. Alkane Energy developed a series of Green Energy Parks based on AMM. They hold acreage in the UK covering $5590km^2$, which includes over 300 abandoned coal mines.

Former and active AMM sites are outlined below:* *Shirebrook, five miles north of Mansfield* AMM extracted from the former colliery drift fuels a 9MW on-site power station. Gas production to June 2000 totalled approximately 9 million m^3, with a production rate of about $3500m^3$ per hour, and a methane concentration of 70 per cent (Sage 2001). However, recent problems such as water and air leaking into the gas extraction pipe means that production is running at about 50 per cent of its original output (Alkane Energy 2003).

- *Markham, east of Chesterfield* AMM is produced from one of the former colliery shafts and supplies gas for industrial heat applications at the nearby Coalite Chemicals and Coal Smokeless Fuels plant. Production during 2000 was reported as running at rate of $6500m^3$ per annum, with a methane concentration of 45 per cent (Sage 2001). However, recently, operational difficulties have been reported, although remediation has resulted in an increase in gas quality (Alkane Energy 2003).
- *Steetley* AMM from Steetley colliery workings fed a 6MW power station just west of Worksop, Nottinghamshire. The Steetley site drew gas for 4.5 days per week at rates <1250 m^3 per hour (2001). Gas production to June 2000 totalled 6.5 million m^3 (Sage 2001). Because of operational difficulties and poor economics, this site ceased production in December 2002 (Alkane Energy 2003).
- *Wheldale, near Castleford, Yorkshire* Gas is supplied to Scottish & Southern Energy. In 2002 output was at 80 per cent of total capacity and was below expectations (Alkane Energy 2003).
- *Barnsley (Monk Bretton), West Yorkshire* CMM is sold to Rexam Glass for process heat. Restricted flows have been reported and a new borehole is required to rectify this problem (Alkane Energy 2003).
- *Prince of Wales colliery, Yorkshire* Pipework is currently being installed in the drift of the former Prince of Wales Colliery, Yorkshire, to extract the AMM. It is planned to use the methane to generate electricity fed into the national network.

Alkane have suspended development of further AMM sites in the UK because the dramatic fall in electricity prices under the New Electricity Trading Arrangements (NETA) and the failure, unlike in Germany, of AMM to qualify as renewable energy, have meant that their electricity-generating operations are no longer financially viable.

In January 2002, StrataGas completed the commissioning of the Bentinck CMM gas plant from the closed drift of the old Annesley Bentinck mine complex near Kirkby-in-Ashfield, Nottinghamshire. The plant is designed to pump up to 3300m^3 per hour of gas and is used for electricity generation in three 3.5MW(e) spark-ignition engines operated by Warwick Energy Ltd. The operation is now wholly owned by Warwick Energy.

From the above cases, it is clear that the fledgling AMM industry in the Yorkshire–Nottinghamshire coalfield is at an early stage of development and its future appears to depend critically on the profitability of generating electricity from this gas source.

1.4 Coal-bed methane from virgin seams (VCBM)

In VCBM production, a well is drilled through a coal seam or group of seams. The seam is then isolated using packers and pumped to lower the pressure within it. This allows methane to desorb from the internal surfaces of the coal and diffuse into the cleat, where it is able to flow towards the production well, either as free gas or dissolved in any water that saturates the seam.

The permeability of UK coal seams is low. Coal-bed methane production probably requires more than 1mD permeability (Hughes & Logan 1990) and coal-bed methane wells are normally stimulated to improve connectivity between the borehole and the cleat system. Hydrofracturing is the method of well stimulation used to date in the UK (e.g. Bacon 1995).

No coal-bed methane exploration wells have so far been drilled in eastern England, probably because the initial seam-gas contents are lower than those found in some coalfields in western Britain (Creedy 1983, 1986, 1991, Ayers et al. 1993). Average seam-gas content measurements are 4.6m^3t^{-1} in north Nottinghamshire, based on 915 samples from 70 boreholes, 4.6m^3t^{-1} in the Till prospect based on 222 samples from 13 boreholes, 1.6m^3t^{-1} in south Nottinghamshire based on 116 samples from 14 boreholes, and 1.5m^3t^{-1} in the Witham prospect, based on 407 samples from 50 boreholes (Creedy 1991). The highest average seam-gas contents are around Barnsley (5.2m^3t^{-1}), with lower values in the North Ouse prospect (3.2m^3t^{-1}), the Selby coalfield (4.7m^3t^{-1}) and North Yorkshire (3.6m^3t^{-1}). East of the Witham and Till prospects, there are no seam-gas content measurements and it is considered that an average seam-methane content of 5m^3t^{-1} may be a reasonable estimate.

These relatively low average seam-gas content measurements suggest that VCBM prospectivity in eastern England is probably low. The presence of anomalously high gas in certain collieries on anticlines in the Yorkshire–Nottinghamshire coalfield (e.g. Harworth Colliery on the Ranskill Anticline) means there is a possibility of tapping into free-gas reserves as well as adsorbed gas in such structures (Young et al. 1994). However, it should be emphasized that some kind of technological breakthrough to enhance gas-production flows may be needed before economic VCBM production can become established in eastern England.

Although the CBM potential of eastern England is believed to be fairly low, areas with different CBM resource densities can be derived (Figure 6). These areas were defined by extrapolating from seam-methane content measurements. A first-order estimate of VCBM resources in eastern England is $1125\times10^9m^3$, or approximately 40tcf (Jones et al. 2004). This compares reasonably well with a previous estimate of 959×109m^3 (Creedy 1999).

1.5 Underground coal gasification (UCG)

Underground coal gasification (UCG) describes the process by which various combinations of air, oxygen, hydrogen and steam are injected into one or more *in situ* coal seams to initiate partial combustion. The process generally involves the drilling of at least two boreholes, one to act as the gasifier and one to collect the product gases. The injectant reacts with the coal, producing heat, and drives off fuel gases (hydrogen, carbon monoxide and methane), which are subsequently recovered through a production well.

The basic chemical processes and the calorific value of the gas produced are very similar to surface gasification processes, although the final gas composition is somewhat different. UCG generally produces a gas of medium calorific value (typically $10^{-1}2MJm^{-3}$), with a heating value of about 30 per cent that of CBM. If air, rather than oxygen, is used as a partial oxidant, then product gas of lower calorific value is produced with a heating value of about 10 per cent that of CBM (e.g. the Australian UCG trial at Chinchilla produced a product gas with a calorific value of about 5 MJm^{-3} (Blinderman & Jones 2002)).

At the Rawlins UCG trial (Wyoming, USA), the main compounds produced by the burn were methane, carbon dioxide and carbon monoxide, although ethane, propane, iso-butane, butane, carbon disulphide, carbonyl sulphide, hydrogen sulphide and sulphur dioxide were also detected (Jones & Thune 1982). The Spanish El Tremedal UCG trial produced a product gas comprising CH4 (13.2%), CO_2 (41%), CO (12.8%), H2 (24.8%) and H_2S (8.3%) and an LHV (low heating value) of 10907 kJ/m^3 (Green 1999).

Three main UCG project designs have been tried worldwide. The first involves drilling a series of vertical boreholes, gasifying the coals and using the natural permeability of the coals to extract the gas, rather than connecting up the boreholes e.g. the Chinchilla project in Australia (Walker et al. 2001, Blinderman & Jones 2002); this generally takes place at shallow depths. The low permeability of UK coal is thought to preclude this method. The second type of UCG can take place in existing or abandoned coal mines (e.g. Liuzhuang Mine, China). In this process, mined galleries are bricked up, air is injected into these galleries, the surrounding coal is gasified and the gaseous products piped up a shaft or borehole to the surface. The third method, most widely used in recent projects, involves the gasification of deeper coals, and connecting up the production and injection wells by using in-seam drilling techniques. Recent technological achievements in UCG have been addressed by Creedy et al. (2001b).

UCG is a particularly cost-effective means of extracting fuel gas from coal, because it avoids the high costs associated with mining and constructing a surface gasifier (typically hundreds of million pounds) and leaves ash and dirt underground. UCG recovers typically 45 per cent of the energy value of coal, whereas CBM production commonly recovers less than 1 per cent.

The environmental impacts of mining and ash disposal are totally negated by UCG. However, some very significant environmental issues remain, including the potential for subsidence, atmospheric emissions, the possible interactions of the UCG cavities with aquifers and the potential for pollutants to migrate away from the cavity (Creedy et al. 2001b).

Interest in UCG in the UK has developed as a result of the DTI Energy Paper 67 (DTI 1999), which identified UCG as one of the potential future technologies to develop the UK coal resource. Energy Paper 67 produced technical and economic goals for UCG, including:* Improve the accuracy of in-seam drilling to achieve a 400m run in a 2m seam, on a consistent basis.

- Examine the implications of burning the gas produced in the Spanish UCG trial in a gas turbine.
- Produce an estimate of the landward reserves of coal, which could be technically suitable for UCG. In the first instance, this could be coal seams at least 2m thick and at a depth not exceeding 1200m.

- Identify a site for a semi-commercial trial of UCG. This would require a block of coal about 600m by 600m, and a seam thickness of at least 2m.
- Identify the parameters that UCG would have to meet if it were to be competitive with current North Sea gas production costs.
- Carry out a pre-feasibility study for the exploitation of UCG off shore in the southern North Sea.

An initial pre-feasibility study was commissioned by the DTI and further studies have followed, such as a geological and site evaluation study (IMC 2001), drilling and a review of the technological advancements (Creedy et al. 2001b). Economic and public perception studies are currently being carried out.

There have been about 20 different UCG trials worldwide since the 1950s. Early UCG trials usually took place at shallow depths (<200m); for example, the Newman Spinney trial in the UK in 1959 was drilled to the Fox Earth Coal at a depth of 75m (Gibb & Partners 1964). Most of the UCG tests so far have generally been carried out over short time periods (1–2 months). The exceptions to this are the large-scale air-blown schemes in Russia and Uzbekistan and at Chinchilla in Queensland (Australia), which was initiated by Linc Energy in December 1999. The former Soviet Union was the first country to industrialize the UCG process, and two plants are still in operation today. Underground coal gasification has been carried out in Kuzbass (Siberia), at the Yuzhno–Abinskaya gasification plant since 1955. This involves the gasification of bituminous coal, 1.3–3.9m thick, producing a gas of low calorific value (CV) used for heating (Walker 1999). The Angren coalfield in Uzbekistan comprises about 1.8 billion tonnes of mostly brown coal (lignite), which is used as fuel for Uzbekistan's power generation. The Angren mine also has underground coal gasification technology in place since 1955 to produce gas for the Angren power station. The gasified seam ranges in thickness from 4m to 20m and lies at depths of 130–350m. The output in 1963 was believed to be about $860\times10^{8}m^{3}$, but present production is believed to be about half of the 1963 figure (Walker 1999). Both the Kuzbass and Angren schemes use low technology and produce a poor-quality gas.

China has considerable experience of UCG, with 16 trials completed since 1990. Feasibility studies have also been carried out in Canada, India, Pakistan, Russia, Slovenia and the Ukraine. Much research was carried out in the 1970s, and trials went ahead. The Thulin scheme in Belgium operated from 1978 to 1986 and gasified a thin seam at a depth of 1000m.

In the USA, UCG research has focused on relatively shallow (100m deep) coal seams, and tests were focused on the development of the process itself. At Hoe Creek (Gillette, Wyoming, USA), three pilot UCG test burns were carried out between 1976 and 1979 (US EPA 1999). Experiments were also carried out at the Rocky Mountain 1 (RM1) site at Hanna (Wyoming), in 1987– 88. Commercial projects were evaluated (e.g. at Rawlins, Wyoming), but the low cost of gas in the early 1990s prevented these projects from being viable.

The El Tremedal European trial in Spain (1993–98) confirmed the technical feasibility of UCG at depths of 500–700m and has shown that improved deviated drilling techniques in deep seams can provide interconnected channels suitable for use in underground coal gasification (Green 1999). In this trial a controlled retraction injection point (CRIP) system was used to control the gasification procedure (Green 1999).

The IGCC project in Chinchilla (Australia) has been under development since 1999 and is the first project to use UCG as a syngas (synthetic gas) producer technology. The project involved construction of an underground gasifier and demonstration of the technology (Walker et al. 2001, Blinderman & Jones 2002). Approximately 32000 tonnes of coal was gasified, producing a low-CV gas of about $5MJm^{3}$ at a pressure of 10 barg (145 psig) and temperature of 300°C. Nine process wells have been producing gas from a 10m-thick seam at a depth of about 140m. Groundwater monitoring has also been taking place in association with this trial and has revealed no contamination. This is probably because the gasifier pressure is lower than the hydrostatic pressure of fluid in the coal seam and surrounding strata.

UCG resource areas have been defined for eastern England using the following criteria:* seams of 2m thickness or greater

- seams at depths 600–1200m from the surface
- 500m or more horizontal and vertical separation from underground coal workings and current coal-mining licences
- greater than 100m vertical separation from major aquifers
- greater than 100m vertical separation from major overlying unconformities.

Following application of these criteria, the resource can be split into three categories: good, unverifiable and poor (Figure 7). Good areas meet the criteria as defined above. Unverifiable areas represent regions where the UCG potential is unknown. This may be related either to the absence of borehole data, or to the lack of deep penetrating boreholes (i.e. >600m) within an area. Poor zones represent areas where coals are present at the required depths, but do not meet the thickness criteria.

There are large areas in eastern England that meet the criteria for UCG. In the west the Coal Measures are too shallow and there are many former and present mine workings and in the east the Coal Measures are too deep (>1200m). However, large areas with good UCG potential exist to the northwest of Lincoln (983km^2) and also around Selby (Figure 7). There are also large areas where the UCG potential is unverifiable, particularly south of Lincoln and northeast of Selby. In these areas, boreholes are present but do not penetrate down to 1200m; those examined do not prove coals in excess of 2m in thickness.

In the east, the 1200m line, drawn on the top of the Coal Measures, marks the eastern limit of UCG resources. However, close to the line only the highest Upper Coal Measures coals actually occur above 1200m. The thickest coals typically come from the Lower and Middle Coal Measures. Hence, as the 1200m line is approached, prospects for UCG diminish because the best coals are too deeply buried. This is marked on Figure 7 as a north–south-trending fringe of poor UCG resources.

Using a minimum thickness of 2m of coal for each good UCG resource area in eastern England gives a total resource of 2.9x109m^3, whereas using a more realistic average thickness of coal per area that meets the criteria gives a resource figure of 5x109m^3. This indicates that large resources are available for this technology in eastern England.

2. Discussion

2.1 Environmental benefits of CMM and AMM

CMM and AMM utilization schemes, which combust methane to form carbon dioxide, significantly benefit the environment by reducing greenhouse-gas emissions as methane has a global warming potential 21 times greater than an equivalent amount of carbon dioxide (Ramaswamy et al. 2001). They also produce useful energy from a waste product of mining and may displace coal use in environmentally sensitive areas. In addition to reducing greenhouse-gas emissions, the extraction and use of AMM can prevent odour emissions and also reduce risks from the uncontrolled migration of gas from abandoned mine workings to the surface. Mine sites benefit in terms of improved seals to mine entries and enhanced surface appearance. Planning and regulatory authorities in the UK, therefore, tend to view AMM schemes favourably.

As mentioned above, UCG has the potential to release a far higher proportion of the energy value of coal than VCBM production. The calculation below indicates that VCBM production is likely to release only <1 per cent of the energy value of the coal from which it is produced:* average calorific value of coal used in UK = $27GJt^{-1}$

- average calorific value of UK natural gas = (similar to VCBM) $39.8MJm^{3}$
- assume $5m^{3}$ natural gas recovered per tonne of coal
- per cent energy value of coal recovered by CBM production = 0.7.

2.2 Environmental issues for UCG

The environmental aspects of UCG have been of concern, with potential impacts on both surface and subsurface environments. The main surface impacts relate to the potential for atmospheric emissions and surface-water pollution; the main subsurface impacts are to the groundwater and possible subsidence. Pollutants that could be generated in the UCG process include benzene, ammonia, nitrate, phenols and pyridine (US EPA 1999). Other unwanted products of the combustion process include carbon dioxide, carbon monoxide, hydrogen sulphide and sulphur dioxide. These are mainly regarded as being fairly low in impact, as the main product of the process is gas and any byproducts can either be left in the ground or removed by conventional processes and re-injected. However, this is not always the case, and these and other pollutants could escape into the local groundwater regime. This is particularly the case where aquifers with good porosity and permeability characteristics are located stratigraphically close by, such as the Triassic Sherwood Sandstone and Permian aquifers in eastern England.

In the USA, some of the tests concentrated on the determination of the environmental impact, particularly on groundwater, of which the Hoe Creek test in Wyoming is one of the best documented. Here the tests were carried out at shallow depths (*c*. 55m) and, at the Hoe Creek 2 and 3 sites, the UCG experiments were carried out at high pressures. This resulted in product gases containing phenols and condensable hydrocarbons escaping into the overlying water-bearing units. In addition, groundwater reentered the burn areas after the test, came into contact with condensed coal tars and became contaminated with organic materials. Local groundwater flow carried contaminants down gradient to the east and south. In the Hoe Creek 1 burn, where high induced pressures were not used, elevated levels of contaminants were not encountered, indicating this had an important control on groundwater.

The Rocky Mountain 1 (RM1) UCG test at Hanna (Wyoming), involved extensive site characterization, instrumentation and monitoring in order to gain a detailed understanding of the environmental and hydrogeological variables. Following the test venting, flushing and cooling of the cavities was carried out to reduce groundwater contamination (Boysen et al. 1990). The results of this test proved that UCG can be conducted in an environmentally benign manner, but that groundwater quality and aquifer head were impacted locally at the test site (Moody 1990, Lindblom & Smith 1993).

The El Tremedal trial in Spain used the knowledge gained from such earlier UCG experiments and here underground conditions were kept as close to hydrostatic pressure as possible. As a result no pollutants were detected apart from hydrogen sulphide, which had been predicted (Green 1999).

3. Conclusions

There is potential for increased CMM utilization in the deep mines of Yorkshire and Nottinghamshire, but future developments are mainly dependent on economics. There is scope for increased AMM production in the abandoned mines of the region where minewater levels have not yet recovered. However, the current economic environment, particularly the low electricity prices that pertain under NETA, is hampering the development of new projects. Successful exploration for VCBM resources is likely to depend on the coincidence of various favourable factors: relatively high seam permeability, relatively high initial seam-gas content and the possibility of tapping into free gas resources in the Coal Measures. Vast resources are available for underground coal gasification. However, environmental issues must be resolved before this technology is likely to be fully exploited.

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