Update of Estimated Methane Emissions from UK Abandoned Coal Mines

Department of Energy and Climate Change

25th May 2011

QUALITY MANAGEMENT

Issue/revision	Issue 1	Revision 1	Revision 2	Revision 3
Remarks	Draft Final Report for Comment	Final Report for approval	Final Report incl. minor revisions	Final Report incl. minor revisions
Date	07/04/2011	04/05/2011	19/05/2011	25/05/2011
Prepared by	Shaun Fernando	Shaun Fernando	Shaun Fernando	Shaun Fernando
Signature				
Checked by	Andrew Marsh-Patrick	Andrew Marsh-Patrick	Andrew Marsh-Patrick	Andrew Marsh-Patrick
Signature				
Authorised by	Andrew Marsh-Patrick	Andrew Marsh-Patrick	Andrew Marsh-Patrick	Andrew Marsh-Patrick
Signature				
Project number	18963.00	18963.00	18963.00	18963.00
File reference	DRAFT FINAL	FINAL rev1	FINAL rev2	FINAL rev3

WSP Environment & Energy
WSP House
70 Chancery Lane
London WC2A 1AF

Tel: +44 (0)20 7314 5000

www.wspenvironmental.com

00018963

CONTENTS

GLOSSARY

- AMM Abandoned mine methane
- CBM Coalbed methane
- CH_4 Methane
- CO_2e Carbon dioxide equivalent (calculated based on GWP of each GHG)
- CRF Common Reporting Format
- DECC Department of Energy and Climate Change
- DEFRA Department for Environment, Food and Rural Affairs
- EU European Union
- GHG Greenhouse gas
- GWP Global warming potential (relative to CO_2 = 1.0)
- IPCC Intergovernmental Panel on Climate Change
- LULUCF Land Use, Land-Use Change and Forestry
- k kilo (unit prefix = 1 thousand)
- M Mega (unit prefix = 1 million)
- MW_e Megawatt electrical generation capacity
- UNFCCC United Nations Framework Convention on Climate Change
- US EPA US Environmental Protection Agency
- WSP WSP Group
- WYG White Young Green
- ±% Uncertainty level quoted at the 95% confidence limit

EXECUTIVE SUMMARY

WSP was commissioned by DECC to update the UK estimates of greenhouse gas (GHG) emissions originating from abandoned coal mines, incorporate data on currently operating coal mines that are expected to close before 2050 and develop consolidated projections of methane emissions to 2050. The results will feed into the UK GHG inventory improvement programme and help to inform future policy decisions to mitigate this GHG source. This study was carried out over the period February to April 2011 and constitutes:

- a review of the mine database and models developed for the previous 2005 DEFRA study
- updating of these models to account for actual and projected mine closures dates to 2050
- comparison of the estimation methods with international best practice
- addition of methane capture and utilisation data
- update of the split of emissions between England, Scotland and Wales
- an uncertainty assessment of the updated estimates

WSP first investigated published methodologies for the estimation of GHG emissions from abandoned mine methane (AMM), specifically those produced by the IPCC, the US EPA and the methodology employed by WYG in the construction of the 2005 inventory. These methodologies involved the estimation of AMM emissions from a first-principles bottom-up approach; physical properties of individual mines and mine areas were measured and then aggregated into a model. In the WYG methodology, a single-value long-term emissions factor was obtained from a regression between the AMM reserves of 8 UK mines and flow rate of methane from those mines. This long-term emissions factor was found to be in-line with best practice and was incorporated into WSP's methodology.

In delivering this update, files from the 2005 inventory were made available to WSP by WYG. These included a synthesis of methane gas reserve estimates for the portfolio of 143 abandoned mines modelled in the 2005 inventory as well as datasets for each of the closed mines which contained both empirical and calculated data.

The complexity of the data files received from WYG was such that they could not be directly transposed to the IPCC and US EPA methodologies. Instead, the WYG data were checked for consistency and robustness in the values of AMM reserve estimates made for the period 1990-2004. Because this data was dependent on measured data on individual mines, WSP was unable to directly corroborate this to a comparative set without replicating the measurements. WSP however did review the treatment of measured data and evaluated this broadly against the principles of the method detailed in the US EPA report and against WSP's expert judgment. The WYG models were found to be in-line with USEPA and IPCC mine modelling methods. From the WYG dataset and additional data sources such as the UK Coal Authority, a catalogue of mines that were flooded, vented or sealed was derived to form a baseline for projections to 2050.

For mines that were determined to be venting, estimates of methane gas reserves were made for the period 2005-2050. These forecasts were based on a combination of gas reserve decay profiles following closure, WYG models of mine flooding rates, and a long-term gas reserve decay function. A total of 11 mines which have closed since 2005 or are due to close by 2050 and their expected flooding profiles were added in to the model using the same methodology. Assumptions made by the previous WYG study on mine closures in the period 1990-2005, and for any mines that had re-opened since 2005, were also updated using actual closure and re-commissioning dates.

Methane emissions rates of 0.74%(with a relative uncertainty level of ±20%) of the gas reserve per annum (based on limited UK mine data) were used to construct a profile of AMM emissions for the period 1990-2050 for the 138 (out of 140) mines that had been determined to have closed before 2000, in thousands of tonnes of carbon dioxide equivalent (ktCO_2e). A simple AMM estimation method for surface mines was applied as these emissions are small compared to those for deep mines. The uptake of AMM utilisation was modelled by inspection of data on current and likely future AMM capture projects. This allowed both gross and net AMM emissions to be estimated.

Table 1 and Figure 1 below summarise the key results of the AMM study. It shows a peak in AMM emissions around 1995, which is due to the closure of a large number of mines around that year, followed by a rapid decline in emissions as 104 mines (out of 143) were fully flooded by 2000. A smaller peak in 2006 is also seen, which is due to the closure of the Harworth mine area, accounting for 0.134MtCO_2e, compared to 2005's total AMM emissions estimate of 0.573MtCO_2e, representing a 23% increase in emissions. Longer-term emissions to 2050 are predicted to be relatively stable and in the range 0.2-0.4 MtCO_2e/annum. The emissions estimate are net of methane utilisation which is forecast to be implemented across 90% of large abandoned mines but will reduce in absolute terms due to the depletion of methane reserves and reduction in the number of newly abandoned mines in future years. In Table 1, emissions for operating mines up to 2005 are also include for comparison based on UK GHG Inventory estimates. It can be seen that abandoned mine methane emissions are small in comparison with operating mine emissions up to 2005.

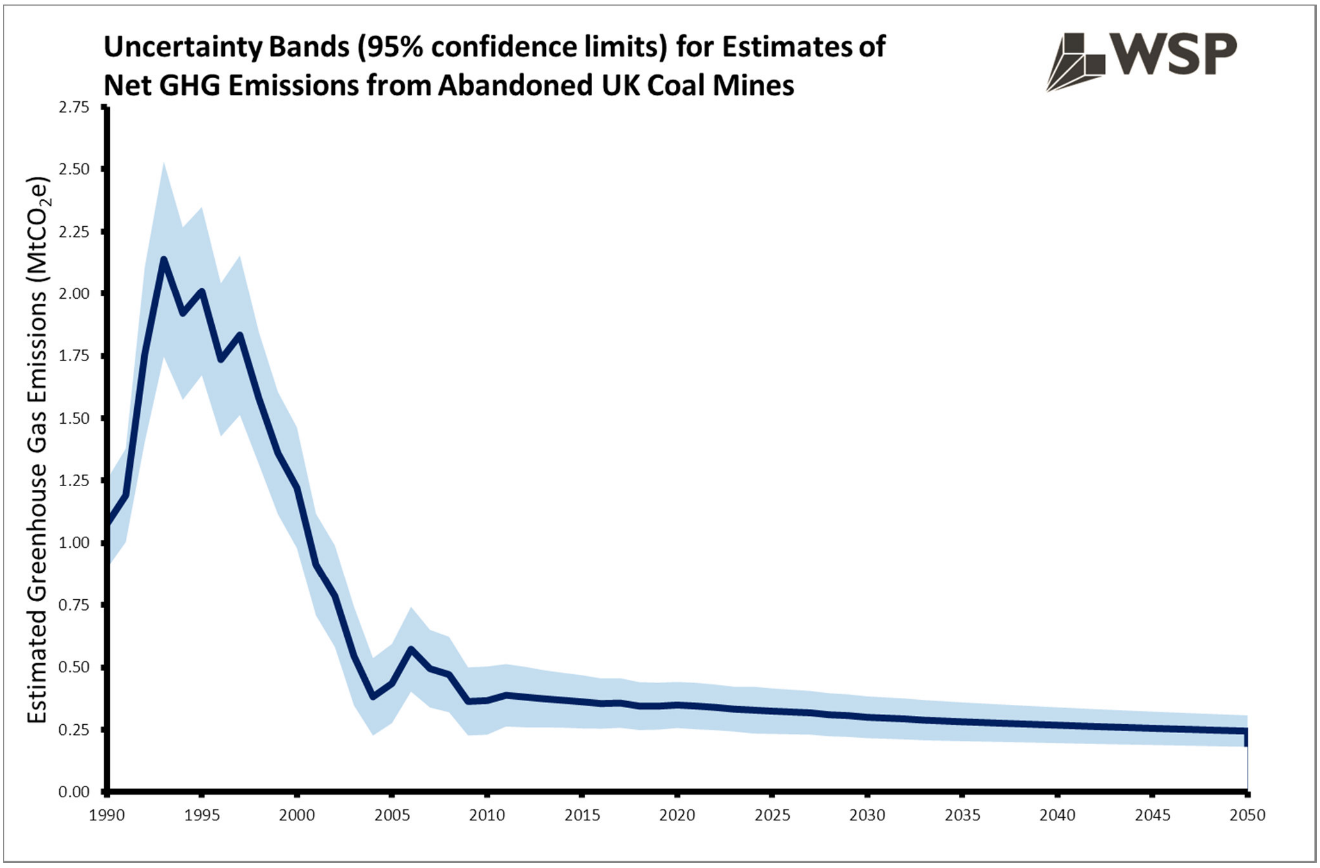
The detailed results, including models of all 154 mines areas/zones and a breakdown of emissions by nation are presented in an Excel model which facilitates future updating. The band of uncertainties derived for the AMM emissions from deep and open-cast mines were found to be consistent with a hybrid of Tier 2 and Tier 3 emissions estimation methodology as stated in the IPCC 2006 report.

Table 1 – Summary Data

Year	1990	1995	2000	2005	2010	2015	2020	2030	2040	2050
No. Abandoned mine areas	121	132	138	144	148	149	152	153	153	153
Abandoned Mine Net Emissions ($MtCO_2e$)	1.08	2.01	1.22	0.44	0.37	0.36	0.39	0.30	0.27	0.24
Uncertainty(±%)*	± 17%	± 17%	± 20%	± 37%	± 37%	± 30%	± 26%	± 27%	± 26%	± 26%
Operating Mine Net Emissions ($MtCO_2e$)	18.27	12.58	6.99	4.08	-	-	-	-	-	-

* Uncertainty levels are quoted at the 95% confidence limits

Figure1 – Summary Graph of AMM Emissions Estimates 1990 – 2050



Note: This trend includes data for all UK mines that are currently in operation and forecast to be abandoned before 2050.

1 INTRODUCTION

1.1 THE OBJECTIVES AND AIMS OF THE RESEARCH

Two of DECC's strategic objectives are to reduce GHG emissions in the UK and to ensure secure energy supplies. In 2009 coal mining and handling activities generated total methane emissions of 0.136 million tonnes (equivalent to 2.86million tCO_2) (AEA 2011). The UK coal mining sector is therefore responsible for around 0.51% of total UK GHG emissions (excluding LULUCF). The coal mining sector also has significant potential for GHG emissions abatement and energy generation from a methane fuel source which is otherwise wasted. Whilst UK coal production continues to decline, output in 2010 was 18 million tonnes and both active and abandoned mines continue to give rise to methane emissions which contribute to anthropogenic global warming. It is important that DECC has access to robust GHG inventory estimates for the UK coal mining sector which enables informed policy decisions. A previous study of abandoned mine methane emissions was completed for Defra in 2005 by the consultants White Young Green (WYG) and this provides a baseline for this update (Kershaw 2005a, 2005b). The objectives of this project are therefore to:

1. Provide up-to-date annual CH_4 emission estimates for *abandoned or closed* UK coal mines, including the update of historic and projected emissions from the 2005 report and the breakdown by nation;

2. Add value for DECC by identifying future areas for improvement in the UK coal mine GHG inventory, for example through uncertainty analysis and comparison with international best practices; and,

3. Provide a concise summary report and results in a format which can easily be integrated into the UK GHG reporting system (at a devolved administration-level) and is compatible with IPCC and UNFCCC guidelines.

Projected GHG emissions estimates for operating coal mines are to be developed separately from this study by DECC's energy projections team. WSP understood that the outputs of this study will support the following UK and Devolved Administration reporting requirements:

- GHG inventory to UNFCCC and EU (including CRF tables);

- UK non-CO_2 projections to 2050; and,

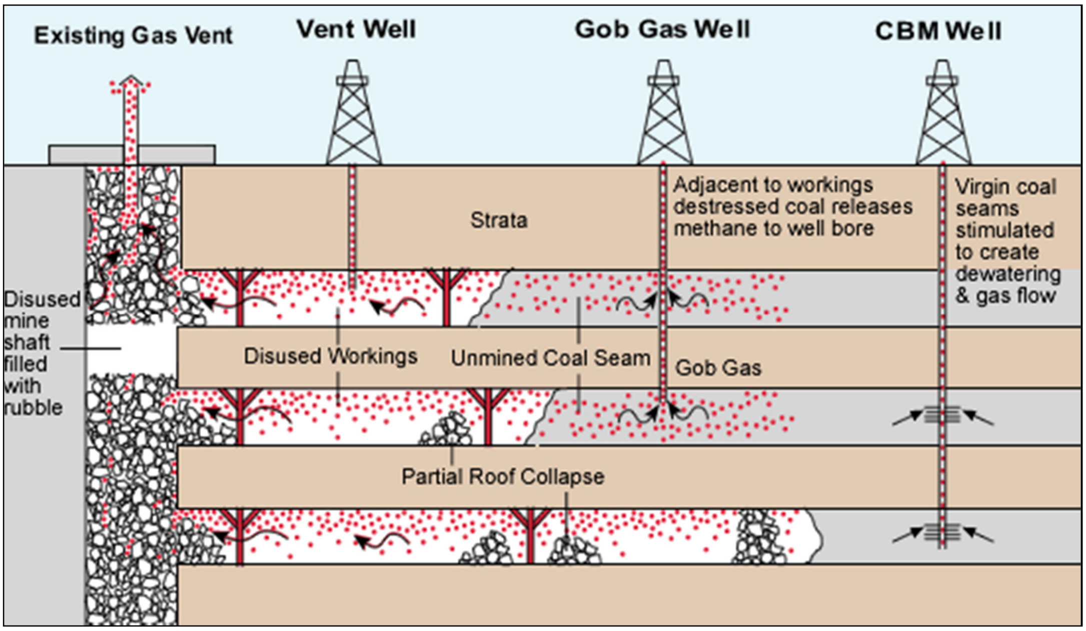
- Devolved administrations GHG inventories.

The study was carried out over the period February to April 2011 and the results were presented at a meeting with the DECC Steering Group on 31st March 2011. WSP would like to thank the DECC Project Officer, Jenny Ward and her colleagues at DECC for their valuable advice and input to the study.

1.2 BACKGROUND TO METHANE LEAKAGE FROM ABANDONED COAL MINES

The majority, 96.6%, of gross (before taking methane utilisation into account) abandoned mine methane emissions arise from deep mines. Surface open-cast mines contribute a relatively small amount, 3.4%, to total abandoned mine emissions. For deep mines, methane is contained within coal seams (known as the 'gas reserve') that, once abandoned, continue to emit gas to the atmosphere via the mine shafts that were used during operation. After decommissioning, these mine shafts are usually vented to prevent the accumulation of underground methane gas as shown in figure 2 below.

Figure 2 – Schematic of Methane Leakage from Deep Mine Workings



The disturbed coal seam will continue to vent methane to the atmosphere until the cavity of the mine is flooded with water, as typically happens as a result of groundwater inflow following closure (during operation, water is actively pumped out of the mine to prevent this). Therefore, abandoned deep mines continue to release methane until such a time when they are completely flooded or the 'gas reserve' is depleted. Flooding effectively seals off a portion of the mine gas reserve due to the low solubility of methane in water. Abandoned mine methane (AMM) emissions are characterised by a high rate of release immediately following closure, then falling to much lower rates of emission over a period of 8-10 years.

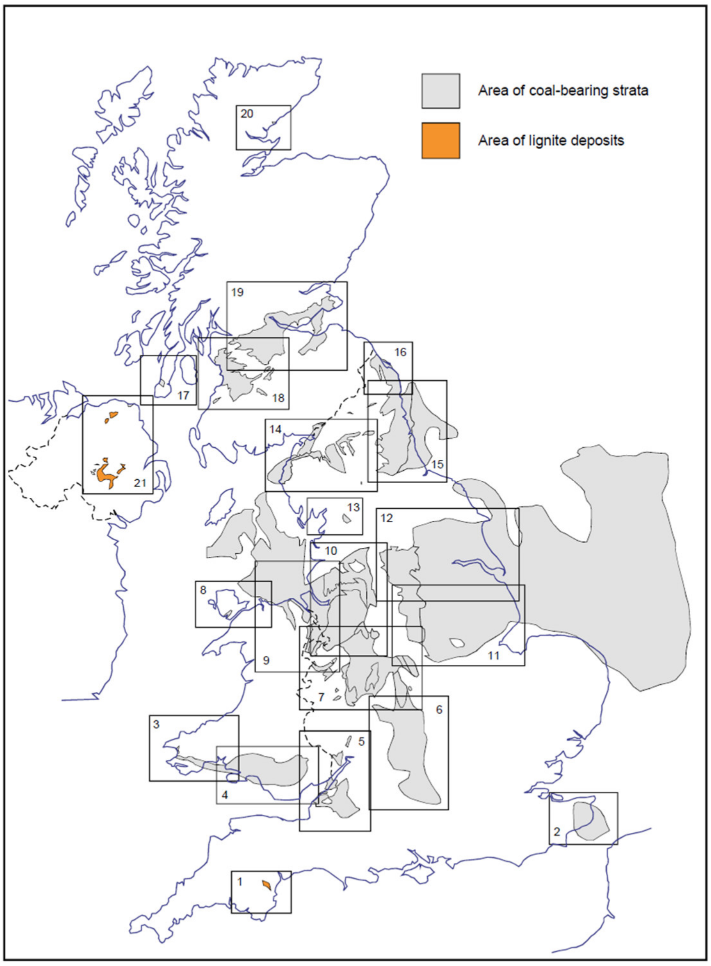
Coal Bed Methane (CBM) extraction is an active method of abstracting methane from virgin coal seams either for onsite electricity generation or piped into a grid. It is achieved by depressurising the coal seam and pumping out any water, allowing the coal matrix to release the methane. CBM extraction is not included in the scope of this study.

Other factors affecting the abandoned deep mine methane release rate are:

- Initial methane content of coal seam (0.5-50 m^3/t for UK coal mines based on WYG model data) – dependent on each specific mine but can usually be clustered by mine basin (e.g. the Hem Heath and Florence mine areas are in a band of 3-9 m^3/t, depending on depth below surface);
- Adsorption isotherm of coal matrix – is a function of the type of coal strata and the surface area of exposed coal surfaces available for adsorption of methane;
- Flow capacity of mine vents (Q_0) – which determines the maximum emissions rate of methane from a mine (typically derived from flows during the mine operational phase);
- Time since closure – as the AMM emissions rate is large immediately following closure, followed by a steep reduction in emissions rate;
- Sealing of mine vents and shafts – again determines the maximum emissions rate of methane from a mine;
- Depth of mine/pressure gradient – describes the thermodynamic properties of the AMM gas;
- Permeability of coal seam to water ingress – which describes the susceptibility to flooding and therefore the rate at which the gas reserve is sealed off by water;
- Water inflow/outflow leading to a rising mine water level and ultimately flooding; and,
- Methane capture and utilisation at source for power generation or connected to grid for wider distribution.

The approximate extent of UK coal-bearing strata and some key mine statistics are shown in Figure 3 below. In this study the UK coal mines have been grouped into 154 area or zones of similar mines as described further in Section 2.

Figure 3- Approximate extent of UK coal-bearing strata and key mine statistics (UK Coal Authority 2010)



Active UK coal mines (2010 data)

No. Underground = 16

No. Surface = 36

No. Total = 52

Active mines by nation: England = 23, Scotland = 16, Wales = 13, Northern Ireland = 0

Total UK coal production = 17.8 million

Abandoned UK coal mines

Total no. of mines = over 900

Split across 32 major coalfields

Methane capture generating capacity installed = c. $50MW_e$

GHG emissions reduction = 0.5 million tCO_2e/annum

Potential for a further c. 150 MW_e generating capacity

2 STUDY METHODOLOGY

WSP's approach to updating the methane emissions estimates for abandoned coal mines was as follows:

2.1 HIGH-LEVEL REVIEW OF GREENHOUSE GAS INVENTORY MODEL AND INTERNATIONAL BENCHMARKS

The baseline for this study is the UK-specific methodology on AMM emissions developed over the period 2002-2004 by WYG which is summarised in their 2005 report to DEFRA (Kershaw 2005b). This AMM methodology is complex and involved significant resources to develop, including collection of mine-specific data, on-site monitoring of selected mines and modelling of 154 UK mines areas/zones.

To allow a comparison with best practice, WSP initially conducted a literature review of the international benchmarks for the estimation of methane emissions from abandoned coal mines. Few countries have estimated AMM emissions and the two key benchmark methods identified were:

- **USEPA** - Methane Emissions from Abandoned Coal Mines in the United States: Emission Inventory Methodology and 1990-2002 Emissions Estimates, April 2004, Coalbed Methane Outreach Program US EPA. Retrieved from http://www.epa.gov/cmop/resources/abandoned_underground.html

- **IPCC** - Chapter 4: Fugitive Emissions, IPCC Guidelines for National Greenhouse Gas Inventories 2006. Retrieved from http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_4_Ch4_Fugitive_Emissions.pdf

A review of these two leading methods indicated that the estimation of methane emissions from abandoned coal mines could be described by a number of equations that are dependent upon the characterisation of the mine and whether they were flooded with water, manually sealed with a plug, or open vented into the atmosphere. These equations were functions of parameters that could only be derived empirically for each coal basin as well as other mine-specific coefficients. Furthermore, these equations were also dependent on mine-specific equations describing the specific volumes, pressures and grades of coal in order to construct isotherms to model gas flow. The USEPA method involved using sampled data from around 600 mines and is therefore equivalent to an IPCC Tier 3 method, being mine-specific and requiring a significant number of empirical data points. Overall, the USEPA method is the most comprehensive and complex and the IPCC guidance is derived from a simplified USEPA method.

In comparison the WYG methodology split each coal mine area into a box/polygon model using spatial characteristics (depth, volume, height). This spatial model was combined with gas content data and flow data to determine the methane 'gas reserve' and depletion rate (typically a hyperbolic decay curve). Water inflow was modelled to calculate the likely year of flooding at various levels within the cavity (50m height intervals). From this combination of gas reserve estimation and flooding predictions, methane emissions were derived for each coal mine area/zone. The UK method involved using sampled data from 8mines combined with a range of other UK mining-sector data sources and is therefore a hybrid of IPCC Tier 2 and Tier 3 methods.

The international literature on AMM emissions also identified a wider number of approaches in use (from no estimation of AMM through to IPCC Tiers 1, 2, and 3), as summarised in Table 2 below. The overall conclusion from the benchmarks view indicates that the current UK method:

- is in line with best practice benchmarks in terms of international methods for estimating methane gas reserves;
- is more advanced than the USEPA method in terms of predicting mine flooding;
- is less robust than the USEPA method in terms of estimating the long-term emissions rate as it is based on fewer data points; and,
- provides an estimate of emissions (using a long-term rate of 0.74% of the gas reserve per annum).

Overall the models developed by WYG are found to provide a robust method for updating UK AMM emission estimates. The method combines limited UK mine-specific data with some assumptions regarding the similarity of certain coal areas/zones as so represents a hybrid of IPCC Tier 2 and Tier 3 methods.

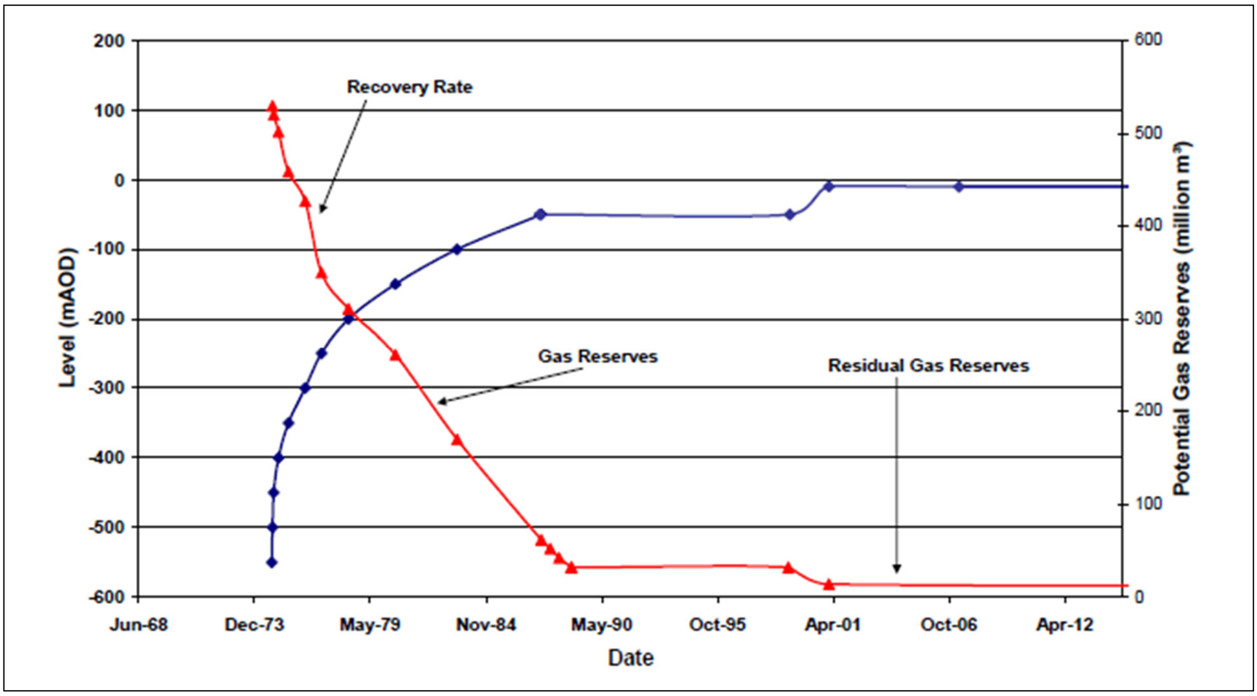
Table 2 - International Benchmarks Summary for AMM Estimation

Country/ Authority	Reference	AMM Emissions Estimate	Estimation Methodology	Uncertainty Levels
UK	Kershaw 2005b; AEA 2011	2004: 47 $ktCH_4$ total for deep abandoned mines(c. 0.18% of total national GHG inventory excl. LULUCF and excl. methane utilisation of 31 $ktCH_4$)	Model of 140 mining areas using area-specific input parameters. Hyperbolic decay of gas reserve based on gas flow during operation, seam gas content and adsorption isotherms. Decay is overlaid with mine water 3-D modelling from inflow/outflow data and spatial data for each mine area. Fixed long-term gas reserve decay rate of 0.74% per annum assumed based on data for 8mines.	No uncertainty analysis performed. Range of closure dates for mines still operating were considered. The mass balance for long-term decay rate of gas reserves in flooded mines was not accounted for.
US	USEPA 2004; USEPA 2011	2008: 429 $ktCH_4$ Gross (c. 0.13% of total national GHG inventory excl. LULUCF and excl. methane utilisation of 148 $ktCH_4$)	Similar model to UK but accounts for additional parameters in hyperbolic decay such as mine pressure gradient and effectiveness of sealing. Total of 457 abandoned mines modelled in 2008. Does not model mine water levels in as much detail as UK method (assumes full flooding after 8 years). Some mines were not modelled in detail but were grouped by type. Exponential long-term gas reserve decay rate (e.g. 1.24% at 7 years since abandonment, 0.19% at 10 years) based on best fit curve for measured mine data	A Monte-Carlo analysis indicates an uncertainty range (95% confidence limits) of 19 percent below to 27 percent above the 2008 emissions estimate. The main reason for this level of uncertainty was due to the unknown status of 40 mines.
IPCC	IPCC 2006	n/a	Method based on USEPA with standardisation of emission factors and decay rates to account for generalised country scenarios. Tier 1 – application of globally-used constants to estimate of emissions Tier 2 – application of nationally-derived constants to estimate of emissions Tier 3 – application of site-specific constants to estimate of emissions	Indicates that an overall uncertainty range of +/-20% to +/-30% is typical for a Tier 3 methodology for countries with a significant number of mines. The range of uncertainty associated with estimated emissions from an individual mine may be large (in the ±50% range).
Global Methane Initiative	GMI 2010	n/a	Does not provide a method for estimation. Provides country summaries of coal mine methane emissions and data on methane capture technologies and projects	n/a
Canada	Environment Canada 2010	Not estimated	Canada do not currently provide estimates of abandoned mine methane	n/a
China	World Bank 2010	Not estimated but likely to be 3-4 times higher than US emissions	China do not currently provide estimates of abandoned mine methane. A number of AMM capture projects are being developed in China (backed by World Bank and generating CER credits)	n/a
South Africa	Department for Environment Affairs and Tourism, SA 2009	1994: 317 $ktCH_4$ (1.8% of total national GHG inventory excl. LULUCF and excl. methane utilisation which is not reported)	Applies IPCC Tier 1 method using standard emission factors based on average mine depth. Need for an improved estimation method in future is recognised.	Medium to high level of uncertainty, values not quoted but likely to be of the order +/-50%.
Australia	Australian Department of Climate Change and Energy Efficiency 2011; ACARP 2006	2008: 83 $ktCH_4$ (0.3% of total national GHG inventory excl. LULUCF and excl. methane utilisation which is not separately reported)	Details not available but Australian Coal Association research Program (ACARP) produced a report in 2006 which follows a mine-specific estimation method similar to that used in the UK but does not allow for flooding.	Not quantified but uncertainties mentioned are due to future closure dates of mines. A number of gassy coal mines have closed in the past five years, resulting in peaks in emissions. Between 2009 and 2020, around 15 underground coal mines are expected to cease producing, resulting in emissions remaining between 0.5 and 1.5 $MtCO_2e$.

2.2 DATA REVIEW FOR ABANDONED DEEP MINES

WSP obtained an inventory of abandoned mines (last updated in 2005) from the previous WYG study files that contained methane gas reserve estimates from 1990 to 2004. This inventory included mines that had been closed and abandoned before 1990 and with complementary data in further modelling files, the expected flooding dates for several of these mines, given the mine's characteristics. From this, profiles of gas reserve estimates (allowing for progressive flooding over time) were developed for each of the mines which were either based on the forecast water levels in the mine (from WYG) or inferred from a long-term emissions rate of 0.74% of gas reserves per annum. This 0.74% long-term emissions rate was obtained by WYG's analysis into a correlation between the gas reserves for 8 closed mine areas and the measured flow rate of methane from exposed vents[1]. The gradient between the two indicated the rate of emissions release and the two series correlated with an r-squared of 0.7053, suggesting that more than 8 data points were required in order to arrive at a stronger correlation. A typical example of the model for each mine zone/area is shown in Figure 4 below indicating how the rising water level leads to rapid decline in the gas reserve, followed by a levelling-off which represents the long-term decay of the gas reserve after flooding.

Figure 4 – Typical projection model output for mine flooding and gas reserve decay over time



Notes: Source is Fig 5.4 in Kershaw (2005b). Blue line refers to depth/level of flooding within the mine, red line indicates the potential gas reserve.

Forecasts of future mine gas reserves generated by the WYG models were generally incomplete for a year-by-year analysis, as they were a function of water depth at 50m intervals. Therefore, in order to construct time-series profiles, the available data points were plotted in Excel and a trendline obtained from which to interpolate and extend the trend to cover all years from 1990 to 2050. For mines where no future forecast data from WYG models was available, the gas reserves volumes were estimated using the 0.74% long-term emissions rate.

Appropriate steps were taken to attempt to minimise the risk in over and underestimating emissions by applying the 0.74% long-term emissions rate after a mine's flooding to characterise the methane emissions from deep abandoned mines. The long-term factor is likely to underestimate the emissions in the years immediately following a mine's closure and overestimate the emissions in later years. This is because the typical emission rate cited in Kershaw 2005b changes over time with 74% of the gas reserve leaking in year 1, 7.4% year 2, 4.1% year 3, 2.6% year 4, 1.8% year 5, 1.3% year 6, 1.0% year 7, and 0.8% in year 8. A key factor which determines this rapid decay in methane leakage, and which is so modelled for each mine is the decline in the 'available' gas reserve due to mine flooding in the years immediately following closure. In order to minimise the risk of over or underestimating emissions appropriate approaches were taken for different types of mines. For those mines that had already been flooded (typically beyond year 8 after closure) the long-term emissions rate of 0.74% was applied as without alternative data

[1] The derivation of the long-term emissions rate is based on data for 8 closed mine areas (Bearmouth, Calverton, Parkside, Cronton, Askern, Horbury, Roughwood, Hem Heath) in Table 10.2 of Kershaw (2005b)

this presents the best estimate of emissions available. For mines that are scheduled to close in the future, the long-term emissions rate was applied after the mine was determined to be fully flooded (as per modelled WYG data). In the years following closure, the long-term emissions factor was also applied to the 'available' gas reserve (in the absence of other data on leakage rates) to mines that were determined to be fully flooded before 2005 (128 out of 140 in the WYG dataset), the 12 mines which were forecast to flood after 2005 (in the WYG dataset) and the 12 additional mines which are forecast to flood from WSP's update.

2.3 DATA REVIEW FOR ABANDONED SURFACE MINES

WSP undertook a mine-by-mine review to update the WYG models including those for mines which have closed or are due to close after 2005, and those that re-opened or were scheduled to do so before 2050. Data on actual/predicted closure dates were obtained from the operating companies and cross-checked with the Coal Authority and DECC in terms of alignment with UK energy projections. A summary of mine status and closure dates for those mines that were still operating post-2005 is given in Appendix A.

After closure, emissions from abandoned surface mines were assumed based on an understanding of the workings of those mines to include the following:

- The standing highwall/face of the coal seam;
- Leakage from the pit floor;
- Low temperature oxidation;
- Uncontrolled combustion; and,
- Mine remediation method (e.g. capping) and timing after closure.

At present, no comprehensive methods to quantify these emissions have been developed by the IPCC, USEPA or other countries. They remain subjects for further research. In the absence of other methods WSP has assumed, based on expert judgment, a simple methane estimation method based on rapid decay of emissions in the year after closure of 50% of the production related emissions. This provides an 'order of magnitude' estimate for comparison with deep mines whereby the surface mine emission are shown to be relatively small. Due to the large surface area of the mine exposed at shallow depth to atmosphere, the majority of the methane in the coal strata is released during operation. By the time of decommissioning the remaining gas reserve is relatively small and will be released rapidly (compared to deep mines) due to the proximity to the surface.

Therefore the projections used in estimating the methane emissions from abandoned surface mines are calculated based on UK energy projections for coal demand from surface mines in millions of tonnes per year, against which a methane emissions factor has been applied to represent the small volume of gas (0.17 $kgCH_4$/t coal, ULAN 2009) released after mine abandonment.

2.4 DATA REVIEW FOR METHANE UTILISATION IN ABANDONED MINES (AMM UTILISATION)

All methane utilisation from mines are currently recorded by the Coal Authority for abandoned, operating mines and virgin coal bed methane (CBM) project. WSP correlated this data with an inventory of current AMM utilisation projects (i.e. excluding operating mines and CBM sources) from the UK Coal Authority (2011) and cross-checked this with operator data (GMI 2010). The research identified 25 projects[2] (all based in England) which are either operational, temporarily closed or planned to be in operation by 2020. It was estimated that total 'active' AMM capacity in 2010 was 35 MW_e based on the 25 projects identified. A further 30 MW_e of capacity was identified which is related to operating mines and CBM projects based on the review of planned projects and therefore is not classed as AMM at this time.

From a given power generation capacity from AMM utilisation, the amount of methane utilised could be calculated from the equation:

$$\textbf{Mass of methane utilisation } (tCH_4) = \frac{\textbf{Installed capacity (MWe)} \times \textbf{Load Factor (\%)} \times \textbf{8760 (hours)}}{\textbf{Generation Efficiency (\%)} \times \textbf{Methane Higher Heating Value (MWh/t)}}$$

[2] A list of which is provided within the model, C36:C60, "6. Methane Utilisation" sheet in WSP– DECC UK CH4 Emissions Abandoned Coal Mines – Final v1.2.xlsx

A forecast of expected power generation from AMM utilisation was made out to 2050 with variable inputs for 10-year intervals until this date, taking into account projections for available methane resources. In absence of other data, it was assumed that methane utilisation in the long term would remain at current levels (68% of available UK AMM from UK Coal Authority data) although there may be increased uptake of CBM utilisation in future.

2.5 DATA REVIEW FOR OPERATING DEEP MINES

In the UK at the end of 2004 there were 10 remaining large deep mines and 12 smaller mines in operation, producing a total of 11.5 million tonnes of coal (Coal Authority 2010). By the end of 2010, only 4 large deep mines remained in operation, along with 31 smaller mines (some newly opened), with total coal production of 10.4 million tonnes (Coal Authority 2010). The combined coal production output of the smaller mines in 2010 was found to be approximately one-tenth that of the combined large mines production (UK Coal Authority 2011). In the absence of other data the aggregate gas reserve of smaller mines still in operation (and subject to closure in future) is therefore estimated to be equivalent to 10% of the combined large mines gas reserve.

Methane emissions from UK operating deep mines are reported based on actual measured data from mine ventilation systems. The latest available data for 2009 indicates emissions of 161 $ktCH_4$, which combined with 2009 production of 7.5 million tonnes of coal, gives an overall emission factor (before any methane capture or utilisation) of 21.5 $kgCH_4$/tonne of coal mined, and is based on a production-weighted average from measurements at all major active UK deep mines (AEA 2011).

In the US the total emissions from operating deep mines is 3189 ktCH4 in 2009 (20 times that in the UK before methane utilisation) using an emission factor of 10.6 $kgCH_4$/tonne of coal mined (USEPA 2011). This emission factor is based on measurements from 135 gassy mines plus basin-specific assumptions for a larger number of non-gassy mines

The IPCC (2006) default emission factor is 7 – 17 $kgCH_4$/tonne of coal mined. The IPCC default factors are based on the range of measured deep mine data from a number of nations including the US, Germany, France and Australia. The IPCC guidance notes that as the gas content of coal typically increases with depth, the low end of the range should be chosen for average mining depths of <200 m, and for depths of > 400 m the high value is appropriate. For intermediate depths, average values can be used.

The UK emission factor is double the emission factor used by the US (10.6 $kgCH_4$/tonne of coal mined compared to 21.5 $kgCH_4$/tonne of coal mined) and above the range suggested by the IPCC. However, emissions factors are expected to vary significantly by country according to the number, type and depth of mines, geology of the coal seams and mine ventilation methods and the IPCC guidance indicates that actual measured data are preferred as country-specific values are highly variable. In the UK the few remaining UK operating deep mines are all gassy (indicating that a high emission factor is to be expected), whilst in the US there is a larger number of both gassy and non-gassy mines, (indicating that an average emission factor is to be expected). Since the UK emission factor for operating mines is based on measured data from mine company returns to the Coal Authority, the emission factors used represent Tier 3, and are therefore the most accurate method to represent UK-specific mine operations.

2.6 ASSUMPTIONS USED IN CONSTRUCTING DATA SERIES

In constructing the AMM emissions profile for each mine, data was collected from a variety of sources; primarily, the gas reserve estimate data from the WYG models were updated to reflect actual mine closure dates. In calculating the corresponding AMM emissions, assumptions were made for several key variables as follows:

- **Gas reserve decay rates**– This parameter gives the reduction in the volume of the gas reserve in a given mine over a period of time, with the reduction being equivalent to the leakage rate of AMM emissions. This is an indirect way, depending on the inference of emissions from a known quantity of gas reserve and no comparable default exists in the methodologies of the IPCC or US EPA which use direct measurement or calculation the emissions dependent on the physical characteristics of the individual mine. For this review, each of the 140mines in the inventory (as of 2005) were inspected to determine their status. 128 mines were found to be flooded by 2005 which indicated that the decay rate for these mines would behave as described by the long-term emissions rate of 0.74% per annum. This value of 0.74% was obtained from the WYG study into the development of a method for AMM emissions estimates (p46) that correlated vent flow rates and gas reserves for 8 mines. This correlation had an r^2

value of 0.7053[3] where the gradient was inferred to be the long-term emissions rate. 20 mines were found to be vented, of which data for 10 of those were available from the WYG models, although covering only a small number of years post-2005 (typically 3-5 years' of gas reserve data). This data was constructed into a trend line with the subsequent years extrapolated. The modelled trend lines were:

Table 3–Trend lines applied to 10 vented mines closed since 2005

Mine Code	Trend line	r^2
YORK 4	$f(x)=-7x10^8 ln(x)+2x10^9$	0.9979
YORK 7	$f(x) = -4166x^3 + 621749x^2 - 31465579x + 539674547$	0.9999
YORK 8 POW	$f(x) = -2x10^8 ln(x)+3x10^8$	0.9899
STAFF 1 (FLO)	$f(x) = -4x10^7 ln(x)+1x10^8$	0.9007
STAFF 2 (HEM)	$f(x) = -4x10^7 ln(x)+1x10^8$	0.9160
SWALES 7L	$f(x) = 3x10^6 e^{-0.97x}$	0.9998
SWALES 8L	$f(x) = -2x10^8 ln(x)+4x10^8$	0.9800
SWALES 9L	$f(x) = -5x10^8 ln(x)+9x10^8$	0.9473
NOTT4	$f(x) = 2x10^8 x^{-0.717}$	0.8399
LANC2	$f(x) = -3x10^7 ln(x)+4x10^7$	0.9915

For the 10 other vented mines; 2 that were abandoned since 2005 were modelled to follow the 0.74% long-term emissions rate, whereas the 8 that were in commission at the end of 2005 had gas reserve data available for them following their closure date. Although this assumed leakage rate may tend to under-estimate emissions in the first few years after mine closure, it is the rate of mine flooding has a more significant impact in terms of reducing the gas reserve available for leakage. In later years after mine closure the 0.74% leakage rate may over-estimate emissions. Overall, across all of the UK mines modelled, many of which closed pre-1990, this effect tends to average out and leads to the best emissions estimate attainable with the present data.

- **Closure dates** – 12 mines were added to the update of the 2005 analysis. These were mines that were forecast to be closed at some point between 2005 and 2030. This was based on research conducted for each mine as to their status and expected closure date.
- **Alignment of coal production with UK energy projections** – the variable of coal production (millions of tonnes) from open cast mines was necessary in order to estimate the AMM from these mines as the two were closely related. This data was obtained from DUKES from 1990 to 2008 with DECC input on energy forecast assumptions to 2050.

2.7 IDENTIFYING AND ADDRESSING KEY UNCERTAINTIES

Given that the methane emissions were based on a combination of the gas reserve forecasts and various assumptions on flooding and emission decay rates, there were a number of points in the calculation where uncertainty could accrue. This was dealt with by performing an uncertainty analysis based on the likely ranges of certain variables and then calculating the propagation of these uncertainties to the final value of methane emissions. Guidance from the IPCC (2006) was applied in making the assessment of uncertainty (e.g. expected error bands in Tier 2 and Tier 3 methodologies) combined with statistical analysis of key mine input data. All uncertainty values are quoted at the 95% confidence limits (assuming a normal distribution).

The uncertainties addressed in the model are as follows:

[3] A perfect correlation would have an r^2 value of 1.0000, indicating a 0.2947 difference from complete agreement although for statistical reasons, this does not directly correspond to an uncertainty of 29.47%. Instead a ±20% uncertainty on this value is judged to be appropriate to convey uncertainty in the correlation

Uncertainty on the closure of currently (2010) operating mines

Of the six currently operating mine areas (YORK 3D MAL, YORK 8KELB, YORK 4HAT, NOTT 2 THO, WRWK DAL and OTH SML), an understanding of their likely closure date was obtained using data from the UK Coal Authority and the relevant operating company's annual reports on coal reserves remaining. However, uncertainty arose as to the closure date due to currently unforeseeable events (rate of coal depletion within the mine, demands on production etc.) and an uncertainty was applied to the analysis given closure dates in a range of ±10 years of the stated closure date.

Uncertainty on the gas reserve estimates

Gas reserve estimates were a consolidation of expected reserve estimates from WYG (and an interpolation of these data points by WSP) and an assumed decay factor of 0.74% per year taken from WYG in the absence of coal mine-specific data and characteristics. In determining the total gas reserve estimates therefore, uncertainty had to be applied to the individual reserve values. These were determined to be large because of various factors affecting reserve estimates and an uncertainty of 50% is therefore assumed.

Uncertainty on methane emissions rate

In the absence of gas reserve forecast data for 2005 to 2050, a decay rate of 0.74% was assumed, based on previous WYG work in the Defra 2005 report comparing gas reserve volume and flow rate on a number of flooded mine areas. Due to the variability of this decay rate depending on individual mine characteristics (e.g. pressure, depth, re-opening) a 20% uncertainty has been assumed but in reality may vary significantly around this.

Uncertainty on open cast mine methane emissions factor

The emissions factor of methane during coal production was obtained as 0.17 $ktCH_4$/Mt coal but varies due to the intensity of production. To reflect this, an assumption of 20% uncertainty has been applied.

Uncertainty on methane utilisation factor

From the inventory of the recovery and utilisation projects, it was clear that some uncertainty existed as to the potential future AMM project capacity and load factors. To reflect this, an assumption of 5% has been applied. This is comparatively small in value due to the high proportion (90% in 2010) of AMM utilised in England, where all of the mines currently in operation are. This indicates that methane utilisation is now exploited where possible and significant variation from the proportion of AMM utilisation is unlikely in future.

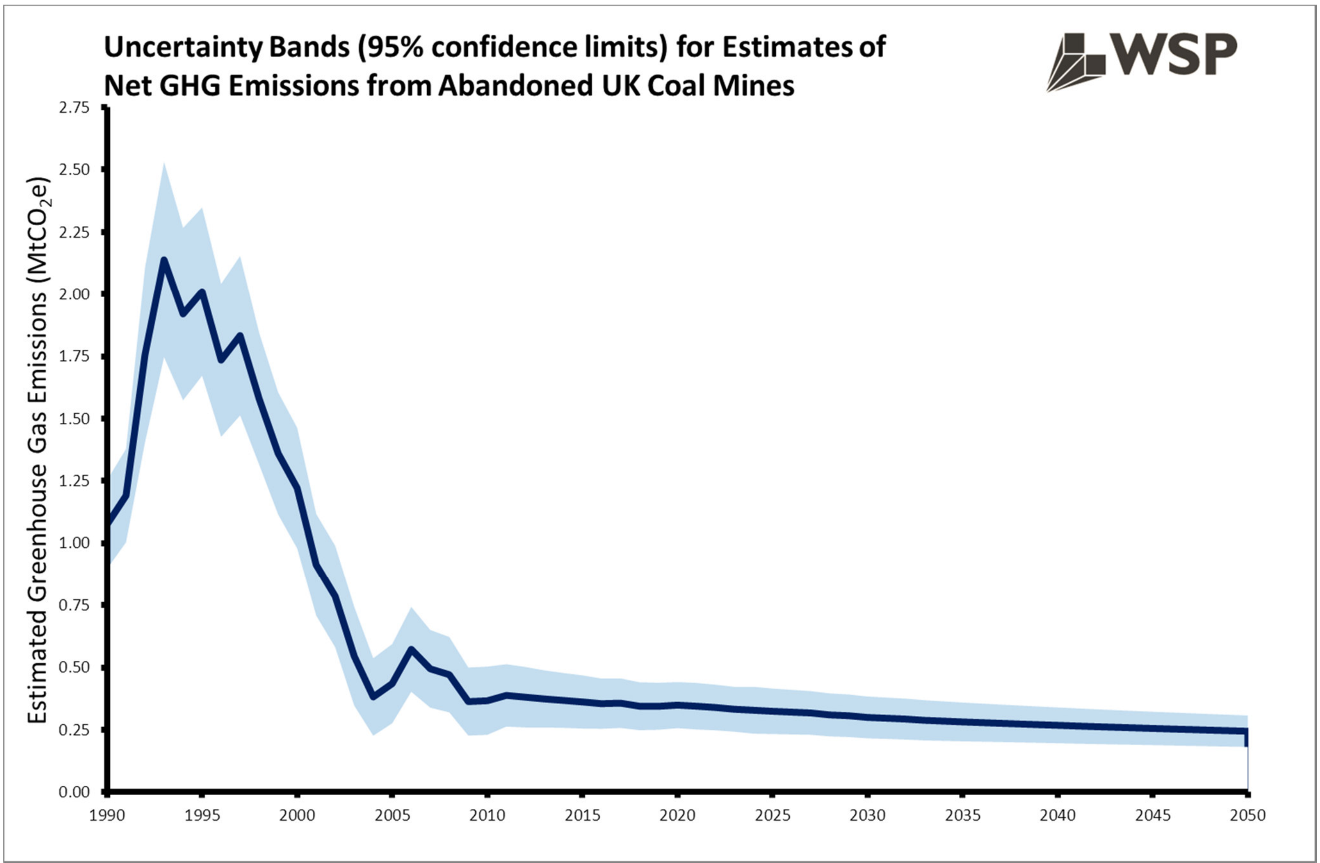
2.8 DEVELOPMENT OF INTEGRATED AMM MODEL

WSP developed an integrated model of abandoned mine methane using the full range of data, correlations and input parameters listed above. This model covered, deep mines, surface mines and methane utilisation from 1990-2050, including predicted future mines closures and a breakdown by nation. The gross and net methane emissions and carbon equivalent savings were also calculated using an GWP for methane of 21 following UNFCCC guidelines based on IPCC Second Assessment Report (IPCC 1997). The model also brought together the associated uncertainties on each variable in order to communicate the range of possible values within a 95% confidence interval. The full model is provided as an Excel workbook entitled 'WSP-DECC UK CH4 Emissions Abandoned Coal Mines.xlsx'.

3 RESULTS

The AMM updated emissions estimates arising from this study are summarised in Figures 5 and 6 and Table 4 below.

Figure 5 – Summary Graph of AMM Emissions Estimates 1990-2050 with uncertainty bands at 95% confidence limits



Based on the detailed analysis carried out into AMM emissions, it was found that:

- The models developed by WYG for DEFRA in 2005 study provide a sound basis for estimating AMM emissions, however, they:
  - are complex and difficult to update (updating has been carried out to reflect actual/future closure dates)
  - rely on a single long-term decay rate of 0.74% per annum (this assumption has been retained)
  - did not fully account for the long-term mass balance once a mine flooded, and the resulting potential gas reserve that would be available because of that (this has been corrected)
  - are in-line with best practice c.f. USEPA and IPCC
- The trend in UK AMM emissions is one of rapid decline as many mines closed some time ago
- Remaining mine closures will lead to temporary spikes in emissions with long term net emissions dropping from a high point of around 2.0 million tCO_2e/annum in the early 1990's to <0.3 million tCO_2e/annum by 2020
- Active AMM utilisation appears to have peaked in recent years and will be supplemented by CBM utilisation in future as available abandoned mine methane resources will become depleted
- Abandoned surface mine methane emissions are estimated to be small in relation to those from deep mines (surface mines represent <6% of total emissions for all UK abandoned mines)

- Unless new UK coal mines were to be opened and then again decommissioned within the 40 year period of this forecast, AMM emissions would continue to decline steadily to 2050

The full Excel model provides a further breakdown and analysis of the results. The model facilitates future updating by highlighting key input cells and assumptions and guidance provided on how to update the model.

Figure 6 – Summary Graph of Mine Closures and Net and Gross AMM Emissions Estimates 1990-2050

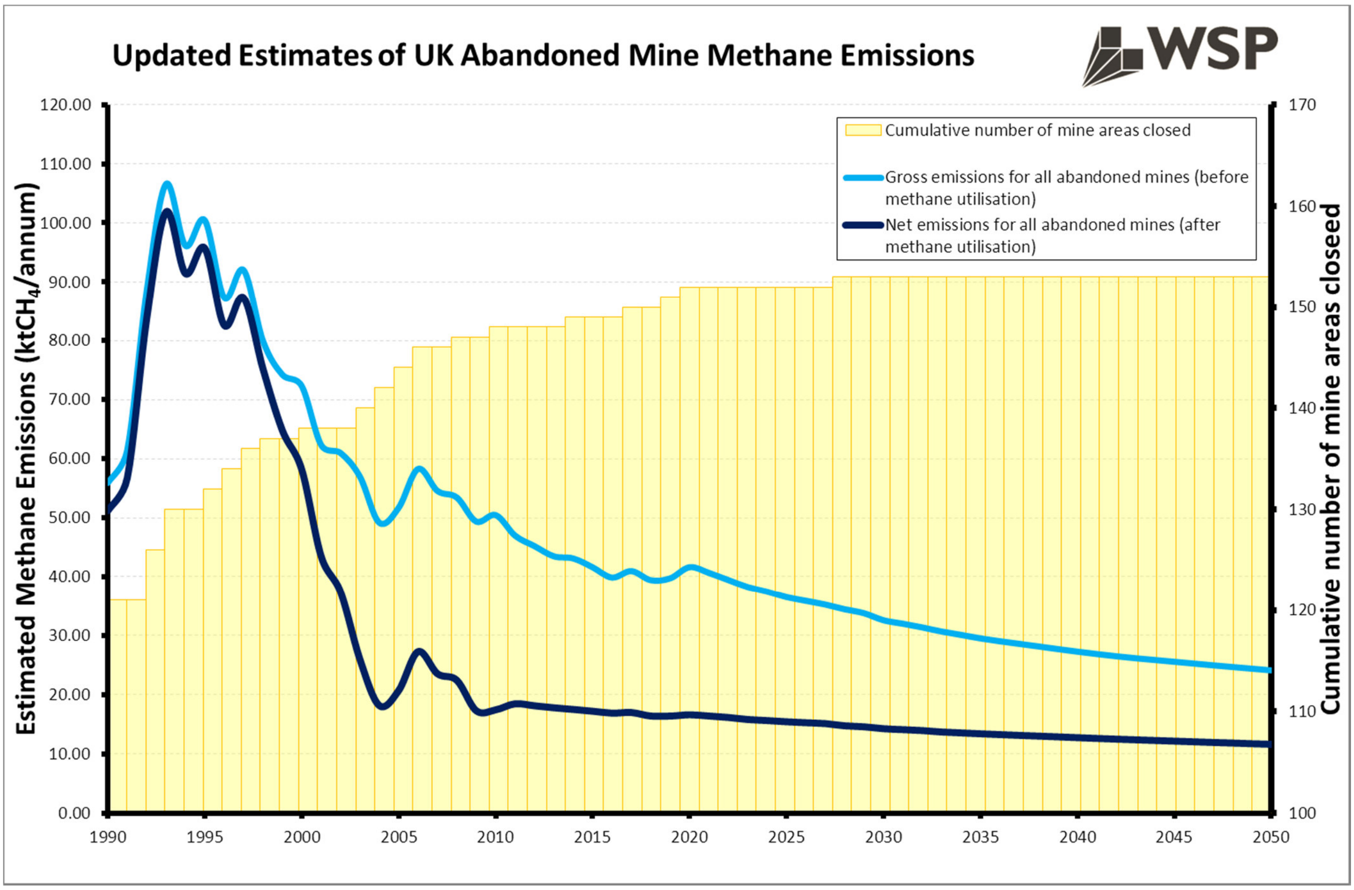


Table 4 – Summary Balance Sheet of UK AMM Emissions from 1990-2050 (excluding Northern Ireland as no abandoned or operational mines since the 1970's)

Updated UK AMM Emissions Estimates ($MtCO_2e$) 1990-2050										
Year	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**	**2030**	**2040**	**2050**
Cumulative Number of Mine Areas Closed	**121**	**132**	**138**	**144**	**148**	**149**	**152**	**153**	**153**	**153**
Deep Mine AMM Emissions Estimates ($MtCO_2e$)	**1.11**	**2.05**	**1.47**	**1.05**	**1.03**	**0.84**	**0.84**	**0.65**	**0.54**	**0.48**
Uncertainty	**±16%**	**±16%**	**±16%**	**±15%**	**±13%**	**±12%**	**±11%**	**±12%**	**±13%**	**±12%**
England	*0.59*	*1.52*	*1.08*	*0.77*	*0.77*	*0.60*	*0.62*	*0.45*	*0.36*	*0.31*
Uncertainty	*±20%*	*±21%*	*±21%*	*±19%*	*±16%*	*±15%*	*±13%*	*±14%*	*±15%*	*±15%*
Scotland	*0.09*	*0.08*	*0.06*	*0.06*	*0.05*	*0.05*	*0.05*	*0.05*	*0.04*	*0.04*
Uncertainty	*±25%*	*±25%*	*±22%*	*±21%*	*±21%*	*±21%*	*±21%*	*±21%*	*±21%*	*±21%*
Wales	*0.43*	*0.46*	*0.33*	*0.22*	*0.20*	*0.18*	*0.17*	*0.15*	*0.14*	*0.13*
Uncertainty	*±31%*	*±26%*	*±25%*	*±26%*	*±26%*	*±26%*	*±27%*	*±28%*	*±28%*	*±28%*
Open Cast AMM Emissions Estimates ($MtCO_2e$)	**0.06**	**0.06**	**0.05**	**0.04**	**0.03**	**0.03**	**0.03**	**0.03**	**0.03**	**0.03**
	±20%	**±20%**	**±20%**	**±20%**	**±20%**	**±20%**	**±20%**	**±20%**	**±20%**	**±20%**
AMM Utilisation ($MtCO_2e$)	**-0.10**	**-0.10**	**-0.30**	**-0.65**	**-0.69**	**-0.51**	**-0.53**	**-0.38**	**-0.30**	**-0.26**
Uncertainty	**±5%**	**±5%**	**±5%**	**±5%**	**±5%**	**±5%**	**±5%**	**±5%**	**±5%**	**±5%**
% Methane Utilised (UK)	9%	5%	20%	62%	68%	61%	63%	59%	56%	55%
England	*-0.10*	*-0.10*	*-0.30*	*-0.65*	*-0.69*	*-0.51*	*-0.53*	*-0.38*	*-0.30*	*-0.26*
Uncertainty	*±5%*	*±5%*	*±5%*	*±5%*	*±5%*	*±5%*	*±5%*	*±5%*	*±5%*	*±5%*
Scotland	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
Wales	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
Net AMM Emissions ($MtCO_2e$)	**1.08**	**2.01**	**1.22**	**0.44**	**0.37**	**0.36**	**0.35**	**0.30**	**0.27**	**0.24**
Uncertainty	**±17%**	**±17%**	**±20%**	**±37%**	**±37%**	**±30%**	**±29%**	**±27%**	**±26%**	**±25%**

4 DISCUSSION OF STUDY FINDINGS

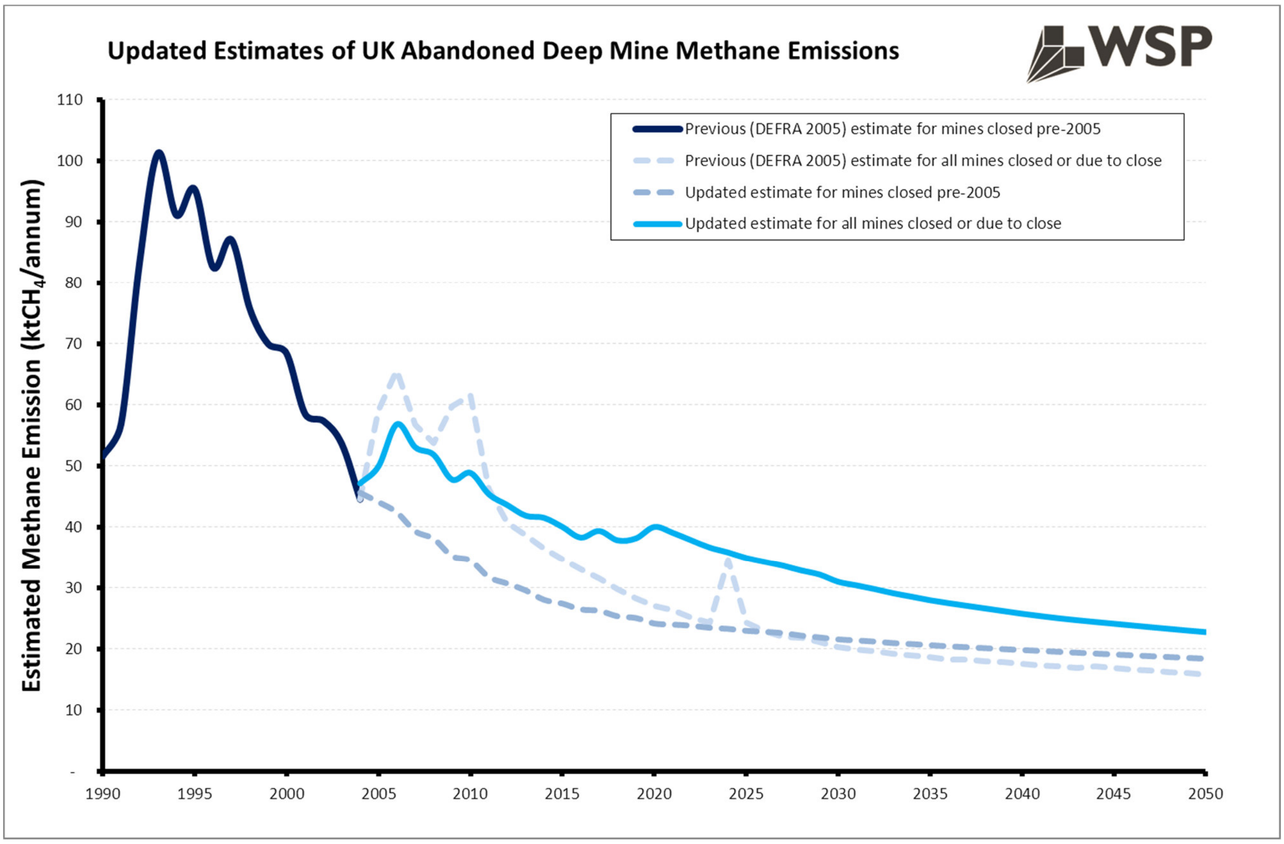
4.1 PUTTING THE EMISSIONS ESTIMATES INTO CONTEXT

After obtaining a wide range of mine data from the literature and previous models and compiling these into an updated set of AMM estimates, WSP see the results as placed in the following context.

The underlying data in the derivation of the methane emissions estimates are the detailed gas reserve models for each abandoned coal mine; each abandoned coal mine was modelled from 1990 to 2050 and gas reserve estimate data either incorporated from previous WYG work or interpolated with an assumption as to the decay rate of the gas reserve. From a mass-balance point of view, this implied that methane emissions from the abandoned mines were analogous to this decay rate. However, this is overlaid with mine flooding rates which effectively close off part of the gas reserve each year. Because of this analogy, the forecast of methane emissions is modelled to behave identically to that of the gas reserve estimates as shown by, for example, some spikes in emissions due to closures of large mines which then rapidly flood.

From the data compiled, and as indicated in Figure 6, it was evident that the number of coal mines decommissioned prior to 1990 was significant, given the general decline of coal mining activity in the 1980s. This trend is likely to continue as economically recoverable UK coal reserves are depleted, energy is supplied from alternative fuel sources, and remaining coal-fired plants in the UK (currently providing c. 29 GW_e of capacity) increasingly rely on imports. The rate of closure of coal mines in the UK is therefore expected to level off with only a few operating mines remaining by 2050. Between 1990 and 2005, the number of abandoned coal mines increased only by 19%, while from 2005 to 2050 this number is predicted to increase by only by 6%. The contributions to AMM emissions of deep mines that were closed pre-2005 (i.e. those included in the previous WYG study) and those that subsequently closed or are due to close by 2050 is shown in Figure 7 below.

Figure 7 – Updated Estimates of UK Abandoned Deep Mine Methane Emissions



Deep mine AMM emissions estimates constitute the largest component of total AMM emissions (97% in 2010). Deep mine emissions in the few years following closure also represent the largest uncertainties associated with AMM estimates due to the uncertainty associated with the rapid decay in gas reserves and flooding rates. The abandoned deep mine gas reserve estimates are forecast to more than halve from 9.2 billion cubic metres in 2010 to 4.3 billion cubic metres in 2050. As a result, the associated uncertainty on the methane emissions will reduce from 38% to 26% in the same time period (n.b. overall uncertainty is not directly proportional to gas reserves as a number of other factors are involved).

Open cast AMM emissions estimates constitute a small proportion of the total emissions from abandoned mines and in this analysis are treated as a single source. The decay characteristics of gas reserves in open cast mines are very different to those for deep mines because these mines have a much larger surface area exposed to atmosphere at shallow depths. Open cast mines release methane from the disturbed coal strata very rapidly – most of the gas reserve is released during their operational phase. Therefore, the rate of release of methane is more closely aligned to the volume of coal produced in the final year of operation and less dependent on specific mine characteristics as in deep mines. The production capacity of open cast coal mines is projected to decrease from 9.51 Mt in 2010 to 8.18 Mt in 2050, a 14% decrease. Methane gas emissions from open cast coal mines are estimated to decrease by the same proportion. There is little data on surface mine AMM emissions and so the estimates for open cast mines have larger uncertainty levels associated with them than for deep mines.

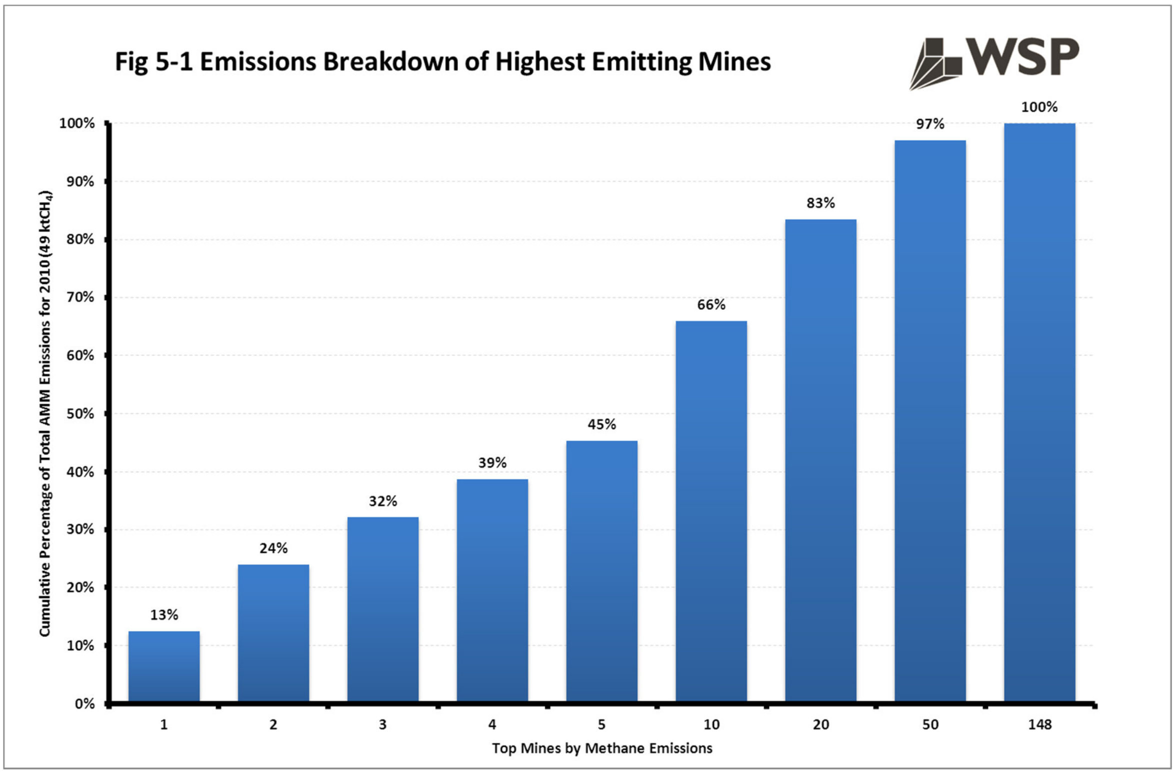
The emissions estimates derived for deep and open cast abandoned mines allows a gross UK methane emissions estimate to be obtained. The contribution of individual large abandoned mines to total emissions can also be analysed. From Table 6 and Figure8below, it can be seen that a small number of the largest mines constitute the majority of total methane emissions. For example, the largest mine LANC 5 emitted 6.12 $ktCH_4$ in 2010, accounting for 13% of the emissions from all abandoned mines. Similarly, the ten largest mines accounted for 66%, and the fifty largest accounted for 97% of all emissions in 2010.

Table 6 – Top 10 Largest Abandoned Mine Areas, by 2010 AMM Emissions

Rank	Mine Code	2010 Methane Emissions ($ktCH_4$)	Proportion of all 2010 emissions
1	LANC 5	6.12	13%
2	YORK 3D HAR	5.60	11%
3	YORK 4	3.96	8%
4	SWALES 9L	3.25	7%
5	SILVERD*	3.21	6%
6	YORK ASK	2.66	6%
7	SWALES 10L	2.47	5%
8	NOTT 2WEL	2.17	4%
9	SWALES 8L	1.47	3%
10	SWALES 4L	1.27	3%

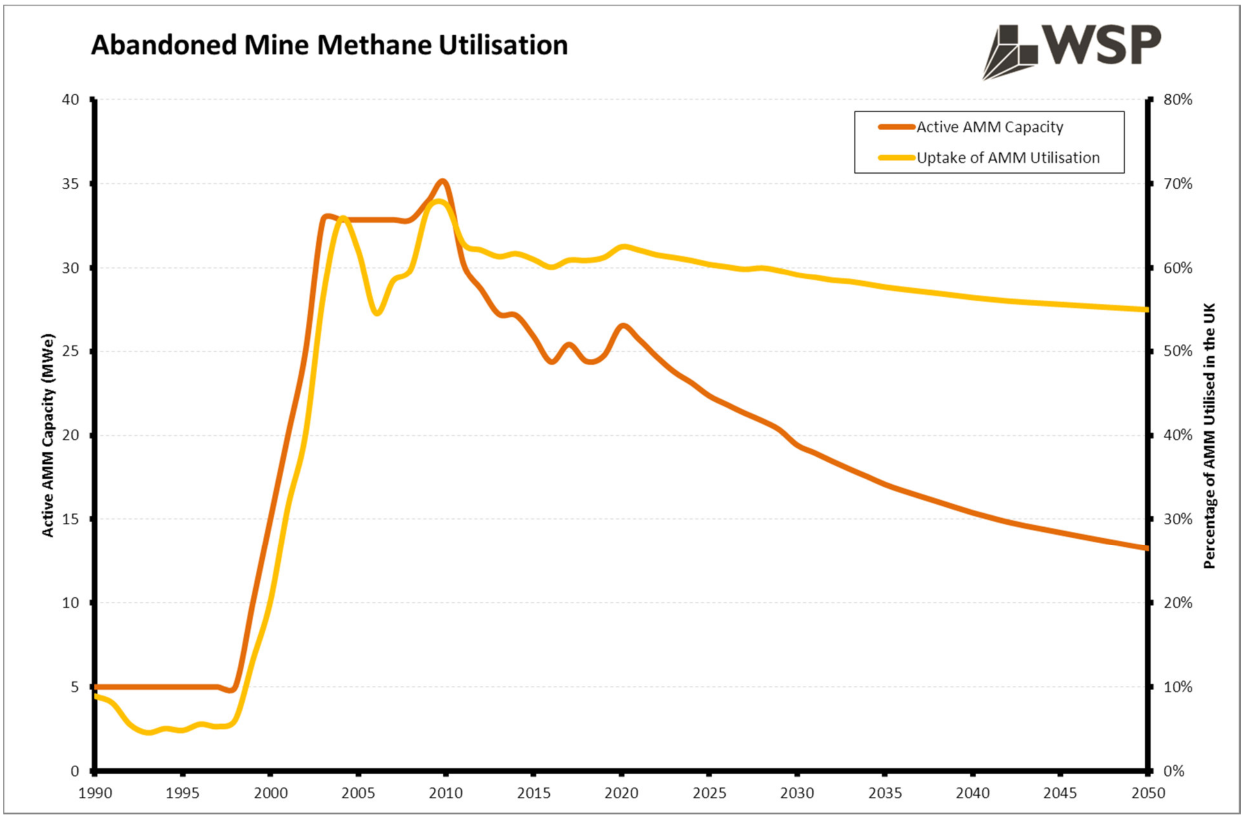
*closed in 2005

Figure 8 – Emissions Breakdown of Highest Emitting UK Deep Abandoned Mines



In order to obtain a net methane emissions estimate from the portfolio of abandoned mine gross emission estimates, it was necessary to quantify the volume of methane recovered for power generation. WSP's analysis found that 25 coal mines currently had facilities for power generation from methane recovery, of which 13 of those were in abandoned mines, giving a total 'active' AMM capacity of 35 MW_e. This AMM capacity is currently forecast to peak around 2008-2015 as in future years recovery projects in operating mines or virgin CBM projects are favoured over AMM recovery. However, the uptake of AMM utilisation has increased dramatically since 2000 and is forecast to remain more or less constant, with methane utilisation equivalent to approximately 60% of total UK AMM emissions for the period 2015 to 2050. The longer-term decline in total 'active' AMM capacity, as summarised in Figure 7, is an indicator that the methane gas reserves of abandoned coal mines are declining. Overall, AMM capture and power generation will continue to generate a net reduction in carbon emission of 0.3 to 0.6 million tCO_2e over the period 2010 to 2050. This reduction includes the net impact of avoided methane release, the CO_2 release from methane combustion and the grid electricity generation (offset of other fuel use for grid electricity generation).

Figure 9 – Comparison of AMM Utilisation (absolute, in MWe) and proportion of total UK AMM Emissions



4.2 UNCERTAINTY

The uncertainty analysis carried out for the key variables in estimating AMM emissions from abandoned coal mines establishes the limitations and boundaries for which future scenarios would affect each variable:

- Uncertainty on the future closure dates of currently (2010) operating mines
- Uncertainty on the gas reserve estimates
- Uncertainty on annual methane emissions rate as % of gas reserve
- Uncertainty on open cast mine methane emissions factor
- Uncertainty on methane utilisation factor

The uncertainty associated with the date of closure for the five operating mine areas (including a number of small mines) has the effect of shifting the methane emissions between ± 10 years. This variation in this may be due to changes in circumstance in each of the mines such as technical extraction potential or may be due to economic factors such as increased demand for coal production and volatility in prices.

The uncertainty associated with the gas reserve estimates is large and currently estimated at ±50% due to the fact that this analysis was performed top-down with general trends applied to individual mines. The emissions of methane from known gas reserves is dependent on a number of variables, which are covered in considerable details in the Defra 2005 report, and mine characteristics vary considerably. The primary variable, and that used in the Defra 2005 report, is that of the water level within the mine void that depends on nearby groundwater flow and pressure. These can only be estimated by mine-specific measurements and from that an emissions rate of methane only inferred. As a result, there are likely to be considerable under- and over-estimates of gas reserves in abandoned mines. The overall uncertainty associated with the estimates of methane emissions from abandoned mines could be reduced through further work in investigating the gas reserve characteristics of each mine.

In order to arrive at a decay rate of the gas reserve (and by analogy, the methane emissions from that reserve), the value of 0.74%/yr has nominally been used. This was based on data presented by WYG correlating gas reserve volume with flow rate with a regression of $r^2 = 0.7025$. Where individual mines did not have forecast gas reserve volumes and were not interpolated in order to arrive at a mine-specific methane emissions rate, this value of 0.74% per annum was applied. Because this value has been arrived at by the correlation of only two variables, and that this correlation is relatively poor (as evidenced by the r-squared value), then this indicates that the uncertainty associated with this value is likely to be high. The overall uncertainty associated with the methane emissions rate from abandoned mines could be reduced through further work in investigating the gas reserve volumes and flow rates for a larger number of mines than was used in the original WYG work.

The results of the overall uncertainty analysis are summarised in Figure 5 and indicate a range of ±17% to ±41% over the period 1990-2050. This level of uncertainty is in line with IPCC guidance on Tier 2 and Tier 3 methodologies.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

WSP's updated estimates of UK AMM emissions from all 143 currently closed coal mines areas as well as those 11 mines scheduled to close by 2050 indicate that there is a general decline in the volume of methane that will be released each year from 2010 to 2050. This is primarily due to the fact that 79% of mine closures had already occurred by 1990 and given that most methane is release immediately following closure, then most AMM emissions have already occurred by 2010. This general trend of decline in methane emissions is overlaid with small perturbations due to the closure of currently operating mines.

This decline in methane emissions is also influenced by an increased uptake of AMM utilisation in the period 2000-2012, meaning that of the AMM available around 60% will be utilised for power generation at abandoned mines. The plateau of approximately 60% utilisation is linked to the proportion of abandoned mines where AMM is economically recoverable. Economically unrecoverable AMM may be accounted for the many small mines and mines that had closed more than ten years ago and are now flooded, where AMM emissions would have declined to a low level.

A number of assumptions were required to update the AMM projections and the impact of the have been assessed by applying the propagation of uncertainties on each value through each mine calculation. This has resulted in a final uncertainty range on the net AMM emissions estimate for 2010, of ±38%. Although this seems high, the IPCC 2006 guidance indicates that an uncertainty range of ±20-30% is typical for a Tier 3 methodology for countries with a significant number of mines. Given that the scope of this study did not involve an individual investigation of each mine, but clustered mines into mine areas and applied national-level emissions factors to the gas reserves, WSP considers this the methodology behind this report to be consistent with a Tier 2+ methodology (where up to ±50% is typical), as described by the IPCC.

Put in the context of a declining domestic coal mining industry, AMM emissions from already and soon-to-be closed coal mines are likely to diminish in significance to <0.3 million tCO_2e by 2050. This compares to a peak in emissions of around 2.0 million tCO_2e in the early 1990's. Although the extent of coal-based power production in the UK is undetermined in the future, the general trend is towards importing coal. Nevertheless, AMM capture and power generation will continue to generate a net reduction in carbon emission of 0.3 to 0.6 million tCO_2e over the period 2010 to 2050 including displacement of other power generation fuels. In the UK context AMM utilisation represents a significant national GHG abatement measure and generates power from a fuel that would otherwise be wasted.

5.2 RECOMMENDATIONS

There are a number of uncertainties associated with the AMM emission estimates that have been developed in this study. The overall uncertainty of the AMM estimates is broadly in the range of ±20 to ±40%. A key step to reduce this uncertainty would involve further research to assess the variability in the assumed long-term emission rate of 0.74% of the gas reserve per annum. As discussed, this value was determined experimentally for a sample of 8 UK mines from a correlation of vent methane flow and gas reserve data. Reducing the uncertainty on this value could be achieved by expanding the sample study to cover a larger number of mines.

However, given that the amount of methane emissions from abandoned coal mines in the UK is forecast to reduce from an already small value. Further work on updating this AMM inventory is unlikely to be necessary in the short term unless there are significant changes in policy impacting any possible recommissioning of abandoned coal mines.

5.3 UPDATING THE MODEL

There are a number of uncertainties associated with the AMM emission estimates that have been developed in this study. The overall uncertainty of the AMM estimates is broadly in the range of ±20 to ±40%. A key step to reduce this uncertainty would involve further research to assess the variability in the assumed long-term emission rate of 0.74% of the gas reserve per annum. The model will also need to be periodically updated to reflect future closures of UK mines that are currently operating and also for changes in UK mine methane utilisation capacity.

6 REFERENCES

A number of reports and data sources were used in order to carry out this update on AMM emissions. These included:

- USEPA 2004. Methane Emissions from Abandoned Coal Mines in the United States: Emission Inventory Methodology and 1990-2002 Emissions Estimates, April 2004, Coalbed Methane Outreach Program US EPA.

  Retrieved from http://www.epa.gov/cmop/resources/abandoned_underground.html

- USEPA 2011. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2009 (April 2011), USEPA #430-R-11-005.

  Retrieved from http://www.epa.gov/climatechange/emissions/usinventoryreport.html

- IPCC 2006. Chapter 4: Fugitive Emissions, IPCC Guidelines for National Greenhouse Gas Inventories 2006.

  Retrieved from http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_4_Ch4_Fugitive_Emissions.pdf

- DUKES 2010. Digest of UK Energy Statistics 2010 – Energy Statistics on Coal, Department for Business, Innovation and Skills 2011.

  Retrieved from http://webarchive.nationalarchives.gov.uk/20091002231531/http://www.berr.gov.uk/whatwedo/energy/statistics/source/coal/page18529.html

- AEA 2011. UK Greenhouse Gas Inventory, 1990 to 2009: Annual Report for submission under the Framework Convention on Climate Change

  Retrieved from http://naei.defra.gov.uk/reports.php

- UK Coal Authority 2011. UK Coal Authority data on methane utilisation 2011.

  Retrieved from http://www.coal.gov.uk/publications/miningtechnology/coalminemethaneukactivity.cfm

- Kershaw, S. (2005a) Projected Methane Emissions from Abandoned Coal Mines in the UK, REPORT/E005832/SK/DATE/Final/V1, Report for DEFRA, WYG Nottingham, UK

- Kershaw, S. (2005b) Development of a Methodology for Estimating Methane Emissions from Abandoned Coal Mines in the UK, REPORT/D5559/SK/May 2005/EMISSIONS/V3, Report for DEFRA, WYG Nottingham, UK

- ULAN Coal Continued Operations Project (2009) Scope 1, 2 and 3 Energy and Greenhouse Gas Assessment, Appendix 14

  Retrieved from http://www.ulancoal.com.au/EN/OperatingApprovals/Volume%20Six/Appendix14.pdf

- Environment Canada 2010. National Inventory Report 1990-2009: Greenhouse Gas Sources and Sinks in Canada Retrieved from http://www.ec.gc.ca/default.asp?lang=en

- Australian Coal Association Research Program (ACARP) 2006.

  Retrieved from http://www.acarp.com.au/documents.aspx

- Australian Department of Climate Change and Energy Efficiency 2011. National Greenhouse and Energy Register.

  Retrieved from http://www.climatechange.gov.au/government/initiatives/national-greenhouse-energy-reporting/nger-register.aspx

- Global Methane Initiative (GMI) 2010. Coal Mine Methane Country Profiles.

  Retrieved from http://www.globalmethane.org/tools-resources/coal_overview.aspx

- Association of Coal Mine Methane Operators (ACMMO) 2007 – UK Mine Methane Facts and Figures 2007.

  Retrieved from http://www.coal.gov.uk/media/BFA/7A/CCT_-_UK_Mine_Methane_-_Facts_and_Figures_-_ACMMO_General_Brief_10_08_07.pdf

- World Bank 2010. Mitigating the Environmental Impact of Coal in China.

  Retrieved from http://web.worldbank.org/WBSITE/EXTERNAL/COUNTRIES/EASTASIAPACIFICEXT/EXTEAPREGTOPENERGY/0,,contentMDK:20491256~menuPK:574044~pagePK:34004173~piPK:34003707~theSitePK:574015,00.html

- Department for Environment Affairs and Tourism, SA 2009. GREENHOUSE GAS INVENTORY SOUTH AFRICA 1990 to 2000

  Retrieved from http://www.pmg.org.za/files/docs/090812greenhouseinventory.pdf

7 APPENDIX A – SUMMARY OF UK COAL MINE CLOSURES POST-2005

7.1 INTRODUCTION

This appendix summarises the available data on closure of UK coal mines post-2005. The previous study covered actual/planned closures up to the end of 2005. The actual/predicted closure dates for mines post-2005 summarised below have been applied to the updated modelling of methane emissions.

Coal production in the UK has declined rapidly since 1980; from approximately 125 tonnes in 1980 to 16-18 tonnes annually within the last few years. However, since 2006 this trend has seemed to change as coal production and consumption has realised a small increase from 16.6 tonnes to 17.8 tonnes per annum as alternative energy sources (i.e. natural gas) have become increasingly expensive(1). UK deep mine and opencast product is largely comparable with 40-50% and 50-60% of total UK output respectively.

As expected in line with production, the total number of producing mines in the UK has also rapidly decreased since 1980 and for the last few years has fluctuated at around 50 sites.

Table A1 - Summary of UK Coal Production and No. of Mines / Sites from 2004 – 2010

Year	Output (Mt)			No of Mines / Sites		
	Deep Mines	Open-cast	Total	Deep Mines	Open-cast	Total
2004	11.5	11.8	23.3	15	45	60
2005	10.3	10.2	20.5	13	33	46
2006	8.2	8.4	16.6	20	33	53
2007	7.5	8.8	16.3	17	33	50
2008	7.9	9.4	17.4	17	37	54
2009	7.5	9.8	17.3	15	36	51
2010*	7.4	10.4	17.8	13	35	48

(Source: The Coal Authority – Production Statistics)

7.2 CLOSURE OF UK DEEP COAL MINES POST-2005

As at March 2011 there were five major deep mines and six medium to small mines in operation. Of the major deep mines Daw Mill, Kellingley and Thoresby are all operated by UK Coal Plc., Maltby is operated by Hargreaves Services. Since December 2010 Hatfield Colliery has gone in to administration as funding for an associated carbon capture and storage (CCS) scheme could not be secured. Hatfield is currently producing under operation of the administrators, PriceWaterhouseCoopers (PwC).

Table A2 and A3 below lists the annual status of UK major and medium/small deep mines that have operated from 2006 to March 2011. Notably, both the Tower and Welbeck collieries and 5 medium to small mines ceased production. Hatfield colliery reopened in 2007 and has continued to operate to the present day.

Table A2 - Status of UK's Major Deep Coal Mines from 2006 – 2011

Mine/Site	2006	2007	2008	2009	2010 (Dec'09)	2011* (March)
Maltby	OPEN	OPEN	OPEN	OPEN	OPEN	PRODUCING
Tower	OPEN	OPEN	CLOSED	CLOSED	CLOSED	SEALED
Daw Mill	OPEN	OPEN	OPEN	OPEN	OPEN	PRODUCING
Harworth	MOTHBALLED	MOTHBALLED	MOTHBALLED	MOTHBALLED	MOTHBALLED	MOTHBALLED
Kellingley	OPEN	OPEN	OPEN	OPEN	OPEN	PRODUCING
Thoresby	OPEN	OPEN	OPEN	OPEN	OPEN	PRODUCING
Welbeck	OPEN	OPEN	OPEN	OPEN	OPEN	CLOSED
Hatfield	DEVELOPING	OPEN	OPEN	OPEN	OPEN	PRODUCING
Rossington	MOTHBALLED	CLOSED	CLOSED	CLOSED	CLOSED	SEALED
Selby Complex	CLOSED	CLOSED	CLOSED	CLOSED	CLOSED	SEALED
Silverdale	CLOSED	CLOSED	CLOSED	CLOSED	CLOSED	SEALED
Ellington	CLOSED	CLOSED	CLOSED	CLOSED	CLOSED	SEALED

(Source: 2006 – 2010 DUKES Table 2.10 - The Coal Authority, 2011 Expired Licence / Agreements March 2011 – The Coal Authority). Mothballed refers to a mine that is temporarily closed and is indicated to reopen in the future. Closed mines are those which are permanently not in operation with open vents to the surface. Sealed mines are closed mines which are permanently not in operation and which have their vents sealed. Developing mines are those which are mine areas due to be opened for coal extraction. Open mines are those which are operational and producing coal. Producing refers to a mine that is currently producing CBM.

Table 3: Status of UK's Medium/Small Deep Coal Mines from 2006 – 2011

Mine/Site	2006	2007	2008	2009	2010 (Dec'09)	2011* (March)
Blaentillery N.2	OPEN	OPEN	OPEN	OPEN	OPEN	MOTHBALLED
Eckington	OPEN	OPEN	OPEN	OPEN	OPEN	PRODUCING
Hay Royds	OPEN	OPEN	OPEN	OPEN	OPEN	PRODUCING
Nant Hir No.2	OPEN	OPEN	OPEN	OPEN	OPEN	MOTHBALLED
Aberpergwm	DEVELOPING	DEVELOPING	PROD/DEV	OPEN	OPEN	PRODUCING
Unity Mine Ltd		DEVELOPING	DEVELOPING	DEVELOPING	DEVELOPING	PRODUCING
Black Barn		PROD/DEV	OPEN	CLOSED	CLOSED	CLOSED
Cannop Drift		PROD/DEV	OPEN	OPEN	OPEN	CLOSED
Gleison		DEVELOPING	DEVELOPING	DEVELOPING	DEVELOPING	DEVELOPING
Hill Top		PROD/DEV	CLOSED	CLOSED	CLOSED	CLOSED
Monument		PROD/DEV	OPEN	OPEN	OPEN	PRODUCING
Ayle				DEVELOPING	DEVELOPING	DEVELOPING
Johnson				DEVELOPING	DEVELOPING	PRODUCING

(Source: 2006 – 2010 DUKES Table 2.10 - The Coal Authority, 2011 Expired Licence / Agreements March 2011 – The Coal Authority)

Table A2 lists all UK major deep mines that have operated since 2005; locations and relevant zoning required for inclusion in this study have been displayed in Figures A1 – A4.

Figure A1 - North East England Coalfield Zones (OS Grid Reference NZ278919)

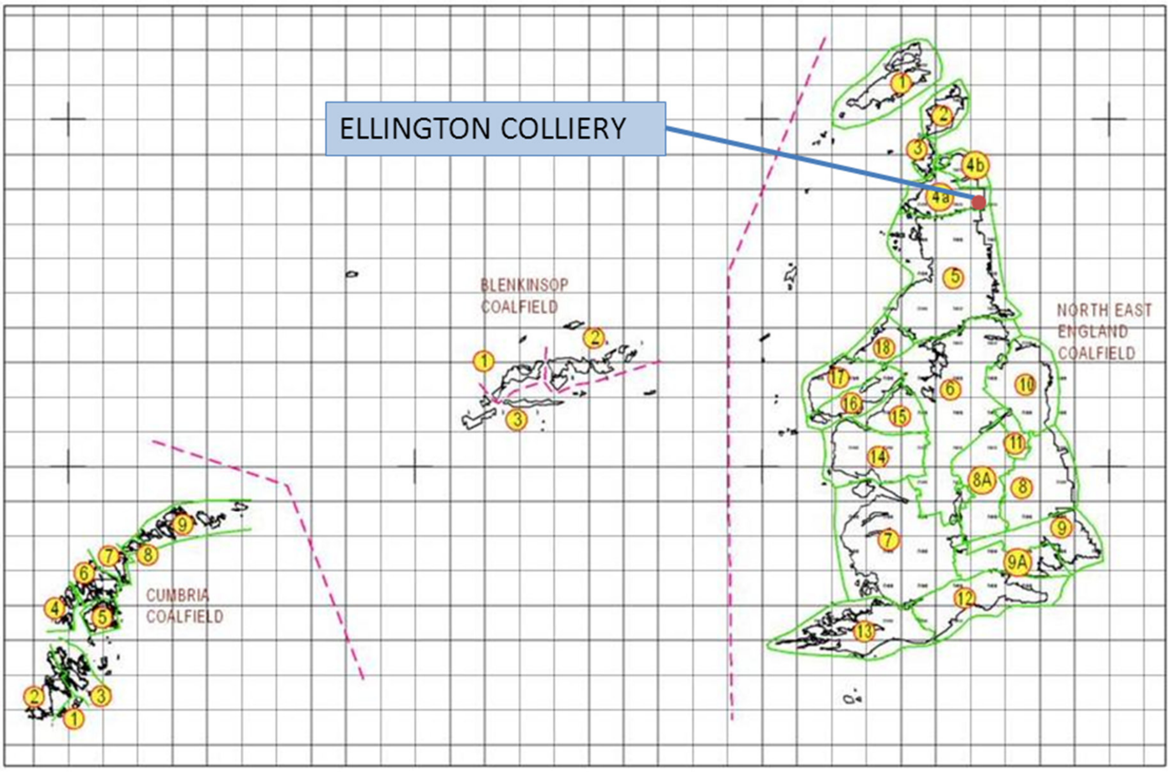


Figure A2 - Yorkshire, Nottinghamshire and North Staffordshire Coalfield Zones (OS Grid Reference SK5292)

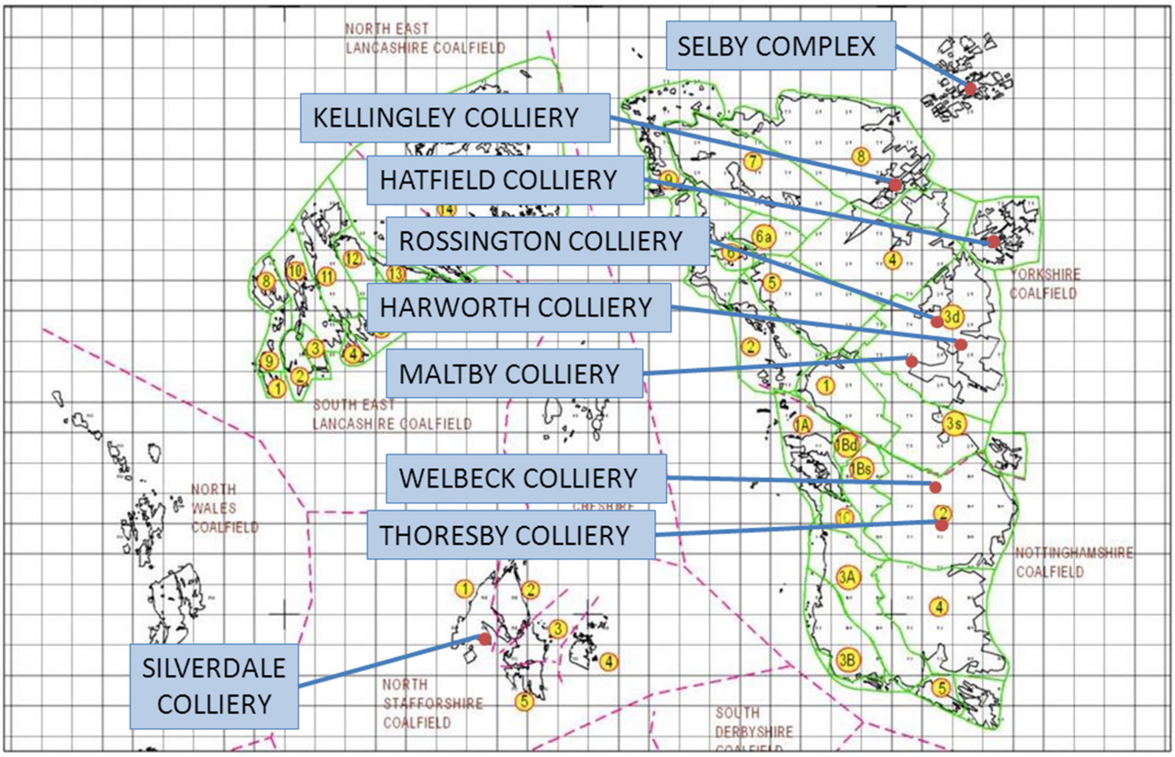


Figure A3 - Warwickshire Coalfield Zones (OS Grid Reference SP361918)

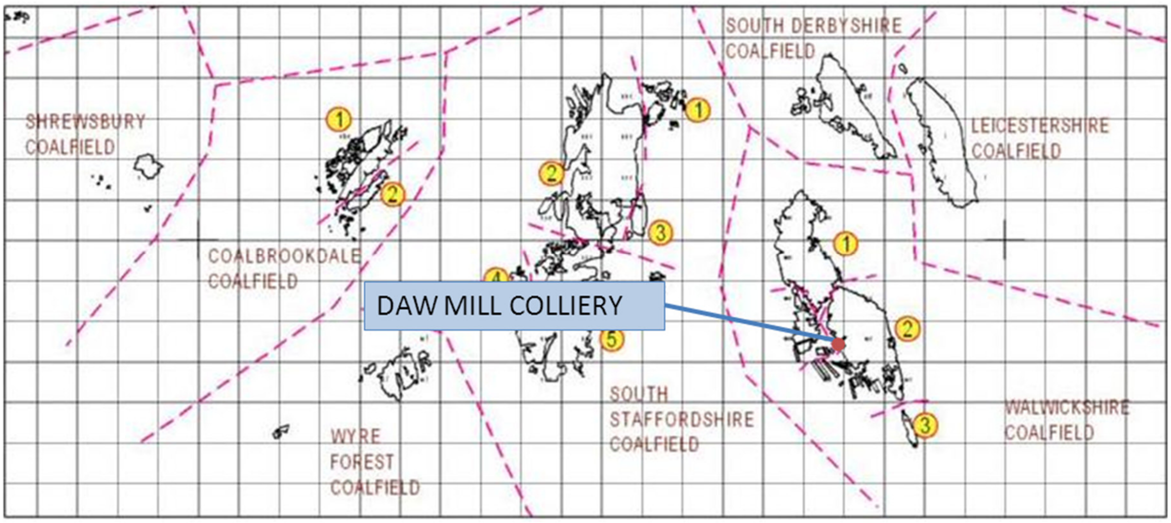
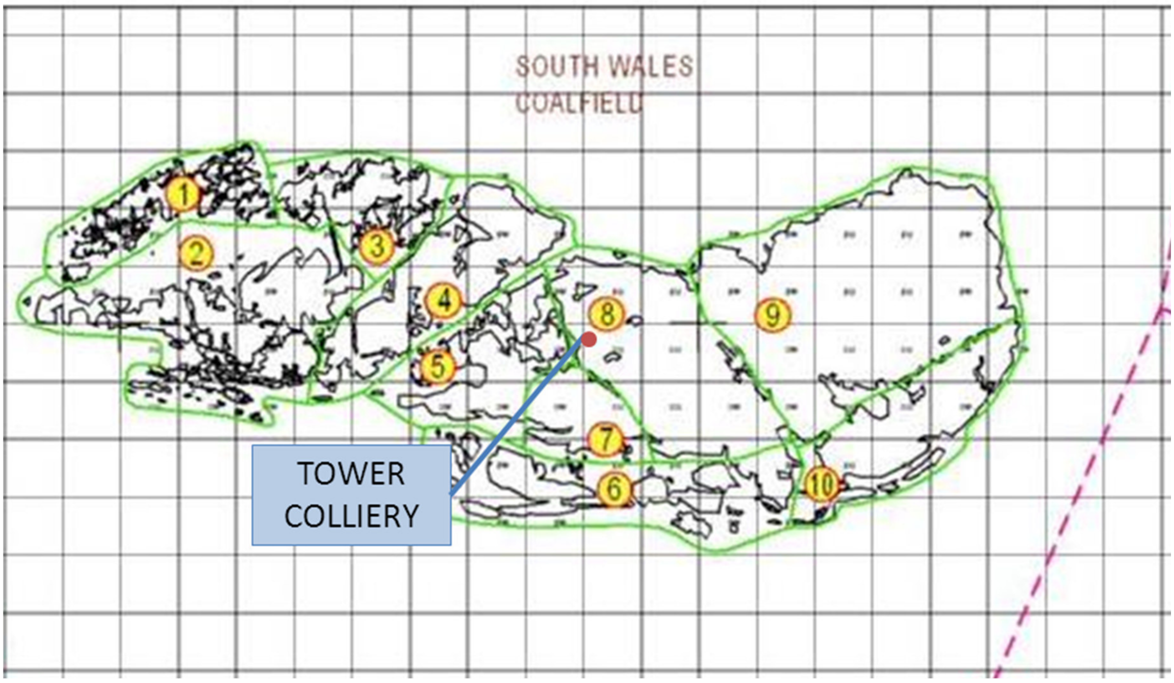


Figure A4 - South Wales Coalfield Zones (OS Grid Reference SN 926 031)



As listed in Table A2 there are, as of 2011, 5 major deep mines producing in the UK. To determine the predicted methane emissions from these collieries it is important to understand their expected date of closure. Expected closure dates for each operating major deep mine has been obtained from the relevant operator. Table A4 below lists these mines, locations and expected dates of closure. These closure dates are consistent with UK energy projections for coal demand, indicating a gradual decline in consumption to 2050 and reflecting the lifetime of economically extractable coal reserves at the remaining UK deep mines.

Table A4 - Location and expected date of closure for large deep mines currently producing in the UK (UK Coal 2010)

Mine/Site	Coalfield	Zone	Expected date of closure
Maltby	Yorkshire	3d	2014
Daw Mill	Warwickshire	2	2028
Kellingley	Yorkshire	8	2019
Thoresby	Nottinghamshire	2	2017
Hatfield*	Yorkshire	4	Not known

* Hatfield Colliery is currently in administration, as such, the expected date of closure is not known.

7.3 CLOSURE OF UK SURFACE COAL MINES POST-2005

The available data on UK surface mines that have closed or are due to close post-2005 was reviewed. The table below summarises the current status of UK surface mines. This data was used to update the estimates of surface mine methane emissions in combination with projections for UK coal demand to 2050.

Table A5: Status of UK's Opencast Coal Mines from 2006 – 2011

Mine/Site	2006	2007	2008	2009	2010 (Dec'09)
Skares Road	OPEN	OPEN	OPEN	OPEN	OPEN
Skares Road Ext	OPEN	CLOSED	CLOSED	CLOSED	CLOSED
Grievehill	OPEN	OPEN	CLOSED	OPEN	CLOSED
Garleffan	OPEN	CLOSED	CLOSED	CLOSED	CLOSED
Cwm YrOnen	OPEN	CLOSED	CLOSED	OPEN	OPEN
Margam	OPEN	OPEN	OPEN	CLOSED	CLOSED
Nant Helen	OPEN	OPEN	OPEN	OPEN	OPEN
Selar	OPEN	OPEN	OPEN	OPEN	CLOSED
DynantFawr	OPEN	OPEN	OPEN	CLOSED	CLOSED
Polkemmet	OPEN	OPEN	CLOSED	CLOSED	CLOSED
Nant Melyn	OPEN	CLOSED	CLOSED	CLOSED	CLOSED
Nant-y-Mynydd	OPEN	OPEN	OPEN	OPEN	OPEN
Kingslaw	OPEN	CLOSED	CLOSED	CLOSED	CLOSED
Bankrigg	OPEN	CLOSED	CLOSED	CLOSED	CLOSED
Delhi	OPEN	OPEN	OPEN	CLOSED	CLOSED
Fox Covert	OPEN	OPEN	CLOSED	CLOSED	CLOSED
Albion Ext	OPEN	CLOSED	CLOSED	CLOSED	CLOSED
Earlseat	OPEN	OPEN	OPEN	CLOSED	CLOSED
Begg Farm	OPEN	CLOSED	CLOSED	CLOSED	CLOSED
Rosebank	OPEN	OPEN	CLOSED	CLOSED	CLOSED
Greenburn Project	OPEN	OPEN	OPEN	OPEN	OPEN
BwlchFfos	OPEN	OPEN	CLOSED	CLOSED	CLOSED
Caughley	OPEN	CLOSED	CLOSED	CLOSED	CLOSED
Broken Cross	OPEN	OPEN	CLOSED	OPEN	OPEN
Chalmerston	OPEN	OPEN	OPEN	OPEN	OPEN
Chalmerston North	OPEN	CLOSED	CLOSED	CLOSED	CLOSED

Mine/Site	2006	2007	2008	2009	2010 (Dec'09)
Glentaggart	OPEN	OPEN	OPEN	OPEN	OPEN
Greenbank	OPEN	OPEN	OPEN	OPEN	OPEN
House of Water	OPEN	MOTHBALLED	OPEN	OPEN	OPEN
Newbigging Farm	OPEN	OPEN	CLOSED	CLOSED	CLOSED
Powharnal	OPEN	OPEN	OPEN	OPEN	OPEN
Spireslack	OPEN	MOTHBALLED	OPEN	OPEN	OPEN
Roundwood	OPEN	CLOSED	CLOSED	CLOSED	CLOSED
BarughBridge	OPEN	CLOSED	CLOSED	CLOSED	CLOSED
Maidens Hall Ext	OPEN	OPEN	OPEN	CLOSED	CLOSED
Glenmuckloch		OPEN	OPEN	OPEN	OPEN
Wilson Town		OPEN	OPEN	OPEN	OPEN
TempleQuarry		OPEN	CLOSED	OPEN	CLOSED
Corporal Lane Quarry		OPEN	CLOSED	OPEN	CLOSED
Chapelhill		OPEN	OPEN	OPEN	OPEN
Stobswood		OPEN	OPEN	CLOSED	CLOSED
Stony Heap		OPEN	CLOSED	CLOSED	CLOSED
Leigh Glenmuir			OPEN	OPEN	CLOSED
East Pit			OPEN	OPEN	OPEN
Ffos-y-Fran			OPEN	OPEN	OPEN
Thorton Wood			OPEN	OPEN	CLOSED
Shewington			OPEN	OPEN	OPEN
Cutacre			OPEN	OPEN	OPEN
Long Moor			OPEN	OPEN	OPEN
Steadsburn			OPEN	OPEN	OPEN
Muir Dean				OPEN	OPEN
Shotton				OPEN	OPEN
Engine				OPEN	OPEN
Dalquhandy Res				OPEN	CLOSED
Poniel				OPEN	CLOSED
Lodge House				OPEN	OPEN
Former Biwater Works					OPEN

(Source: 2006 – 2010 DUKES Table 2.11 - The Coal Authority)

(1) Global Methane Initiative – UK CMM Country Profiles (p 281)

8 APPENDIX B – TABLE OF UPDATED AMM EMISSIONS ESTIMATES

The data presented below is obtained from the accompanying model “WSP-DECC UK CH4 Emissions Abandoned Coal Mines.xlsx”.

Table B1 - Abandoned UK Coal Mine Methane Emissions Estimates 1990-2050

AMM Emissions (ktCH_4)	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Cumulative Number of Mine Areas Closed	**121**	**121**	**126**	**130**	**130**	**132**	**134**	**136**	**137**	**137**
Deep Mine Methane Emissions Estimates	**52.8**	**58.3**	**85.3**	**103.7**	**93.3**	**97.7**	**84.6**	**89.2**	**77.5**	**71.6**
Uncertainty	±8.5	±8.9	±16.7	±18.7	±16.5	±16.1	±14.6	±15.3	±12.6	±11.6
England	28.0	27.7	57.5	76.1	67.4	72.4	59.3	65.7	57.1	51.8
Uncertainty	±5.5	±5.3	±15.5	±17.5	±15.4	±15.0	±13.5	±14.3	±11.7	±10.8
Scotland	4.5	3.9	3.7	3.7	3.6	3.6	3.5	3.5	2.9	3.2
Uncertainty	±1.1	±1.0	±1.0	±1.0	±0.9	±0.9	±0.9	±0.9	±0.6	±0.8
Wales	20.4	26.6	24.1	23.9	22.3	21.7	21.7	20.0	17.5	16.6
Uncertainty	±6.4	±7.1	±6.3	±6.3	±5.8	±5.7	±5.7	±5.3	±4.5	±4.2
Open Cast Mine Methane Emissions Estimates	**3.1**	**3.2**	**3.1**	**2.9**	**2.9**	**2.8**	**2.8**	**2.8**	**2.4**	**2.6**
Uncertainty	±0.6	±0.6	±0.6	±0.6	±0.6	±0.6	±0.6	±0.6	±0.5	±0.5
Total All Mines Methane Emissions Estimates	**55.9**	**61.4**	**88.4**	**106.6**	**96.2**	**100.4**	**87.3**	**92.0**	**80.0**	**74.2**
Uncertainty	±8.5	±8.9	±16.7	±18.7	±16.5	±16.1	±14.7	±15.3	±12.6	±11.7
Methane Utilisation	**-4.7**	**-4.7**	**-4.7**	**-4.7**	**-4.7**	**-4.7**	**-4.7**	**-4.7**	**-4.7**	**-9.4**
Uncertainty	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.5
% Methane Utilised (UK)	0.1	0.1	0.1	0.0	0.1	0.0	0.1	0.1	0.1	0.1
England	-4.7	-4.7	-4.7	-4.7	-4.7	-4.7	-4.7	-4.7	-4.7	-9.4
Uncertainty	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.5
Scotland	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wales	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Net Methane Emissions	**51.2**	**56.7**	**83.7**	**101.9**	**91.4**	**95.7**	**82.6**	**87.3**	**75.2**	**64.8**
Uncertainty	**±8.5**	**±8.9**	**±16.7**	**±18.7**	**±16.5**	**±16.1**	**±14.7**	**±15.3**	**±12.6**	**±11.7**

AMM Emissions (ktCH_4)	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Cumulative Number of Mine Areas Closed	**138**	**138**	**138**	**140**	**142**	**144**	**146**	**146**	**147**	**147**
Deep Mine Methane Emissions Estimates	**70.0**	**59.9**	**58.8**	**54.9**	**47.1**	**49.9**	**56.8**	**53.0**	**51.8**	**47.8**
Uncertainty	±11.5	±9.7	±9.6	±9.3	±7.2	±7.4	±8.0	±7.3	±7.0	±6.3
England	51.2	43.6	42.6	39.3	33.1	36.6	44.0	40.3	39.5	35.6
Uncertainty	±10.7	±9.0	±9.0	±8.6	±6.5	±6.8	±7.5	±6.8	±6.6	±5.8
Scotland	2.9	2.7	2.7	2.7	2.7	2.7	2.7	2.6	2.6	2.6
Uncertainty	±0.6	±0.6	±0.6	±0.6	±0.6	±0.6	±0.6	±0.6	±0.6	±0.5
Wales	15.9	13.6	13.4	12.9	11.3	10.7	10.1	10.1	9.7	9.6
Uncertainty	±4.1	±3.5	±3.5	±3.5	±3.1	±2.8	±2.6	±2.6	±2.5	±2.5
Open Cast Mine Methane Emissions Estimates	**2.3**	**2.4**	**2.2**	**2.1**	**2.0**	**1.8**	**1.5**	**1.5**	**1.6**	**1.6**
Uncertainty	±0.5	±0.5	±0.4	±0.4	±0.4	±0.4	±0.3	±0.3	±0.3	±0.3
Total All Mines Methane Emissions Estimates	**72.3**	**62.3**	**61.0**	**57.0**	**49.2**	**51.7**	**58.3**	**54.5**	**53.4**	**49.4**
Uncertainty	±11.5	±9.7	±9.7	±9.3	±7.2	±7.4	±8.0	±7.3	±7.0	±6.3
Methane Utilisation	**-14.1**	**- 18.9**	**- 23.6**	**- 31.0**	**- 31.0**	**- 31.0**	**- 31.0**	**- 31.0**	**- 31.0**	**- 32.1**
Uncertainty	±0.8	±1.0	±1.3	±1.6	±1.6	±1.6	±1.6	±1.6	±1.6	±1.7
% Methane Utilised (UK)	0.2	0.3	0.4	0.6	0.7	0.6	0.5	0.6	0.6	0.7
England	-14.1	- 18.9	- 23.6	- 31.0	- 31.0	- 31.0	- 31.0	- 31.0	- 31.0	- 32.1
Uncertainty	±0.8	±1.0	±1.3	±1.6	±1.6	±1.6	±1.6	±1.6	±1.6	±1.7
Scotland	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wales	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Net Methane Emissions	**58.2**	**43.5**	**37.4**	**26.0**	**18.2**	**20.7**	**27.3**	**23.5**	**22.4**	**17.3**
Uncertainty	**±11.5**	**±9.8**	**±9.7**	**±9.4**	**±7.4**	**±7.6**	**±8.1**	**±7.4**	**±7.2**	**±6.5**

AMM Emissions ($ktCH_4$)	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
Cumulative Number of Mine Areas Closed	**148**	**148**	**148**	**148**	**149**	**149**	**149**	**150**	**150**	**151**	**152**	**152**	**152**	**152**	**152**	**152**	**152**	**152**	**153**	**153**
Deep Mine Methane Emissions Estimates	**48.9**	**45.4**	**43.6**	**41.9**	**41.5**	**40.0**	**38.3**	**39.3**	**37.8**	**38.1**	**40.0**	**39.0**	**37.8**	**36.6**	**35.8**	**34.9**	**34.3**	**33.6**	**32.8**	**32.1**
Uncertainty	±6.3	±5.8	±5.6	±5.3	±5.1	±4.9	±4.7	±4.7	±4.5	±4.5	±4.6	±4.5	±4.4	±4.3	±4.2	±4.1	±4.0	±4.0	±3.9	±3.8
England	36.7	33.6	31.9	30.3	30.2	28.8	27.1	28.3	27.2	27.5	29.5	28.6	27.5	26.5	25.7	24.9	24.3	23.7	23.2	22.6
Uncertainty	±5.8	±5.2	±5.1	±4.7	±4.5	±4.3	±4.0	±4.1	±3.9	±3.8	±4.0	±3.9	±3.8	±3.7	±3.6	±3.5	±3.4	±3.4	±3.3	±3.2
Scotland	2.6	2.6	2.5	2.5	2.5	2.5	2.5	2.4	2.4	2.4	2.4	2.4	2.4	2.3	2.3	2.3	2.3	2.3	2.2	2.2
Uncertainty	±0.5	±0.5	±0.5	±0.5	±0.5	±0.5	±0.5	±0.5	±0.5	±0.5	±0.5	±0.5	±0.5	±0.5	±0.5	±0.5	±0.5	±0.5	±0.5	±0.5
Wales	9.5	9.2	9.1	9.1	8.8	8.7	8.7	8.6	8.2	8.2	8.1	8.1	8.0	7.8	7.8	7.7	7.7	7.6	7.3	7.3
Uncertainty	±2.5	±2.4	±2.4	±2.4	±2.3	±2.3	±2.3	±2.3	±2.2	±2.2	±2.2	±2.2	±2.2	±2.1	±2.1	±2.1	±2.1	±2.1	±2.0	±2.0
Open Cast Mine Methane Emissions Estimates	**1.6**	**1.6**	**1.6**	**1.6**	**1.6**	**1.6**	**1.6**	**1.6**	**1.6**	**1.6**	**1.6**	**1.6**	**1.6**	**1.6**	**1.6**	**1.6**	**1.6**	**1.6**	**1.6**	**1.6**
Uncertainty	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3
Total All Mines Methane Emissions Estimates	**50.5**	**47.0**	**45.2**	**43.5**	**43.1**	**41.6**	**39.9**	**41.0**	**39.4**	**39.7**	**41.6**	**40.7**	**39.4**	**38.3**	**37.4**	**36.5**	**35.9**	**35.2**	**34.4**	**33.8**
Uncertainty	±6.3	±5.8	±5.6	±5.3	±5.1	±4.9	±4.7	±4.7	±4.5	±4.5	±4.6	±4.5	±4.4	±4.3	±4.2	±4.1	±4.0	±4.0	±3.9	±3.9
Methane Utilisation	**-33.0**	**-28.5**	**-27.1**	**-25.7**	**-25.6**	**-24.4**	**-23.0**	**-24.0**	**-23.0**	**-23.4**	**-25.0**	**-24.3**	**-23.3**	**-22.4**	**-21.8**	**-21.1**	**-20.6**	**-20.1**	**-19.7**	**-19.2**
Uncertainty	±1.8	±1.5	±1.4	±1.4	±1.4	±1.3	±1.2	±1.3	±1.2	±1.2	±1.3	±1.3	±1.2	±1.2	±1.2	±1.1	±1.1	±1.1	±1.0	±1.0
% Methane Utilised (UK)	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
England	-33.0	-28.5	-27.1	-25.7	-25.6	-24.4	-23.0	-24.0	-23.0	-23.4	-25.0	-24.3	-23.3	-22.4	-21.8	-21.1	-20.6	-20.1	-19.7	-19.2
Uncertainty	±1.8	±1.5	±1.4	±1.4	±1.4	±1.3	±1.2	±1.3	±1.2	±1.2	±1.3	±1.3	±1.2	±1.2	±1.2	±1.1	±1.1	±1.1	±1.0	±1.0
Scotland	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wales	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Net Methane Emissions	**17.5**	**18.5**	**18.1**	**17.8**	**17.5**	**17.2**	**16.9**	**17.0**	**16.4**	**16.4**	**16.6**	**16.4**	**16.2**	**15.8**	**15.6**	**15.4**	**15.3**	**15.1**	**14.7**	**14.6**
Uncertainty	**±6.5**	**±6.0**	**±5.8**	**±5.5**	**±5.3**	**±5.1**	**±4.8**	**±4.9**	**±4.7**	**±4.6**	**±4.8**	**±4.7**	**±4.6**	**±4.4**	**±4.4**	**±4.3**	**±4.2**	**±4.1**	**±4.1**	**±4.0**

AMM Emissions ($ktCH_4$)	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Cumulative Number of Mine Areas Closed	**153**	**153**	**153**	**153**	**153**	**153**	**153**	**153**	**153**	**153**	**153**	**153**	**153**	**153**	**153**	**153**	**153**	**153**	**153**	**153**	**153**
Deep Mine Methane Emissions Estimates	**31.0**	**30.4**	**29.8**	**29.1**	**28.5**	**27.9**	**27.5**	**27.0**	**26.6**	**26.2**	**25.7**	**25.4**	**25.0**	**24.7**	**24.4**	**24.1**	**23.8**	**23.5**	**23.3**	**23.0**	**22.7**
Uncertainty	±3.8	±3.7	±3.6	±3.6	±3.5	±3.5	±3.4	±3.4	±3.3	±3.3	±3.2	±3.2	±3.2	±3.1	±3.1	±3.1	±3.0	±3.0	±3.0	±2.9	±2.9
England	21.6	21.1	20.5	20.0	19.5	19.0	18.6	18.2	17.9	17.5	17.1	16.8	16.5	16.3	16.0	15.8	15.6	15.4	15.2	14.9	14.7
Uncertainty	±3.2	±3.1	±3.0	±3.0	±2.9	±2.8	±2.8	±2.8	±2.7	±2.7	±2.6	±2.6	±2.5	±2.5	±2.5	±2.4	±2.4	±2.4	±2.3	±2.3	±2.3
Scotland	2.2	2.2	2.2	2.2	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.9	1.9	1.9
Uncertainty	±0.5	±0.5	±0.5	±0.5	±0.5	±0.5	±0.4	±0.4	±0.4	±0.4	±0.4	±0.4	±0.4	±0.4	±0.4	±0.4	±0.4	±0.4	±0.4	±0.4	±0.4
Wales	7.1	7.1	7.0	6.9	6.9	6.8	6.8	6.7	6.7	6.6	6.6	6.5	6.5	6.4	6.4	6.3	6.3	6.2	6.2	6.1	6.1
Uncertainty	±2.0	±2.0	±2.0	±2.0	±1.9	±1.9	±1.9	±1.9	±1.9	±1.9	±1.9	±1.8	±1.8	±1.8	±1.8	±1.8	±1.8	±1.8	±1.8	±1.7	±1.7
Open Cast Mine Methane Emissions Estimates	**1.6**	**1.6**	**1.6**	**1.6**	**1.6**	**1.6**	**1.6**	**1.6**	**1.6**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.4**	**1.4**	**1.4**	**1.4**	**1.4**
Uncertainty	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3	±0.3
Total All Mines Methane Emissions Estimates	**32.6**	**32.0**	**31.4**	**30.7**	**30.1**	**29.5**	**29.0**	**28.6**	**28.2**	**27.7**	**27.3**	**26.9**	**26.5**	**26.2**	**25.9**	**25.6**	**25.3**	**25.0**	**24.7**	**24.4**	**24.1**
Uncertainty	±3.8	±3.7	±3.7	±3.6	±3.5	±3.5	±3.4	±3.4	±3.3	±3.3	±3.3	±3.2	±3.2	±3.1	±3.1	±3.1	±3.0	±3.0	±3.0	±2.9	±2.9
Methane Utilisation	**-18.3**	**-17.9**	**-17.4**	**-17.0**	**-16.6**	**-16.1**	**-15.8**	**-15.5**	**-15.1**	**-14.8**	**-14.5**	**-14.3**	**-14.0**	**-13.8**	**-13.6**	**-13.4**	**-13.2**	**-13.0**	**-12.8**	**-12.7**	**-12.5**
Uncertainty	±1.0	±0.9	±0.9	±0.9	±0.9	±0.9	±0.8	±0.8	±0.8	±0.8	±0.8	±0.8	±0.7	±0.7	±0.7	±0.7	±0.7	±0.7	±0.7	±0.7	±0.7
% Methane Utilised (UK)	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.5
England	-18.3	-17.9	-17.4	-17.0	-16.6	-16.1	-15.8	-15.5	-15.1	-14.8	-14.5	-14.3	-14.0	-13.8	-13.6	-13.4	-13.2	-13.0	-12.8	-12.7	-12.5
Uncertainty	±1.0	±0.9	±0.9	±0.9	±0.9	±0.9	±0.8	±0.8	±0.8	±0.8	±0.8	±0.8	±0.7	±0.7	±0.7	±0.7	±0.7	±0.7	±0.7	±0.7	±0.7
Scotland	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wales	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Net Methane Emissions	**14.3**	**14.1**	**14.0**	**13.7**	**13.6**	**13.4**	**13.3**	**13.1**	**13.0**	**12.9**	**12.8**	**12.6**	**12.5**	**12.4**	**12.3**	**12.2**	**12.1**	**11.9**	**11.8**	**11.7**	**11.6**
Uncertainty	**±3.9**	**±3.8**	**±3.8**	**±3.7**	**±3.6**	**±3.6**	**±3.5**	**±3.5**	**±3.4**	**±3.4**	**±3.3**	**±3.3**	**±3.3**	**±3.2**	**±3.2**	**±3.2**	**±3.1**	**±3.1**	**±3.0**	**±3.0**	**±3.0**