Carbon sequestration potential of the South Wales Coalfield

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Abstract

This paper presents a preliminary evaluation of the carbon dioxide storage capacity of the unmined coal resources in the South Wales Coalfield, UK. Although a significant amount of the remaining coal may be mineable via traditional techniques, the prospects for opening new mines appear poor. In addition, many of the South Wales coal seams are lying unused since they are too deep to be mined economically using conventional methods. There is instead a growing worldwide interest in the potential for releasing the energy value of such coal reserves via alternative technologies, for example through carbon sequestration with enhanced coalbed methane recovery. In this study, Geographical Information Systems and three-dimensional interpolation are used to obtain the total unmined coal resource below 500 m deep, where the candidate seams for carbon sequestration are found. The 'proved', 'probable' and 'possible' carbon dioxide storage capacities of the South Wales Coalfield are then obtained using an established methodology. Input parameters are based upon statistical distributions, considering a combination of laboratory coal characterisation results and literature review. The results are a proved capacity of 70.1 $MtCO_2$, a probable capacity of 104.9 $MtCO_2$, and a possible capacity of 152.0 $MtCO_2$.

Keywords: energy, government, statistical analysis

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Notation list

C_f	Completion factor
$EGIP$	Effective gas in place
E_r	Exchange ratio
G_{CH_4}	In situ CH_4 content expressed in cubic meters per tonne of coal
M_{CO_2}	Effective CO_2 storage capacity
R_f	Recovery factor
W_c	Total unmined coal tonnage
ρ_{CO_2}	Density of CO2 at standard pressure and temperature
CCS	Carbon capture and sequestration
ECBM	Enhanced coalbed methane
kW	kilo Watt
m	meter
Mt	Million tonnes
MW	Mega Watt
OD	Ordnance Datum
SDSS	Spatial decision support system
t	tonne

1. Introduction

A great challenge facing the UK is to reduce greenhouse gas emissions whilst meeting potential increases in energy demand (DECC, 2014a). In the coming years, this challenge will be underlined by the need to meet the Kyoto protocol and the planned closure of a number of large power stations. In 2012, UK carbon dioxide (CO_2) emissions were 474.1 million tonnes carbon dioxide ($MtCO_2$) (DECC, 2014b), a 19.8% decrease compared to 1990 levels. This has been attributed to increases in energy efficiency and the transition from coal to less carbon intensive fuels, most notably natural gas (DECC, 2014b). Implementation of the Large Combustion Plant Directive (LCPD) is currently resulting in the closure of coal fired plants in the UK amounting to one third of the nation's coal power generating capacity. In addition, the UK is moving away from being self-sufficient in oil and gas as production from the North Sea declines (Great Britain Parliament, House of Lords, 2014). This is illustrated by the fact that the UK has been a net importer of energy since 2005 (DECC, 2012).

An increase in the exploration of unconventional gas, for example shale gas and coalbed methane (CBM), has the potential to curb the UK's increasing dependence on energy imports. As the cleanest burning fossil fuel, a shift towards natural gas would also have positive implications for carbon dioxide emissions (IEA, 2011). However, the International Energy Agency (IEA) (2011) predicts that the increased exploration of unconventional gas must be accompanied by carbon capture and sequestration (CCS), if a significant advance towards emissions targets is to be achieved.

CCS is an emerging technology intended to avoid the atmospheric emission of carbon dioxide. A carbon sequestration scheme involves three distinct stages: a) CO_2 capture at point sources; b) transportation; and c) geological sequestration by injecting into a suitable deep rock formation (IPCC, 2005). Of greatest interest for carbon sequestration are deep saline aquifers, depleted oil and gas reservoirs, and unmineable coalbeds. The focus for carbon sequestration in the UK is undoubtedly on the oil and gas reservoirs and saline aquifers of the North Sea basins, where the majority of the estimated 22.395 $GtCO_2$ storage capacity exists (Holloway et al., 2005). However, the carbon footprint and cost implications of transporting CO_2 emitted in Wales to future North Sea storage sites are most likely prohibitive. An alternative option for Wales is to implement carbon sequestration in deep lying coalbeds. This is particularly true in the South Wales Coalfield where the remaining coal reserves are significant with a generally poor potential to be mined in the future. In addition, the South Wales Coalfield is in close proximity to the biggest point source emitters of CO_2 in Wales, namely, the Port Talbot steel works (c. 6.6 $MtCO_2$/year) and Aberthaw power station (c. 4.8 $MtCO_2$/year) (NAW, 2013).

Carbon sequestration in coal has the added benefit of enhancing CBM recovery for electricity generation, and the resulting CO_2 can be sequestered back into the targeted coalbed. This process is called enhanced coalbed methane (ECBM) recovery. The amount of the CO_2 that can be held in a coalbed depends on the reservoir conditions, i.e. the reservoir pressure and temperature, and the petrographic characteristics of the coal. Ideally, targeted coal seams should be located deep enough to ensure sufficient reservoir pressure as this is a key control on the amount of gas adsorbed on the coal. On the other hand, the permeability of the coals decreases with increasing depth. According to Laenen and Hildenbrand (2005), the optimal depth window for effective CO_2-ECBM is situated between 300 and 1500 m. At greater depths, the permeability of the coalbeds can become critically low and considerably more engineering input is needed to initiate and sustain the gas injection.

The aim of this study is to evaluate the CO_2 storage potential of the deep-lying coal seams of the South Wales Coalfield. Only coal seams lying at depths greater than 500 m are considered as candidate seams for carbon sequestration. Geographical Information Systems (GIS) software, combined with mine workings legacy data and three-dimensional interpolation, is used to obtain the unmined coal resource at depths greater than 500 m. A preliminary evaluation of the CO_2 storage capacity of the South Wales Coalfield is completed based on the methodology used by Hamelinck et al. (2001) and Fang and Li (2014) for similar studies conducted in the Netherlands and China, respectively.

To consider the range of reservoir conditions found across the Coalfield, the key input parameters are defined as statistical distributions based on a combination of laboratory coal characterisation results and literature review. A Monte Carlo simulation is then performed to obtain a statistical distribution for the effective CO_2 storage capacity of the Coalfield. The resulting P10, P50 and P90 percentiles are defined as the ‘proved’, ‘possible’ and ‘probable’ capacities, respectively. In other words, the proved capacity is that which will be exceeded with a confidence of 90%, whereas the possible capacity will be exceeded with a confidence of 10%. The probable capacity is regarded the most likely scenario.

As part of the methodology, the total CBM resource is also evaluated. This is important because the injected CO_2 preferentially displaces the in situ methane (CH_4) due to its greater affinity for adsorbing on coal. The recovery of the displaced CH_4 provides a stream of unconventional gas for electricity generation, with recovery rates approaching 100% compared to 50 % by reservoir pressure depletion alone (Stevens et al., 1996). Thus, the combination of carbon sequestration and CBM recovery has the potential to deliver low or even zero carbon energy.

The results of this study are presented in terms of the estimated carbon dioxide storage capacity and the energy potential (i.e. size and lifespan of a 500 MW power station) that can be achieved via CBM recovery. This reflects the close technical and economic relationship between these technologies. The estimated carbon storage capacity is compared with the emissions of the large point source emitters located in the region, thereby providing a valuable insight into the potential for implementing carbon sequestration.

2. Geology of the South Wales Coalfield

The South Wales Coalfield is an erosional remnant of a once extensive area of Carboniferous geology which extended from Pembrokeshire in the west to the Forest of Dean in the east (Gayer et al., 1996). There are three separate Coalfields, namely, the Pembrokeshire, the South Wales and the Forest of Dean across the English border. In the context of South Wales, the Pembrokeshire Coalfield is small and comprised of highly contorted and difficult to mine anthracitic coal seams. The main South Wales Coalfield extends from Kidwelly in the west to Pontypool in the east, and from Taff's Well in the south to Merthyr in the north, a roughly rectangular area some 90 miles by 25 miles in extent. Large variations in the depth of the coal seams exist over this area. In the east, the deepest seams do not reach depths greater than 60 m below ordnance datum (OD), whereas in the west (near Gorseinon) they are found at much greater depths exceeding 1,800 m below OD (Adams, 1967).

Figure 1**Error! Reference source not found.** shows a generalised vertical section of the Westphalian phase rocks which form the Upper, Middle and Lower Coal Measures in the South Wales Coalfield (Barclay, 1989). The maximum thickness of the Upper Coal Measures is in the region of 180 m, southwest of Ammanford in the north-west. In order from the shallowest to deepest seams, the Upper Coal Measures consist of seams such as the Mynyddislwyn, Cefn Glas, Brithdir, No. 1 Rhondda (Rider and Group), and No. 2 Rhondda, with an average minimum thickness of 0.6 m and an average maximum thickness of 1.2 m (Barclay, 1989). The Middle Coal Measures range from 120 m thick in the eastern outcrop to 240 m thick in the Swansea area, and consist of seams such as the Gorllwyn Rider, Two Feet Nine, Four Feet, Six Feet, Red Vein, Nine Feet (Upper and Lower) and Bute. These seams have an average minimum thickness of 0.2 m and an average maximum thickness of 0.9 m. Finally, the Lower Coal Measures are 80 m thick in the eastern outcrop and 300 m thick in the Swansea area, with coal seams such as the Yard, Seven Feet, Five Feet Gellideg and Garw providing an average minimum thickness of 0.4 m and an average maximum thickness of 2.4 m.

A complex feature of the South Wales Coalfield is the range of coal ranks present. As illustrated in Figure 2**Error! Reference source not found.**, the coal rank varies from high volatile bituminous coals in the southern and eastern outcrops to anthracite coals in the north-western part of the Coalfield (Gayer et al., 1997). Moreover, the Lower Coal Measures can be seen to have more anthracitic coal seams compared to the Middle and Upper Coal Measures.

At least 125 separate coal seams have been formerly worked, with the majority of these being the thicker seams found in the Middle and Lower Coal Measures. The main seams which achieve a thickness greater than 1.5 m are the Mynyddislwyn, No. 2 Rhondda Rider, Two Feet Nine, Four Feet, Six Feet, Red Vein, Nine Feet, Bute, Yard, Seven Feet, and Gellideg. Since the Mynyddislwyn and No. 2 Rhondda Rider are situated in the Upper Coal Measures, it is considered that they generally do not satisfy the 500 m depth constraint taken in this study as the lower limit for carbon sequestration and CBM recovery. Thus, the candidate seams considered in this work are the Two Feet Nine, Four Feet, Six Feet, Red Vein, Nine Feet, Bute, Yard, Seven Feet, Five Feet and Gellideg.

3. Mine workings legacy data

As part of the operational development of the coal mines in South Wales, detailed surveying was undertaken of all operations. The surveying of coal mines in the UK became statute law from 1850 under the Coal Mines Inspection Act. Since this date, mine records are thought to be fairly accurate, although there will be unrecorded workings from earlier mining, predominantly of the shallower seams. The Coal Authority is the custodian of the mine workings legacy data and in 2005 set about digitising the data for all of the coalfields in the UK. This is a work in progress and so the dataset is continually being updated as new data becomes available. As part of an agreement with the Coal Authority which began in February 2011, mine workings legacy data was made available to Cardiff University for the purposes of developing a digitised, three-dimensional map of the geological structure of the South Wales Coalfield. This work has allowed preliminary reserve estimates to be calculated for the unmined portion of the South Wales coal resource.

4. 3D mapping of the South Wales Coalfield

The mine workings legacy data described above were collected from the Coal Authority as Esri shapefiles (.shp) and imported into MapInfo, a Geographical Information Systems (GIS) software supplied by Pitney Bowes. The MapInfo software used to develop the three-dimensional model included the Discover and Discover 3D add-on packages, also supplied by Pitney Bowes, which have been used as part of this study. It was first necessary to convert these files into the MapInfo native format (.tab). The files were then organised according to the seam names and the digitised map was developed in 2 km by 1 km tiles according to the UK National Grid. A complex merging and splitting of the seams from the Middle and Lower Coal Measures was reflected in the mapping process. An example of this is provided in the cross section of the group of Nine Feet seams and the Bute seam shown in Figure 3**Error! Reference source not found.** (not to scale) (Adams, 1967). As a result of this complexity, the datasets were combined into seam 'packages' as appropriate, as shown in Figure **Error! Reference source not found.**4. It can be seen that the Four Feet seam was merged with the Big Vein seam, the Six Feet seam with the Red Vein, the Nine Feet with the Bute, the Seven Feet with the Yard, and the Five Feet with the Gellideg. These merges were largely dictated by the clear boundaries present in the raw mine workings legacy data.

The data for each seam were imported into a workspace and merged. It was not possible to merge the tiles automatically due to the complexity of the data and polygon shapes. Moreover, in some instances there were errors or overlaps which required the data to be manually organised to form and check the merges. After the mine working's polygons had been merged, they were checked using the check regions and clean functions to make sure no regions had been overlooked. The entire data set was then merged to create one polygon of mine workings for each worked seam. Contour plots were constructed using a similar approach with the Discover gridding function and spot height data to fill gaps in the data sets. Seam thickness data allowed three-dimensional Voxel models to be produced, which were then used to estimate the volume of coal extracted and the volume of coal remaining for each seam. Further information on the coal resource model and reserve estimates can be found in Brabham et al. (2015). As an example of the work undertaken, a contour plot showing the elevation of the Nine Feet seam is shown in Figure **Error! Reference source not found.**5. The results of the analysis suggest that the cumulative reserves for the seams considered are around 12,700 Mt coal. A breakdown of the total tonnage of coal in South Wales is shown in Table 1.

5. Methodology for evaluating the carbon sequestration capacity in coalbeds

5.1. Resource pyramid

As with any natural resource, the calculation of the volume of CO_2 which can be stored in a coalbed is based on various levels of uncertainty (Bachu et al. 2007; EASAC 2013). The resource pyramid for the assessment of the CO_2 storage capacity in geological media at the regional scale is shown in Figure 6**Error! Reference source not found.** (Bachu et al., 2007). This is based on previous works by the Carbon Sequestration Leadership Forum (2005), Holloway et al. (2005), Bachu et al. (2007), and Scottish Government (2009). The relationship between the theoretical, effective, practical and matched resource capacities are shown. At the bottom of the pyramid is the "*theoretical storage capacity*", which represents the capacity of the geological system as a whole at full utilisation. It is the most optimistic scenario since it is assumed that the injected CO_2 will occupy the entire pore space and be adsorbed at saturation in the entire coal mass. The next stage is the "*Effective Storage Capacity*", which is obtained by considering the part of the theoretical storage capacity that can be physically accessed based on a range of geological and engineering criteria (Bachu et al., 2007). At the next stage of the resource pyramid is the "*Practical Storage Capacity*". This is the part of the effective capacity obtained by considering technical, legal, social, regulatory, infrastructural and general economic barriers to geological CO_2 storage. At the apex of the pyramid is the "*Matched Storage Capacity*", which is obtained through detailed matching of large stationary CO_2 sources with geological storage sites that are adequate in terms of the capacity, injectivity, supply rate, and proximity. Moving from the bottom of the pyramid to the apex, the uncertainty for the storage capacity reduces and more effort and data are required.

5.2. Effective CO_2 storage capacity in coalbeds

The methodology used to estimate the storage capacity of the South Wales Coalfield is based on the effective storage capacity **Error! Reference source not found.**(ref. Figure 6). Comprehensive studies and techniques on gas in place estimations have been carried out by several researchers (Karacan et al. 2012; Karacan & Olea 2013) in the past. These take into account the local geology and rock properties of the area and in most cases show spatial variability in continuity and geometric anisotropy. Probabilistic studies using geostatistical method are commonly used to predict gas amounts and for assessing uncertainty (Karacan and Goodman 2011). However, for the purpose of this preliminary study, simple averaging equations have been adopted. Following similar studies conducted for coalfields in the Netherlands (Hamelinck et al., 2001) and China (Fang and Li, 2014), the methodology adopted in this work for estimating the effective regional CO_2 storage capacity is based on an analogy with the reserves estimation for CBM. The remaining coal resource in the South Wales Coalfield is therefore quantified in terms of the CO_2 storage capacity and CBM recovery potential, paving the way for a more rigorous evaluation of the practical and matched capacities in the future.

The starting point is the calculation of the total initial CH_4 gas in place, GIP_{CH_4}, given by:

$$GIP_{CH_4} = W_c G_{CH_4} \tag{1}$$

where W_c is the total unmined coal tonnage. This is obtained by multiplying a representative coal density by the volume of the unmined coal polygons produced from the three-dimensional geological mapping described in section 4. G_{CH_4} is the in situ CH_4 content expressed in cubic meters per tonne of coal at 0.101 MPa and 293.15 K.

Equation 1 gives the total theoretical CH_4 content of the Coalfield. The use of GIP_{CH_4} in evaluating the resource implies that all of the CH_4 is recoverable. This is almost certainly not the case, and so GIP_{CH_4} is converted to the effective gas in place, $EGIP_{CH_4}$, by applying engineering factors, namely, the completion factor, C_f, and the recovery factor, R_f, giving (Bachu, 2007; van Bergen et al., 2001):

$$EGIP_{CH_4} = GIP_{CH_4} \times C_f \times R_f \tag{2}$$

The factors C_f and R_f consider different restrictions on the gas storage or recovery that can be achieved in deep rock formations. C_f accounts for the influence of the wellbore and near-wellbore conditions on the gas injection or recovery, and R_f accounts for the effects of reservoir conditions and interactions between the fluid and host rock.

Completion is a critical stage in the construction of a well since it involves preparing the wellbore for injection or production. This includes the preparation of the interface between the well and the targeted formation and so can have a significant bearing on the flow efficiency achieved (Rahman et al., 2007). The purpose of C_f in Equation 2 is to consider both the positive and negative effects of completion on the near-wellbore performance. This includes the effects of wellbore and formation damage, casing perforation, stimulation, and partial penetration (Bellarby, 2009). C_f is therefore used to consider the deviation in radial flow around the wellbore due to these effects compared to an undamaged, fully penetrated, open-hole well. Values ranging from 0.1 to 0.9 have been used in other studies evaluating the carbon sequestration potential of deep lying coalbeds (van Bergen et al., 2001; Bachu, 2007; Fang and Li, 2014). The size of this interval implies that the initial choice of a value is somewhat arbitrary and should be improved upon by considering the engineering of the wellbore(s) and where possible on field scale gas injection or recovery experience in the study region.

The recovery factor, R_f, is defined as the fraction of the gas in place that can be recovered from the contributing coal seams (Dake, 1983; Hamelinck et al., 2001). It can be used to consider economic, environmental and ecological constraints on the recovery as well as technical constraints based on the physics of the reservoir-gas system. Only the latter constraints are considered in this work. For conventional CBM recovery, a key variable in determining R_f is the pressure drop that can be achieved via water abstraction, with values of R_f ranging from 0.2 to 0.6 (van Bergen et al., 2001). For ECBM recovery via CO_2 injection, R_f depends on the sweep efficiency and values approaching 1.0 may be achieved. The sweep efficiency that can be achieved in turn depends on the water content of the coal, whether the CO_2 is injected in sub- or super-critical phase, the nature of the coal porosity and permeability, and the extent to which the coal preferentially adsorbs CO_2 ahead of CH_4.

From equations (1) and (2), the CO_2 storage capacity of the seams considered can be evaluated by considering the exchange ratio, E_r, for the preferential displacement of the in situ CH_4 by the injected CO_2, giving (van Bergen et al., 2001):

$$M_{CO_2} = W_c G_{CH_4}\left(C_f \times R_f \times E_r\right)\rho_{CO_2} \tag{3}$$

where M_{CO_2} is the effective CO_2 storage capacity in tonnes expressed in tonnes of CO_2. ρ_{CO_2} is the density of CO_2 at standard pressure and temperature, i.e. 1.83×10^{-3} t m^{-3}. The value of E_r may be determined by laboratory testing of coals from different seams and locations in the coalfield, or in accordance to the coal rank if such data is not available (Fang and Li, 2014).

6. Carbon sequestration capacity of deep coalbeds in South Wales

To consider the range of reservoir conditions and engineering factors influencing the output of equation 3, statistical distributions were defined for each of the input parameters and the evaluation of the effective CO_2 storage capacity, M_{CO_2}, was performed via a Monte Carlo simulation. Table 2 shows the minimum values, most likely values, maximum values, and standard deviations defining the distributions of the input parameters.

Laboratory analyses of available core materials from boreholes and accurate borehole logs of coal measure rocks are necessary for any gas recovery and geological storage prediction (Karacan, 2009). A combination of literature survey and site specific data obtained as part of the current work have been used to gain an understanding of the CH_4 content of the South Wales coalbeds, G_{CH_4}. The minimum and maximum values are those reported in the CBM resource report by Jones et al. (2004). Creedy (1991) reported methane contents for 173 coal samples taken from 24 boreholes across the South Wales Coalfield, with an average value of 13.3 $m^3\ t^{-1}$. This is similar to a more recent exploration by Centrica Energy, which found an average methane content of 13.0 $m^3\ t^{-1}$ in 20 to 30 target coal seams (DECC, 2010). The methane contents collected in the literature survey show a good agreement with those from site specific tests conducted in the course of this work, which produced an average value of 13 $m^3\ t^{-1}$ from 17 samples taken from depths of 493 to 610 m. Hence, the most likely CH_4 content was set to 13 $m^3\ t^{-1}$. A standard deviation of 2.0 $m^3\ t^{-1}$ was used since the spread of the collected data is relatively narrow compared to the range reported by Jones et al. (2004).

As mentioned in Section 5.2, literature values of the completion factor, C_f, range from 0.1 to 0.9 (van Bergen et al., 2001; Bachu, 2007; Fang and Li, 2014). In this work, the minimum, maximum and most likely values used in a similar study by van Bergen et al. (2001) for coalbeds in the Netherlands have been used. This is because the details of the wellbore engineering are not considered here and there is a lack of experience of gas injection or recovery in the South Wales Coalfield. The values of the recovery factor, R_f, were likewise taken from van Bergen et al. (2001). Particular uncertainty surrounds the recovery factor which could be achieved in the field in light of the potential restrictions on flow in the coalbeds due to the generally low UK coal permeability (DECC, 2010). However, this uncertainty can only realistically be addressed through gaining more field experience in the region.

Whilst there is very limited adsorption data for South Wales coal, the CO_2:CH_4 exchange ratio, E_r, was found to be 1.15 in laboratory testing for a low-volatile bituminous (84.39% fixed carbon) coal sample from the Six Feet seam, taken at a depth of 550 m at Unity Mine in the centre of the South Wales Coalfield (Hadi Mosleh 2014). Coal rank is an important factor in determining this ratio. As an example, Garnier et al. (2011) studied a range of coal ranks and reported an exchange ratio of 1.4 for high rank coals compared to 2.2 for low rank coals. Considering the Unity Mine sample is a high rank coal, a minimum value of 1.1 was selected for E_r. To account for the presence of lower rank coals in other regions of the South Wales Coalfield, as shown in Figure 2**Error! Reference source not found.**, the maximum value of E_r was set to 2.0, with a most likely value of 1.4.

The Monte Carlo simulation for the effective CO_2 storage capacity was performed with 100,000 trials and produced the results shown in Figure **Error! Reference source not found.**7 and Figure **Error! Reference source not found.**8. An example of the effective CO_2 storage capacity calculations using the most likely values from Table 2 is shown in Table 3. Considering the unmined coal resources present in the seams considered**Error! Reference source not found.**, it can be seen the total proved effective storage capacity is 70.1 $MtCO_2$, with a probable capacity of 104.9 $MtCO_2$ and a possible capacity of 152.0 $MtCO_2$. These figures have been calculated using the methodology outlined in section 5.2 and correspond to effective CBM resources of 31.8×10^9 m^3, 40.4×10^9 m^3 and 49.7×10^9 m^3, respectively. As a result of the linear dependence of the effective CO_2 storage capacity on the unmined coal tonnage in the methodology applied, the fractional contribution of each seam to the storage capacity follows the volumetric fractions given in Table 1. Thus, the Six Feet, Nine Feet and Five Feet seams have a roughly equal share of over 25% each of the capacity, followed by the Four Feet seam with 18.11% and the Seven Feet seam with 1.57%.

It is useful to express the calculated CBM resources and CO_2 storage capacities in more practical terms by: i) considering the volume of methane required to supply a 500 MW power station, and ii) considering the major point source emissions of CO_2 in the region. The probable CBM resource has the potential to supply a 40% efficient 500 MW power station for 41 years, assuming a calorific value of 39.8 MJ m^{-3}. Taking an average domestic load of 15 kW, this is equivalent to the supply required for in excess of 33,000 dwellings.

The National Assembly Wales (NAW 2013) reported that CO_2 emissions in Wales were 39.1 Mt in 2010, with the TATA steelworks in Port Talbot and the Aberthaw power station identified as the two largest point sources, at 6.6 Mt and 4.8 Mt, respectively. Only point source emissions are considered since they provide the more straightforward opportunities for capturing large quantities of CO_2 compared to distributed emissions such as those from the transport sector. The locations and sizes of the two principle point sources are illustrated in Figure 9**Error! Reference source not found.**, where it can be seen that the Port Talbot steel works in particular are suitably located to minimise the technical and economic problems associated with CO_2 transportation.

The evaluation results suggest that the proved effective CO_2 storage capacity of the Coalfield is equivalent to 11 years of emissions from Port Talbot steel works in 2010, with the probable capacity providing for 16 years, and the possible capacity providing for 23 years. For the slightly lower emissions produced by Aberthaw power station in 2010, these capacities correspond to 15, 22, and 32 years, respectively.

Whilst the evaluation results presented are encouraging, it is important to recognise that the effective CO_2 storage capacities obtained consider the geological and engineering constraints in limited detail and omit the legal, social and economic constraints entirely. These additional constraints should be considered to build upon the present work and establish the practical and matched CO_2 storage capacities of the Coalfield. A bespoke Spatial Decision Support System (SDSS) would be a useful tool towards this end by identifying those areas of the Coalfield which are most promising for carbon sequestration with enhanced methane recovery. Based on a combination of socio-economic, environmental-health and technical-regulatory criteria, selected areas could then be subjected to more detailed geological characterisation and engineering design, allowing a more rigorous evaluation of the CO_2 storage capacity and CBM resource provided by the Coalfield.

7. Conclusions

An evaluation of the potential for carbon sequestration in the South Wales Coalfield has been presented in this work. This has been achieved by applying a methodology based on an analogy with the reserves estimation for coalbed methane (CBM) recovery. To account for the considerable historical mining activities in the region, mine workings legacy data were utilised in a Geographical Information Systems (GIS) software to obtain the total unmined coal resource at greater than 500 m depth, where the candidate seams for carbon sequestration are found.

The complex merging and splitting of the seams from the Middle and Lower Coal Measures was simplified by defining seam 'packages' according to the clear boundaries present in the raw mine workings legacy data. The product of the three-dimensional mapping process was an estimated unmined coal resource of 12,700 Mt.

Since there is a considerable spatial variance in the reservoir conditions across the Coalfield, the key input parameters required for the evaluation were defined as statistical distributions based on a combination of laboratory coal characterisation results and literature review. A Monte Carlo simulation was then performed to produce a statistical distribution for the effective carbon sequestration capacity of the Coalfield. From the results obtained, the 'proved', 'probable' and 'possible' capacities were defined using the P10, P50 and P90 percentiles, respectively. The proved capacity, i.e. that which will be exceeded with a confidence of 90%, was found to be 70.1 $MtCO_2$, with a possible capacity, i.e. that which will be exceeded with a confidence of 10%, of 152.0 $MtCO_2$.

A probable effective storage capacity of 104.9 $MtCO_2$ was found and is regarded as the most likely scenario. This is equivalent to 16 years of the 2010 emissions from the Port Talbot steel works, which is located in the Coalfield and is the largest point source emitter of carbon dioxide in Wales. As a consequence of the methodology employed in the evaluation, the corresponding coalbed methane resource in place in the Coalfield was also established. It was found that there is a probable resource of 40.4×10^9 m^3 with the potential to supply a 40% efficient 500 MW power station for 41 years. It can be concluded that at the regional scale considered there is reasonable potential for deploying carbon sequestration in coal with enhanced methane recovery.

To build upon the effective capacity established in the present work, the next stage is to consider the wider socio-economic, environmental-health and technical-regulatory constraints in greater detail and ultimately select and rank or omit areas of the Coalfield accordingly. This could be achieved using a bespoke Spatial Decision Support System. The geology and engineering requirements of selected areas could be characterised in greater detail to allow a more rigorous evaluation of the carbon dioxide storage capacity of the South Wales Coalfield.

Acknowledgement

The work described in this paper has been carried out as part of the GRC's (Geo-environmental Research Centre) SEREN project, which is funded by the Welsh European Funding Office (WEFO). This funding is gratefully acknowledged.

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List of Figures

Figure 1 Generalised vertical section of the Westphalian phase rocks of the South Wales Coalfield (adapted from Barclay, 1989). Figure not in scale.

Figure 2 Variation in coal rank across the South Wales Coalfield for three different seams representing: a. the Upper, b. the Middle, and c. the Lower Coal Measures, respectively (Adams, 1967). Figure not in scale.

Figure 3 Diagrammatical representation of structural variation of Nine Feet and related seams along the Cross section A-A refers to that indicated in **Error! Reference source not found.**3c (Adams, 1967). Figure not in scale.

Figure 4 Schematic illustrating how the various seams of the Middle and Lower Coal Measures were merged into packages as dictated by the raw mine workings legacy data.

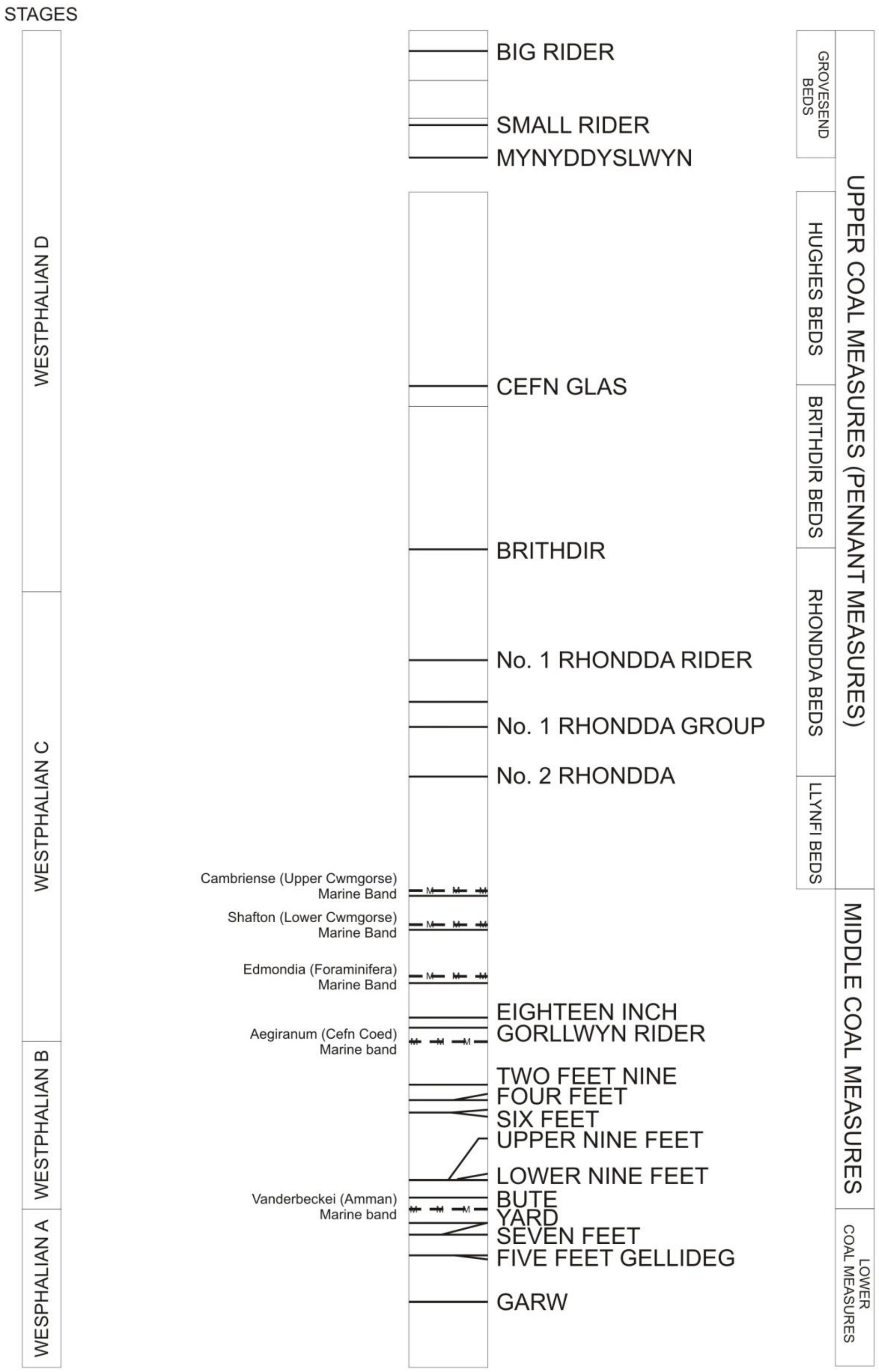
Figure 5 Contour plot showing the elevation (in meters) of the Nine Feet seam (ref. **Error! Reference source not found.**), produced in MapInfo using the mine workings legacy data. Figure not in scale.

Figure 6 Storage pyramid illustrating different stages in CO_2 storage capacity assessment (after Bachu et al., 2007).

Figure 7 Histogram of the Monte Carlo simulation results for the effective CO_2 storage capacity of the South Wales Coalfield.

Figure 8 Cumulative probability plot of the Monte Carlo simulation results for the effective CO_2 storage capacity of the South Wales Coalfield. P10, P50 and P90 percentiles are indicated.

Figure 9 Results of the preliminary evaluation for the CO_2 storage capacity and CBM potential of the South Wales Coalfield (emissions figures from NAW (2013)).



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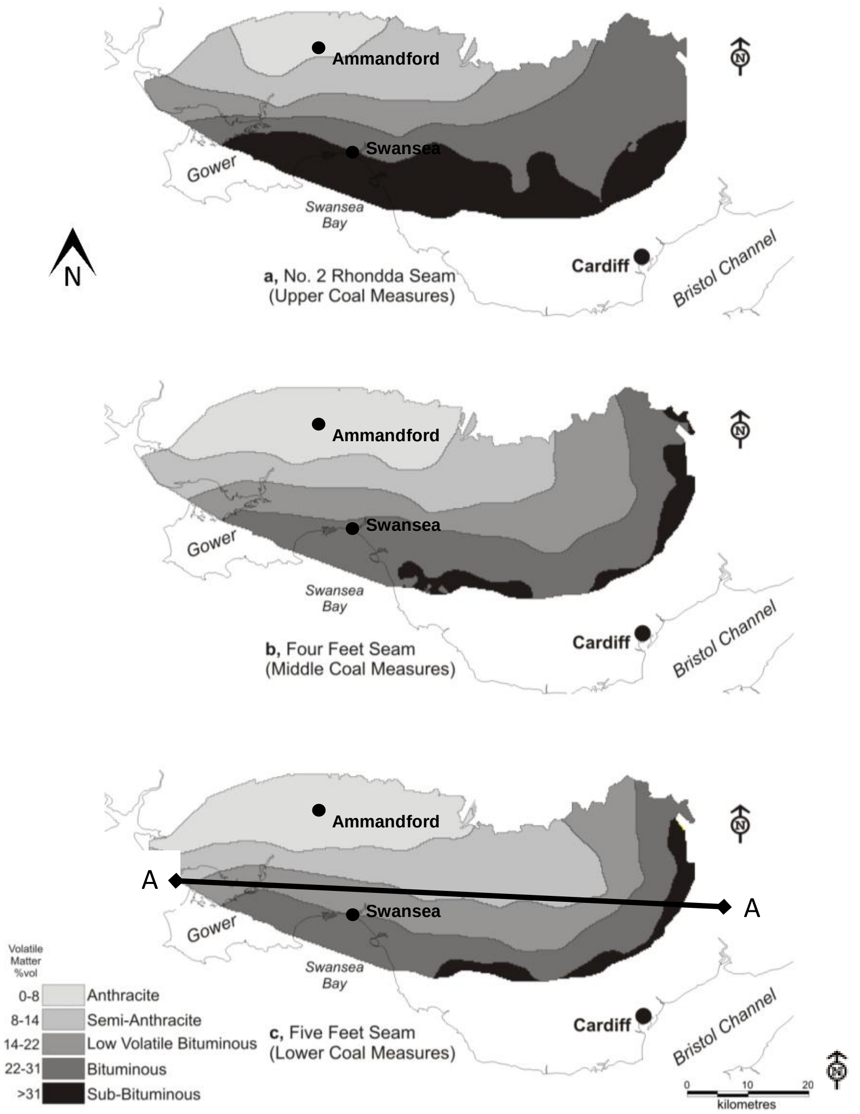

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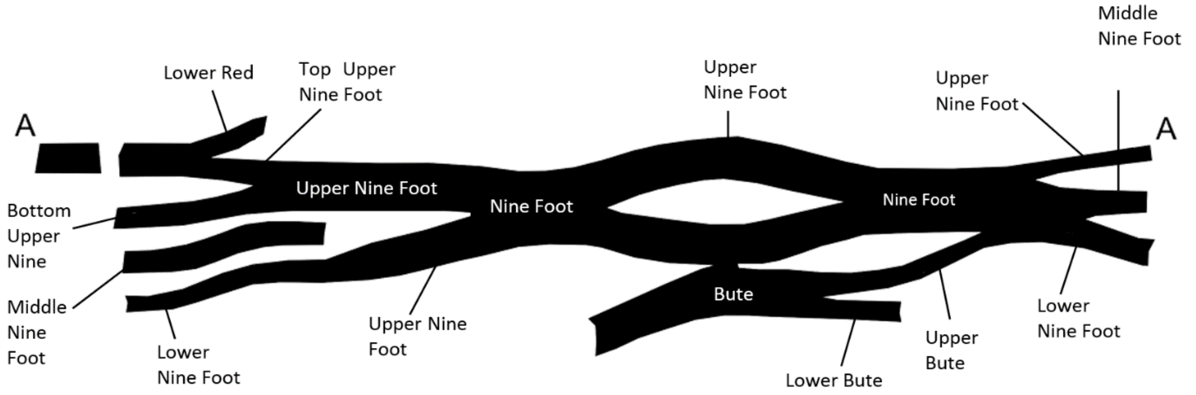

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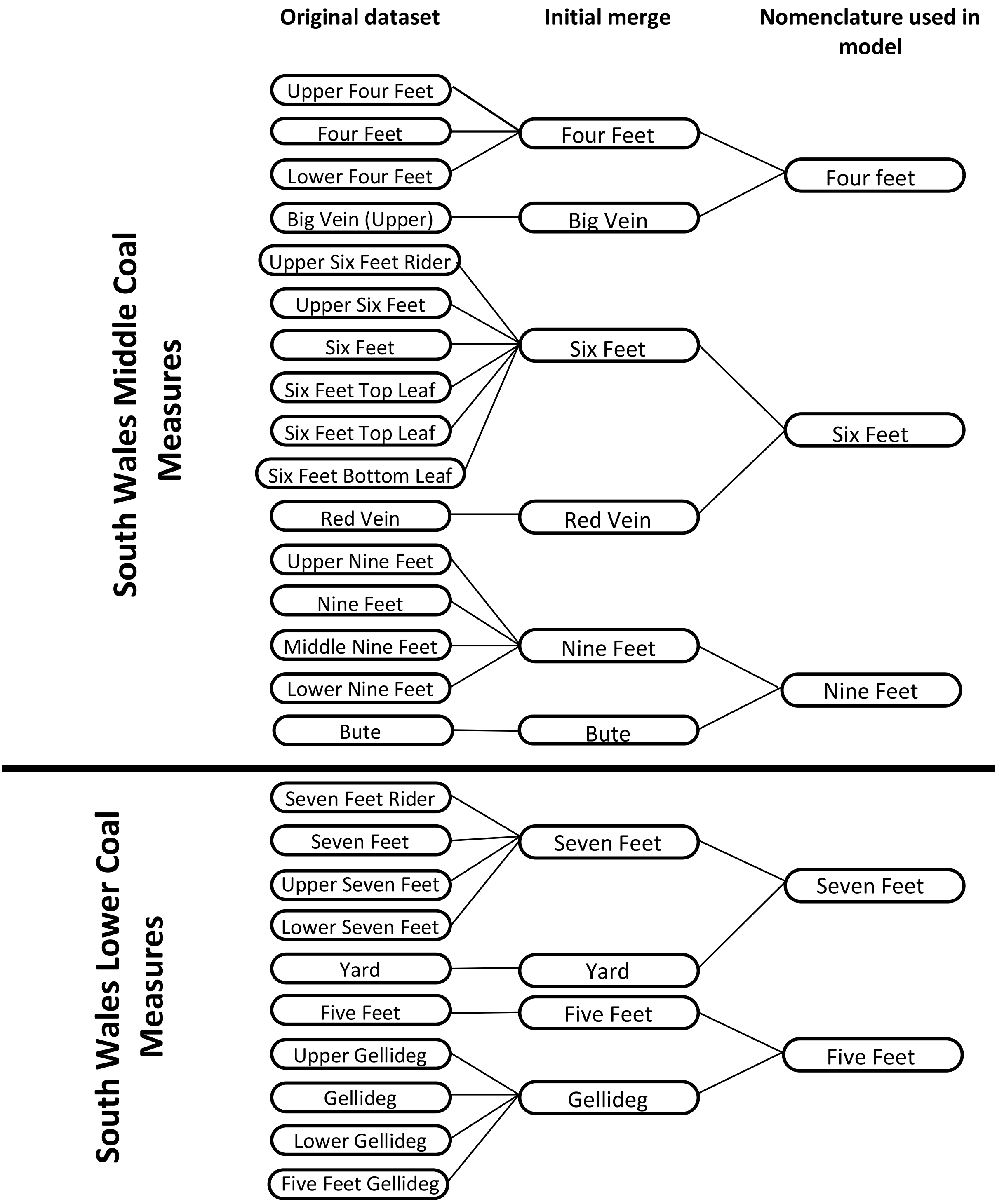
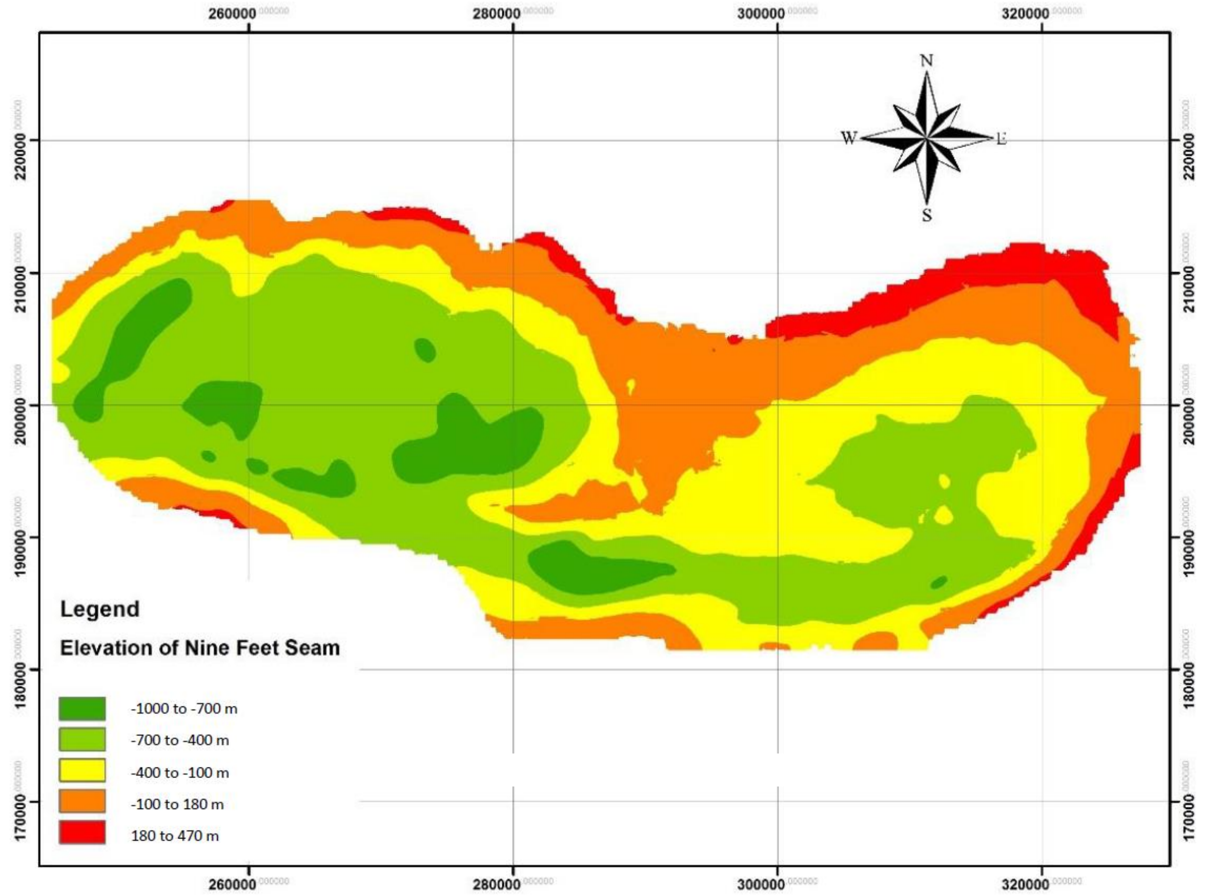


Figure 4 Schematic illustrating how the various seams of the Middle and Lower Coal Measures were merged into packages as dictated by the raw mine workings legacy data.



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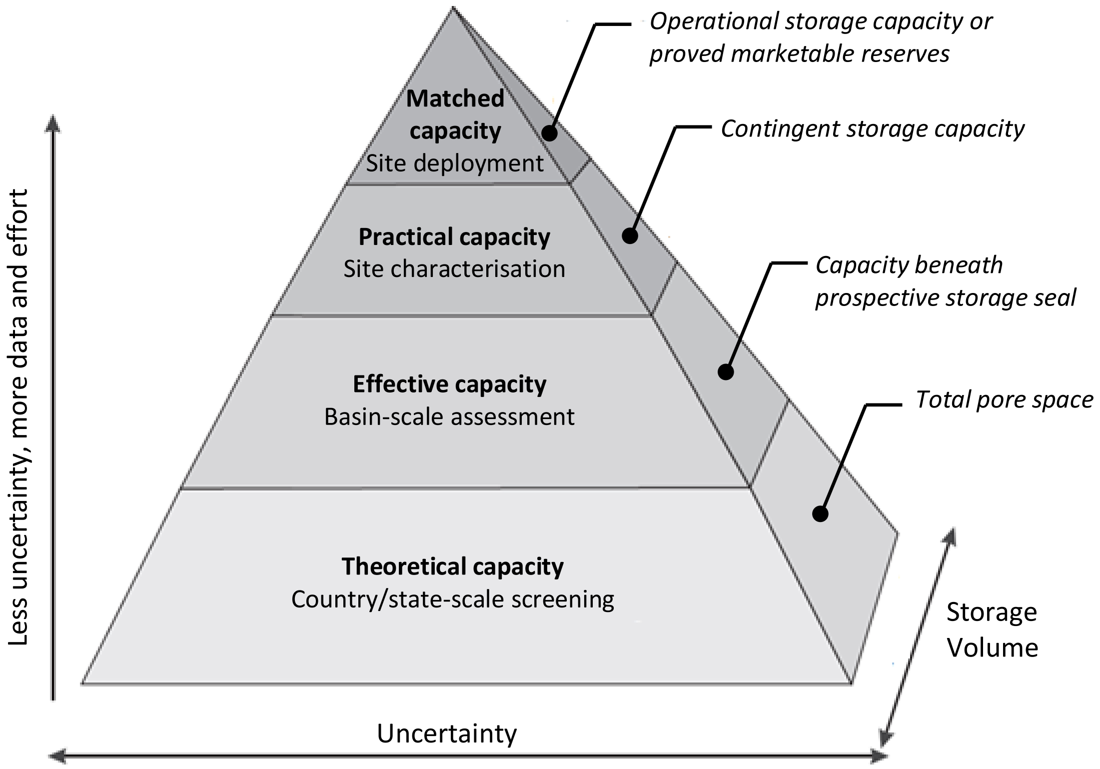

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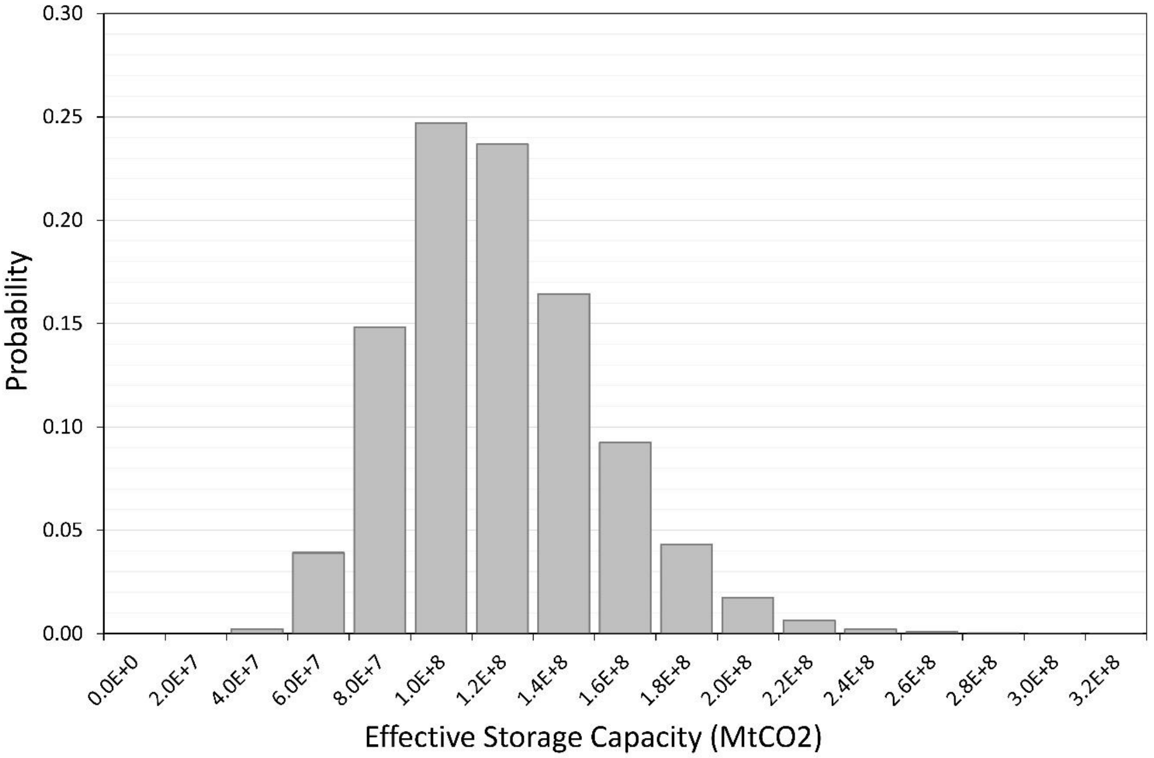
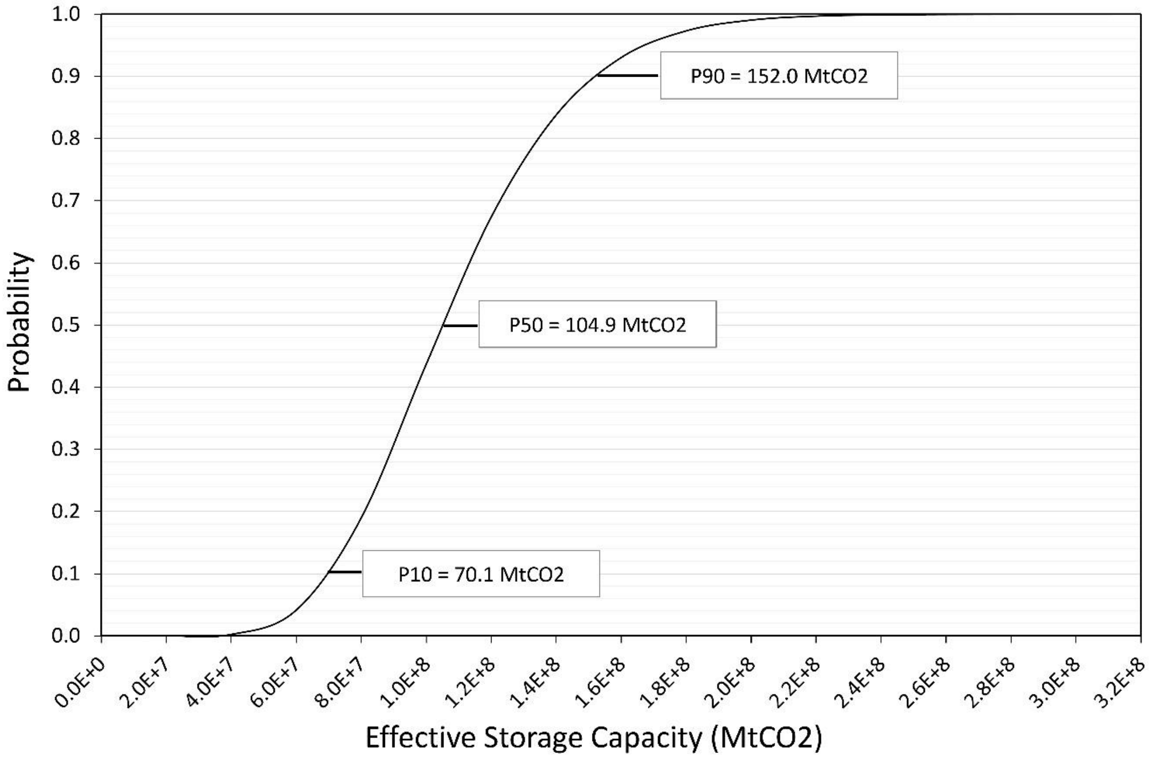


Figure 7 Histogram of the Monte Carlo simulation results for the effective CO_2 storage capacity of the South Wales Coalfield.



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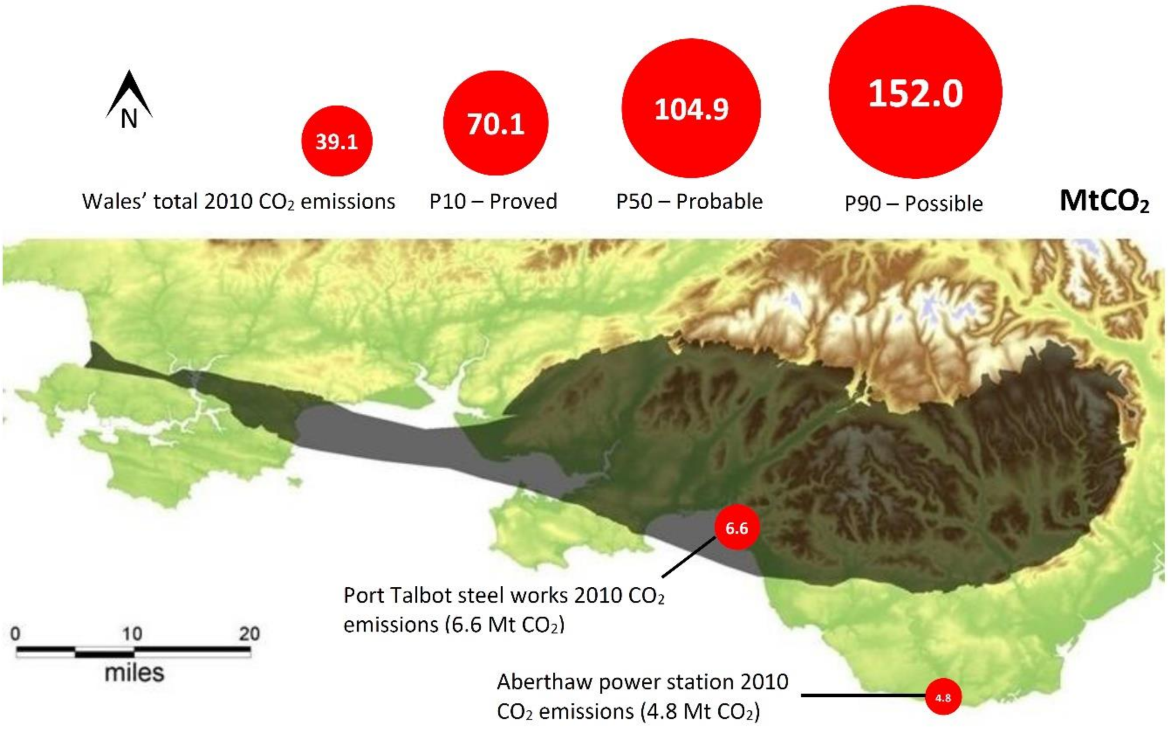

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Table 1 Summary of coal affected and unmined coal for the main productive seams in the Middle and Lower Coal Measures.

Seam	**Coal Affected t**	**Unmined Coal t**	**% of Total Unmined Coal**
Four Feet	6.00E+08	2.30E+09	18.11
Six Feet	1.10E+09	3.40E+09	26.77
Nine Feet	1.80E+09	3.30E+09	25.99
Seven Feet	4.50E+08	2.00E+08	1.57
Five Feet	7.20E+08	3.50E+09	27.56
Total	4.67E+09	1.27E+10	100.0

Table 2 Summary of the input values used for Monte Carlo simulations of the key parameters used to evaluate the effective CO_2 storage capacity of the South Wales Coalfield.

Parameter	**Minimum**	**Most Likely**	**Maximum**	**Standard Deviation**
Coal CH_4 content, G_{CH_4} (m^3 t^{-1})	5.50	13.00	22.50	2.00
Completion factor, C_f	0.40	0.50	0.90	0.05
Recovery factor, R_f	0.20	0.50	0.85	0.10
Exchange ratio, E_r	1.10	1.40	2.00	0.20

Table 3. Effective CO_2 storage capacity calculations.

Seam Name	**Coal Affected t**	**Coal Unmined t**	**GIP (CH_4) m^3**	**EGIP (CH_4) m^3**	**M_{Ef} (CO_2) t**
Four Foot	6.00E+08	2.30E+09	2.99E+10	7.48E+09	1.92E+07
Six Foot	1.10E+09	3.40E+09	4.42E+10	1.11E+10	2.84E+07
Nine Foot	1.80E+09	3.30E+09	4.29E+10	1.07E+10	2.75E+07
Seven Foot	4.50E+08	2.00E+08	2.60E+09	6.50E+08	1.67E+06
Five Foot	7.20E+08	3.50E+09	4.55E+10	1.14E+10	2.92E+07
Total	4.67E+09	1.27E+10	1.65E+11	4.13E+10	1.06E+08

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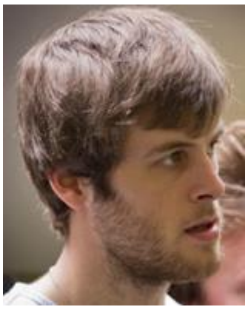

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