IT'S NOT ONLY ABOUT COAL MINING: COAL-BED METHANE (CBM) AND UNDERGROUND COAL GASIFICATION (UCG) POTENTIAL IN BANGLADESH

A brief independent technical review written for Mines and Communities Website

www.minesandcommunities.org

partizans@gn.apc.org

by

Mark Muller, Ph.D.

mmuller.earthsci@gmail.com

17 March 2009

ABBREVIATIONS USED

m	Meters
km	Kilometers
km^2	Square kilometers
kg	Kilograms
t	Ton (metric)
J	Joule
Mt	Mega or Million (1,000,000) tons (of coal)
Gm^3	Giga or Billion (1,000,000,000) cubic meters (of gas)
Tcf	Trillion (1,000,000,000,000) cubic feet (of gas)
m^3/t	Cubic meters per ton (of gas in coal)
kcal/kg	Kilo (1,000) calories per kg (of energy in coal)
GJ/t	Giga (1,000,000,000) Joules per ton (of energy in coal)

UNIT CONVERSION FACTORS

Gas volume:	1 Tcf = 28.3286 Gm^3
Energy:	1 kcal = 4186.75 J

ENERGY EQUIVALENCE

1 Mt coal = 0.6967 Gm^3 gas

1 Gm^3 gas = 1.4354 Mt coal

CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

As the newly elected government is establishing an energy strategy for Bangladesh, and indeed while the Asian Development Bank is potentially reconsidering its stalled involvement in the highly contentious Phulbari coal project, it is opportune to examine the potential role that both coal-bed methane (CBM) and underground coal gasification (UCG) might play in providing a less socially and environmentally disruptive energy resource for Bangladesh, in comparison with conventional coal mining. This review examines currently available geological information and attempts to quantify the size of the CBM resource that might be derived from known coal deposits in northwest Bangladesh and the contribution the resource might make towards Bangladesh's energy requirements.

The review highlights, particularly, the very significant implications of two scientific studies published in 2008, one assessing the coal-bed methane potential of coal-seams in the Barapukuria coal basin [1], and the other examining the magnitude of subsurface stresses created by multi-slice longwall mining at Barapukuria [2], the latter being of direct relevance to surface subsidence above the mine and the long-term feasibility of on-going mining operations. The results of these studies have not yet received any wide attention in the discussion of energy and coal exploitation in Bangladesh.

It is important to note that ***there have been no direct measurements made of the methane gas content of any of Bangladesh's coal deposits***, which is a glaring omission in the exploration assessments of the region's coal carried out to date. The single published scientific work that does attempt to quantify the gas content of the coal at Barapukuria [1], Bangladesh's only currently operating coal mine, does so using industry standard prediction methods based on the (known) coal quality and depth of the coal-seams. Such predictions of the gas content of coal, while useful in the absence of hard measurements, are notoriously inaccurate, subject to errors as large as 200% [3]. It is therefore critical that any future exploration in the coalfields incorporates the direct measurement of the coal-bed methane gas content into the work program. It is remarkable that such measurements have not been made in the past, as they have a direct bearing on mine safety and the risk of underground methane explosions. An underground methane "emission" at a producing coal-face at Barapukuria Mine in 2005 has, in fact, been reported [1], and provides, as the only positive outcome of a dangerous incident, some indication of the gas potential of the coal-seams*.

CBM extraction and UCG are two methods, entirely different from each other, of extracting, *in-situ*, two different types of gas from subsurface coal deposits, where the coal itself is located at depths greater than the reach of conventional mining, or where mining is not possible, or not preferred, for technical, social or environmental reasons. In both cases, surface boreholes are used to liberate and extract the gas. In CBM projects, the methane gas that is naturally resident in the coal-seam is extracted, leaving the coal fractured, but otherwise intact, underground. UCG consists of initiating and controlling the burning of a coal-seam underground from one borehole, while extracting the product hydrogen-methane gas mixture (as well as carbon-monoxide, carbon-dioxide and hydrogen-sulphide) via a second borehole. The coal-seam is completely consumed by UCG. Both CBM and UCG output gas can be liquefied, or used as a direct feedstock to local power stations. CBM is currently classified as a clean energy resource by the World Bank.

Production CBM projects are well established and currently underway in a number of countries, including USA, Australia, Canada, China and South Africa. Pilot or evaluation UCG projects are underway in several countries, including China, Australia, USA, and in Spain, UK and Belgium for the EU. Production UCG projects are only operating currently in Uzbekistan (Angren plant) and South Africa (Eskom's Majuba plant). The former Soviet Union had up to 14 industrial-scale UCG plants running in Ukraine by the end of the 1960s, all of which are now closed [4].

* It is not clear whether the methane emission referred to in [1] is in any way related to the spontaneous combustion of coal, and subsequent carbon monoxide build-up, that occurred on about 30 September 2005 and closed down longwall panel 1110 (together with one of the mine's two sets of longwall mining machinery) for three years.

While the energy delivery of both CBM and UCG is less than that provided by conventional coal mining, as illustrated later in the report, the energy is delivered with significantly lower infrastructural, social and environmental costs, and also in circumstances where coal resources cannot be practically or economically accessed at all by mining. It is a significant shortcoming in the current energy debate that CBM and UCG have not featured more prominently. This review hopes to encourage the inclusion of CBM and UCG in future debate.

2. WHY COAL? AND HOW MUCH OF IT IS AVAILABLE?

Bangladesh is facing a critical energy shortage and, while requiring an estimated 5,000 MW of electricity, is currently generating only about 3,200 MW [5]. With the exception of the unreliably productive 250 MW power station at Barapukuria, Bangladesh derives all of its electricity from natural gas. The annual natural gas production rate in Bangladesh is 17 Gm^3, of which about 50% is used to generate electricity [5]. With total proven and recoverable natural gas reserves of between 142 and 340 Gm^3 [5], if the current annual rate of consumption were allowed to increase at 10% per year, the natural gas would last for just over 12 years, assuming the greater resource of 340 Gm^3 is available. Increasing at a rate of 10% per year, electricity production would exceed 5,000 MW by 2012, and ***all natural gas reserves would be exhausted by 2019***, at which time the annual gas consumption would be about 48.5 Gm^3.

While it may not be practically possible, or sustainable, to achieve a 10% year-on-year growth rate in consumption, what these illustrative figures do show is that Bangladesh's gas reserves are finite. In the absence of new natural gas discoveries, coal must, by necessity, form a central part of Bangladesh's energy strategy.

All of Bangladesh's exploitable coal reserves are located in Permian-aged Gondwana sedimentary basins located in NW Bangladesh (Figure 1), and were discovered over the period 1959 – 1997 [6, 7], largely through the efforts of the Bangladesh Geological Survey (BGS). Currently five of these basins have well defined resource estimates (Table 1), of which four are either being mined, actively assessed or explored:

- Barapukuria: currently being mined underground by a consortium consisting of China National Machinery Import & Export Corporation (CMC) and Xuzhou Coal Mining (XMC), under contract to Petrobangla.
- Phulbari: currently the subject of a highly contested open-cast mining proposal by GCM Resources.
- Khalaspir: an exploration license has been awarded to the Hosaf Group, who also represented the CMC at the time of the development of the mine at Barapukuria [8].
- Dighipara: an exploration license has been awarded to Petrobangla [8].
- Jamalganj.

The deposit located at Kuchma (Bogra), is associated with very deep coal-seams that are beyond the reach of current extraction methods. Two other coal-bearing basins are known (Nawabgonj and Dangapara), but have undefined reserves. A further four Gondwana basins (Badargonj, Osmanpur, Burirdoba and Shimnagar) have been identified in the area, but are not yet known to host coal measures.

Bangladesh's total known coal resource, i.e. the total amount of coal in the ground, is about 4,744 Mt (Table 1). The depths of the coal-seams below surface lie in the range 118 – 1158 m. While the cumulative coal-seam thickness in each of the five basins is similar, in the range 38.4 – 64.0 m (Table 1), the number of seams in each basin is highly variable, as well as the thickness of individual seams. Coal-seam depth, thickness and separation are the primary geological controls on the extraction method chosen: all seams are not equally well suited to one particular extraction method, and many seams, being either too deep or too thin, will not be amenable to extraction at all using any of the methods available, i.e., mining, CBM extraction or UCG.

Table 1. Summary of the known coal resources in NW Bangladesh. All resource estimates are from the work of Islam and Hayashi [1], except for the case of the Dighipara coalfield [8]. Discovery dates are from Akhtar [7].

Coal field	Discovery date	Areal extent of basin (km^2)	Number of coal seams	Depth range of coal-seams (m below surface)	In-situ coal resource (Mt)	Average aggregate thickness of coal-seams (m)	Comments
Coalfields with known or estimated coal resources							
Jamalganj	1962	11.7	7	650 - 1158	2,513	64.0	(a)
Barapukuria	1985	5.2	6	118 - 518	377	51.0	
Phulbari	1997	51.9	2	150 - 250	426	38.4	
Khalaspir	1987	12.3	8	257 - 483	828	42.3	
Dighipara	1995	Unproven	1	328 - 422	600	42.0	(b)
Coalfields with reported coal but unproven resources							
Nawabgonj							
Dangapara							
Coalfield with known coal, but too deep for current exploitation							
Kuchma (Bogra)	1959	Unproven	5	2380 - 2876	Unproven	51.8	(c)
Gondwana basins with no coal reported to date							
Badargonj							
Osmanpur							
Burirdoba							
Shimnagar							
TOTALS					**4,744**		

(a) Earlier, lower estimates of the Jamalganj coal resource, equal to about 1,053 Mt, are reported elsewhere [9].
(b) 600 Mt is the "probable" resource at Dighipara, while the "proven" resource is 100 Mt [8].
(c) Information from Akhtar [7].

Published estimates of the recoverable coal resource appear to have focused primarily on ***mining***, with little direct consideration of CBM and UCG as alternative methods of extraction, and little obvious, if any, consideration of social and environmental criteria. The resource that is currently believed to be recoverable using mining methods is estimated to be about 1,400 Mt [5], which is equivalent to 975 Gm^3 of natural gas, or ***about three times Bangladesh's current recoverable natural gas resource***. If the natural gas consumption rate were to be about 48.5 Gm^3 per year by the year 2019, as illustrated above, then the recoverable coal resource could take over from that gas consumption for a period of about 20 years, in the absence of any further increase in the consumption rate.

Notwithstanding the uncertainties of future energy consumption rates (which directly affect the longevity of its resources), it is clear that if Bangladesh is to achieve energy security for itself lasting until at least 2040, coal must from part of its energy strategy.

3. MINING MAY NOT DELIVER TO EXPECTATIONS

Since development work started at Barapukuria in 1996, the mine has suffered a litany of technical problems underground (Appendix 1), and has generated significant impacts on surface above the mine. Not only have very high social and economic costs been incurred, but the mine will also not meet its original coal recovery projections. In 2000, estimates of the recoverable resource were as high as 64 Mt [7]. Flooding of the mine by water from the overlying Upper Dupi Tila acquifer, during early phases of mine development, necessitated a change in mine design, restricted mining activities to the southern portion of the coal basin, and effectively cut the recoverable resource down 34 Mt, to be mined over 30 years [1]. Coal production started in September 2005 [1] and output has yet to reach the planned extraction rate of 1 Mt per year. Achieving the projected production rate has not been helped by the fact that one of the mine's (only two) sets of longwall mechanised mining machinery was left trapped and unused inside panel 1110 in October 2005, when the panel was sealed off in response to carbon-monoxide emissions from the spontaneous coal combustion of an unattended coal pile in the panel [10, 11]. The equipment was only recovered in August 2008 [11].

Considering how little of the resource has been mined to date, almost certainly less than 3 Mt of coal, the impact on the surface above the mine has been devastating. Land subsidence of between 0.6 – 0.9 m has been reported over an area of approximately 1.2 km^2; the water-table has dropped leaving commonly used water reservoirs dry in 15 villages; at least 81 houses have developed cracks in 5 villages; and untreated water (acknowledged by the mine to contain phosphorous, arsenic and magnesium) is passing through canals in farming areas [12, 13]. The scale of the problem has the government currently considering the establishment of a new "coal city" near Barapukuria that would provide housing and (potential) employment to people whose livelihoods are at risk in 15 villages around the mine [13].

A major cause for concern is the extent to which the surface has already subsided in response to the single 3 m high "slice" extracted to date from six longwall panels underground, where mining is taking place at a depth of around 400 m. The mine's acknowledgment of the extent of the subsidence problem, at such an early stage of mining, remains ambiguous[†]. The coal-seam mined at Barapukuria is particularly thick (22 – 42 m). In order to achieve the projected 34 Mt coal recovery, the mine proposes to extract, in total, an 18 m high slice through the coal seam, using six downward progressing, 3 m high, slices in each longwall panel (hence the term "multi-slice" longwall mining being used to describe the mining method). A recently published

[†] Several ambiguous statements attributed to sources from within the mine suggest the mine authorities may (or may not) be aware of the potential magnitude of the subsidence problem: One BCMCL official acknowledges that "If one foot of coal is extracted from the mine, then the land surface could subside by half a foot" [14], and on another occasion a highly placed Petrobangla source notes "For ***each*** [author's italics] such slicing, the land subsidence would eventually be two meters" [12]. The obvious inference is that a total of 9 – 12 m of subsidence should be anticipated in response to removing the full 18 m slice underground, and yet there has been no explicit statement to that effect reported from the mine. The same highly placed Petrobangla source is also quoted as saying both that "About 4.2 square kilometer-area of the underground Barapukuria coal mine site [sic] will subside by up to two meters in the mine's 30 year-life", (which may be underestimating the problem) and "Such a subsidence will create a large lake". Two meters of subsidence may not create a large lake, but 9 meters certainly would.

scientific study [2] is able to provide several very important insights by comparing the subsurface stresses induced in the overburden above both 3 m and 18 m high longwall slices. The work shows that the induced stresses at surface are roughly three times greater for an 18 m slice than for a 3 m slice, and therefore that significantly greater surface subsidence should be anticipated above an 18 m slice. Also revealed for an 18 m slice, is a high risk of the induced fracturing (of the overburden around the mining panel) propagating upwards into the base of the Upper Dupi Tila acquifer, creating a serious water inflow hazard. Whether the mine will remain viable in the long term, in the light of increasing surface subsidence and its many impacts, and facing a serious water inflow risk, remains to be seen.

In short, the Barapukuria mining experience, one of delivery well below expectations, and the ongoing resistance to the proposed open-cast Phulbari mining project[‡], provides strong motivation to explore coal-bed methane extraction and underground coal gasification as alternative means of deriving an energy supply from Bangladesh's coal deposits.

4. BANGLADESH'S COAL-BED METHANE POTENTIAL

What is CBM?

Coal-bed methane (CBM) refers to the methane gas that resides naturally within the micro-porosity (microscopic voids between carbon particles) and the macro-porosity (cleats and fractures) of coal seams. The gas is formed, and trapped, during the geological process of diagenesis, in which the thick layers of vegetable and organic matter that ultimately form the coal seams, are buried beneath younger overlying sediments and converted into coal, under high temperature and pressure. Gas is also formed by biological processes as a result of microbial action within the coal seam. The

[‡] Phulbari is not discussed directly in this review – see, for example, a recent critique of the Phulbari project's environmental and social impact assessments [15] for more information.

amount of gas contained in the coal-seam depends on the burial history of the deposit (which determines the final "quality" of the coal), as well as the extent to which the strata around the coal are impermeable, preventing the gas from escaping. Coal-bed methane is almost identical in character to the "natural gas" recovered from oil deposits, and may be utilised in exactly the same way, as a feedstock for power plants or for liquefaction. There are currently many active projects around the world in which CBM is extracted, for example, in Canada, USA, China, Australia and South Africa, and there is good potential for extraction in many other countries.

The gas content (concentration) in coal-seams is normally measured directly by adsorption or desorption laboratory tests, using samples taken from borehole intersections of the coal. A critical shortcoming of coal exploration in NW Bangladesh to date is that no such direct measurements have been made of any coal samples, which limits the accuracy with which the CBM potential can be assessed. In the absence of laboratory measurements, the CBM concentration in bituminous coals can be estimated using fairly well established empirical formulae that predict the gas concentration from other (known) characteristics of the coal – its density (which relates to coal rank or quality, and the carbon and ash content), depth of burial and moisture content [1]. Greater depths of burial and higher coal density (i.e., higher quality) are associated with higher gas concentrations. Such predictions of gas concentration are, however, subject to errors as large as 200% [3]. The optimal depth-range for CBM development is 300 – 1200 m: at shallower depths the gas concentrations tend to be lower, as the confining pressure is not high enough to hold the gas; and at greater depths, while the gas concentration might be higher, the high pressures and lower coal permeability make gas recovery less efficient.

What is the potential CBM resource, and what is the potential energy return?

Islam and Hayashi [1] have recently estimated the CBM concentration for the high-volatile B bituminous coals at Barapukuria using the predictive method described in the section above, and find gas concentrations in the range 6.51 – 12.68 m^3/t. Observations of similar quality coals elsewhere in the world suggest it is unlikely that the gas concentrations in Bangladesh will be higher than the upper limit, nor significantly lower than the lower limit. By extrapolating the Barapukuria gas concentration estimates to all other basins in NW Bangladesh where the in-situ coal resource is known, an estimate of the ***total in-situ CBM resource*** (for all seams in all basins) can be determined, as shown in detail in Table 2, and summarised below:

Upper-limit estimate:	60.15 Gm^3
Average estimate:	45.52 Gm^3
Lower-limit estimate:	30.88 Gm^3

While the CBM resources for the Barapukuria, Phulbari, and Dighipara basins are most likely to fall close to the average-value estimates in Table 2, there is good reason to expect, or at least hope, that the resources at both Khalaspir and Jamalganj might fall closer to the upper-limit estimates. The coal at Khalaspir is known to have a 25% higher calorific value when compared to the other basins, suggesting higher quality coal: Khalaspir 7902 – 8427 kcal/kg, Barapukuria 5860 – 7087 kcal/kg and Jamalganj 6596 – 6722 kcal/kg [7]. At Jamalganj the greater depth of burial of the seams would favour higher resident gas concentrations.

Table 2. Estimated in-situ coal-bed methane (CBM) resources in Bangladesh. The CBM resource has been calculated for all basins using estimated (not measured) values for the concentration of methane gas in coal in the Barapukuria basin (from the work of Islam and Hayashi [1]). Estimates are shown for three different gas concentrations: a high value of 12.68 m^3/t, an average value of 9.56 m^3/t and a low value of 6.51 m^3/t.

Coal field	Number of coal seams	Depth range of coal-seams (meters below surface)	In-situ coal resource (Mt)	High estimate in-situ CBM resource 12.68 m^3/ton (Gm^3)	Average estimate in-situ CBM resource 9.56 m^3/ton (Gm^3)	Low estimate in-situ CBM resource 6.51 m^3/ton (Gm^3)
Jamalganj	7	650 - 1158	2,513	31.86	24.11	16.36
Barapukuria	6	118 - 518	377	4.78	3.62	2.45
Phulbari	2	150 - 250	426	5.40	4.09	2.77
Khalaspir	8	257 - 483	828	10.50	7.94	5.39
Dighipara	1	328 - 422	600	7.61	5.76	3.91
TOTALS			**4,744**	**60.15**	**45.52**	**30.88**

The particular CBM potential of the Jamalganj basin was identified as early as 2002 by Imam *et al*. [9], who calculated a maximum ***theoretical*** methane content (for Seam III) of between 10.7 – 12.8 m^3/t, and identified several additional positive characteristics of the basin that include: high net thickness of coal-seams in which two seams (III and VII) account for as much as 80% of the resource; deep burial-depth within the optimum depth range for CBM; large coal reserves; significant indications of gas during drilling; and low permeability in the rocks above and below the coal seams.

It is undeniable that the energy return of CBM is much less than that of the coal hosting the gas: the total in-situ CBM resource is equivalent to 1 – 2% of the total in-situ coal resource (1 Gm^3 gas = 1.4354 Mt coal) and equivalent to 3 – 6% of the coal resource recoverable through mining. It is also true that not all of the CBM is technically and economically recoverable (as is the case for coal mining). Yet CBM provides a valuable alternative to mining in instances where the coal is inaccessible to mining because of its great depth, as is the case at Jamalganj, or where population density and pressure on agricultural land make the loss of land to surface-mining too costly.

The estimated CBM gas concentration, in-situ resource and seam thickness in the Bangladeshi deposits is comparable with that at other active CBM projects elsewhere in the world (Table 3). Recovery factors (the percentage of gas recovered relative to the total gas contained in the target seams) in these comparative projects are between 20 – 66%. The scale of the CBM resource at Recluse Rawhide Butte Field in the Powder River Basin, USA, suggests that the relatively small individual resources in each of the Bangladeshi basins could potentially form viable local-scale projects. Jamalganj, in particular, looks to be the single basin with the most potential as a stand-alone project. If the two seams hosting 80% of the in-situ resource were to be targeted at Jamalganj (seams III and VII), the recoverable CBM would be about 10 Gm^3, assuming a 50% recovery factor. In comparison with the 0.9 Mt per year coal-feed to the 250 MW power-plant at Barapukuria [10], ***10 Gm^3 of gas at Jamalganj could power the same 250 MW plant for over 15 years***.

Table 3. Coal-bed methane in selected commercially producing gas projects elsewhere in the world (From Jenkins and Boyer [16]). All projects exploit CBM hosted in bituminous coals, with the exception of the Yangcheng-Qinshui Field in China, where high-quality anthracite coals, with high gas concentrations, are exploited.

Basin	Field	CBM gas concentration (m^3/t)		In-situ CBM (Gm^3)	Recovery Factor (% of in-situ CBM)	Coal seam thickness (m)		Project area (km^2)	Well count	Average well density (wells/km^2)
		Minimum	Maximum			Minimum	Maximum			
San Juan (US)	Ignacio Blanco	8.5	17.0	49.9	66	12.2	21.3	155	130	0.84
Uinta (US)	Drunkard's Wash	12.0	12.0	44.5	57	1.2	14.6	311	450	1.45
Black Warrior (US)	Cedar Cove	7.1	14.2	22.9	53	7.6	9.1	168	520	3.09
Powder River (US)	Recluse Rawhide Butte	0.8	2.0	8.2	62	12.2	27.4	194	600	3.09
Western Canadian Sedimentary (Alberta)	Horseshoe Canyon	1.6	3.1	124.4	28	10.7	33.5	1,606	3,300	2.06
Bowen Basin (Australia)	Fairview	5.7	11.3	12.7	60	15.2	30.5	1,114	80	0.07
Qinshui (China)	Yangcheng-Qinshui	8.5	25.5	2.8	20	6.1	12.2	57	40	0.70

How is CBM exploited?

CBM is recovered using a closely spaced network of surface boreholes drilled into the target coal-seam at depth. Extraction is often initiated by hydraulically fracturing the coal-seam in the vicinity of the boreholes (by pumping fluid under high pressure into the borehole), to provide a high density of pathways for gas migration from the seam into the borehole. Gas passively desorbs out of the coal in response to the low in-seam pressure that is maintained by pumping gas and water out of the seam. There is no surface subsidence risk associated with CBM production, as only the gas resident in the coal-seam is extracted, leaving the host coal fractured, but still in place, underground

While the surface impact of CBM projects is much reduced relative to that of mining, the impact is by no means negligible. Even though much of the piping infrastructure associated with a CBM project can be buried, the major impact of the operation on the surface lies in the very high density of wells (boreholes) required to recover the gas, and the access tracks leading to all of them. Well densities typically vary between 1 to 3 wells per kilometer (Table 3). Figures 2 to 16 illustrate examples (both good-practice and less-impressive-practice) of different components of currently active CBM projects elsewhere, and provide some indication of the impact of the high well densities and other associated infrastructure. The impact of CBM extraction on the subsurface Dupi Tila acquifer system in Bangladesh is likely to low, as wells extracting the gas can be isolated from the acquifer by using casing. Product water derived from the coal-seams themselves during CBM extraction is generally released into the surface drainage system, and its impact depends on the quality of the coal-seam water. Elsewhere coal-seam waters are known to be both saline, with high sodium concentrations, and clean enough to provide a water source for domestic and agricultural use [17].

The social and environmental impacts of a CBM project might be more tolerable to affected communities where the local communities close to the infrastructure benefit directly from the project's electricity production. The Powder River project in the USA is characterised by the use of small-scale power plants fueled by local CBM gas (Figure 10), while in Jincheng City in China, the Sihe coal methane power plant will operate to a capacity of 120 MW using sixty 2 MW methane powered generators [18]. Such small-capacity generators could provide great flexibility and expandability when used on the local to regional scale. In terms of maximising the use of ground, and minimising the spatial area disrupted by CBM well-heads, it is possible to place several wells in close proximity, each drawing gas from different coal-seams at different depths (Figure 4).

It is interesting to note that two of the current projects in Table 3 (Fairview and Horseshoe Canyon) are supported over areal extents well in excess of 1,000 km^2. None of the basins in NW Bangladesh are further than 55 km apart from each other (Figure 1), and all are found within an area of less than 1,200 km^2. Suitable seams from two or more individual basins in Bangladesh could potentially be exploited within the framework of one larger project, benefiting from shared infrastructure and economies of scale.

As a final word on CBM, it is worth mentioning a future trend in CBM extraction, still under investigation and not yet implemented anywhere, in which methane extraction is coupled with the injection of carbon-dioxide into the (intact) coal-seam [16]. Coal absorbs CO_2 in preference to methane, and as CO_2 is absorbed into the coal-seam, methane is desorbed, providing the dual benefit of enhanced methane recovery and carbon sequestration. It is possible to look ahead to a power generation scenario in which a local power-station, powered by coal-bed methane, has its CO_2 emissions sequestered in the same seam that provided the methane. Naturally, if that seam were ever to be mined later, the trapped CO_2 would be released into the atmosphere.

<u>An aside on coalmine methane (CMM)</u>

Coalmine methane (CMM) refers to the coal-seam methane that is released into the underground workings of coalmines as coal is extracted (it is the same gas as CBM). Where the gas is emanating from abandoned underground mines, the term "abandoned mine methane" (AMM) is also used. Since the 1990's CMM and AMM has been recovered from many mines around the world (e.g., in USA, UK, China, South Africa and Ukraine), both as a significant energy source and as a means of ensuring safety in operating mines. Between 1994 and 2006, the USA is reported as having effectively recovered more than 15 Gm^3 of methane: 14 Gm^3 from active underground mines and 1 Gm^3 from abandoned underground mines [19].

Globally, CMM accounts for 6% of methane emissions resulting from human activities [20]. Because methane is a greenhouse gas, which according to the Inter-Governmental Panel on Climate Change has a global warming potential which is 21 times greater than that of carbon dioxide [21], the need to capture mine methane emissions is urgent. It is far preferable to capture methane and burn it (ideally generating energy in the process), than to allow the gas to escape into the atmosphere. Notwithstanding the disappointments at Barapukuria, if any future underground coalmines were to be considered in Bangladesh, it would be important to incorporate CMM capture technology. ***Coalmine methane cannot be captured in opencast coalmine operations***, resulting in the loss of a potential energy resource, and producing a significant additional emissions impact.

5. THE POTENTIAL ROLE FOR UNDERGROUND COAL GASIFICATION

<u>What is UCG, and what are its benefits and problems?</u>

Underground coal gasification (UCG) is a surface-based borehole method of extracting a hydrogen-methane gas mixture (containing lesser methane) from an underground coal-seam by burning the coal ***in-situ***. The process consists of one production well drilled into the coal-seam for injection of an oxidant (either air or oxygen), used to initiate and subsequently control and “direct” the burn; and another well to bring the product gas to surface [4]. In addition to the output hydrogen-methane gas mixture (which can be liquefied or used directly to fuel a power-station), waste gases consisting of carbon-monoxide, carbon-dioxide and hydrogen-sulphide are also produced.

In the UCG method, all operations are conducted from surface, no underground infrastructure is developed, nor are personnel required underground. UCG differs distinctly from the “accidental” coal fires that develop underground during conventional mining in that the underground coal fires and their hazardous combustion gases are uncontrolled. No infrastructure exists in conventional mines to recover the combustion gases.

The single major advantage of UCG is that mining can be avoided, while still recovering a large percentage of the energy-value of the coal deposit, in situations where surface disruption by mining is undesirable, or where the coal is beyond the reach of conventional mining methods, both of which are, again, directly relevant in the case of Bangladesh. Industry experience to date suggests that the energy generated by UCG per ton of coal is in the range 10 – 20 GJ/t [22]. As the analysis in the section below shows, the UCG energy return is significantly higher than that of CBM.

UCG is not currently used routinely in the west – several pilot or evaluation projects are underway in China, Australia and USA, while in the EU there are projects in Spain, UK and Belgium. The former Soviet Union, which was largely responsible for developing production UCG technology, had up to 14 industrial-scale UCG fired power plants operating between the 1950s and 1960s. With the exception of the Angren plant still operating in Uzbekistan, all the USSR’s plants were closed down by the end of the 1960s, following significant natural gas discoveries that replaced UCG. In South Africa Eskom operates the Majuba UCG plant.

An often raised criticism of the UCG approach is that it fails to control the carbon-dioxide (CO_2) emissions generated by the underground burn. Given that the net CO_2 emissions of a UCG-powered plant are no greater than one in which solid, mined coal is burned directly, the particular criticism seems unreasonable – ***all*** hydrocarbon fueled power-plants (coal, CBM, natural gas and UCG) need equally to establish the means of sequestering their emissions. There is some indication that net output of sulphur-dioxide (SO_2) and nitrogen-oxide (NO_X) into the atmosphere is lower for UCG-powered plants than coal burning equivalents, which is significant, as NO_X has a global-warming potential of 239 times that of CO_2 [23]. The need for solid waste-rock and coal-ash management on surface is also absent in UCG operations.

Problems associated with UCG production include difficulties in keeping control of the underground burn, and the potential for contamination/acidification of groundwater by the product gases as they pass upwards through the recovery boreholes (mitigated by using borehole casing) or where groundwater interacts with the combustion chamber, leaching toxic materials such as phenol and benzene [4]. In the case of Bangladesh, the extent to which the Upper Dupi Tila acquifer might be affected by contaminated coal-seam waters would depend on the (unknown) extent to which these deeper coal-seam acquifers are connected hydrologically to the shallower Dupi Tila acquifer. A further concern is that because the entire coal-seam is consumed by UCG, wherever the underground burn is directed, if adequate support in the form of unburned coal is not left behind, there is a high risk of surface subsidence in response to the underground combustion – the problem is not unlike that associated with longwall coal mining.

<u>What are the expected energy returns?</u>

Published measurements of the calorific value of coal samples are available for three of Bangladesh's coal basins: the average values are 6423 kcal/kg for Barapukuria [1, 7]; 6658 kcal/kg for Jamalganj [7, 9]; and 8164 kcal/kg for Khalaspir [7]. These measurements can be converted into equivalent values expressing the amount of energy contained in each ton of coal, and compared with the typical UCG energy return of 10 – 20 GJ/t:

Barapukuria:	26.9 GJ/t
Jamalganj:	27.9 GJ/t
Khalaspir:	34.2 GJ/t

While the "generic" estimate of typical UCG energy return is not locality-specific, in the sense that the calorific value of the particular coal going into the process – a critical part of the energy equation – is not specified, it does provide some bounds indicating that ***between 30 – 75% of the in-situ energy value of the Bangladeshi coal could be recovered by UCG, without having to mine it.***

6. CONCLUSIONS AND SUMMARY

The purpose of this review is not to laud the benefits of coal exploitation, but to raise awareness of two extraction approaches, CBM and UCG, that provide an alternative to potentially destructive surface- and underground-mining practice, within a context in which it seems unavoidable that Bangladesh should use its coal resources to resolve its critical energy needs.

An electricity supply of around 5,000 MW is currently required to meet the needs of Bangladesh, yet only about 3,200 MW is being produced. Most of the electricity supply is generated by power-plants fueled by "natural" gas, and the country's natural gas reserves are finite. If the present-day natural gas consumption rate were to increase at a rate of 10% per year, the proven and recoverable gas reserves (a maximum of about 340 Gm^3), would be exhausted by 2019. At that rate of increased consumption, electricity production would exceed 5,000 MW by 2012.

Not all of the coal present in Bangladesh is recoverable by mining; much of it is in seams either too deep or too thin for economic extraction. Of a total of about 4,744 Mt of coal believed to be buried in five Gondwana basins, the resource recoverable by mining is estimated to be about 1,400 Mt (equivalent to 975 Gm^3 of gas - about three times Bangladesh's current recoverable natural gas resource). At a nominal consumption rate equivalent to 48.5 Gm^3 of gas per year, which is the projected gas consumption rate at 2019, the recoverable coal would last for 20 years. However, acknowledging the lessons learned at Barapukuria, it seems unreasonable to expect that all the resources "recoverable" by mining will in fact be recovered, in the face of a set of geological and technical problems, and social and environmental costs, that are likely to be present in all of the coal-bearing basins.

No direct laboratory measurements have yet been made of the CBM gas content of coal samples from any of the Bangladesh coal basins. In the absence of such measurements, the current best estimate of the gas content of the coals is provided by predictions of gas concentration based on the known characteristics of coal from Barapukuria. These predictions suggest CBM gas concentrations of between 6.51 – 12.68 m^3/t. Extrapolation of these concentrations to all of the coal basins yields an estimate of the total in-situ CBM resource in Bangladesh of 31 – 60 Gm^3.

The value of the CBM resource is best illustrated at Jamalganj, where 80% of the coal is hosted in two thick seams that are too deep for mining. Here, the recoverable resource is estimated to be about 10 Gm^3, which could power a 250 MW plant, equivalent to the one currently at Barapukuria, for over 15 years. Given that none of the basins in NW Bangladesh are further than 55 km apart, good potential exists to share infrastructure and benefit from economies of scale by exploiting suitable seams in a number of basins within the framework of one larger project.

Both CBM and UCG provide an energy return that is less than that provided by the coal itself, were it to be mined. In the case of CBM, it is significantly less: at best 2% of the energy value of the coal containing the CBM. In the case of UCG, the return is much higher: between 30 – 75% of the energy value of the coal could be recovered, without the need for mining. Yet both methods provide many distinct advantages over mining:

- Coal-seams not accessible by mining are within reach of both CBM and UCG, and can add to the recoverable resource.
- The impact on surface is significantly lower and the loss of valuable agricultural land to the process of energy production is greatly reduced; the need for solid waste-rock and coal-ash management on surface is entirely removed; there is no subsidence risk associated with CBM extraction, and

subsidence in the case of UCG can be avoided provided adequate unburned coal is left in place.

- The impact on the surface and subsurface hydrological systems should be much reduced, particularly in the case of CBM.
- A CBM project could deliver its electrical power output in half the time period required by mining. Industry experience provides a reasonable expectation that CBM-based power could be brought online within about 5 years of starting a feasibility drilling program and study, particularly if a local-scale project is established initially. (The feasibility study at Barapukuria was initiated in 1989, and the first coal production from the mine started in 2005).

No single extraction method is ideally suited to all coal-seams within all five coal basins of NE Bangladesh. To limit the available options to mining only would fail to maximise the resource recovery. It would also, almost certainly, maximise the social and environmental costs of energy provision. To date the full cost of mining has not been acknowledged: at Barapukuria Mine, authorities admit they are unable to make the huge capital payments necessary to compensate for subsidence-related damage without help from the government, and that these costs were not built into the original financial model.

Given the close proximity of all the basins, there would be distinct advantages in developing an integrated and centrally controlled approach to exploiting the resources, one in which the appropriate extraction methodology is identified for each particular target coal-seam or group of coal-seams, based on an optimal balance between the amount of energy delivered and its true economic and social cost.

LIST OF REFERENCES

[1] Islam, M.R and Hayashi, D., 2008. Geology and coal bed methane resource potential of the Gondwana Barapukuria Coal Basin, Dinajpur, Bangladesh. *International Journal of Coal Geology*, 75(3), 127-143, doi:10.1016/j.coal.2008.05.008.

[2] Islam, M.R., Hayashi, D. and Kamruzzaman, A.B.M., 2008. Finite element modeling of stress distributions and problems for multi-slice longwall mining in Bangladesh, with special reference to the Barapukuria coal mine. *International Journal of Coal Geology*, doi:10.1016/j.coal.2008.10.006.

[3] Bustin, R.M. and Clarkson, C.R., 1998. Geological controls on coaled methane reservoir capacity and gas content. *International Journal of Coal Geology*, 38, 3-26.

[4] http://en.wikipedia.org/wiki/Underground_coal_gasification (04/03/2009).

[5] Khalequzzaman, Md., September 2007. Same-side coal. *Forum, a monthly publication of The Daily Star* (Bangladesh), Volume 2, Issue 8.

[6] Haque, M.I., October 25, 2007. The coal debate in Bangladesh. *New Age* (Bangladesh).
http://banglapraxis.wordpress.com/2007/10/25/the-coal-debate-in-bangladesh/

[7] Akhtar, A., March 2000. Coal and hard rock resources in Bangladesh. *Episodes*, 23(1), 25-28.

[8] Staff correspondent, March 17, 2008. Petrobangla gets license for first time to explore coal in Joint Venture. *EnergyBangla*.
http://www.energybangla.com/index.php?mod=article&cat=CoalSector&article=47

[9] Imam, M.B., Rahman, M. and Akhter, S.H., 2002. Coalbed methane prospect of the Jamalganj coalfield, Bangladesh. *The Arabian Journal for Science and Engineering*, 27(14), 17-27.

[10] Staff correspondent, May 9, 2007. Work begins from next week to purge tunnel of poisonous gas. *New Age* (Bangladesh).
http://www.newagebd.com/2007/may/09/nat.html

[11] Staff correspondent, August 9, 2008. $10m equipment retrieved from sealed mine site in Barapukuria. *Bangladesh News*.

http://www.bangladeshnews.com.bd/2008/08/09/10m-equipment-retrieved-from-sealed-mine-site-in-barapukuria/

[12] Khan, S., January 18, 2009. Over 4sq km area to subside up to 2m. *The Daily Star* (Bangladesh). http://www.thedailystar.net/story.php?nid=71810

[13] Khan, S., February 17, 2009. Coal city planned to rehabilitate victims. *The Daily Star* (Bangladesh). http://www.thedailystar.net/newDesign/news-details.php?nid=76179

[14] Talukder, A., September 5, 2008. Land subsides again in B'pukuria mine area. *EnergyBangla*. http://www.energybangla.com/index.php?mod=article&cat=CoalSector&article=684

[15] Moody, R. (Nostromo Research and Bank Information Center), November 12, 2008. Phulbari coal: a parlous project. http://www.minesandcommunities.org//article.php?a=8968

[16] Jenkins, C.D. and Boyer, C.M., 2008. Coalbed- and shale-gas reservoirs. Distinguished Author Series, *Journal of Petroleum Technology*, February Issue, 92-99, SPE 103514.

[17] The Department of Land Resources and Environmental Sciences, Montana State University – Bozeman. http://waterquality.montana.edu/docs/methane/cbmfaq.shtml

[18] InfoPetro Technology Development, Ltd, August 2007. China, US to jointly develop 15 coalbed methane projects. *China Coalbed Methane Report*, No. 4, Vol . 1, 7-8.

[19] U.S. Environmental Protection Agency, Coalbed Methane Outreach Program (CMOP). http://www.epa.gov/cmop/accomplishments.html

[20] Methane to Markets Partnership, March 2008. Underground coalmine methane recovery and use opportunities. http://www.methanetomarkets.org/resources/factsheets/coalmine_eng.pdf

[21] The Coal Authority, UK. http://www.coal.gov.uk/resources/cleanercoaltechnologies/CoalMineandbedmethane.cfm

[22] Chadwick, J., February 19, 2009. Massive Australian coal deposit has great CTL and gasification potential. *Mineweb*. http://www.mineweb.com/mineweb/view/mineweb/en/page38?oid=78720&sn=Detail

[23] Shu-qin, L. and Jun-hua, Y., 2002. Environmental benefits of underground coal gasification. *Journal of Environmental Sciences*, 12, 284-288.

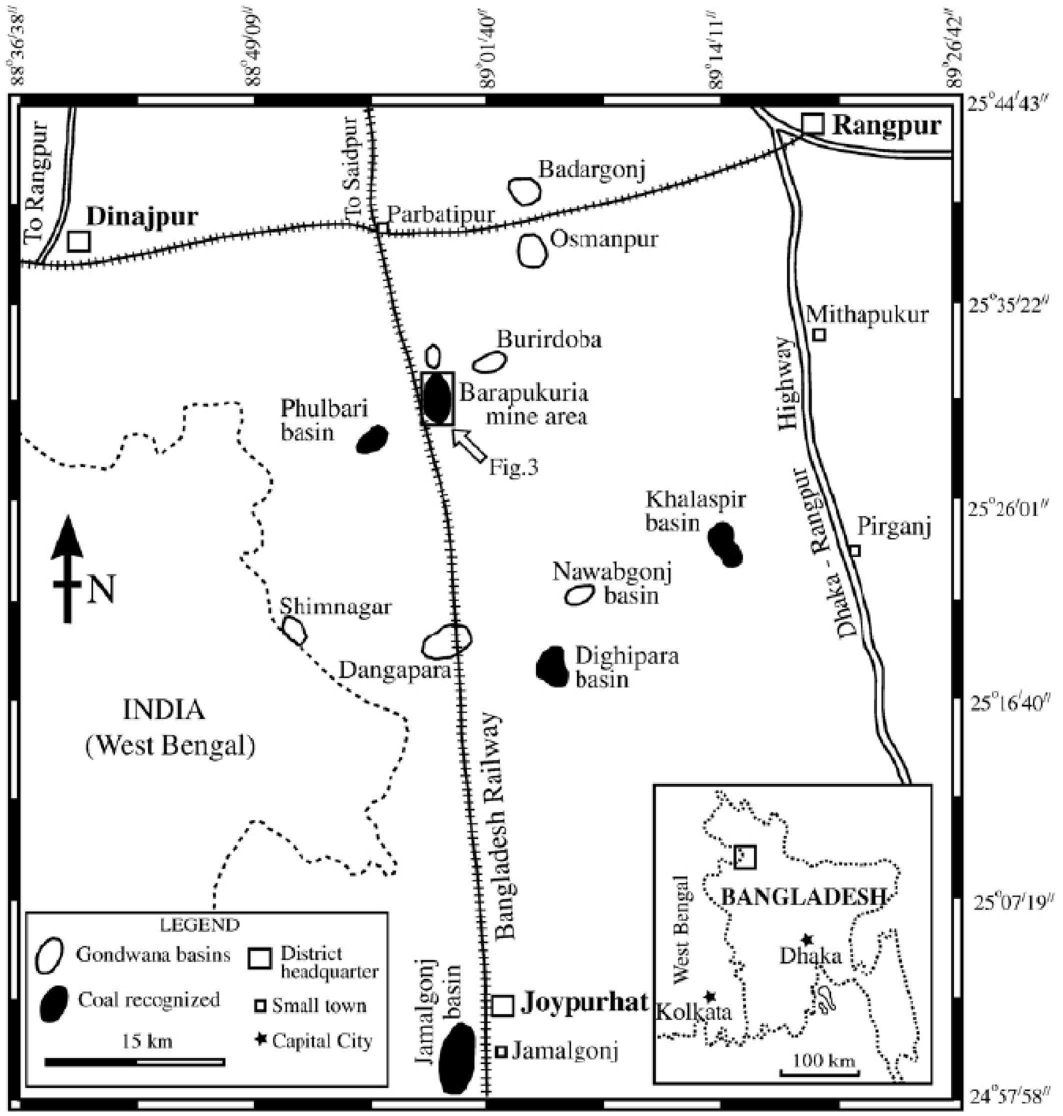

Figure 1. Gondwana coal deposits of NW Bangladesh. (From Islam and Hayashi [1]).

Figure 2. CBM development landscape in the Powder River Basin of Wyoming. Note the roads, pods of well heads, and in-channel and off-channel product water impoundments.
http://waterquality.montana.edu/docs/photo/cbm_landscape.shtml

Figure 3. CBM development in the Powder River Basin of Wyoming. The Tongue River appears in the upper portion of the photo.
http://waterquality.montana.edu/docs/photo/tongue_river3.shtml

Figure 4. Pod of well heads in the Powder River Basin of Wyoming. Each well is drilled into a different CBM-producing coal seam.
http://waterquality.montana.edu/docs/photo/well_pod.shtml

Figure 5. Typical CBM well head, Powder River Basin of Wyoming.
http://waterquality.montana.edu/docs/photo/well_head.shtml

Figure 6. New pipeline being laid in the Powder River Basin. One line carries methane, and the other transports product water away from the well. http://waterquality.montana.edu/docs/photo/pipeline_1.shtml

Figure 7. Compressor station in the Powder River Basin of Wyoming.
http://waterquality.montana.edu/docs/photo/compressor_station.shtml

Figure 8. A second stage compressor station in the Powder River Basin.
http://waterquality.montana.edu/docs/photo/compressor_second_stage.shtml

Figure 9. Progressive cavity pumps located very near the city of Durango, Colorado, in the San Juan Basin. These pumps are a best engineering practice to reduce noise typically associated with CBM wells.
http://waterquality.montana.edu/docs/photo/progressive_cavity_pump.shtml

Figure 10. Electricity generator near Gillette, Wyoming, run entirely off coal bed methane.
http://waterquality.montana.edu/docs/photo/methane_electricity_generator.shtml

Figure 11. Shell coal-bed methane exploratory well site, Wheeler Creek, Elk Valley, British Columbia, Canada, December 2004. (From Flathead basin Commission).
http://www.earthjustice.org/library/factsheets/annex-of-photos-june-27-2008.pdf

Figure 12. Encana/StormCat coal-bed methane pilot project, 2004, Elk Valley, British Columbia, Canada. (From Citizens Concerned About Coalbed Methane).
http://www.earthjustice.org/library/factsheets/annex-of-photos-june-27-2008.pdf

Figure 13. Encana/StormCat exploratory CBM well site. (From Flathead Basin Commission).
http://www.earthjustice.org/library/factsheets/annex-of-photos-june-27-2008.pdf

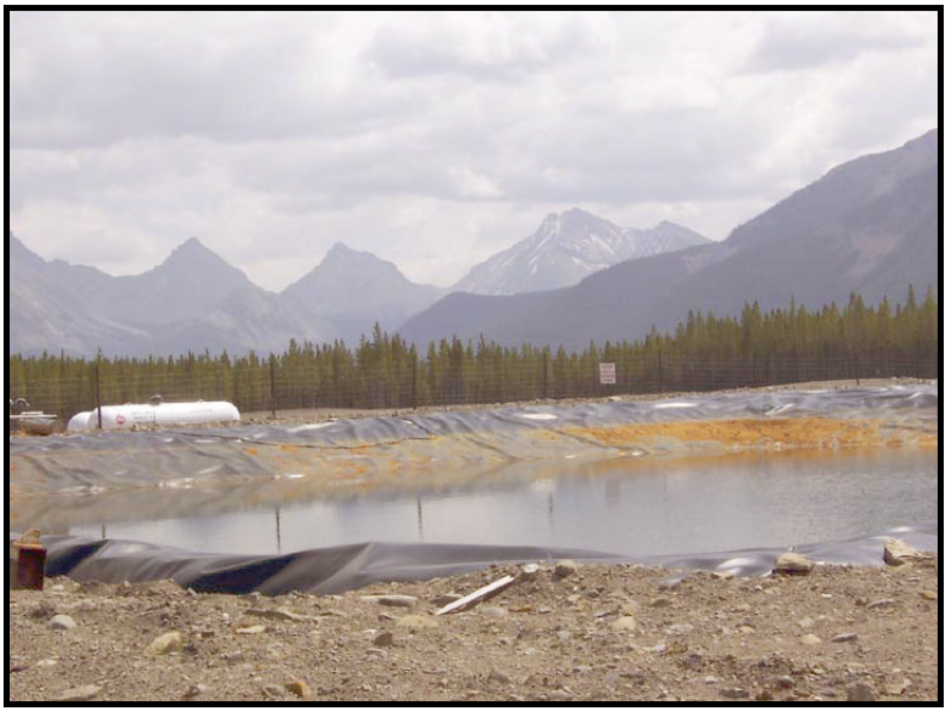

Figure 14. Encana/StormCat wastewater settling ponds at exploratory CBM well site. (From Flathead Basin Commission).
http://www.earthjustice.org/library/factsheets/annex-of-photos-june-27-2008.pdf

Figure 15. Shell Canada Ltd.'s Wheel Creek CBM site, collapsed and slumped into Wheeler Creek in heavy rains, southeast British Colombia, Canada. Photo by Erin Soxton. (From Flathead Basin Commission).
http://www.earthjustice.org/library/factsheets/annex-of-photos-june-27-2008.pdf

Figure 16. A typically dense network of well sites in the USA at an un-named CBM field. (From Citizens Concerned About Coalbed Methane).
http://www.earthjustice.org/library/factsheets/annex-of-photos-june-27-2008.pdf

APPENDIX 1. BRIEF HISTORY OF BARAPUKURIA COALMINE

DATE	ACTIVITY
1985 - 1988	Exploration drilling (7 holes) in the Barapukuria area by Geological Survey of Bangladesh [i].
1989 - 1990	Feasibility study by Wardell Armstrong Mining Consultants. 12 additional boreholes drilled [i].
March 1992	Barapukuria project approved. Target completion date of July 31, 2001, at planned cost of Tk 887 crore [vi]. Contractors China National Machinery Import & Export Corporation (CMC) eventually hand over a "productive" mine in 2005, more than four years behind schedule, and at cost of more than Tk 1,600 crore [vi].
1994	Further 15 boreholes drilled by mine developers CMC [i].
1996	Construction and development of the mine commenced [i]. Mine is originally planned to deliver 64 Mt of coal, at a rate of 1 Mt per year over 64 years [ii]. Alternative sources [iii, v] indicate the original plan was to recover 2 Mt per annum for 30 years.
April 5 1998	Mine is flooded during development work by uncontrollable influx of water from overlying acquifer [i, iv]. Required revision of mine design, limiting extraction to the southern part of the mine, and relocation of the mine's shaft [i, vi]. Recoverable resource downgraded to 34 Mt, mined over 34 years [i].
During 1999	Two Bangladeshi mine-workers died in an accident inside the mine [vi].
May 31, 2005	Development and construction of underground mine reported complete by CMC [xiv].
June 4, 2005	Production, Maintenance and Management (M&P) contract signed between mine owners Barapukuria Coal Mining Company Limited (BCMCL, 100% Petrobangla) and the operator consortium consisting of CMC and Xuzhou Coal Mining (XMC) [xiv].
September 2005	Commercial coal production starts with mining of longwall panel 1101 [i] and 1110.
September 30, 2005	Alarming increase in carbon-monoxide levels detected in vicinity of face 1110 [iv, vi].
October 5, 2005	Working face 1110 closed and sealed-off because of carbon-monoxide gas release caused by spontaneous combustion of unattended coal piles left underground since May 2005. One set of longwall mining equipment (of the two sets inside the mine) is left trapped inside sealed-off area [iv]. The combustion event may have been associated with a methane "emission" reported to have occurred around this time [i].
2006	Land subsidence in the mining area above the mine is first reported [ix].
October 2006 - April 2007	Mine work completely suspended due to payment dispute between BCMCL and CMC. Power production by 250 MW power plant also affected during this period [iv, viii].
March 2007	Production started on panel 1109 in March 2007, but delayed for six months due to unexpected geological and environmental problems. 176 m of excavated roadway abandoned due to a large roof-fall and hot strata-water ingress [xiv]. Face 1109 required a redesign in response to problems [xiv], but it is not clear if panel was ever completed.

April 26, 2007	British mining consultant, Albert Banes Davis (62) from IMC (UK) died, most likely from carbon-monoxide poisoning underground, while investigating a recovery plan for the abandoned equipment in panel 1110. A second IMC consultant, Nicolas Sharon Woodburn (26) was also recovered unconscious from the mine at the same time, requiring hospital treatment [vii].
May 2007	Work due to start during May to purge the sealed-off part of the mine (working panel 1110) [vii]. Mine is reported as having failed to produce at full capacity since operations started: current daily production rate reported at this time as between 700 - 1,500 tons per day [viii].
2007 - 2008	Mine's operation suspended for 6 month period. The 250 MW power station shut down due to lack of coal supply [iii].
February 3, 2008.	A record daily production of 4,085 tons coal reported - almost three times higher than daily production rate in 2007 [v].
July 14, 2008	Operations launched to re-open sealed face 1110 and recover stranded equipment (worth US$ 10 Million). Operation launched following months of preparation and injection of anti-flammable chemicals and nitrogen into the working area [iv].
August 9, 2008	Stranded mining equipment finally recovered from panel 1110 [iv].
End 2008	BCMCL reported as having incurred a loss of Tk 156 crore between 2005 and 2008 [xiii].
January 2009	Surface subsidence above the mine reaches alarming levels, despite mining to date having extracted only one single 3 meter high slice from six longwall mining panels. (The mine proposes to extract 6 slices, with a total 18 m extraction height, in order to achieve its target recovery of 34 Mt). A 1.2 km^2 area has subsided by 0.3 - 0.9 m. At least 81 houses in 5 villages have developed cracks. Mine authorities predict a total area of 4.2 km^2 will be affected by subsidence during the 30 year life-of-mine. Mine estimates of total subsidence are ambiguous, varying between 2 m in total and 2 m per slice mined. Common tube-well water reservoirs in about 15 villages have dried up. Boro crops in large areas are reported to have been flooded prior to harvesting. The mine is also releasing hazardous water (acknowledged by the mine to contain phosphorous, arsenic and magnesium) through canals in farming areas [ix, x].
February 17, 2009	The government announces it is considering the establishment of a "coal city" near Barapukuria to provide housing and occupation to people in at least 15 villages affected by the coalmine and to become the center for mining related higher studies [xi].
February 18, 2009	Protesting villagers stop the mine from starting coal production in panel 1114, by preventing surface boreholes from being closed-off, demanding compensation for loss of arable land. Contract operators CMC retrenches 800 people and threaten to withdraw from Bangladesh if coal mining not allowed to continue [xii]. Mine sources indicate the mine has paid Tk 24.22 lakh as food-grain compensation to owners of 60.76 acres of land that has subsided since 2006, but is unable to make huge capital payments for damage without help from the government [xii].
March 8, 2009	Coal production resumed, following demonstrations that halted production. Forest and Environment State Minister Mostafizur Rahman Fizar visited the area and assured the villagers of compensation to overcome the subsidence crisis. CMC reinstates retrenched miners [xiii].

	Generic mining problems at Barapukuria
	Mine official admitted to Daily Star Reporter around April 27, 2007: "The mine is constantly being flooded with water having a temperature of 48 degrees Celsius, which we need to pump out around the clock. There are frequent roof collapse [sic], and the mine's columns supporting the roof have developed alignment mismatches. The air and working condition inside the mine is now very hazardous even for a healthy man. It is so hot and humid that a few hours of stay underground can make you very ill." [vi]
	Comments about difficulties encountered in the mining of panel 1109, from BMCL webpage: Due to geological constraints, it was necessary to install the Heavy Hydraulic Powered Roof Support (HPRS) on an inclined floor, which resulted in the HPRS slipping and tilting downward [and therefore functioning sub-optimally]. Adverse strata condition - coal is friable and prone to caving. Adverse environmental conditions - high temperature (39 degrees Celsius and 100% humidity. Relatively high strata-water inflow washing down the floor of the longwall face and causing instability to the HPRS. Miners become faint and sick, and develop heat stroke due to the adverse environment [xiv].

REFERENCE LIST FOR APPENDIX 1
[i] Islam, M.R and Hayashi, D., 2008. Geology and coal bed methane resource potential of the Gondwana Barapukuria Coal Basin, Dinajpur, Bangladesh. International Journal of Coal Geology, 75(3), 127-143, doi:10.1016/j.coal.2008.05.008.
[ii] Akhtar, A., March 2000. Coal and hard rock resources in Bangladesh. Episodes, 23(1), 25-28.
[iii] Staff correspondent, October 6, 2008. Barapukuria Coal Mine Company to export 200,000 tonnes Coal mine exploration result. Paguntaka.org. http://paguntaka.org/2008/10/06/barapukuria-coal-mine-company-to-export-200000-tonnes-coal-mine-exploration-result
[iv] Staff correspondent, August 9, 2008. $10m equipment retrieved from sealed mine site in Barapukuria. Bangladesh News. http://www.bangladeshnews.com.bd/2008/08/09/10m-equipment-retrieved-from-sealed-mine-site-in-barapukuria/
[v] Staff correspondent, February 6, 2008. Barapukuria coalmine gets into full swing. Bangladesh News. http://www.bangladeshnews.com.bd/2008/02/06/barapukuria-coalmine-gets-into-full-swing/
[vi] Staff correspondent, April 27, 2007. British consultant dies 430 m down Barapukuria mine. Bangladesh News. http://www.bangladeshnews.com.bd/2007/04/27/british-consultant-dies-430m-down-barapukhuria-mine/
[vii] Staff correspondent, April 29, 2007. Probe body starts work, to place report in 7 days. The Daily Star (Bangladesh). http://www.thedailystar.net/2007/04/29/d70429012716.htm
[viii] Staff correspondent, May 9, 2007. Work begins from next week to purge tunnel of poisonous gas. New Age (Bangladesh). http://www.newagebd.com/2007/may/09/nat.html
[ix] Khan, S., January 18, 2009. Over 4sq km area to subside up to 2m. The Daily Star (Bangladesh). http://www.thedailystar.net/story.php?nid=71810
[x] Talukder, A., September 5, 2008. Land subsides again in B'pukuria mine area. EnergyBangla. http://www.energybangla.com/index.php?mod=article&cat=CoalSector&article=684
[xi] Khan, S., February 17, 2009. Coal city planned to rehabilitate victims. The Daily Star (Bangladesh). http://www.thedailystar.net/newDesign/news-details.php?nid=76179
[xii] Karmakar, K. and Khan, S., March 6, 2009. Barapukuria coal mine in trouble. The Daily Star (Bangladesh). http://www.thedailystar.net/story.php?nid=78611
[xiii] Own correspondent, March 9, 2008. Production resumes at Barapukuria coal mine. The Daily Star (Bangladesh). http://www.thedailystar.net/newDesign/news-details.php?nid=79070
[xiv] Official Barapukuria Mining Company Limited webpage: Section on "Activities & Analysis of Coal". http://www.bcmcl.org.bd/