INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING
ISSN: 2229-838X e-ISSN: 2600-7916

IJIE

Vol. 16 No. 1 (2024) 1-13
https://publisher.uthm.edu.my/ojs/index.php/ijie

Assessing Potentiality of Underground Coal Gasification for the Coalfields of Bangladesh

Arup Kumar Biswas[1,2], Mohd Faizal Mohideen Batcha[3], Makatar Wae-hayee[4]*

[1] *Hydrocarbon Unit, Energy and Mineral Resources Division, People's Republic of Bangladesh, Dhaka, 1000, BANGLADESH*
[2] *Faculty of Environmental Management, Prince of Songkla University, Hat Yai, Songkhla 90110, THAILAND*
[3] *Center for Energy and Industrial Environment Studies, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Johor, MALAYSIA*
[4] *Department of Mechanical and Mechatronics Engineering, Faculty of Engineering, Prince of Songkla Universit, Hat Yai, Songkhla 90110, THAILAND*

*Corresponding Author: wmakatar@eng.psu.ac.th
DOI: https://doi.org/10.30880/ijie.2024.16.01.001

Article Info

Received: 25 October 2023
Accepted: 11 January 2024
Available online: 25 April 2024

Keywords

Underground coal gasification, unconventional coal mining, potentiality of UCG, factors governing UCG potential, coalfields of Bangladesh

Abstract

Underground Coal Gasification (UCG), an atypical technique for mining coal, could potentially unlock vast untapped coal reserves of Bangladesh. However, there was very little work done on UCG potentiality analysis considering the properties of all the coalfields collectively based on the worldwide experiences. To increase a better understanding from that perspective, this study was therefore of interest. The study explored the essential factors required to assess the potentiality of UCG application for the five coalfields of the country. The threshold values were retrieved from published data of known trials occurred around the world. These were then compared with the available data of indigenous coalfields. In terms of the UCG prospects, all the coalfields passed the depth, thickness, ash content and rank factors to a significant extent. But faulting, overburden or aquifer proximity are somewhat critical for all the coalfields except Jamalganj. In addition, Khalaspir field, despite having few discontinuities, would be a good candidate for UCG implementation once Jamalganj field reaches the marker. This work might help initiating further steps through the analogous approach for siting the first UCG trial in the country.

1. Introduction

Energy needs of Bangladesh are growing quickly to meet the country's aspirations as it emerges. Regretfully, the nation has already begun to struggle with the issue of not having enough energy to support economic growth [1]. Unfortunately, among the indigenous sources of energy (natural gas and coal only), natural gas reserve is depleting soon enough. Almost all petroleum products (fuel oil, crude oil, lubricants etc.) are imported. With the above limited options, coal-based industry (mainly power plants) is becoming lucrative.

Nomenclature	
CCT	Clean Coal Technology
EGR	Enhanced Gas Recovery

JICA	Japan International Cooperation Agency
PSI	Preference Selection Index
PSMP	Power Sector Master Plan
SDB	Steeply Dipping Bed
UCG	Underground coal gasification

Accordingly, the coal demand is increasing very rapidly, as such the imminent necessity is being met through imports. In 2020 and 2021, among the national demand of 7.6 and 7.5 million tons of coal, import volume was 6.8 million tons in both cases [2]. Power Sector Master Plan (PSMP) of Bangladesh devised by JICA (2016) predicted that in 2030 and 2041, against the demand of 27.2 and 71.2 million tons of coal, around 21.0 and 60.0 million tons respectively, will be imported [3]. While energy security is a worldwide concern, such dependency on imports is a grave concern for the nation.

Large coal reserves were first discovered in the country in 1960s. Later on, four more coalfields were discovered in the Northwestern region [4]. However, those were unable to meet the nation's energy needs using traditional mining methods (i.e., underground or opencast) [5]. Even in the face of constantly increasing energy demand that often outpaces supply, the country still does not have a comprehensive plan to exploit the vast indigenous coal resources due to various techno-environmental issues. In this case, the study is expected to support academics' and professionals' cognitive processes in the energy industry.

In the scenario of global awakening of promoting Clean Coal Technology (CCT) options, unconventional coal mining methods, such as UCG could lead the way when it comes to sustainable coal resource extraction. This can effectively reduce many obstacles of conventional mining straightaway. Because UCG does not bring the coal to the surface, there is no need for coal handling, washing, or transportation, nor is there an ash problem or underground mining [6], [7].

However, research work is found scarce while assessing UCG potentiality of available coal resources of the nation, considering the attributes derived from well-established global trials. Only UCG prospect of Jamalganj coalfield has been studied theoretically by few researchers. Maybe because Jamalganj needed exceptional mining technique other than the conventional ones being the deepest coal deposit, or maybe, any kind of resource exploitation scheme has been long unaddressed even after containing the biggest possible coal reserve of the country. A review of the hydrology and geology of coal bearing region of Bangladesh was performed by Sajjad *et al.* (2014) [5]. Thomas Kempka *et al.* (2011) suggested theoretical feasibility based on economics of coupled UCG-Urea process along with CO_2 storage options [8]. Following up this work, Nakaten *et al.* (2014) projected a techno-economic assessment of UCG application in Bangladesh for supporting the scarcity of electricity and fertilizer from syngas product along with Enhanced Gas Recovery (EGR) option through additional CO_2 utilization [9]. Recently, Biswas *et al.* (2023) conducted an analytical investigation through Preference Selection Index (PSI) method of critical factors to prioritize coalfields of the country for UCG applicability [10].

This study intends to find out whether coalfields in the country meet the prerequisites for UCG application, also focuses on identifying the most suitable coalfield of the nation for gasifying coal in the underground based on the factors which govern the UCG potential.

2. Coal Resources of Concern and UCG Potentiality Factors

2.1 Bangladesh Coal Resources

Five underground Gondwana sedimentary basins dating back to the Permian were found in north-western part of the country (Fig. 1). Noticeably, the region appears to have all exploitable coal deposits within the territorial boundary of the nation. The coal basins were formed on top of the Precambrian basement complex during geologic past (Permo-carboniferous, 355–270 million years ago). Tectonically, these Permian coal basins are bordered by the Indian Shield to the west, the Shillong Massif to the east, the Bogra Shelf to the south, and the Himalayan Foredeep to the north. The Bogra slope of the stable platform zone contains the Gondwana basin of the Jamalganj coal region. While the other four basins lie in the extended intra-tectonic basins of Rangpur saddle trending NNW-SSE. The stratigraphic, structural, and depositional histories of these basins are comparatively comparable. Thereby, the Permian rocks, beneath the Precambrian basement complex, are generally covered by either Tertiary or Cretaceous deposits. The sedimentary strata include of dark grey carbonaceous shale and sandstones, variegated conglomerates, thick coal seams, and light to dark grey, fine to extremely coarse grained, sub-angular to sub-rounded feldspathic sandstones [11]–[13].

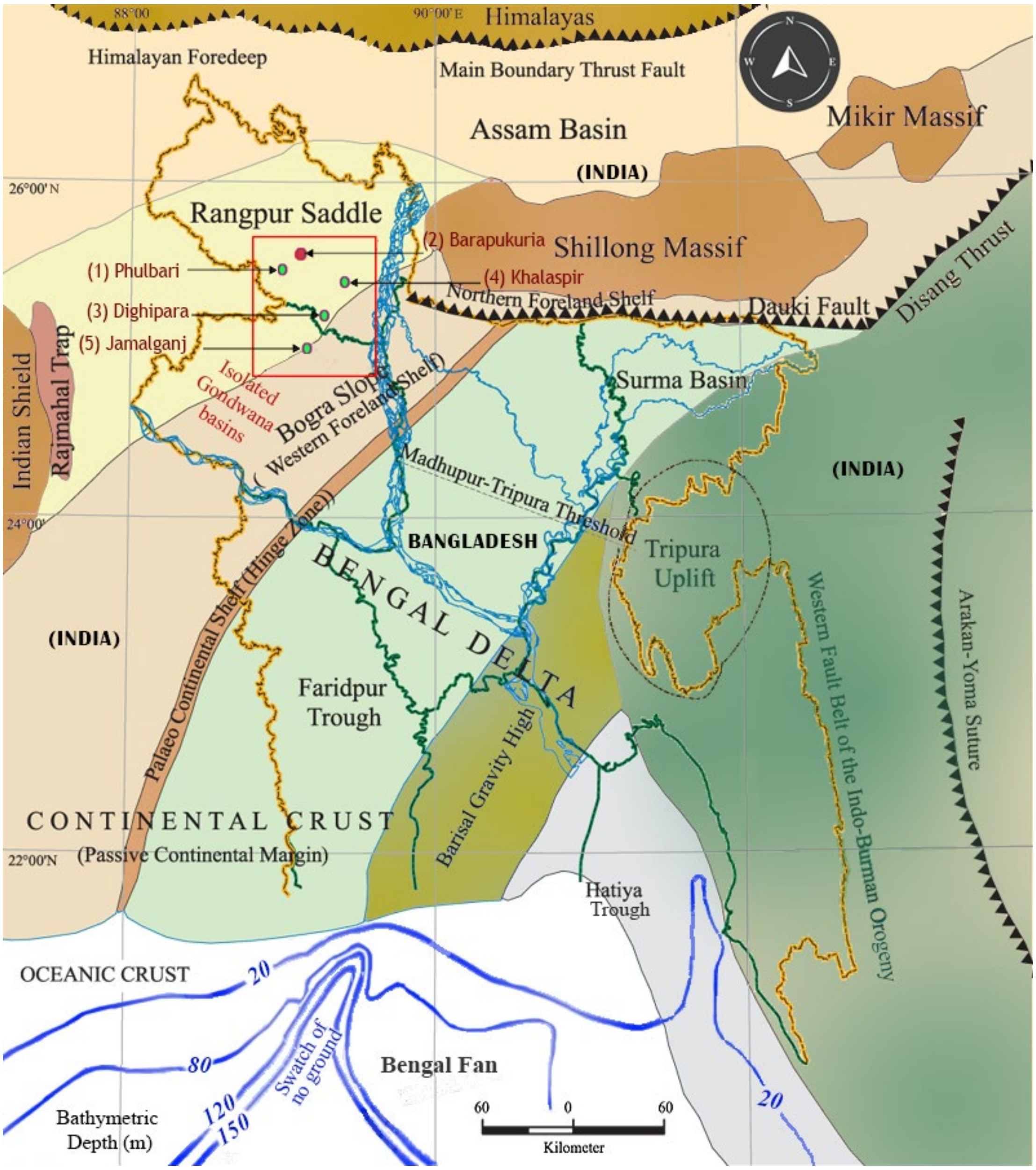


Fig. 1 *Regional coal occurrences in north-western Bangladesh within Gondwana basins with adjoining tectonic elements; redrawn and simplified after* [11], [12]

Permian coals are intersected at 118m-1150m in small graben structures found in Phulbari, Barapukuria, Dighipara, Khalaspir, Jamalganj, and other places in Dinajpur and Rangpur districts as High Volatile C to A type bituminous coal. The cumulative coal reserves are estimated to be around 3.3 billion tons [4], [14]–[16].

Out of the five discovered fields, coal from four deposits (depths ranging within 118-509 meters) excluding the Jamalganj deposit, may be extractable at present by conventional methods (i.e., underground or opencast mining). Only Barapukuria coalfield (discovered in 1985) has been operated through underground mining method since 2005. Phulbari (discovered in 1997) was proposed for open pit mining after a feasibility study in 2006, but halted due to local violent resistance[17]. A German company conducted a feasibility study (2017-2019) for underground mining development in Dighipara (discovered in 1995); 1st revision was completed on 31st March 2020. Khalaspir (discovered in 1989) coalfield is still undeveloped after the underground mining feasibility study held in 2006 [18]. After several attempts to develop Jamalganj (first coalfield discovery of the nation in 1962) it is assumed that adoption of any conventional mining techniques (i.e., underground or opencast) has been difficult due to greater depth (~1100 m). A recent (2016) feasibility study focusing on CBM prospects found operation non-profitable [19]. Therefore, the government is currently looking for piloting deep underground mining or UCG in this coalfield.

2.2 UCG at a Glance

An efficient industrial technique of extracting energy from coal could be UCG application which provides an alternative to conventional underground mining for apparently untapped coal resources (in view of uneconomical, especially when the deposit is too deep, of low grade, or very thin) with minimal surface disturbance. Through partial oxidation, this thermochemical process turns coal into a high-quality but inexpensive synthesis gas or fuel. In order to create a flow path within the coal seam, it entails drilling injection and production wells from the surface to the target coal seam (Fig. 2) and then building a highly permeable channel between those two wells [6], [7], [20].

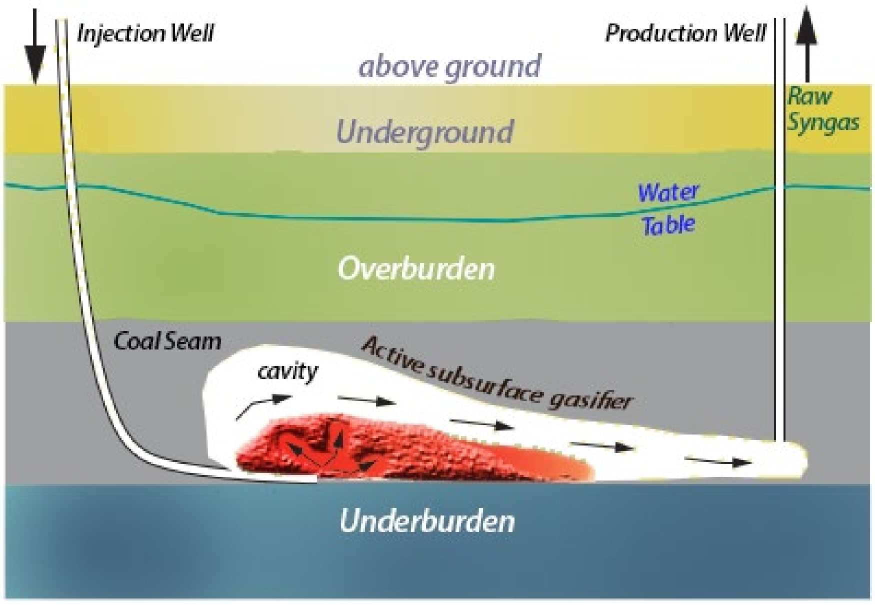


Fig. 2 *Schematic of underground coal gasification*

The process requires injecting steam and an oxidant (either pure oxygen or air) which are the only feed materials to sustain the gasification process, and their effective proportion manoeuvres the gasification performance [21]. As coal is not dug out of the subsurface, the ashes remain underground. The UCG objective is to produce a syngas with a high percentage of CO and H_2, while the coal geology and the gasification parameters strongly impact the composition. The resultant gas can be utilized as a feedstock for chemical products such as hydrogen, methanol, ammonia, fertilizers, and synthetic natural gas, or it can be used to generate electricity. It contains H_2, CO, and CO_2 with minor amounts of CH_4, higher hydrocarbons, and traces of tars and pollutants [6], [7].

2.3 Identification of Essential Factors Governing UCG Potentiality of a Coalfield

There are notable factors which administer the UCG success. Among those, some physical parameters of a coalfield perhaps bear the most significance. These factors have been proved worthy by comprehensive UCG experiences from previous trials and research [6], [7], [22], [23]. Integration of those factors has been performed to assess potentiality of UCG for the discovered coalfields of Bangladesh.

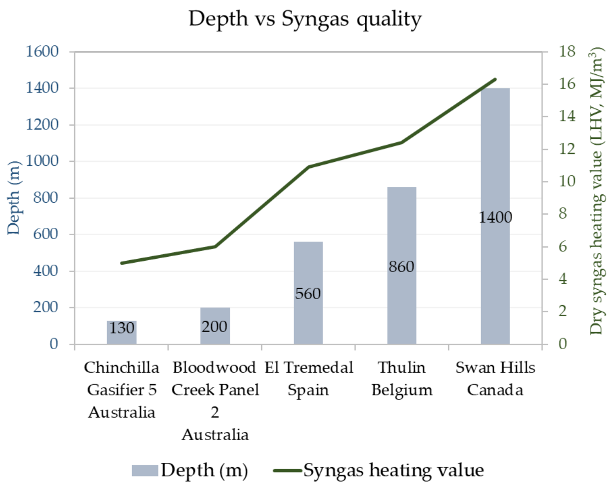
2.3.1 Thickness of Coal Seam

High net coal seam thickness is very prospective for UCG application. The thicker the coal seam, the better [6]; in this case, fewer wells are required, thus drilling cost is reduced. Considerable heat losses occur in case of thinner seams, less than 2 m thick, resulting low thermal efficiency and lower quality product gas [7]

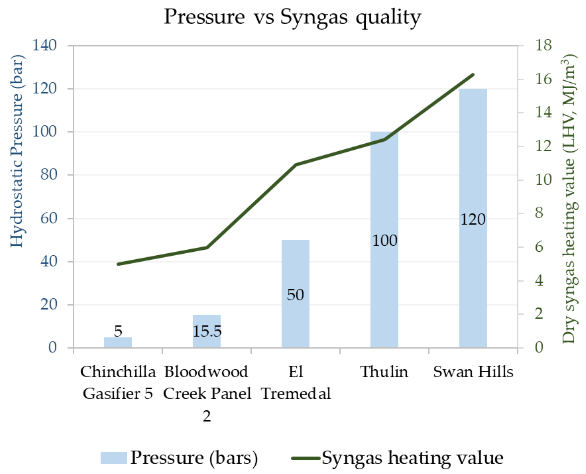
2.3.2 Depth of Coal Seam to be Gasified

The depth factor is very significant. Usually, the deeper the UCG system is operated, the higher the calorific value of syngas is attained (Fig. 3.a). This has been verified by many UCG trials around the world. Fig. 3 is constructed by compiling data from the established demonstrations viz. Chinchilla and Bloodwood Creek in Australia, El Tremedal in Spain, Thulin in Belgium and Swan Hills synfuels project in Australia [24]–[31].

Int. Journal of Integrated Engineering Vol. 16 No. 1 (2024) p. 1-13



(a)



(b)

Fig. 3 *Worldwide UCG trials exhibiting significance of (a) Depth; (b) Reservoir pressure*

Also, deeper seams are usually not linked to potable aquifers, thus it is less likely to interfere with other groundwater users, either by polluting or depleting water near the coal seam. Besides, additional compression may become unnecessary if product gas is used in gas turbines. Any possibility of surface subsidence is greatly decreased due to increase of extraction depth [6], [7]. Thus, depth of coal resources development is also associated with environmental concern.

But there are also some negative aspects. Deeper seams require higher drilling costs for directional drilling and linking the injection and production well. Those also need higher injection and operating pressure, as the operating pressure of the gasifier is limited to the hydraulic head at the coal seam [6] and expenses grow at the successive processing, such as pump-and-treat works.

2.3.3 Impact of Hydraulic Head

The ambient hydrostatic pressure could be significant for underground gasification. Reservoir hydraulic head increases with growing depth. From the experiences of different trials around the world, it was seen that, higher the hydraulic head, better the heating value syngas (Fig. 3.b); therefore better the efficiency and easier the downstream processing of UCG-derived syngas [6], [22].

2.3.4 Amount of Ash Content in the Coal

Ash in coal acts as energy sink, more oxygen may be needed to maintain the optimum operating temperature. Gasification performance shows a plateau below 40% ash content. Above 50% ash shows a marked decline in product gas quality, this might have an impact on profitability [6], [22], [32].

2.3.5 Coal Rank

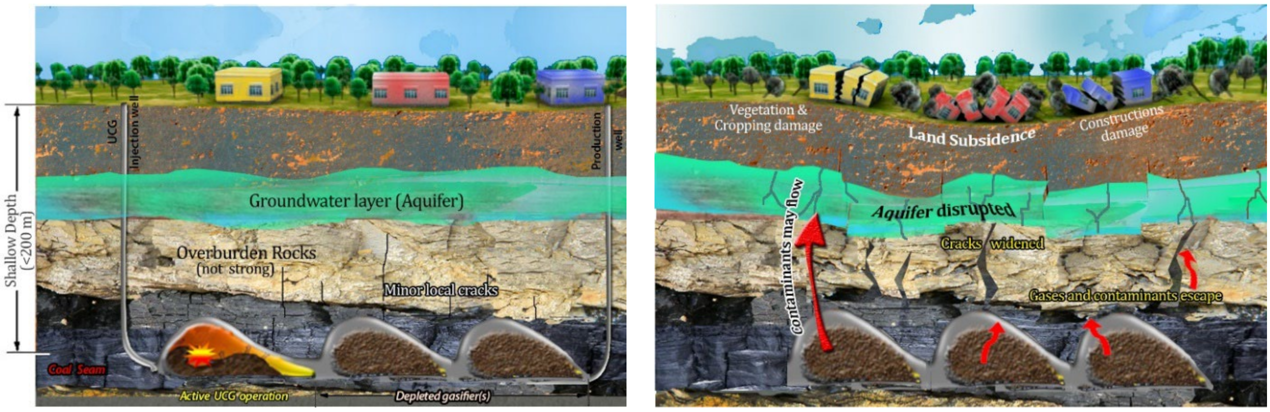
Surface plants can gasify any ranks of coal (from lignite to anthracite) and UCG operations have been tested for all. Low rank coals (i.e., lignite and sub-bituminous) seem to be easily gasified in-situ. There had been one failed attempt of UCG in anthracite in the former U.S.S.R. Probably UCG is better for coals of lower ranks, as they usually shrink while heated, thereby improves the permeability connecting the injection and production wells [7]. Contrarily, high rank coals are less porous, less reactive and have lower moisture and volatile matter contents than low rank coals [33].

Bituminous coals usually tend to swell. Several researchers [5], [22] inferred that high rank coal is difficult to ignite and to limit the risk of blockages, swelling bituminous coals required careful scheme for UCG development. Moreover, lower volatile matter containing bituminous coal yields gas of less heating value.

2.3.6 Discontinuities in or Around the Coal Deposit

The coal bearing formations are sometimes connected directly or indirectly with the surrounding rock formations by diverse joints, faults, and fractures. This can be attributed to the crustal extension and basin development, which may have resulted from several discrete episodes of deformation [14], [34].

The presence of faulting may disturb lateral continuity of coal seams and initiate problems for an efficient resource recovery. These faults pose danger when a path is initiated between the coal deposits and overlying water-bearing aquifer in course of gasification progress. There might be an outflow of high-pressure, contaminated water towards the groundwater layer (Fig. 4).



(a) **(b)**

Fig. 4 *Example of a poorly selected UCG site; (a) Before UCG operation; (b) After operation - shallow depth may pose danger through UCG-induced land subsidence, initiated by a weak overburden; also risk of groundwater layer disruption due to a nearby presence of aquifer from UCG operation*

2.3.7 Distance from Aquifers

For a successful UCG operation, no aquifer in the vicinity is highly preferred. In this case, the possibility of connecting with overlying aquifer becomes negligible. In case of a nearby aquifer presence, excessive water influx may disrupt the gasification efficiency, also there is a fear of outward movement of contaminants through the cracks [35]–[37] (Fig 4.b).

A poorly selected along with ill-contrived UCG site operation can lead, in the worst-case scenario, to groundwater contamination. The best example might be Hoe Creek UCG trial where the aforementioned issues led to cavity roof failure and product gas seeped into the local groundwater system.

Contrarily most of the UCG sites around the world didn't have any aquifer contamination problem as there was no groundwater formation in the vicinity of the UCG site. Even if there is any, UCG reactor might have to be operated below hydrostatic pressure, so that the connate water could be flown into the reactor, which will meet the water demand for the syngas production to some extent and lead to overall clean-up and reduction of aquifer benzene and VOCs [38].

2.3.8 Overburden Materials

A significant factor for selecting a potential UCG target seam is structurally robust overburden with low permeability and essentially dry rock to reduce loss of heat and hinder product gas leakage through overlying strata. The roof formation has vital significance also in that the overburden with low permeability restricts water influx into the gasification zone and minimizes gas loss.

Strong overburden materials can avoid the risk of subsidence. For example, Bloodwood Creek 2 trials, though operated at shallow depths (at 200 m), yet exhibited negligible surface subsidence due to strong overburden materials [22]. Surface subsidence can take place due to coal gasification in the underground (Fig. 4), what resembles somewhat extraction of coal from the subsurface, like the longwall mining. Nevertheless, selecting appropriate UCG site and leaving walls and pillars in place can mitigate this issue to a greater extent, but in all cases this approach must be managed [6], [7]. In general, deeper UCG projects will have lesser risk of subsidence.

2.3.9 Seam Dipping

Low dipping coal seams reduce the drilling complexity considerably. <20° dipping has been found optimal for most UCG techniques (Figure 10.a). While dipping is >50° only Steeply Dipping Bed (SDB) techniques can be employed as in Figure 10.b [6], [22], [23].

Noteworthy, steeply dipping seams usually occur in a disturbed geological setup. Therefore, UCG application might require a complex drilling solution. Also, groundwater flow pattern becomes less predictable, making the hydrostatic pressure differ considerably at the top and bottom of the UCG gasifier. Thus it poses great troubles on process control than the low dipping seams [39].

Int. Journal of Integrated Engineering Vol. 16 No. 1 (2024) p. 1-13

2.4 Quantification of UCG Potentiality Factors

Several studies have developed lists of the key factors for UCG siting suitability based on previous experiences from trials and research [6], [7], [22], [23]. Noteworthy to mention that these factors (Table 1) should not be treated as strict criteria as there is no large-scale UCG operation attempted to date. Nevertheless, site design and risk reduction, or management strategies largely depend on these factors.

Table 1 *Factors for considering UCG potential and threshold limit*

Factor(s)	Recommended limit	Cut-off value	Consideration	Cited
Burial depth	> 200 m preferred	Lowest 100 m Highest 1400 m	As deeper it goes, as lower the pressure is required for sustained process; also the surface impacts are decreased.	[25], [40]
Thickness of seam	> 6 m preferred	2 m	Thin seams (<2m) suffer more heat loss; Thick seams reduce cost by drilling fewer wells.	[6], [22], [23]
Ash content (air dried)	<40%	60%	syngas quality is declined for >50% ash; thus, affects profitability.	[6], [22], [40]
Coal rank	Bituminous with high volatiles	Not very low (e.g., peat), not very high (anthracite)	Lower the rank the better. Very low rank coals have high moisture and very high rank is difficult to ignite.	[6], [22]
Discontinuities	Free from any major discontinuities	Minor faulting	less faulting/parting/ intrusions preferred which simplifies layout and operation; discontinuities could induce product gas loss or contaminant transport to surrounding strata.	[6], [22], [41]
Closeness to aquifers	No aquifer within a distance of 25 times the seam height	No aquifer within 31 m	Proximity of aquifer increases possibility of overlying aquifer connectivity.	[35]–[37]
Overburden/ Roof materials	Compacted, very thick (>40 m), essentially impervious	40 m thick Hard rock (to some extent impervious)	Typically strong, considerably thick and structurally stable to hold cavity, minimise subsidence and prevent heave; to regulate water inflow and gas containment.	[22], [25], [41]
Hydraulic head	High (>20 bar)	20 bar	Good gasification efficiency and downstream processing require high pressure zone; also operating pressure of the gasifier is limited to the prevailing hydraulic head at the coal seam.	[6], [22]
Seam dipping	Not steeply, <20°	<30°	Horizontal or gently sloping coal seams (<20°) lower the drilling complexity; >50° seams are limited to SDB techniques.	[6], [22], [23]
Scale of deposit	>100 MT preferred	100 million tonnes	To ensure that the volume of resources is sufficient to support the planned project's capacity for a fair amount of time.	[22], [41]

note: SDB – Steeply Dipping Bed

3. Results

The consistency of the desired factors for applying UCG in the coalfields of Bangladesh was assessed and is summarized in Table 2. Acceptability of the factors for different coalfields are displayed by green 🟢, yellow 🟡 and red 🔴 circles, for denoting “Positive”, “Prospective”, and “Critical” respectively. It is worth noting that, any “Positive” demarcation is highly suitable, while assigning “Prospective” is manageable under defined conditions and any factor designated as “Critical” means those are below cut-off value as mentioned in Table 1 but could still be acceptable in a different geologic-engineering setup. Since large scale UCG experience is still immature around the world, there could be one or more parameters varying in values outside the mentioned range for a proposed project. If this happens, additional risk management strategies could help succeed any hurdles in the prevailing conditions [22].

Table 2 *UCG potentiality assessment of the coalfields of Bangladesh*

Screening factor	Jamalganj	Barapukuria	Khalaspir	Dighipara	Phulbari
Depth (m)	🟢	🟢	🟢	🟢	🟡
Thickness (m)	🟢	🟢	🟢	🟢	🟢
Ash content	🟢	🟢	🟢	🟢	🟢
Coal rank	🟢	🟢	🟡	🟡	🟢
Major discontinuities (e.g., faults)	🟡	🔴	🔴	🔴	🔴
Groundwater layer in the vicinity	🟢	🔴	🟡	🔴	🔴
Overburden/ Roof materials	🟢	🔴	🟡	🔴	🔴
Hydraulic head	🟢	-	-	-	-
Seam dipping	🟢	🟢	-	🟢	-
Scale of deposit (Million Ton)	🟢	🟢	🟢	🟢	🟢

note: supplementary data can be found in ***Appendix A****.*

Symbol: 🟢 = “Positive”, 🟡 = “Prospective”, 🔴 = “Critical”

4. Discussion

The suitability of UCG application in the said five coalfields can be deduced by screening the quantification of UCG potentiality factors as stated in Table 1. All of them except Phulbari (a prospective Seam II that is located at a shallow depth), would meet UCG requirements based on their burial depths. All the coalfields have positive seam thicknesses (>10 m) and ash contents (air dried basis) less than 40%, which makes them suitable for UCG application. Coal types with higher volatiles (lower ranks) are preferred for UCG, even though coal rank is less significant. Accordingly, the medium volatile coal in the Khalaspir and Dighipara coalfields ranks higher than the other three fields, making them less promising for a UCG trial.

A generalized lithologic succession comparing the five coal-bearing areas is shown in Fig. 5. This figure exhibits the rationalization of these coalfields with the important multi-factors like depth, thickness, proximity to the regional aquifers in a comprehensive manner. Noteworthy that the primary obstacle to the development of coal resources in the country is the Dupi Tila formation, a regional groundwater layer that sits directly on top of coal seams in areas like Barapukuria, Phulbari, and Dighipara. Given the above, the coal deposits in Jamalganj are very advantageous because of the substantial overburden (roughly 200 m) of effectively impervious layers.

Because the overburden is typically of a loosely consolidated sandy type that is either in hydraulic continuity with the Dupi Tila formation or itself the said formation, Barapukuria, Dighipara, and Phulbari indicate somewhat unfavorable circumstances regarding the presence of faults and fractures. The major aquifer and the coal seam in Khalaspir are separated by the overburden, which is the second aquifer with lower hydraulic conductivity [42], despite the aquifer having a significant number of discontinuities (7 normal faults). On the other hand, the Jamalganj coalfield can be a prime candidate for UCG because it has a strong overburden (a 150–200 m layer of hard, consolidated, impermeable Gondwana sandstone) and is situated a significant distance (more than 600 m in some places) from the major aquifer [4], [15], [19]. Because the sandstone is so tightly packed and cemented—especially due to the presence of kaolinitic cement—the roof of the coal seams is practically impassable [15]. On top of the coal seams, this formation will form an active shield that will prevent any de-pressuring, or dewatering, problems. There would be less likelihood of a water inflow than in Barapukuria. There would also be less chance of a roof collapsing during mining because of the hard rock [19]. It is best to avoid significant discontinuities like faults or fractures [6], [22].

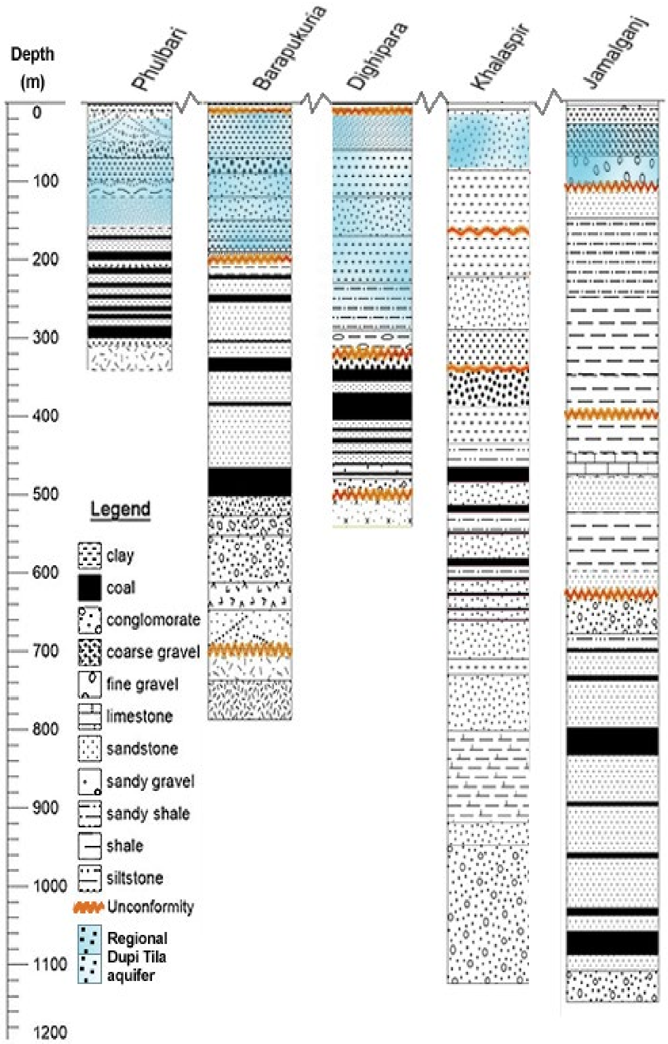


Fig. 5 *Simplified succession of subsurface lithology of indigenous coalfields; hydrogeological layer along with the coal intersections are shown; modified after* [10]

Given the aforementioned factors, the Jamalganj coal basin is probably the one with the most potential for UCG pilot projects. Profitable UCG exploitation could be predicted by the high-volatile bituminous (HV-B type) coal at a favorable depth, beneficial coal seam thickness, low ash content, manageable discontinuities, and safe distance from local groundwater reservoir. Noteworthy that the Khalaspir deposit, being the second deeper coalfield, has a dense overburden with a reduced hydraulic conductivity acting as a buffer between the Dupi Tila aquifer and the coal seam. Khalaspir thus came up as the second most promising location after Jamalganj, provided that the discontinuities could be well addressed during the UCG implementation process so as to avoid any possible risk of aquifer contamination.

5. CONCLUSION

Abundant coal deposits of Bangladesh in five discovered coalfields could conveniently serve the country's energy need for a long period reducing the dependency on imported fuel. Nevertheless, traditional mining methods (i.e., underground or opencast) failed to promptly exploit the resources even after 60 years from the discovery. Though coal from the four deposits may be extractable by conventional methods, Jamalganj coal deposit is difficult to develop due to its greater depth (around 1 km) in the world perspective. While conventional mining techniques might be socially and environmentally deleterious for a country like this, unconventional coal mining method such as underground coal gasification (UCG) can be a viable solution to harness energy from the resources. UCG is essentially less polluting with a high recovery efficient method and has been termed as a potential clean coal technology.

Suitability of coalfields for UCG exploitation depends on some critical factors which are mainly associated with the preferable UCG site-specific coalfield characteristics. This study evaluated the integration of multiple factors to ascertain the UCG potential of the country's five discovered coalfields. Also, information of previous trials and research have been enumerated to facilitate the selection and credibility of the most significant factors. There are major factors including burial thickness of coal seam, depth, hydraulic head, ash content, coal rank, discontinuities, proximity to aquifers, overburden/roof materials, seam dipping, and scale of deposit.

All the said coalfields have passed considerably the depth, thickness, ash content and rank factors regarding the potentiality of UCG. However, faulting, overburden or aquifer proximity are somewhat critical for all the coalfields except Jamalganj. Mainly Jamalganj coalfield has got the advantage of an appreciable depth of occurrence and a workable structurally robust overburden keeping a safe distance from the regional major aquifer, Dupi Tila. Even after having a number of discontinuities, Khalaspir deposit also has considerable UCG potential being the second deepest coalfield of the country.

The main drawbacks of the current research stem from the fact that the essential factors for an appropriate UCG implementation may not be functional in isolation or in combination in various contexts. Any conceptual ambiguity about the geotechnical problems facing UCG might lead to a poor judgment that compromises the study's overall conclusion. Consequently, the most extensively tested site-specific attributes have been chosen and examined in order to reach a thorough conclusion on the selection of the optimal alternate coalfield for UCG deployment.

The study might shed a spot-light while choosing UCG site comprehensively. Nevertheless, significant research interventions will be required before UCG deployment. Future research directions could be projected towards delineating the syngas properties of these coals, simulating gasifiers and inherent processes through CFD modeling, etc. Following the surge of UCG research initiatives worldwide, now may be the opportune time to investigate technological developments and gather environmental data needed to assess this technique.

Acknowledgement

This work was supported by National Science, Research and Innovation Fund (NSRF) and Prince of Songkla University (Ref. No. ENG6701209S), and also technically assisted by the Faculty of Environmental Management, Prince of Songkla University, Hat Yai, Thailand, and Hydrocarbon Unit, Energy and Mineral Resources Division, Government of Bangladesh.

Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Arup Kumar Biswas, Makatar Wae-hayee;* ***data collection:*** *Arup Kumar Biswas;* ***analysis and interpretation of results:*** *Arup Kumar Biswas, Mohd Faizal Mohideen Batcha, Makatar Wae-hayee;* ***draft manuscript preparation:*** *Arup Kumar Biswas. All authors reviewed the results and approved the final version of the manuscript.*

References

[1] Katekar, V. P., Deshmukh, S. S., & Elsheikh, A. H. (2020). Assessment and way forward for Bangladesh on SDG-7: Affordable and clean energy. *International Energy Journal*, *20*(3), 421–438. BD SDG7

[2] Hydrocarbon Unit. (2023). *Energy Scenario of Bangladesh 2021-22*. Ministry of Power, Energy and Mineral Resources; Government of Bangladesh. https://hcu.gov.bd/site/view/publications/-

[3] Power Division, & JICA. (2016). Power System Master Plan-2016. *Ministry of Power, Energy and Mineral Resources, Government of the People's Republic of Bangladesh*, *Dhaka*, *Bangladesh*. https://powerdivision.gov.bd/

[4] Imam, B. (2013). *Energy Resource of Bangladesh*, Second Ed. University Grants Commssion.

[5] Sajjad, M., & Rasul, M. G. (2015). Prospect of underground coal gasification in Bangladesh. *Procedia Engineering*, *105*(Icte 2014), 537–548. https://doi.org/10.1016/j.proeng.2015.05.087

[6] Beath, A., Craig, S., Littleboy, A., Mark, R., & Mallett, C. (2004). Underground Coal Gasification : Evaluating Environmental Barriers. *CSIRO Energy Transformed Flagship Report*. UCG eval env bar

[7] Burton, E., Friedmann, J., & Upadhye, R. (2006). Best Practices in Underground Coal Gasification. In *Lawrence Livermore National Laboratory*.

[8] Kempka, T., Plötz, M. L., Schlüter, R., Hamann, J., Deowan, S. A., & Azzam, R. (2011). Carbon dioxide utilisation for carbamide production by application of the coupled UCG-Urea process. *Energy Procedia*, *4*, 2200–2205. https://doi.org/10.1016/j.egypro.2011.02.107

[9] Nakaten, N., Islam, R., & Kempka, T. (2014). Underground coal gasification with extended CO2 utilization - An economic and carbon neutral approach to tackle energy and fertilizer supply shortages in Bangladesh. *Energy Procedia*, *63*, 8036–8043. https://doi.org/10.1016/j.egypro.2014.11.840

[10] Biswas, A. K., Islam, M. R., & Habib, M. A. (2023). An analytical investigation of critical factors to prioritize coalfields for Underground Coal Gasification – Bangladesh case. *Heliyon*, *9*(7), e18416.

https://doi.org/10.1016/j.heliyon.2023.e18416

[11] Guha, D. K. (1978). Tectonic Framework and Oil & Gas Prospects of Bangladesh. *4th Annual Conf. Bangladesh Geol. Soc.*, 65–75.

[12] Reimann, K.-U. (1993). *Geology of Bangladesh*. Berlin-Stuttgart: Gebruder Borntraeger.

[13] Islam, M. N., Uddin, M. N., Resan, S. A., Islam, M. S., & Ali, M. W. (1992). Geology of the Khalaspir Coal Basin, Pirgonj, Rangpur, Bangladesh. *Records of Geological Survey of Bangladesh*, *6*(5), 1–76.

[14] Islam, M. R., Hayashi, D., & Kamruzzaman, A. B. M. (2009). 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*, *78*(2), 91–109. https://doi.org/10.1016/j.coal.2008.10.006

[15] Imam, B., Rahman, M., & Akhter, S. H. (2002). Coalbed Methane Prospect of Jamalganj Coalfield, Bangladesh. *The Arabian Journal for Science and Engineering*, *27*(1), 17–27. Link

[16] Farhaduzzaman, M., Abdullah, W. H., Islam, M. A., & Sia, S. G. (2015). Quality Assessment of the Permian Coals from Dighipara Basin, Bangladesh Based On Proximate, Ultimate and Microscopic Analyses. *Journal of Bangladesh Academy of Sciences*, *39*(2), 177–194. https://doi.org/10.3329/jbas.v39i2.25951

[17] GCM. (2020). *Phulbari coal resources*. Resources (accessed Mar. 10, 2023).

[18] IMC. (2009). Review of "Techno-Economic Feasibility Study" Khalashpir Coal Mine. *Hydrocarbon Unit*. Report Link

[19] Petrobangla, & MAPL. (2016). Drilling and testing of three core holes for feasibility study for the extraction of Coal Bed Methane at Jamalganj. *Petrobangla Mines Division*.

[20] Khadse, A., Qayyumi, M., Mahajani, S., & Aghalayam, P. (2007). Underground coal gasification: A new clean coal utilization technique for India. *Energy*, *32*(11), 2061–2071. https://doi.org/10.1016/j.energy.2007.04.012

[21] Ranade, V., Mahajani, S., & Samdani, G. (2019). Computational Modeling of Underground Coal Gasification. In *Computational Modeling of Underground Coal Gasification*. CRC Press. https://doi.org/10.1201/9781315107967

[22] Perkins, G. (2018a). Underground coal gasification – Part I: Field demonstrations and process performance. *Progress in Energy and Combustion Science*, *67*, 158–187. https://doi.org/10.1016/j.pecs.2018.02.004

[23] Creedy, D. P., Garner, K., Holloway, S., Jones, N., & Ren, T. X. (2001). Review of UCG Technological Advancements. In *Technical Report: Vol. COAL R211* (Issue DTI/Pub URN 01/1041). Link

[24] Perkins, G., du Toit, E., Cochrane, G., & Bollaert, G. (2016). Overview of underground coal gasification operations at Chinchilla, Australia. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*, *38*(24), 3639–3646. https://doi.org/10.1080/15567036.2016.1188184

[25] Mallett, C. W. (2018). Environmental controls for underground coal gasification. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, *232*(1), 47–55. https://doi.org/10.1177/0957650917723733

[26] Walker, L. (2018). The development of UCG in Australia. In M. S. Blinderman & A. Y. Klimenko (Eds.), *Underground Coal Gasification and Combustion* (pp. 175–212). Elsevier Ltd. https://doi.org/10.1016/B978-0-08-100313-8.00006-2

[27] Chappell, R., & Mostade, M. (1998). The EL Tremedal underground coal gasification field test in Spain first trial at great depth and high pressure. *The Fifteenth Annual International Pittsburgh Coal Conference, September*, 1–19.

[28] Debelle, B., Malmendier, M., Mostade, M., & Pirard, J. P. (1992). Modelling of flow at Thulin underground coal gasification experiments. *Fuel*, *71*(1), 95–104. https://doi.org/10.1016/0016-2361(92)90198-W

[29] Chandelle, V., Jacquemin, C., Létolle, R., Mostade, M., Pirard, J. P., & Somers, Y. (1993). Underground coal gasification on the Thulin site: results of analysis from post-burn drillings. *Fuel*, *72*(7), 949–963. https://doi.org/10.1016/0016-2361(93)90292-A

[30] Dufaux, A., Gaveau, B., Létolle, R., Mostade, M., Noël, M., & Pirard, J. P. (1990). Modelling of underground coal gasification process at Thulin on the basis of thermodynamic equilibria and isotopic measurements. *Fuel*, *69*(5), 624–632. https://doi.org/10.1016/0016-2361(90)90149-K

[31] AI-EES. (2012). Swan Hills In-Situ Coal Gasification Technology Development. *Final Outcomes Report*. https://pdfcoffee.com/swan-hills-ucg-pdf-free.html

[32] Skafa, P. V. (1960). Underground Gasification of Coal. *Gosudurstvennoe Hauchno-Tekhnicheskoe Izdatel'stvo Literatury Po Gornomu Delu, Lawrence L*(Rept. UCRL Trans-10880 (1975)).

[33] Perkins, G. (2018b). Underground coal gasification – Part II: Fundamental phenomena and modeling. *Progress in Energy and Combustion Science*, *67*, 234–274. https://doi.org/10.1016/j.pecs.2018.03.002

[34] Nicol, A. (1993). Haumurian (C. 66-80 Ma) half-graben development and deformation, mid waipara, North Canterbury, New Zealand. *New Zealand Journal of Geology and Geophysics*, *36*(1), 127–130. https://doi.org/10.1080/00288306.1993.9514560

[35] Vyas, D. U., & Singh, R. P. (2015). Worldwide Developments in UCG and Indian Initiative. *Procedia Earth and Planetary Science*, *11*, 29–37. https://doi.org/10.1016/j.proeps.2015.06.005
[36] Sury, M., White, M., Kirton, J., Carr, P., Woodbridge, R., Mostade, M., & Rendell, N. (2004). Review of environmental issues of underground coal gasification. *WS Atkins Consultants Ltd., University of Liège Belgium, FWS Consultants Ltd*, *November*, 1–126. http://large.stanford.edu/courses/2014/ph240/cui2/docs/file19154.pdf
[37] Camp, D. W., & White, J. A. (2015). Underground Coal Gasification: An Overview of Groundwater Contamination Hazards and Mitigation Strategies. In *Lawrence Livermore National Laboratory* (Issue LLNL-TR-668633).
[38] Friedmann, S. J., Upadhye, R., & Kong, F. M. (2009). Prospects for underground coal gasification in carbon-constrained world. *Energy Procedia*, *1*(1), 4551–4557. https://doi.org/10.1016/j.egypro.2009.02.274
[39] Couch, G. R. (2009). Underground coal gasification. In *IEA Clean Coal Centre* (Vol. 183, Issue 4129). https://doi.org/10.1126/science.183.4129.1036-b
[40] Beath, A. (2006). Underground Coal Gasification Resource UtilisaFriedmann, S. J., Upadhye, R., & Kong, F. M. (2009). Prospects for underground coal gasification in carbon-constrained world. *Energy Procedia*, *1*(1), 4551–4557. https://doi.org/10.1016/j.egypro.2009.02.274ion Efficiency. *CSIRO Exploration and Mining Report*, *August*, 271–277. UCG Resource Utilisation Efficiency
[41] Couch, G. (2009). Underground coal gasification. *Fourth International Conference on Clean Coal Technologies*. https://doi.org/10.1533/9780857097309.2.226
[42] Mohanta, T., Akter, S., Quamruzzaman, C., Rahman, A., & Hossain, K. M. I. (2017). Mining Proposal of Khalashpir Coal Field, Mining Proposal of Khalashpir Coal Field, Rangpur, Bangladesh. *International Journal of Emerging Technology and Advanced Engineering*, *7*(7), 31–40.
[43] Howladar, M. F. (2013). Coal mining impacts on water environs around the Barapukuria coal mining area, Dinajpur, Bangladesh. *Environmental Earth Sciences*, *70*(1), 215–226. https://doi.org/10.1007/s12665-012-2117-x
[44] Swapan, K. B., Quamruzzaman, C., Alim, S., Rahim, M., Ahmed, D., & Ahmed, M. T. (2016). Selection of Mining Method and Mine Design in Dighipara Coal Field, Dinajpur, Bangladesh. *International Journal of Emerging Technology and Advanced Engineering*, *6*(5), 342–350. http://www.ijetae.com/files/Volume6Issue5/IJETAE_0516_55.pdf
[45] Uddin, M. N. (2022). Gondwana deposits of the Bengal Basin (Bangladesh) and coal potential. In *Bangladesh Geosciences and Resources Potential* (Issue August). https://doi.org/10.1201/9781003080817-3

Int. Journal of Integrated Engineering Vol. 16 No. 1 (2024) p. 1-13

Appendix A

Table A1. *Important attributes of coalfields of Bangladesh (Supporting data for table 2)*

Factors considered	Jamalganj coalfield	Barapukuria coalfield	Khalaspir coalfield	Dighipara coalfield	Phulbari coalfield
Depth (m) of the thickest seam	Seam III; 660 m to 977 m	Seam VI; 118 m to 450 m	Seam I; 285 m to 318 m	Seam II; 348 m	Seam II; from 140 m to 250 m
Thickness (m) of the thickest seam	Seam III; 8 m to 47 m	Seam VI; 21.63 m to 42.30 m	Seam I; Average 16.95 m	Seam II; 36.58 m	Seam II; 10.59 m
Ash content (air dried basis)	7-16 % (seam I-IV); 23-28% (seam V-VII)	12.4 %	21.80%	5.70 - 28.80% (arithmetic mean is 15%)	12%
Coal rank	Seams I-V: HV-B; seams VI-VII: HV-A bit.	HV-B	MV bituminous low sulfur coal	Ranging from HV-B to MV bit. coal	HV-B
Major Discontinuities (Faulting and fractures)	E-W trending boundary fault in the north and another 2 minor faults in the south	37 faults were found with 1–3m throw; Fracture intensity from 7–10 per meter	7 normal faults sub-parallel to NW-SE; >50m max. vertical displacements	A NW-SE trending major fault marking the northern limit of the basin	A N-S trending bounding fault marking the eastern limit of the basin
Groundwater layer in the vicinity	No aquifer in the vicinity; safer distance (~600m) from overlying Dupi Tila aquifer.	Active aquifer is unconformably overlying	Minor GW source in the vicinity; 2nd aquifer with lower hydraulic conductivity	Coal beds are overlain by Dupi Tila aquifer, major GW source	Regional aquifer Dupi Tila on top
Overburden/ Roof materials (preferably somewhat Impervious)	150-200m cover of hard, compacted, impervious Gondwana sandstone	140 m thick Permian Gondwana sandstone (aquifer) in hydraulic continuity with the seam VI	184 m grey mudstone, sandstone and pebble interbeds of Surma group, lower permeability	>300 m of poorly consolidated water-bearing sandy layer forming Dupi Tila aquifer	unconformably overlain by loosely consolidated Upper Tertiary Dupi Tila sandy formation
Hydraulic head	108 bar	-	-	-	-
Seam dipping	5°-15°	12° (seam VI)	-	13.4° (seam-II)	-
Scale of deposit (Million Ton)	5,450	390	685	865	572
Cited	[4], [15], [19]	[4], [14], [43]	[13], [42]	[16], [44]	[17], [45]