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ULASAN GASIFIKASI BATUBARA BAWAH TANAH PADA DAERAH YANG DIAJUKAN DI CEKUNGAN SUMATERA SELATAN

REVIEW OF UNDERGROUND COAL GASIFICATION PROPOSED SITE IN SOUTH SUMATRA BASIN

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ABSTRAK

Indonesia memiliki sumber daya batubara yang mencapai 124,6 miliar ton dan cadangan hingga 26,2 miliar ton. Dalam melaksanakan kegiatan penambangan perlu dilakukan upaya untuk meminimalisir dampak terhadap lingkungan dengan menerapkan penambangan berkelanjutan. *Underground Coal Gasification* (UCG) adalah metode untuk mengekstrak *syngas* dari lapisan batubara bawah tanah *in-situ* yang tidak dapat diproses oleh penambangan konvensional. Tujuan dari makalah ini adalah untuk memberikan informasi yang komprehensif tentang potensi metode UCG untuk memanfaatkan lapisan batubara di Cekungan Sumatera Selatan. Dengan membandingkan dan menganalisis data dari berbagai literatur, lapisan batubara di Sumatera Selatan berpotensi untuk dimanfaatkan dengan menggunakan metode UCG. Potensi risiko penerapan metode UCG terhadap lingkungan di antaranya penurunan lapisan tanah, kontaminasi udara dan air tanah, serta bahaya dari produk samping. Terdapat beberapa peraturan pemerintah yang harus dipenuhi untuk menjamin kualitas lingkungan dan sumber daya alam yang baik. Jika *syngas* langsung diolah untuk menghasilkan listrik di pembangkit listrik UCG maka dapat menghemat hingga sekitar 33% dari modal jika dibandingkan dengan IGCC. Kriteria pendukung untuk mengoptimalkan proses UCG meliputi zona jenuh air tanah pada batuan, desain saluran terbuka, serta pemodelan penurunan tanah dan perambatan panas. UCG merupakan teknologi batubara yang bersih karena penyebaran gas rumah kaca di atmosfer yang minim, tidak memerlukan fasilitas penampungan abu setelah pembakaran batubara, serta dapat diintegrasikan dengan penangkapan dan penyimpanan karbon untuk penangkapan CO_2 lebih lanjut.

Kata kunci: Gasifikasi Batubara Bawah Tanah, Penambangan Berkelanjutan

ABSTRACT

Indonesia has coal resources reaching 124.6 billion tonnes and reserves of up to 26.2 billion tonnes. In carrying out mining activities, it is necessary to minimize the impact on the environment by implementing sustainable mining. Underground Coal Gasification (UCG) is a method to extract syngas from in-situ underground coal seams that could not be processed by conventional mining. The objective of this paper is to give comprehensive information about the potential of UCG method to utilize coal seams in South Sumatra Basin. By comparing and analyzing data from various literature, the coal seam in South Sumatra has the potential to be utilized using UCG method. The potential risks of implementing UCG method to the environment include subsidence of soil layers, contamination of air and groundwater, and hazards from the by-products. There are several government regulations that must be fulfilled to ensure the good quality of the environment and natural resource. If the syngas is directly processed to generate electricity in UCG power plant, it can save up to about 33% of the capital costs when compared to IGCC. The supporting criteria to optimize UCG process include the groundwater saturated zone on the rock, design of open channel, land subsidence, and heat propagation. UCG is a clean coal technology because the spread of greenhouse gas in the atmosphere is minimal, no ash disposal required after burning the coal, and can be integrated with carbon capture and storage for further CO_2 *capture.*

Keywords: *Underground Coal Gasification, Sustainable Mining*

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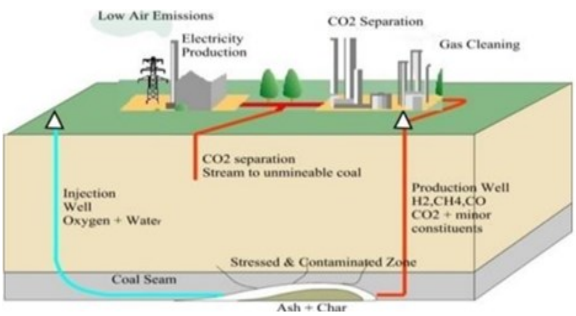
INTRODUCTION

Coal is the form of solid hydrocarbon fuel organic sediments formed from plants that have undergone biochemical, chemical, and physical decomposition in oxygen-free conditions that take place at certain pressures and temperatures for a very long period (PT. Bukit Asam). According to the latest data from the Geological Agency of the Ministry of Energy and Mineral Resources (ESDM), Indonesia has coal resources reaching 124.6 billion tonnes and reserves of up to 26.2 billion tonnes. Coal still exists up to a depth of 1,000 m, and even the potential is much greater than what is currently reported[1]. Deep-seated coal can be utilized by the coal bed methane method and Underground Coal Gasification (UCG)[2]. Therefore, the government needs to maximize the exploration and utilization of this coal.

In carrying out mining activities, it is necessary to consider sustainable mining which is the solution that can minimize the negative impact on environment, social, and economic associated with mining and processing activities[3]. Sustainable mining is related to two concepts, namely operational efficiency to reduce environmental impacts, and the consideration of materials extraction rates and the total life cycle of a mined material[4]. Sustainable mining includes several dimensions, namely the economics of the mine, community support and engagement, high standards of safety, a focus on mining the resource efficiently, and high environmental standards[5].

UCG is an example of the application of sustainable mining. This method extracts the synthesis gas (syngas) from in-situ underground coal seams that could not be processed by conventional mining[6]. In UCG, air or oxygen and water are injected through an injection well to gasify the pre-ignited coal seam. As the result of the gasification reaction, the coal seam will produce syngas that are drawn to the surface through the production well as shown at Picture 1[7]. The UCG process is the most environment-friendly utilization of coal-related to its recovery, chemical feedstock value, environmental impact, health and safety benefits, process efficiency, and economic potential[8].

UCG has been compared to surface mining, underground mining, surface coal gasification, and coal bed methane. Surface mining is commonly used for coal seam with the depths that are less than 200 m [9]. Surface coal gasification has a higher cost as it requires investment in other equipment such as coal preparation, ash collection, storage, etc. An example of a company developing surface coal gasification is PT Bukit Asam Tbk. PT Bukit Asam Tbk's coal gasification development project is located in Tanjung Enim Mine with a capacity of around 780,000 tons/year of Urea-based fertilizer; 450,000 tons/year of polypropylene (PP); 400,000 tons/year of Dimethyl Ether (DME). Also, in Banko Tengah area, not only develop coal gasification but also can be integrated with palm plantation[10]. And the last is coal bed methane which is applied to coal containing high methane content of more than 10 m^3/t in shallow depths[9]. There are several coal seam criteria that must be fulfilled for an economical UCG operation. These criteria and parameters based on Kepmen ESDM No. 1827 K/2018 are presented in Table 1. These criteria and parameters based on Kepmen ESDM No. 1827 K/2018 are presented in Table 1. Based on these criteria, not all coal seams can be used for UCG activities. Coal explorations need to be carried out to minimize geological risks and to determine the condition of the coal seams. In the operation of UCG, there are other criteria that can support the exploration process which include the groundwater saturated zone on the rock, design of open channel, land subsidence, and heat propagation that occurs in the UCG area. Besides that, it is also necessary to pay attention to environmental criteria such as controlling air, water and soil pollution which are stated in government regulations.



Picture 1. Underground gasification coal process[7]

Table 1. Coal seam criteria for UCG operation[11]

No	Criteria, unit	Min.	Max.
1	Rock layer of roof and floor	Impermeable	
2	Thickness, m	5	-
3	Depth, m	200	-
4	Geological structure	Simple	Moderate
5	Ash content + Inherent moisture, adb	-	60 %
6	Coal rank	-	Bituminous

Coal resources in Indonesia are scattered in Sumatra, Kalimantan, Sulawesi, Java, and Papua with various ranks. One of the regions in Indonesia that has a lot of coal resources and reserves is the South Sumatra Basin. According to studies that have been carried out on 7 coal seams, the South Sumatra Basin has measured resources of 89 million tonnes, indicated resources of 267 million tonnes, and inferred resources of 445 million tonnes.

This basin also has a hypothetical gas resource of 4.77 TSCF[12].
Gasification is a method to process coal that converts it from solid to a gas state (syngas). The syngas can be processed further to generate some other end product such as ethanol, methanol, fuel, petrochemical, urea and even electricity with an environment-friendly technology, namely integrated gasification combined cycle (IGCC)[13]. Gasification using UCG method operates at a lower temperature so it has higher efficiency compared to the surface gasifier[14].

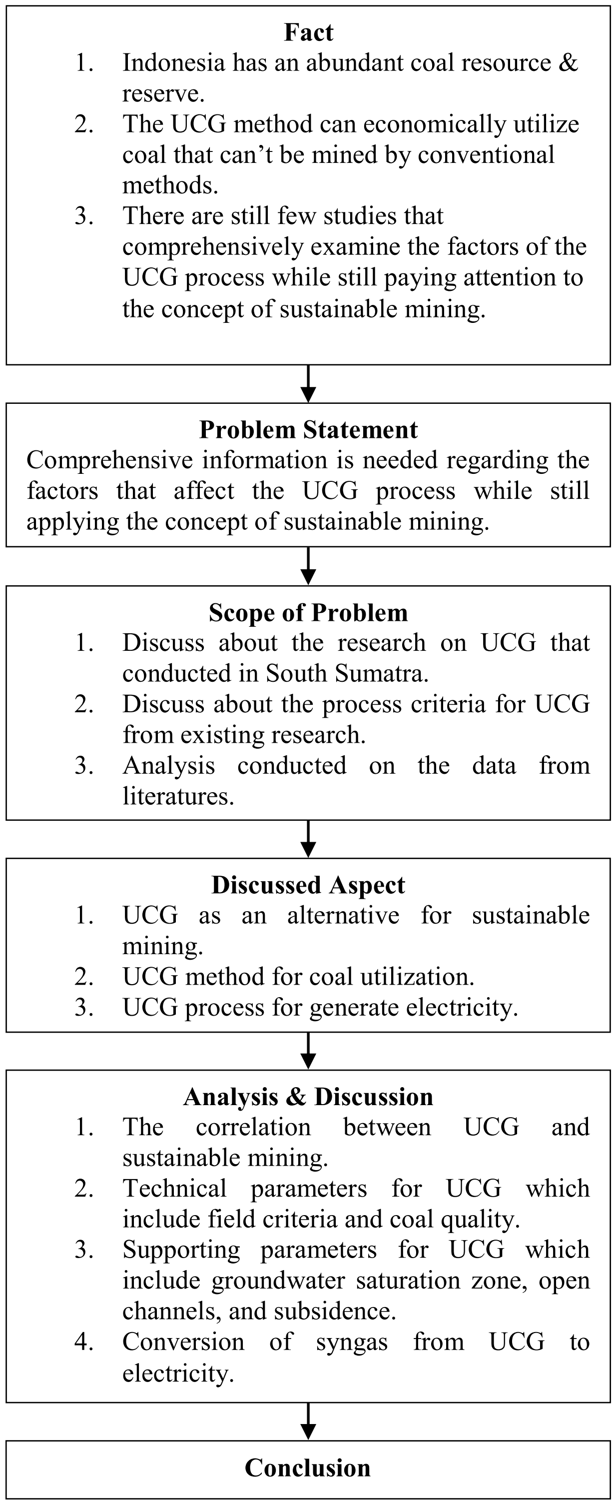
There has been no comprehensive review of the criteria for the UCG process and other parameters carried out in the South Sumatra basin. Comprehensive information is needed regarding the factors that affect the UCG process while still applying the concept of sustainable mining. This study discusses the various factor that affects the UCG process. This study also compared and analyzed the criteria for UCG process. The objective of this paper is to give comprehensive information about the potential of UCG technology to utilize coal seams in South Sumatra Basin.

RESEARCH METHOD

Indonesia is a country that has abundant coal both in the form of resources and reserves. Most of the coal in the world, including Indonesia, still can't be mined economically by conventional methods. One of the reasons is the depth of the coal deposits, e.g., coal with a depth of 300-1000 meters. The UCG method can economically utilize coal at this depth to produce syngas which can be used further to generate electricity. Compared to other methods, UCG can minimize the impact on the environment to support sustainable mining. Currently there are not many applications of this UCG method. A further study that discusses the various factor that affects the process is required to maximize the potential of UCG. This research is conducted using the literature study method which collects data from various literature to be compared and then analyzed based on the criteria for the UCG site selection process. At the end of the study, conclusions are drawn that answer the objectives. From these conclusions, further processed and produce suggestions for further research. The research flow diagram is presented in Picture 2.

RESULTS AND DISCUSSION

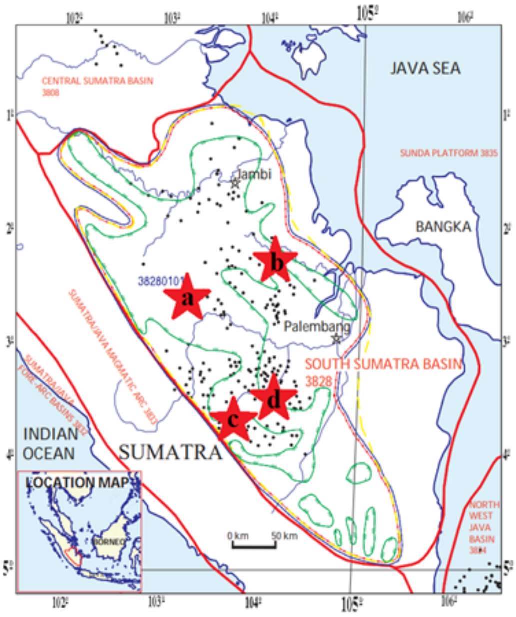
The South Sumatra basin is one of the basins that is important in the availability of coal, oil, and gas[15], [16]. The Directorate General of Mineral and Coal (2015) states that the South Sumatra Basin contributes a third of coal resources in Indonesia. The South Sumatra Basin experienced three orogenesis periods, namely in the Middle Mesozoic, Late Cretaceous-Early Tertiary, and Plio-Plistocene. The research results on the sedimentation cycle in this basin concluded that these rocks and coal deposits have a regressive cycle [15], [16].



Picture 2. Research flow chart

The South Sumatra basin is in an active tectonic area, so that the coal carrier seam is generally affected by fold, fault, and intrusive and extrusive activities. As a result, in some places coal rank ranges from lignite to bituminous. These coals are found suitable for UCG development[2]. Several areas in South Sumatra that have coal resources and reserves that comply with the UCG criteria include Macang Sakti (Picture 3.a), Suban Burung (Picture 3.b), Banjarsari (Picture 3.c), and Muara Tiga Besar (Picture 3.d).

Various research has been carried out in this area. Several aspects have also been reviewed to find out whether the coal seams in South Sumatra are economical enough to be used as UCG resources and reserves or not. The research in Macang Sakti Village was conducted to determine the suitability of geological conditions, thickness, depth, total water content, and ash content for UCG. In addition, the calculation of coal resources is carried out using software that refers to the SNI 5015-2011 regulation. The results of the study found that coal resources in Macang Sakti Village have a great opportunity to be used as an activity area for UCG research[2]. Based on coal drilling activities that have been carried out at seam D, the depth, thickness, coal rank, geological structure, and rock layer of this coal seam has met the requirements to be turned into UCG coal.



Picture 3. Coal seam in the South Sumatra basin for UCG[17]

Then, research was also carried out in the Suban Burung Block, Muara Enim Formation. This study's purposes is to investigate the characteristics of coal and the environment on the Coal Seam D samples from UCG research drilling activities. The research method used was coal petrographic analysis, vitrinite reflectance values, and interpretation of the depositional environment based on the Diesel diagram and the Calder diagram. Based on the results of the reconstruction using four parameters TPI (Tissue Preservation Index), GI (Gelification Index), GWI (Ground Water Index), and VI (Vegetation Index) it is known that this coal seam is deposited in a limnic environment[18]. The results of the study found that this coal seam was dominated by vitrinite, and it is very suitable for use in the development of UCG.

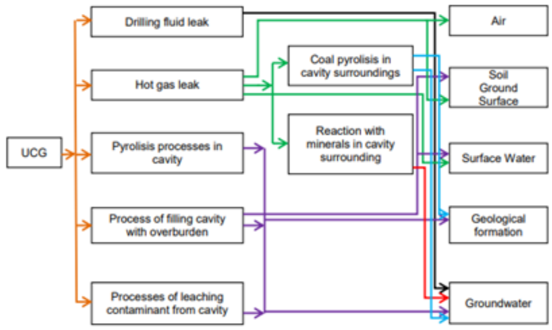
Research was carried out in the Banjarsari area, Tanjung Enim to determine the depth, thickness, ash and moisture content, and estimate the coal resources. In this research, a technical study of UCG resources was carried out to build a comprehensive model of the simulation of UCG potential. The circular method is applied to process data (geophysical logging data and coal quality data) with the help of software (MineScape 5.7 and Surfer 13)[19]. According to the results obtained for several criteria, Seam Enim at the research location has the potential for development in the utilization of coal using the UCG method.

Other research was carried out in Muara Tiga Besar District, Lahat Regency to analyze the potential and build a comprehensive model of coal resources that could be utilized for the UCG process. The method used in this research is proximate analysis and wireline logging analysis of 7 borehole points in an area of 200 hectares. The results of the study indicate that there are 5 coal seams in the research area and 3 coal seams that have the potential to be utilized by UCG[20]. Another study in the northern area was carried out with the same criteria for testing the physical and chemical properties of the vitrinite, liptinite, and inertinite maceral[13]. Based on the results, it was found that the coal seams in Muara Tiga Besar District had met the several criteria for the use of UCG. All the result in the past studies above is summarized in Table 2. Although the research in Banjarsari and Muara Tiga Besar did not show sufficient depth for the UCG project, this research has become a good step to determine the potential of UCG in South Sumatra basin. Both areas have been proven to have thickness, ash and moisture content, coal rank, geological structure, and rock layers suitable for the UCG project. With these results, further research for this area in the deeper zones has the potential for implementing the UCG project on a commercial scale.

The UCG is a coal conversion technique which of course has an impact on the environment and humans that must be considered for human health and environmental sustainability. The potential risks of implementing UCG techniques to the environment include subsidence of soil layers, contamination of air and groundwater, and hazards from the by-products. The relation of the UCG process to environmental influences such as processes of leaching containment from the cavity can affect groundwater and geological formation, the complete relations can be seen in Picture 4.

Table 2. Result of UCG research in South Sumatra

Parameter	[19]	[20]	[2]	[13]	[18]
Depth, m	148.62	159.31	285.73		
Thickness, m	14.63	14.58	9.20		
Ash, adb	3.85 %	6.71 %	2.87 %	1.65 %	
Total Sulfur, adb	0.18 %	0.42 %		0.90 %	
Inherent Moisture (IM), adb	29.11 %	12.97 %		11.00 %	
Total Moisture (TM), adb			33.75 %	29.45 %	
Ash + IM, adb	32.96 %	19.68 %		12.65 %	
Volatile Matter (VM), adb		50.50 %	39.53 %	42.05 %	
Fixed Carbon (FC), adb		32.00 %	41.56 %	44.70 %	
Calorific Value (CV), kkal/kg	6,782	12,580	5,869	5,750	
Vitrinite				91.40 %	71.10 %
Liptinite				3.90 %	5.90 %
Inertinite				4.70 %	17.60 %
Vitrinite Total			0.35	0.66	0.32
Coal Rank	High. Vol. Bitum. C	High Vol. Bitum. B – C	Lignit – Sub-bitum.	High Vol. Bitum. B – C	Lignit – Sub-bitum.
Inferred Resource (tonne)	241,529		3,316,578		
Indicated Resource (tonne)	123,818		1,909,560		
Measured Resource (tonne)			2,479,951		
Geological structure	Simple		Moderate		
Rock layer	Impermeable	Impermeable	Impermeable	Impermeable	Impermeable



Picture 4. Environmental impact of UCG[12]

This environmental observation was carried out by establishing a UCG pilot plant in South Sumatra. This pilot plant covers an area of 5 hectares with a depth of 80 m below ground level. The environmental conditions observed were the geological structure, pollution in the air and groundwater as previously mentioned. Some of the environmental risks that may occur due to the implementation of UCG are:

a. Ground water and surface water
   This groundwater is polluted because phenols and polycyclic aromatic hydrocarbon, benzene, carbon dioxide, ammonia, and sulfide from the gasification process emigrate and contaminate groundwater.
b. Air contamination
   Polluted air is caused by gas leaking from UCG activities. Air emissions by sulfur dioxide and nitrogen oxides can cause acid rain.
c. Change in geological structure
   This aspect is reviewed when the UCG process has been completed, namely leaving a hole under the ground which allows subsidence to occur. This land subsidence needs to be handled properly to reduce local impacts.

The dangers of implementing this UCG method need to be identified to maximize handling and minimize losses. The stages in identifying hazards and environmental risk assessment are as follows[12]:

a. Define the system and its subsystem and the future operations.
b. Define and describe globally the hazard, including its physical characteristics, magnitude and severity, causative factors, and locations or areas affected.
c. Analyze theoretically the probability, frequency, or likelihood of the potential losses associated with a hazard.
d. Rating the value of hazard or calculate risk class to give the required action which should be taken by forming a table of risk classification screening.
e. Resolving risk will make corrective action recommendations for preventing, reducing, or transferring the risks in the short and long-term planning.

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Several regulations have been made by the government to ensure that the environment and natural resources are in a good quality even though there are activities around the location that may change natural conditions. Things that can be affected due to the UCG process are the quality of soil, water, and air which includes noise levels. The regulations governing these things and environmental conditions around the plant after UCG activities are presented in Table 3. Based on data, the air condition around the pilot plant is excellent because all criteria do not exceed the threshold value. The water condition is not as good as the air condition, although it is still quite good because most of the criteria are below the specified value. However, the soil conditions are bad considering that certain parameters are outside the normal range. This is indicated by the pH becoming acidic and decreasing content of C and N in the soil[12]. Therefore, it is necessary to adjust the process parameters before the UCG method is applied on a larger scale.

Table 3. Regulation about environment

No	Regulation	Parameter	Condition
1	Government Regulation No. 82/2001	Water	Good
2	Ministerial Regulation on Health No.416/Men.Kes/PER/IX/1990		
3	Ministerial Regulation on Health No. 492/Men.Kes/PER/IV/2010		
4	Government Regulation No. 41/1999	Air and Noise	Excellent
5	Ministerial Decree on Environment and Forestry No. 48/MENLH/11/1996		
6	Government Regulation No. 4 of 2001	Soil	Bad

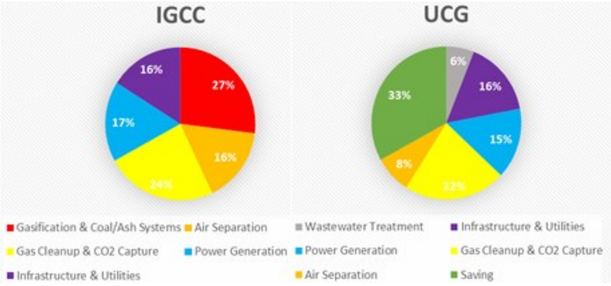
Recently there are only a few plants that directly utilize syngas produced by UCG to generate electricity. As far as the authors know, coal in South Sumatra region has not been used for this. Therefore, the authors predict the costs required based on the information for the UCG power plant from Bengkulu which is a nearby area[21]. By comparing the data available in previous studies, a rough estimate of the cost required for the UCG power plant can be obtained. For the Combined Cycle of UCG power plant that utilizes coal in the South Sumatra basin with a total hypothesis syngas of 4.77 TSCF, the plant construction capital cost is estimated at US $ 1.79 billion, while the operation and maintenance costs are estimated at US $ 388.37 million per year.

From the economic point of view, coal utilization through UCG method combined with a power plant that used the syngas produced from UCG can give more benefit. This is possible because this combination does not require some of the parts required with conventional steam power plants that burn coal above the surface. Based on equipment design and simulation results, required facilities for power generation from UCG when compared to IGCC (based on GE entrained flow gasifier with carbon capture) can save up to about 33% of the capital costs. Although there is additional cost required for facilities in a UCG power plant such as wastewater treatment facilities, the overall cost will be lower because some facilities need smaller capacities or even does not needed at all. Detailed comparison for required facilities in each power plant is given in Table 4, while the projected direct cost for power plants that utilize IGCC and for UCG power plant can be seen in Picture 5[14].

Table 4. Facilities comparison for IGCC and UCG[14]

Unit Operation	Surface IGCC	UCG + CCGT
Coal and Ash System	Required	Not required
Gasification Island	Required	Not required
Air Separation Unit		Smaller capacity
Syngas Scrubbing and Cooling	Required	Required
CO shift unit	Required	Not required
AGR and CO_2 Compression	Required	Required
Power Generation		Smaller capacity of steam turbine generator
Utilities and infrastructure	Required	Required
Wastewater Treatment	Simple	Required

Research has also been carried out on various supporting aspects of the UCG project. The research in Macang Sakti Village was conducted in the UCG pilot plant area to predict the groundwater saturation zone in the rock based on the resistivity method. Groundwater saturation data in rock is needed in UCG operations to support the coal seam combustion and gasification process. The results suggest conducting a pump test to determine aquifer potential quantitatively because almost all of the rock below the surface in the research plan area shows saturated conditions with groundwater to a depth of 300 meters [22].



Picture 5. Projected direct cost distribution[14]

Another study was also carried out to design an open channel at the UCG project site in the Musi area. An open channel was built to prevent rainwater from entering the UCG site which could interfere with the gasification process. Data collection methods are used in the form of topographic maps and rainfall in the study area. Data analysis and processing were performed using Map Info 9.0 software. The research results showed that the most ideal shape is trapezium made from soil with a cross-sectional area of 0.86 m^2, the upper channel width of 1.5 m, the width of the canal base 0.65 m, 1.05 m high, and slope 45°[23].

The aspects of soil subsidence and heat propagation induced by UCG activity in the Muara Enim formation were also investigated. Simulations and modeling were carried out to determine the level of risk of subsidence and the effect of high temperatures due to these activities. Modeling results show that the thickness of the rock above the UCG coal seam greatly affects surface subsidence. Types of claystone that do not contain kaolinite minerals are more prone to collapse than those that contain kaolinite minerals. The heat propagation modeling results show that at a depth of 50 m the temperature is estimated to be 213-289° C, but if the thickness of the cap rock is >200 m, the temperature is around 29-28 °C[24].

The demand for energy will always increase day by day because most of the equipment that we use consumes electricity. Until now coal still becomes the major source of energy, which is around 40% of the total electricity. We need to concern about global warming, greenhouse gas emissions when we use fossil energy. It is important to develop clean mine technology to succeed in the global goal of the sustainability of the environment. A sustainable mine covers five aspects that are safety, economy, resource efficiency, environment, and community. UCG is considered a clean coal technology because the spread of greenhouse gas in the atmosphere is minimal, without creating problem of ash residue after burning the coal, and can be integrated with carbon capture and storage for further CO_2 capture. The product of UCG is syngas consist of CO, CO_2, H_2, CH_4, C_mH_n, O_2, N_2, H_2O, H_2S, SO_2, SO_3. It can be used to generate power, or make urea for fertilizer, or produce ammonia and methanol and their derivatives, and/or can be converted into synthetic liquid fuels by using various methods or processes. The advantage to use UCG for future coal gasification is increased worker safety, reduced sulfur emissions, reduced discharge of Hg and tar, no ash disposal required and coal tailings, low dust and noise pollution, low water consumption, greater exploitation of coal resources, and low methane emissions to the atmosphere[25]. Other than that, the UCG process is more economical than conventional coal gasification because the capital cost is lower.

CONCLUSIONS

The coal seam in South Sumatra basin has the potential to be utilized using UCG technology. By considering depth, thickness, geological structure, ash content, inherent moisture, coal rank, and rock layer, there are several areas that meet the criteria which consist of Macang Sakti, Suban Burung, Banjarsari, and Muara Tiga Besar. The potential risks of implementing UCG techniques to the environment include subsidence of soil layers, contamination of air and groundwater, and hazards from the by-products. This process must ensure the quality of soil, water, and air which includes noise levels doesn't violate government regulation. UCG is considered a clean coal technology because the spread of greenhouse gas in the atmosphere is minimal, without the need of ash residue disposal area after burning the coal, and can be integrated with carbon capture and storage for further capture CO_2. If the syngas is directly processed to generate electricity in UCG power plant, it can save up to about 33 % of the capital costs when compared to IGCC. There are several supporting criteria include the groundwater saturated zone on the rock, design of open channel, and land subsidence and heat propagation that must be considered to optimize UCG process.

REFERENCES

[1] Fatimah, Suryana, A., Wibisono, SA. (2014). Potensi Deep Seated Coal di Indonesia, *M&E, 12(2)*, 18–28.

[2] Purnama, AB., Subarna, YS., Sendjadja, YA., Muljana, B., Santoso, B. (2017). Potensi batubara untuk pengembangan gasifikasi bawah permukaan : Studi kasus Desa Macang Sakti, Provinsi Sumatera Selatan, *J. Teknol. Miner. dan Batubara, 13(1)*, 13–30.

[3] Allan, R. (1995). Introduction : sustainable mining in the future, *J. Geochemical Explor., 1(2)*, 1–4.

[4] Gorman, MR., Dzombak, DA. (2018). A review of sustainable mining and resource management: Transitioning from the life cycle of the mine to the life cycle of the mineral, *Resour. Conserv.*

Recycl., 137(may), 281–291.

[5] Laurence, D. (2011). Establishing a sustainable mining operation: An overview, *J. Clean. Prod., 19(2–3)*, 278–284.

[6] Verma, RP., Mandal, R., Chaulya, SK., Singh, PK., Singh, AK., Prasad, GM. (2014). Contamination of groundwater due to underground coal gasification, *Int. J. Water Resour. Environ. Eng., 6(12)*, 303–311.

[7] Kumar, HRN., Udayakumar, DL., Stojcevski, A., Oo, AMT. (2014). Underground Coal Gasification: an alternate, Economical, and Viable Solution for future Sustainability, *Int. J. Eng. Sci. Invent., 3(1)*, 57–68.

[8] Imran, M., Kumar, D., Kumar, N., Qayyum, A., Saeed, A., Bhatti, MS. (2014). Environmental concerns of underground coal gasification, *Renew. Sustain. Energy Rev., 31*, 600–610.

[9] Pratiwi, R. (2012). Underground coal gasification: A safe, secure and clean unconventional gas technology for development in Indonesia, *Thirty-Sixth Annual Convention & Exhibition*, Jakarta: Indonesian Petroleum Association.

[10] Rostiarti, P., Ibrahim, E., Toha, T. (2017). Strategy for technology energy selection to achieve coal value added in PT. Bukit Asam (Persero), Tbk., *Indones. J. Fundam. Appl. Chem., 2 (3)*, 66–77.

[11] Kementerian Energi dan Sumber Daya Mineral (2018). *Keputusan Menteri ESDM Nomor 1823 K 30 MEM.*

[12] Damayanti, R. (2018). Study on environmental quality and hazard identification of underground coal gasification project: A literature study and field survey, *Indonesian Mining Journal, 21(2)*, 141-161.

[13] Rahmad, B., Raharjo, S., Rahmanda, HA. (2019). Underground Coal Gasification in the North Muara Tiga Besar Utara Area, East Merapi District, Lahat Regency, South Sumatera. *Prosiding Seminar Nasional Teknik Kimia "Kejuangan"*, Yogyakarta: Fakultas Teknik Industri.

[14] Doucet, D., Perkins, G., Ulbrich, A., du Toit, E. (2016). Production of power using underground coal gasification, *Jurnal Energy Sources, Part A Recover. Util. Environ. Eff, 38(24)*, 3653-3660.

[15] Susilawati, R., Evans, PN., Esterle, JS., Robbins, SJ., Tyson, GW., Golding, SD., Mares, TE. (2014). Temporal changes in microbial community composition during culture enrichment experiments with Indonesian coals, *International Journal of Coal Geology, 137*, 66-76.

[16] Friederich, MC., Moore, TA., Flores, RM. (2016). A regional review and new insights into SE Asian Cenozoic coal-bearing sediments: Why does Indonesia have such extensive coal deposits?, *International Journal of Coal Geology, 166*, 2-35.

[17] Bishop, MG. (2001). *South sumatra basin province, indonesia: the lahat/talang akar-cenozoic total petroleum system*. Laporan Terbuka, *United States Geological Survey*.

[18] Purnama, AB., Salinita, S., Sendjaja, YA., Muljana, B. (2018). Penentuan Lingkungan Pengendapan Lapisan Batubara D, Formasi Muara Enim, Blok Suban Burung, Cekungan Sumatera Selatan, *Jurnal Teknologi Mineral dan Batubara, 14(1)*, 1-18.

[19] Kurniawan, E., Jati, SN., Gandapradana, MT. (2020). Estimasi Sumberdaya Underground Coal Gasification (UCG), Daerah Banjarsari, Tanjung Enim, Sumatera Selatan. *Pros. TPT XXIX PERHAPI 2020*, Bandung: Perhapi.

[20] Rafsanjani, D., Akbar, M., Gandapradana, MT. (2020). Potensi Gasifikasi Batubara Bawah Tanah Daerah Muara Tiga Besar, PT. Bukit Asam Tbk. Kabupaten Lahat, Sumatera Selatan. *Pros. Semin. Nas. Tek. Lingkung. Kebumian Ke-II*, Yogyakarta: Fakultas Teknologi Mineral.

[21] Rezky, M. dan Susanto, B. (2020, Oktober). *Study Economic Analysis of Underground Coal Gasification to Supply As Fuels For Power Plant In Bengkulu*. Makalah disajikan dalam International Conference on Science and Technology, Jakarta: Universitas Islam Negeri Syarif Hidayatullah Jakarta.

[22] Pujianto, E. dan Nugroho, A. (2017). Prediksi Zona Jenuh Airtanah pada Batuan di Areal Pilot Plant Underground Coal Gasification, Musi Banyuasin, Sumatera Selatan, *Jurnal Teknologi Mineral dan Batubara, 13(3)*, 171-183.

[23] Fajrin, M., Komar, S., Handayani, RHE. (2018). Desain Saluran Terbuka untuk Lokasi Penelitian Underground Coal Gasification (UCG) di Musi Banyuasin Sumatera Selatan, *Jurnal Pertambangan, 2(1)*, 62-70.

[24] Zulfahmi, Syafri, I., Abdurrokhim, Wattimena, RK. (2020). Subsidence and Heat Propagation Modeling on The Underground Coal Gasification (Case Study at Muara Enim Formation, South Sumatera), *Indonesian Mining Journal, 23(2)*, 83-98.

[25] Kostúr, K., Laciak, M., Durdan, M. (2018). Some Influences of Underground Coal Gasification on the Environment, *Sustainability Journal, 10(5)*. 1512.