Techno-economic analysis of producing low heating value underground coal gasification gas in Indonesia

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Abstract. Indonesia is currently reviewing the use of underground coal gasification (UCG) technology to utilize deep-seated coal. UCG may exploit the coal deposit that is not feasible for open-pit mines due to its great depths. In this study, the UCG plant in two coal mines, the Kideco Jaya Agung (KJA) and the Indominco (IMM) coal mines, will be compared their economics in producing low heating value gas with a capacity of 170,000 MJ/hour. The UCG plants implement the linking vertical well (LVW) technique combined with reverses combustion linking (RCL). The discounted cash flow (DCF) method is used for financial analysis to determine the minimum selling price of UCG low heating value gas. The study aims to understand the economic feasibility of applying UCG technology to Indonesia's different characteristics of coal deposits. The results show the minimum prices of the low heating value UCG gas of KJA and IMM UCG plants are USD 3/MMBTU and USD 3.57/MMBTU, respectively. The operating cost of the IMM UCG is higher than that of the KJA UCG plant due to its thinner and deeper coal seams.

1. Introduction
Since 2011 Indonesia has become the world's largest exporter of steam coal [1]. However, the reserve to production ratio (R/P) of Indonesian coal is shorter (67 years) than the USA (365 years), Australia (304 years), and India (132 years) [2]. Indonesia's coal production grew by more than 6%/year, from 462 million tons in 2015 to 616 million tons in 2019 [3]. Along with the increase in cumulative production, the coal production cost also increases since the coal seam is getting deeper. Increasing production cost is predicted to cause Indonesia's coal production to peak in the next few years and decline [1]. Indonesia is currently reviewing the use of underground coal gasification (UCG) technology to utilize deep-seated coal [4]. The deep-seated coal may not be suitable for conventional mining due to its great depths, but it may be exploitable by UCG.

UCG is an in-situ gasification process in deep coal seams carried out by injecting oxidant (air or oxygen/steam) through injection wells into the previously ignited coal seams to produce gas, namely producer-gas or syngas. The term producer-gas is used for gas-product that uses air as the oxidant, whereas syngas is used when steam or oxygen is used as the oxidant. Producer-gas has a lower heating value than syngas since the nitrogen in the air remains unchanged during the gasification and dilutes the product gas. Low heating value UCG gas is suitable for fuel in boiler or power generation. In contrast, syngas is used to synthesize various products such as hydrogen, methanol, synthetic natural gas, synthetic oil, and ammonia.

Several studies have been conducted to investigate the economics of large-scale UCG syngas plants (>100MW) for a variety of uses, including for fuel in combined cycle power plants [5,6] and raw
materials in liquid fuel synthesis [7], methanol [8] and hydrogen [9]. Although the above study shows results suggesting that UCG synthetic gas can generate electricity or produce chemicals at competitive prices, no large-scale UCG plant has yet been built. On the other hand, the small-scale (<100 MW) UCG plant in the Angren City of Uzbekistan constructed in 1960 to produce low-heating value gas for fuel in a power plant still operates today.

In this study, the economic feasibility of the construction of UCG plants in the Kideco Jaya Agung coal mine (KJA-UCG) and the Indominco coal mine sites (IMM-UCG) will be compared using the internal rate of return (IRR) as an economic indicator. Besides, the sensitivity analysis of the IRR value on operating pressures, electricity prices, well spacings, and syngas selling prices will be evaluated. Also, the UCG well drilling and construction cost will be described in more detail based on the socio-economic conditions of Indonesia since the drilling and construction costs of UCG wells found in the literature are varied. Khadse [10] assumes the drilling and completion cost of UCG vertical wells is USD 630/m, while Pei et al. [11] reported the cost of USD 820/m. Nakaten and Kempka [8] reported drilling costs based on drilling stages that are € 80/m for vertical drilling, €480/m for deviated drilling, and € 230/m for horizontal drilling. The cost of drilling a UCG well should be lower than the cost of drilling an oil and gas well because the depth of the UCG well is shallower so that smaller and cheaper mining drilling rigs can be used. The study aims to understand the economic feasibility of applying UCG technology to different coal deposit characteristics in Indonesia.

2. Materials and Methods

In contrast to surface coal gasification, the UCG plant did not need capital to purchase gasifiers; however, it requires the cost to construct UCG wells. Therefore, the number of wells required to produce syngas to meet the designed capacity and the life span of the wells should be calculated. Figure 1 showed the flowsheet for calculating UCG capital costs and operating costs. The number of wells to be constructed depends on UCG syngas production capacity, the cold gas efficiency (CGE), the calorific value of coal, the air injection rate for each well, and the number of modules of the UCG plant. Module (M) is defined as the volume of coal between each injection and production wells, while CGE is defined as the ratio between energy in product gas at room temperature and the energy in the gasified coal. In this study, the UCG plant was designed at a capacity of 170,000 Mega Joule/hour (MJ/hr), and the CGE is assumed to be 61%. The CGE value is the same as the CGE value of UCG in Angren Uzbekistan [12]. The calorific value and the characteristics of the coals used, IMM and KJA coals, are shown in Table 1. IMM coal has a higher heating value (25.54 MJ/kg) but a thinner coal seam (6 m) than KJA coal. Due to these characteristics, the CGE of both coals is assumed to be the same; however, the IMM-UCG plant is expected to have a higher wells-drilling and construction cost than the KJA-UCG plant due to its deeper coal seam. The UCG plants implement the linking vertical well (LVW) technique that uses a reverse combustion linking (RCL) method to connect the wells. Using the above technique, two types of compressors, namely a high-pressure compressor for the linking process and an operating-pressure compressor for the gasification process, are needed. The wastewater treatment and gas cleaning units did not include in the UCG plant design to reduce the uncertainty during cost estimation. As a result, the plant would produce low-heating value UCG gas that is wet and dirty.
Figure 1. Flowsheet to calculate capital and operational expenditure.

Table 1. Characteristics of KJA and IMM coal.

| Parameters                        | KJA coal | IMM coal |
|-----------------------------------|----------|----------|
| Total Moisture (TM) (%) ar        | 31.42    | 14.23    |
| Moisture (M) (%) adb              | 19.2     | 10.2     |
| Volatile Matter (VM) (%) adb      | 41.31    | 40.98    |
| Ash (%) adb                       | 4.09     | 3.99     |
| Fixed Carbon (FC) (%) adb         | 35.39    | 44.83    |
| Coal high heating value (Hc) (MJ/kg, gar) | 18.33    | 25.54    |
| Coal high heating value (Hc) (kcal/kg, gar) | 4379    | 6100    |
| Coal seam thickness (Tc) (m)      | 14       | 6        |
| Average coal seam depth (m)       | 250      | 350      |

Coal characteristics influence gasification efficiency. Cold gas efficiency (CGE) will increase with the increase of coal heating value or seam thickness. CGE is defined as the ratio between energy in product gas under room temperature and the power in the gasified coal. Table 1 shows the characteristics of IMM and KJA coals. IMM coal has a higher heating value (25.54 MJ/kg) but a thinner coal seam (6 m) than those of KJA coal.

3. Results and Discussion

3.1. UCG process description

In this study, the UCG plant was designed to implement the linking vertical well (LVW) technique that uses a reverses combustion linking (RCL) method to connect the wells. The LVW technique was used extensively during the Russian UCG experiments and early trials in the USA. The LVW was also used by Solid Energy (New Zealand), Eskom (Majuba, South Africa), Cougar Energy (Kingaroy, Australia), as well as other companies in other locations such as China and Canada (Laurus Energy) [13].

Figure 2 shows the layout of the UCG vertical well. The arrangement of modules in the direction along the gasifier length is called a channel (C). Gasifier (G) is defined as coal volume surrounded by
pillars and consists of one or more channels. The width of each module is assumed to be the same as the wells spacing (40m). Each gasifier is designed to consist of two channels with the following objectives: i) if a problem occurs in one injection well, gasification can be continued using another injection well and ii) to reduce subsidence risk due to broader cavity. Pillar has two functions, namely preventing subsidence and gas seepage to neighboring gasifiers.

Two compressors of different pressures are used for the two stages of the LVW technique, the wells linking stage and the gasification stage. Figure 3 shows an illustration of the air supply for the LVW technique. A high-pressure (HP) compressor (4 MPa) is used to supply air during the wells linking stage, and an operating pressure (OP) compressor (0.3 MPa) is used for the gasification stage. Initially, only three wells in one channel were operating, R1-well as a production well, R2-well as an OP air injection well for gasification, and R3-well as an HP air injection well for the reverse combustion process. After the coal between R1 and R2-well has been gasified, R2-well is used as a production well, R3-well is used as a low-pressure air injection well for the gasification process, and R4-well is used for high-pressure air injection well for the reverse combustion process. These processes are repeated until the injection well reaches the end of the gasifier. After the initial module, only one well is required to construct a module, and it is included in the operational cost.

In contrast, the initial wells are included in the capital expenditure since this well is used for start-ups only. There is no capital expenditure for power plant construction since the electricity to run the UCG plant is supplied by another company. The depth of the coal seam is 250-350m, and it is predicted that the air pressure of 4MPa is enough to withstand the groundwater pressure so that air can flow through the cracks in the coal seam for reverse combustion purposes.

Figure 2. Layout of the UCG well.
3.2. UCG process parameter calculation

Both UCG plants were designed at the capacity of 170,000 Mega Joule/hour (MJ/hr), and the CGE is assumed to be 61%. The amount of gasified coal per hour or coal gasification rate ($G_r$) is calculated based on the energy balance expressed in equation one (1), where $P_g$ and $H_g$ are gas production rate and gas heating value, respectively. $G_r$ can be calculated by inserting each coal's heating value ($H_c$) (Equation 2).

$$G_r \times H_c \times CGE = P_g \times H_g$$

$$P_g \times H_g = 170,000$$

$$G_r = \frac{170000}{H_c \times 0.61}$$

(2)

In ideal conditions, the air injection rate ($I_a$) required to meet the designed gas production rate ($P_g$) can be calculated by the mass balance of the gasifier. However, in the case of UCG, there is a possibility of air injection loss and/or product-gas loss due to the high permeability of the surrounding rocks. Therefore, the total air injection rate ($I_a$) is calculated based on the assumption that the ratio value $P_g/I_a = 1.5$ (Equation 3) [14]. Further, using the $I_a$ value and UCG operating pressure of the UCG, the power requirement of the compressor can be estimated.

$$I_a = \frac{P_g}{1.5} = \frac{170000}{H_g \times 1.5}$$

(3)

The number of modules that are operated simultaneously ($N_{ms}$) required to meet the UCG design capacity is calculated from the value of the total air injection rate ($I_a$) divided by the air injection rate per module ($I_{am}$), as presented in equation 4. Boysen [15] developed a formula to calculate the maximum air injection rate based on module length and coal thickness. Using the formula, the maximum air injection rate per module for KJA and IMM coals are 10,500 m$^3$/hr and 17,800 m$^3$/hr, respectively. The air injection rate selected here, 7500 m$^3$/hr, is below the maximum air injection rate. The number of modules operated simultaneously ($N_{ms}$) is four.

$$N_{ms} = \frac{I_a}{I_{am}} = \frac{30062}{7500} \approx 4$$

(4)

The life span of a module ($L_m$) is calculated to estimate the total number of modules that must be constructed annually. It is calculated from the mass of coal in all modules that operated simultaneously multiplied by coal sweep efficiency (CSE) and divided by the weight of coal that must be gasified.
annually (Equation 5). CSE is defined as the fraction of the total volume of coal within a module contacted by gasification. A CSE value used here is 80%, although CSE values up to 95% have been claimed by Ergo Exergy Technology [14]. The number of modules that must be prepared annually ($N_{ma}$) is calculated from the number of modules operated simultaneously ($N_{ms}$) divided by the life span of the modules (Equation 6)

$$L_m = \frac{N_{ms} \times L_m \times d_m \times t_c \times \rho_c \times \text{CSE}}{G_c \times 365 \times 24}$$

$$N_{ma} = \frac{N_{ms}}{L_m}$$

Table 2 summarizes the calculation results of the KJA and IMM UCG plant process parameters. The amount of coal gasified ($Gr$) of IMM-coal is less than KJA-coal since IMM-coal has a higher calorific value than KJA-coal. However, the number of modules that must be constructed annually at the IMM UCG plant is larger (10 units) than that of the KJA (6 units) since IMM's module life span is shorter due to its thinner coal seam. As the number of modules increase, the operating cost will also increase.

| Parameters                              | Symbol | KJA  | IMM  |
|-----------------------------------------|--------|------|------|
| UCG Plant Capacity, MJ/hr               | $P_g \times H_g$ | 170,000 | 170,000 |
| Syngas production rate, m$^3$/hr        | $P_g$  | 45,093 | 45,093 |
| Air demand, m$^3$/hr                    | $I_a$  | 30,062 | 30,062 |
| Coal gasified, ton/hr                   | $G_r$  | 15.20  | 11.09 |
| Number of modules                       | $N_{ms}$ | 4     | 4.0  |
| Number of initial well, unit            |        | 4     | 4    |
| The life span of each module, year      | $L_m$  | 0.7   | 0.4  |
| Number of new injection Well/year, Unit | $N_{ma}$ | 6     | 10   |

3.3. UCG-well cost estimation

UCG-well drilling and construction costs include the cost of labor, equipment, casing string, material, and cementing. The above prices are influenced by UCG well design, labor productivity, and local market conditions.

3.3.1. Labor cost. Figure 4 shows the UCG well design. The well uses two casing sizes installed at different depths, a casing size of 10.75-inch to a depth of 70 m and a casing size 7-inch to a depth of 300 m. The bottom part of the coal seam with a thickness of one-third of the total coal thickness is not cased because the coal surface is required for the airflow path. The drilling stages and required working hours are described in Table 3. After drilling preparation, the next step is to install and cement the 10.75-inch casing to a depth of 70m. For this purpose, firstly, a 4-inch hole is drilled, then the hole is reamed to 6.8-inch, 9.8-inch, and 13-inch, respectively, to a depth of 70m. Once the holes are prepared, a 10.75-inch casing is installed and cemented. The 10.75-inch casing serves to protect the surface water and cover unconsolidated formations. The next stage is installing 7-inch casings, which begins with core drilling with HQ size bit and then several reaming works and casing installation.
The core drilling is conducted until it reaches a depth of 1 meter below the coal seam to collect a core sample for analysis. After the cement in the annulus of 7 inches casing has dried, the well-integrity test and well logging are conducted. The last stage is wells cleaning. It is run by drilling with a bit size of 6-inch to remove the remaining cement inside the casing and to reveal a fresh coal seam below the casing. The number of man-hours is calculated based on the penetration rate of 3 m/hr for open-hole drilling and 1 m/hr for core drilling. The total time required for drilling, testing, and well construction is 33 days or 2632 man-hours. A labor rate of USD 6 per man-hour is used, and the total labor cost is USD 15,792.

Table 3. Labor cost for drilling and construction of UCG well.

| No | Drilling Stage | Number of shift & labor/shift | Working Days | Working hour/shift (hrs) | Time (hrs) |
|----|----------------|-------------------------------|--------------|--------------------------|------------|
|    | Drilling preparation |                               |              |                          |            |
| 1  | Land preparation   | 1 & 2                         | 2            | 8                        | 32         |
| 2  | Machine transporting| 1 & 4                         | 1            | 8                        | 32         |
| 3  | Machine set up     | 1 & 4                         | 1            | 8                        | 32         |
|    | Installation of 10.75-inch surface casing-string up to a depth of 70 m | | | | |
| B  | Open hole 4" drilling; reaming to 6,8"; 9.87" and 13" | 3 & 3 | 4 | 8 | 288 |
|    | Casing set up and annulus cementing | 3 & 4 | 1 | 8 | 96 |
|    | Installation of 7-inch casing string up to a depth of 300m | | | | |
| C  | HQ size touch core drilling | 3 & 4 | 10 | 8 | 960 |
|    | Gamma-ray logging  | 1 & 5                         | 1            | 8                        | 40         |
|    | Hole reaming to 6.8" | 3 & 4                         | 4            | 8                        | 384        |
|    | Hole reaming to 9.87" | 3 & 4                         | 4            | 8                        | 384        |
|    | Casing set up      | 2 & 7                         | 1            | 8                        | 112        |
|    | Casing cementing   | 2 & 7                         | 1            | 8                        | 112        |
|    | Well testing       |                               |              |                          |            |
| D  | Integrity testing  | 1 & 3                         | 1            | 8                        | 24         |
|    | Logging/CBL (cement bound log) | 1 & 5 | 1 | 8 | 40 |
|    | Preparation of high-pressure oxidant injection | | | | |
| E  | Re-drilling cement plug | 1 & 3 | 1 | 8 | 24 |
|    | Well clean-up      | 1 & 3                         | 1            | 8                        | 24         |
|    | Wellhead installation | 1 & 2                     | 1            | 8                        | 16         |
|    | Drilling machine moving | 1 & 4                     | 1            | 8                        | 32         |
|    | Total working hours | 104                          | 33           |                          | 2,632      |
|    | Drilling labor cost (USD) |                          |              |                          | 15,792     |
3.3.2. Casing cost. The outer diameter and thickness for the 10.75-inch casing are 273.05mm and 7.085mm, respectively while for the 7-inch casing are 177.8 mm and 9.195 mm, respectively. The cost of procuring the casing is assumed to be 2,000 USD/ton. If the density of metal is 7.87 tons/m³, then the cost of procuring the casing can be calculated. The expenses of casing are USD 93.2/m and USD 76.6/m for casing sizes of 10.75 and 7-inch, respectively. By multiplying the cost per meter length of the casing with the total length of the casing, the overall casing procurement cost can be calculated that is USD 29,507 per well. The casing cost obtained from this calculation is slightly higher than that reported by Gul & Aslanoglu [16] but lower than the assumption used by Kipsang [17]. Casing prices may vary by country, possibly due to differences in regulations and infrastructure availability.

3.3.3. UCG well drilling and construction cost. The total cost of drilling and well construction is shown in Table 4. Cement material costs are calculated with the assumption that 80kg cement is needed per meter well. In contrast, fuel cost is calculated using the assumption that the fuel consumption for drilling machines, cement pumps, and other heavy types of equipment is 3 liters/hr. Rental fees for the drilling machine, cementing pumps, and other equipments are calculated from the purchase cost divided by their economic age. The average drilling and well construction cost is USD 296/m, with casing procurement occupied the most considerable portion. The above result is slightly different from the results of the previous study [8,10,11]. The cost of drilling a UCG well should be lower than the cost of drilling an oil and gas well because the depth of the UCG well is shallower so that smaller and cheaper mining drilling rigs can be used.

Table 4. UCG-well cost.

| Cost Components                      | Cost (USD) | Cost (%) |
|--------------------------------------|------------|----------|
| Labor                                | 15,792     | 17.8%    |
| casing string                        | 29,507     | 33.2%    |
| cement material                      | 6,000      | 6.8%     |
| fuel, bit & chemicals                | 10,858     | 12.2%    |
| equipment rent                       | 11,666     | 13.1%    |
| wellhead                             | 5,000      | 5.6%     |
| equipment mobilization and demobilization | 10,000   | 11.3%    |
| Total Cost                           | 88,822     | 100%     |
| Cost per meter                       | 296        |          |

3.3.4 Compressor cost. The UCG process requires pressurized oxidants for reverse combustion and the gasification process. Reverse combustion linking (RCL) requires higher pressure than hydrostatic pressure, while for gasification, the operating pressure is lower than hydrostatic pressure [18]. Since the coal seam depth is 250-350m, the pressure for RCL is estimated at 4 MPa with airflow 1500 m³/hr. The RCL duration for UCG wells with a spacing of 40 m is approximately one month (RCL rate 1.33m/day). Thus, the time for reverse combustion linking for the UCG IMM plant (10 modules) and the UCG KJA plant (6 modules) each year is ten months and six months, respectively. As a result, both the IMM and KJA UCG plants only need one high-pressure compressor for the RCL because there is an idle time of the compressor (more than two months) that can be used for maintenance activities. For reference, the RCL at the UCG Chinchilla plant shows a linkage speed of between 0.9 m/day and 11.3 m/day [6]. While, six (five operating and one spare) operating pressure compressors, each with an airflow of 6000 m³/hr, are needed to meet the airflow rate of 30,000 m³/hr (Table 3).

Capital and operational (electricity) costs of a compressor depend on its power. The compressor’s power depends on its airflow rate and discharge pressure. In this study the compressor power was calculated using the polytropic compression formula with a polytropic efficiency of 71%. The results of
the calculation show the high-pressure and operating-pressure compressor need a power of 420 kW and 438 kW, respectively. Compressor capital cost is linearly correlated with compressor size (power) (Equation 7) [19]. The equation shows an increase in one horsepower (HP) in compressor size corresponds to a USD 492 increase in capital cost. Using equation 7, the calculated capital cost of a high-pressure compressor and operating pressure are USD 430,624/unit and USD 442,491/unit, respectively. The total procurement cost of compressor can be calculated by multiplying the number of compressors needed and the unit cost of the compressor.

\[
\text{Capital Cost (USD)} = 492 \times \text{HP} + 153.726
\]  

(7)

Electricity is mainly needed to run the compressor. The maximum power required at the two UCG plants is the same at 3.14 MW. Electric power for other needs such as lighting and operating apparatus in office and laboratory is assumed to be 20% of the compressor power. Due to the shorter operating time of high-pressure compressors at UCG KJA, the total annual electricity usage for UCG KJA (25. million KWh) is lower than that of UCG IMM (26.2 million KWh). The electricity costs per year assuming an electricity price of USD 0.07/KWh for UCG KJA and UCG IMM are USD 1.75 million and USD 1.835 million, respectively.

3.3.5. Financial Analysis. The method used in this financial analysis is Discounted Cash Flow (DCF), with the internal rate of return (IRR) as an indicator of profitability. The lowest UCG gas selling price, defined as the price of UCG gas at an IRR value equal to the Weighted Average Cost of Capital (WACC), of the two UCG plants will be compared. Indonesia's WACC value is estimated to be 12%, which is slightly higher than the WACC of renewable energy projects in India [20]. The assumptions used in this analysis are: the project life is 20 years, depreciation is distributed evenly over the life of the plan, duration of plant construction is two years, corporate tax is 22%, annual plant operation time is 8520 hours, financing scheme is 100% equity, and there is no escalation of plant costs as well as gas prices during the life of the project. The result of capital cost and operational cost estimation and the financial analysis are described in the next section.

3.3.6. Capital cost. The total capital cost of the UCG plant to produce low-heating value UCG gas consisted of the costs of purchasing compressors, laboratory equipment, workshop tools, truck-mounted crane and a light vehicle, mechanical and electrical, building, management and supervision, and contingency was summarized in Table 5. The cost of procuring compressors and the cost of UCG well have been described in the previous section. Laboratory capital costs include purchasing a syngas analyzer, a spectrometer for water quality analysis, a gas-chromatography, an analytical balance, laboratory glassware, and others is about USD 200,000. Double cabin trucks used to mobilize personnel, and a crane-mounted truck used to transport the casing and construct surface facilities required a capital cost of about USD 150,000. Building construction costs and equipment installation costs (mechanical and electrical) are assumed to be 10% of surface facility costs. The cost of land and other infrastructure procurement costs, such as electricity grid, roads, etc., are not included in the investment costs because the factory will use existing facilities owned by the open-pit mine. The construction time is estimated to be less than two years. Since the surface facilities do not consist of many equipment units, the management and supervision costs are assumed to be only 5% of surface facility costs. More than 65% of the capital costs are for purchasing compressors; therefore, compressor type and brand selection are crucial. The selected compressor must provide air output according to specifications, has a longer economic life, and has a shorter maintenance time at a reasonable price. KJA has a lower investment cost than IMM because it has a shallower coal seam to lower the UCG-well construction costs.
Table 5. Capital cost components.

| Cost components                        | KJA                | IMM                |
|----------------------------------------|--------------------|--------------------|
| Operating-pressure compressor          | 2,654,944          | 2,654,944          |
| High-pressure compressor               | 430,624            | 430,624            |
| Initial-well construction cost         | 296,685            | 415,360            |
| Laboratory instrument                  | 200,000            | 200,000            |
| Light vehicle and pipeline crane       | 150,000            | 150,000            |
| Workshop’s tools & equipment           | 50,000             | 50,000             |
| M&E and building: 10% of surface       | 373,225            | 385,093            |
| facility cost                          |                    |                    |
| Management and supervision: 5% of      | 186,613            | 192,546            |
| surface facility cost                  |                    |                    |
| Contingency: 5% of surface facility    | 186,613            | 192,546            |
| cost                                   |                    |                    |
| Total Capital cost                     | 4,528,703          | 4,671,112          |

3.3.7. Operational cost. The total operational costs comprise electricity, wells, royalty, labor, maintenance, environment, and contingency (Table 6). The electricity and UCG-well cost have been described in the previous section. Royalty fee was calculated assuming a coal price of USD 20/ton and a royalty rate of 3%. The number of UCG plant laborers, excluding the drilling laborers, was estimated at 58 people. Maintenance costs were assumed 3% of the total capital cost of compressor, laboratory, workshop, vehicle, and well costs. Environmental costs assumed 10% of the well-costs, include the cost of monitoring groundwater and well abandonment. As shown in Table 6, the operating costs of the IMM-UCG plant are higher than the KJA-UCG plant since the IMM coal seam is deeper and thinner than the KJA coal seam. The thinner the coal seam, the more modules to be constructed annually, and the deeper the coal seam, the higher the cost of drilling and construction of the well.

Table 6. Operational cost.

| Cost Components                        | KJA                | IMM                |
|----------------------------------------|--------------------|--------------------|
| Electricity cost                        | 1,750,463          | 1,835,501          |
| Well cost                              | 428,740            | 1,022,055          |
| Coal royalty cost                      | 77,714             | 56,712             |
| Personnel cost                         | 580,000            | 580,000            |
| Maintenance                            | 189,113            | 195,046            |
| Environmental compliance &             | 42,874             | 102,206            |
| abandonment                            |                    | 2.6                |
| Contingency                            | 161,521            | 199,554            |
| Total operational cost                  | 3,230,424          | 3,991,075          |

3.3.8. The minimum selling price of the low heating value gas. The relationship between IRR and low heating value UCG gas prices is shown in Figure 5. As one might expect, due to lower capital and operational costs, the KJA UCG produces gas at a lower price than the IMM UCG plant. The minimum UCG gas selling prices of KJA and IMM are USD 3/MMBTU and USD 3.57/MMBTU, respectively. The IRR value of UCG IMM will increase above 20% if the UCG gas price is above USD 4/MMBTU.
This UCG gas price is economically feasible since the price of natural gas in the East Kalimantan Fertilizer plant, which is about 20 km from the IMM-UCG plant, is much higher (USD 5.4/MMBTU).

**Figure 5.** The minimum selling price of UCG low heating value gas.

### 3.3.9. Sensitivity Analysis

The minimum selling gas prices of KJA-UCG and IMM-UCG above are the financial analysis results using base-case assumptions: electricity price of USD 0.07/kWh, well spacing, or module length of 40m, and operating pressure of 0.03 MPa. Sensitivity analysis was then conducted to understand the influence of the above variables on the IRR value of the UCG IMM. The IRR value increases from 12% to 18% when the operating pressure was lowered from 0.3 to 0.2 MPa (Figure 6). The UCG process at high pressure is needed to prevent excess groundwater from entering the gasifier. However, the lower operating pressure is preferable to lower the capital and operating costs or increase the project's economic viability. UCG at low operating pressure can be accomplished by reducing the groundwater hydrostatic pressure. It can be done, for example, by extracting some of the groundwater around the gasifier through pumping.

The IRR value also increases as the distance between the wells gets longer. The IRR value increased from 12% to 19% when the well spacing (length of a module) increased from 40m to 60m. Wells spacing can be increased by shifting the wells linking method from reverse combustion to in-seam borehole linking [10]. The in-seam borehole allows for greater distances between the vertical wells, enabling a greater volume of coal to be converted per wells pair. Another effort that can be made to improve the economy is to reduce electricity costs. The IRR increases from 12% to 16% when the electricity price falls from USD 0.07/kWh to 0.06/kWh. It could be done using an internal power plant that uses UCG low heating value UCG gas fuel. A more detailed study needs to be done to reduce UCG gas production costs, including an option to increase plant capacity.
4. Conclusions
Techno-economic studies on the implementation of UCG with a capacity of 170,000 MJ/hr raw-low heating-value UCG gas in KJA and IMM open-pit coal mines have been conducted. This study presents the UCG economic calculation method, including the detailed calculation of wells construction costs based on socio-economic conditions in Indonesia that have not been studied by other researchers yet. The conclusions obtained from the study are as follows: The drilling and construction cost of the UCG well is approximately USD 300/m, with the highest cost being the purchase of the well’s casing. The operating cost of the IMM UCG is higher than the KJA UCG plant due to its thinner and deeper coal seams of IMM. The thinner the coal seam, the more wells to be prepared annually, and the deeper coal seams will result in higher drilling and construction costs. Compressor capital cost and compressor operational costs (electricity cost) contribute the most to capital and operating costs, respectively. The minimum prices of the low heating value UCG gas for KJA and IMM UCG plants are USD 3/MMBTU and USD 3.57/MMBTU, respectively. The UCG plant is economically feasible since the price of natural gas in the East Kalimantan Fertilizer plant, about 20 km from the IMM-UCG plant, is much higher (USD 5.4/MMBTU). UCG economics can be improved by reducing operating pressure, lowering electricity prices, and extending the distance between wells. The IRR value increased from 12% to 19% when the well spacing was increased from 40m to 60m. Wells spacing can be increased by shifting the wells linking method from reverse combustion linking to in-seam borehole linking.

References
[1] Rosyid F A and Adachi T 2016 Forecasting on Indonesian Coal Production and Future Extraction Cost: A Tool for Formulating Policy on Coal Marketing Nat. Resour. 07 677–96
[2] British Petroleum 2019 BP statistical review of world energy 2019 68th Edition
[3] Directorate General Mineral and Coal 2021 Realisasi Produksi dan Penjualan Batubara Minerba One Data Indones.
[4] Purnama A and Huda M 2019 A preliminary study of Indonesian coal basins for underground coal gasification development Indones. Min. J. 22 61–76
[5] Nakaten N, Schlüter R, Azzam R and Kempka T 2014 Development of a techno-economic model for dynamic calculation of cost of electricity, energy demand and CO2 emissions of an integrated UCG–CCS process Energy 66 779–90
[6] Blinderman M S and Jones R M 2002 The Chinchilla IGCC project to date: UCG and
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