Utilization of Low-Rank Coals for Producing Syngas to Meet the Future Energy Needs: Technical and Economic Analysis

Usama Ahmed 1,2,*, Muhammad Arsalan Hussain 3, Muhammad Bilal 3, Hassan Zeb 3, Umer Zahid 1,4, Sagheer A. Onaizi 1,2 and Abdul Gani Abdul Jameel 1,5

1 Chemical Engineering Department, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia; uzahid@kfupm.edu.sa (U.Z.); onaizi@kfupm.edu.sa (S.A.O.); a.abduljameel@kfupm.edu.sa (A.G.A.J.)
2 Interdisciplinary Research Center for Hydrogen and Energy Storage, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia
3 Institute of Energy & Environmental Engineering, New Campus, University of the Punjab, Lahore 53700, Pakistan; arsalanpu@yahoo.com (M.A.H.); m.bilalibrahim078@gmail.com (M.B.); hassanzeb.ieee@pu.edu.pk (H.Z.)
4 Interdisciplinary Research Center for Membranes & Water Security, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia
5 Center for Refining & Advanced Chemicals, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia

* Correspondence: usama.ahmed@kfupm.edu.sa

Abstract: Increased energy demand in recent decades has resulted in both an energy crisis and carbon emissions. As a result, the development of cleaner fuels has been under the research spotlight. Low-rank coals are geographically dispersed, abundant, and cheap but are not utilized in conventional processes. Syngas can be produced from coal-using gasification which can be used in various chemical engineering applications. In this study, the process model for syngas production from low-rank coal is developed and the effects of various process parameters on syngas composition are evaluated, followed by a technical and economic evaluation. The syngas production rate for the low-rank coal has been evaluated as 25.5 kg/s, and the contribution to H2 and CO production is estimated as 1.59 kg/s and 23.93 kg/s, respectively. The overall syngas production and energy consumed in the process was evaluated as 27.68 kg/GJ, and the CO2 specific emissions were calculated as 0.20 (mol basis) for each unit of syngas production. The results revealed that the syngas production efficiency for low-rank coals can be as high as 50.86%. Furthermore, the economic analysis revealed that the investment and minimum selling prices per tonne of syngas production are EUR 163.92 and EUR 180.31, respectively.

Keywords: syngas; low-rank coals; gasification; cold gas efficiency; techno-economic analysis

1. Introduction

Due to an abundance of coal reserves around the globe, coal will remain the main contributor to the energy supply chain, not only for power and heat generation, but also for fuel and chemical processing. The world’s coal reserves are estimated to be over 861 billion tonnes. Coal generates 42% of the world’s electricity and provides about 30% of the world’s primary energy [1]. About 45% of the world’s coal has a high moisture or ash content. Many of the developing and developed countries, including China, Turkey, India, South Africa, Romania, etc., still rely heavily on coals to meet their power generation needs [2]. To meet the energy demand and supply gap, low-rank coals can be an attractive option due to the availability of huge reserves for at least the next few decades [3,4]. Coal has the greatest capacity compared to any non-renewable fuel, accounting for 56% of global reserves and 89% of global capital [5]. As coal is the most plentiful, efficient, and inexpensive fuel, it has the potential to become the most reliable and accessible energy source, contributing
significantly to global energy security. The environmental effects of coal, both in processing and in use, are one of the most pressing issues faced by the power generation industry. The coal industry emits pollutants, such as SOx, NOx, COx, and particulate matter of various sizes that significantly contribute towards global warming and climate change. Over the last few decades, various pollutant management systems have been developed and are still developing. Clean coal technologies are emerging technologies that make it easier to use coal in a more environmentally friendly way by significantly reducing pollutant emissions [6].

Recent advancements in syngas, H2, and technologies for energy production using natural gas and coal as fundamental fuels have emphasized meeting energy demands while lowering greenhouse gas emissions [7]. Steam methane reforming (SMR), auto-thermal reforming (ATR), dry methane reforming (DMR), tri-methane reforming (TMR), Partial Oxidation (POX), and gasification are some of the industrial processes that can generate H2 from fossil fuel [8]. Different modes of gasification with multi-fuel and multi-products have been evaluated as one of the most effective strategies for future electricity and H2 production with reduced carbon footprints. Furthermore, coal use has been on the rise for decades, with an estimated annual growth of 0.6% [9]. When it comes to fossil fuel stocks, coal outnumbers natural gas by a large margin. Because of the plentiful and relatively low-cost coal reserves around the world, coal is to remain in the future a viable fossil fuel with primary power and hydrogen (H2) applications.

Moreover, the diversity of products obtained from gasification, in particular H2, has increased the popularity of the technology [10,11]. Furthermore, the versatility of the gasification process, allowing it to integrate with various technologies, reflects its long-term potential. The SMR method produces syngas with H2 and CO at a ratio of 3:1, using natural gas and steam, which shows a more significant production potential. It is one of the most sophisticated, widely used, and cost-effective H2 production technologies [12]. Furthermore, the technology’s high efficiencies and low operating and production costs, as well as the readily available natural gas, reinforce it [13]. Dry methane reforming (DMR), on the other hand, produces syngas from CO2 and natural gas. Endothermic reactions are one of the key downsides of this technique, which, in comparison to SMR, increase operational and production costs. Furthermore, the carbon monoxide and hydrogen ratio is 1:1, indicating lower H2 output than SMR [14]. However, catalyst deactivation and energy consumption are some of the operation issues that need to be addressed [15]. Similarly, POX is a non-catalytic method that produces syngas after burning with pure oxygen. The key disadvantages are the high cost of oxygen separation, the high operating temperature of 1300–1500 °C, and the pressure of 3–8 MPa needed to carry out reactions [8]. Furthermore, syngas generated by the POX process gives a 1:1 ratio of hydrogen and carbon monoxide, which is significantly lower than that of SMR [8,16]. The major advantage of steam methane reforming and gasification over partial oxidation and dry methane reforming is that both SMR and gasification are more suitable for increasing H2 yield with minimum energy requirements.

Process optimization [17,18], intensification [19,20], monitoring [21,22], and integration [23] with current technologies can contribute to the development of more viable energy generation systems with carbon capture, thereby improving the economics of the process in terms of the cost of electricity (COE). Recently, there has been huge attention paid to integrating IGCC with natural gas reforming processes to increase the H2/CO ratio in syngas. Most of the effort is focused on developing gasification processes incorporating CO2 capture technologies using various feedstocks for the production of synthesis gas, H2, energy, and polygeneration [19,24–26]. Recently, Alibrahim et al. [27] developed different pathways for producing syngas by integrating gasification and DMR technologies followed by their comparative analyses for analyzing the sustainability of the process. Qian et al. [28] proposed an integrative approach for the efficient use of coke oven gas and coal through gasification by a tri-reforming method to improve the H2/CO ratio in syngas for methanol synthesis. Likewise, Yi et al. [29] conducted a techno-economic analysis of connecting
coal gasification and the DMR procedures to improve syngas synthesis, which may be used in a variety of polygeneration processes. Adams et al. [30] investigated and analyzed several design paths for combining IGCC with methane reforming systems for process performance and economics. The combination of coal reforming and gasification processes has also been shown to have the potential to improve the robustness of the design and the sustainability of the process [30].

The energy strategy requires developing the energy-mix and fuel-switching technology to reduce both greenhouse gas emissions and the CO$_2$ footprint. Using the energy-mix technologies to integrate with advanced technology leads to producing several products during the polygeneration process while minimizing reliance on a single fuel [31–33]. The fuel switchover strategies of merging secondary and primary fuels and reducing greenhouse gas emissions have lately been examined by Bazzanella et al. [34] and Rehfeldt et al. [35]. Ahmed et al. [36] undertook a study to develop a unique and commercially viable energy-efficient process, increasing methanol production capacity and reducing energy needs and process economies. This study integrates the coal gasification process with the gas reforming technology in a parallel design configuration to improve the syngas caloric value in order to synthesize methanol and the controlled emissions of GHG.

The primary benefit of energy-mix and fuel-switch technology is that no large process adjustments are required. Recently, energy-mixed systems that use different fuels to create numerous chemicals have also been created. Chen et al. [37] designed the process model to produce methanol in the CTM (coal to methanol) process by using different feedstocks. The proposed model reduced emissions of carbon dioxide by 14% and enhanced the production of methanol by 6.5%. Lv et al. [38] showed a 55.8% process efficiency based on a process model of power, dual methanol based on natural gas, and charcoal feedstocks but did not disclose any information on the economics of the process. The study has demonstrated that the combining of gas and coal technologies can increase the potential of syngas with a higher level of hydrogen and carbon ratio. Due to inherent pollutants, the coal-based syngas composition is difficult to retain and therefore needs further treatment before it can be utilized in downstream operations. The coal-based syngas can be coupled with the natural gas-based syngas to optimize the HCR for the efficient generation of cleaner fuels [39]. Models for merging coal gasification with natural gas reforming procedures for the production of hydrogen and power generation have been proposed by Ahmed et al. [40–42]. Ahmed et al. [43] also studied the techno-economic assessment of a process integration model to boost the potential of hydrogen production by using natural gas and coal feedstock. The studies have found that coal gasifiers can be connected with the gas reforming technologies using an efficient heat exchanger network without using additional power sources, thus increasing overall process performance.

Furthermore, more research is focused on the integration and intensification of the gasification process with the reforming technologies to improve the syngas yield. Cormos et al. [44] investigated the techno-economics of flexible hydrogen and electricity generation by the gasification of coal. Ahmed et al. [41] proposed to boost H$_2$ production by using steam and syngas-heat from the process of gasification by incorporating integrated models of coal gasification and SMR. The techno-economic analyses of both integrated coal gasification and conventional coal gasification and steam methane reforming processes are also carried out by Ahmed et al. [40] concluded that the integrated model is the most effective method. On the other hand, previous processes of reforming units and the integration of gasification in series had technical problems in the reforming section because the synthesis gas obtained from coal has a higher sulfur content than the acceptable limits of the reforming catalyst.

The disadvantages of the harmonious blend of gasification and reforming technology insights show that the indirect use of gasification-derived syngas in the SMR process, employing a radiant cooler with no risks of catalytic deactivation, has become a realistic new incorporation approach. A simultaneous process integration network strategy will be used in the proposed integration to exploit the essential technological and economic
benefits of several technologies, which will improve the total viability of the system without having to rely on one fuel. The primary aim of gasification technology is to produce syngas, which can be utilized in a wide range of applications, from fuel and chemical production to electricity and power generation. The Fischer–Tropsch (FT) process can be used to make gasoline, diesel, and other chemicals. In the presence of suitable catalysts, syngas can also be easily converted to methanol or dimethyl ether (DME), which can then be converted to gasoline. Synthetic natural gas (SNG) production is also another important application of syngas. Syngas is also used in the production of medium-BTU gas for turbine fuel and in advanced gasification [45].

Coal gasification is an environmentally sustainable and effective solution for producing a range of chemicals, such as methanol, ammonia, hydrogen, and synthetic fuels. The gasification of low-ranked coals is even more tempting due to the low pricing of coal and the local availabilities or even the lack of other resources, such as natural gas and oil [6]. Low-rank coals are extensively available but offer less power generation efficiencies and are usually ignored in power plants. Low-rank coals can be converted into syngas or hydrogen with better process feasibility instead of power generation. This study will focus on the production of syngas from low-rank coals, where the coal composition is found from experiments and then modelling is done in Aspen Plus to carry out the technical and economic analyses to evaluate the process feasibility.

2. Experimental and Simulation Approach

Coal samples were taken and crushed with a local roller crusher and disc mill and sieved in −60 mesh for performing the proximate and ultimate analyses. Standard procedure for proximate analysis (D3173), ash (D3174), volatile matter (D3175), sulfur (D3177), and gross calorific value (D5865) was adopted. The results of the proximate and ultimate analyses are shown in Table 1.

Table 1. Proximate and ultimate analyses and heating value of the fuels.

| Ultimate Analysis of Coal (Weight %) | Dry Basis |
|------------------------------------|-----------|
| Coal Type: Lakra Coal (Low-Rank)   |           |
| Carbon                             | 30.62     |
| Hydrogen                           | 3.59      |
| Oxygen                             | 31.07     |
| Nitrogen                           | 0.82      |
| Sulphur                            | 6.63      |
| Ash                                | 27.23     |

| Proximate Analysis of Coal (Weight %) | Dry Basis |
|--------------------------------------|-----------|
| Moisture                             | 24.96     |
| Fixed Carbon                         | 32.60     |
| Volatile Matter                      | 40.15     |
| Ash                                  | 27.23     |

After getting the coal composition from the experimental results, a simulation study is performed to analyze the syngas composition from the coal and to perform parametric analysis. The simulation model is developed in the commercial chemical and process engineering software, namely Aspen Plus V11®. The Peng-Robinson equation of state was used as the thermodynamic package with the Boston Mathias function (PR-BM). The coal is an un-conventional component in Aspen Plus and is defined based on ultimate, proximate, sulfur, and heating value analyses obtained from experimental results. The RYield reactor model is used in Aspen Plus for converting the coal into its constituents, followed by its integration with the RGibbs reactor model to generate synthesis gas. The gasification
process involves a series of complex endothermic and exothermic reactions to generate syngas, as shown in the following equations:

\[
\text{Volatiles} + \left( x + \frac{1}{2}y \right) \text{O}_2 \rightarrow x\text{CO}_2 + y\text{H}_2\text{O} \quad (1)
\]

\[
\text{C} \left( s \right) + \frac{1}{2}\text{O}_2 \rightarrow \text{CO} \quad \Delta H = -111 \text{ MJ/kmol} \quad (2)
\]

\[
\text{C} \left( s \right) + \text{CO}_2 \leftrightarrow 2\text{CO} \quad \Delta H = +172 \text{ MJ/kmol} \quad (3)
\]

\[
\text{CO} + \frac{1}{2}\text{O}_2 \rightarrow \text{CO}_2 \quad \Delta H = -283 \text{ MJ/kmol} \quad (4)
\]

\[
\text{C} \left( s \right) + \text{H}_2\text{O} \leftrightarrow \text{CO} + \text{H}_2 \quad \Delta H = +131 \text{ MJ/kmol} \quad (5)
\]

\[
\text{H}_2 + \frac{1}{2}\text{O}_2 \rightarrow \text{H}_2\text{O} \quad \Delta H = -242 \text{ MJ/kmol} \quad (6)
\]

The RGibbs reactor model works based on the Gibbs free energy minimization principle to produce syngas at the specified pressure and temperature conditions. Figure 1 represents the gasification model developed in Aspen Plus in which coal at the flow rate of 62.01 kg/s is fed to the RYield Reactor to get the yield of coal in terms of mainly C, H₂, N₂, O₂, S, and ash contents. The RYield model is specified to achieve 99% of the coal conversion into syngas and char. The separator is used to separate the volatiles from the un-converted char. The volatiles are then sent to the RGibbs reactor model to generate the reaction products at the gasifier operational conditions. Furthermore, the char is mixed with oxygen (95% pure) and steam to convert the elemental carbon into CO and CO₂, which is mixed with the volatiles and fed to the gasification unit to get the desired syngas composition at the pressure and temperature of 55 bar and 1165 °C, respectively. The syngas composition from the gasification model was compared with the literature and the results of the syngas composition are within the range of the reported data as represented in Table 2.

**Figure 1.** Development of Gasification Model in Aspen Plus®.
Table 2. Syngas Composition and Comparison with the Literature.

| Component | Syngas from Gasifier | Mansouri, et al. [46] | Hyun-Taek, et al. [47] | Kale et al. [48] | Cao et al. [49] | He and Kim [50] | Range       |
|-----------|----------------------|-----------------------|------------------------|------------------|----------------|----------------|-------------|
| CO        | 47.40%               | 48.61%                | 61.84%                 | 22.40%           | 31.12%         | 60.40%         | 22.4–61.8% |
| H₂        | 30.30%               | 20.35%                | 25.05%                 | 29.00%           | 40.89%         | 25.40%         | 25.4–40.9% |
| H₂O       | 11.35%               | 18.29%                | 3.87%                  | 12.08%           | -              | 2.00%          | 2.0–18.3%  |
| CO₂       | 7.26%                | 3.62%                 | 2.33%                  | 23.00%           | 17.29%         | 3.70%          | 3.7–31.5%  |
| Others    | 3.61%                | 9.13%                 | 6.89%                  | 64.91%           | 10.70%         | 3.40%          | 3.4–64.91% |

The sensitivity studies were also performed to see the variation in the synthesis gas composition by varying the process parameters.

3. Results and Discussion

3.1. Evaluation of the Temperature Effect on Syngas Composition

Figure 2 shows the effect of temperature on the formation of CO₂, CO, H₂, and CH₄. As gasification includes a series of endothermic and exothermic reactions, temperature plays a significant role in modifying the syngas composition. For extreme temperatures > 1300 °C, the quantity of CO was significantly high. With the rise in temperature, both the CO and the H₂ increased in gas phase concentration, while the CO₂ and the CH₄ decreased. Beyond the temperature of 1000 °C, the concentration of H₂ decreased to a less significant level while that of the CO increased. From this study, it was seen that the temperature range of 1000–1200 °C can be considered as the optimum for the production of syngas. As shown in Figure 2, syngas is predominantly constituted of methane and CO₂ at low temperatures. The methane content fell as the temperature of the gasifier increased from 600 °C to 800 °C. This drop is due to the reforming reaction that converts methane into H₂ and CO. The increase in temperature in the gasifier leads to a higher oxidant consumption which leads the process towards combustion, which can reduce the cold gas efficiency of the syngas.

![Figure 2. Effect of the Gasification Temperature on Syngas Composition.](image-url)
3.2. Effect of Pressure on Syngas Composition

Figure 3 shows the effect of pressure on the gasification products, including the CO and the H$_2$, for the pressure range of 5–40 bars. The results showed that the pressure has a negligible effect on the products of gasification. The composition of syngas remains nearly constant for this pressure range. There was a slight decrease in the concentration of H$_2$ from 35.4% to 34.1% at a high pressure of 45 bars. The decrease in the CO concentration was nearly 0.5% by increasing pressure. On the other hand, the values of the CO$_2$ and the CH$_4$ showed a tendency to increase in composition by 0.5–0.7%, respectively. Some gasification processes are carried out at atmospheric pressure, depending on the syngas composition, and the pressure in the gasification section can be tuned in accordance with the downstream process requirements. The pressure in the gasification sections did not show much variation in the syngas composition; however, it might affect the oxidant and the steam requirements. For instance, the conversion of syngas to FT chemicals is usually achieved at elevated pressures, which requires the gasification unit to operate at higher pressures in order to avoid the syngas compression, which may take a huge amount of energy. Moreover, if the objective is to produce hydrogen from syngas then gasification is also done at higher pressures to reduce the energy demand in the downstream processes for purification, compression, and storage.

![Figure 3. Sensitivity analysis for pressure variation on syngas composition.](image)

3.3. Effect of Oxygen on CGE and Temperature

Most of the gasification processes require an oxidant for partial oxidation. As the flow of oxidant increases, more partial oxidation occurs, and the gasifier’s temperature increases as shown in the graph in Figure 4. The cold gas efficiency is also important in analyzing the gasifier’s performance output, and it usually reflects the syngas heating value. The cold gas efficiency also increases with the increase in the oxidant flow up to a certain limit and decreases after reaching its maximum limit at the specific value of the oxidant flow and the temperature in the gasifier unit. The reason behind the downfall of the CGE after reaching its maximum value is that the process starts shifting toward complete combustion and reducing the H$_2$ and the CO content in the syngas. The increase in the H$_2$O in the syngas and the conversion of CO into CO$_2$ is because of the higher flowrate of the oxidant. The graph shows that at a 1165 °C temperature and 13 kg/s of oxygen flow (oxidant), a maximum value of the cold gas efficiency of 55% is achieved.

![Figure 4. Effect of Oxygen on CGE and Temperature.](image)
3.4. Impact of Oxidant and Gasification Temperature on Syngas Flow Rates

The oxidant flow rate is one of the most important operating parameters in controlling the gasification process in terms of the syngas composition, yield, temperature and CGE. Figure 5 shows the effect of the oxidant on the flow rates of the gasification components. Initially, the flow rates of the CO and the CO₂ increase with the increase in oxygen flow because of the oxidation reactions and then the CO starts to decrease after reaching its maximum value. The reason behind the downfall of the CO is the conversion of CO to CO₂ because of the high availability of the oxidant. Similarly, the flow rate of the CH₄ starts to decrease with an increase in the oxygen flow rate due to the oxidation reactions in the gasifier. The flow rate of the H₂ is also decreased with the increase in the oxidant flow rate due to the partial oxidation of the H₂. In addition, the CGE of the syngas is with an increase in the oxidant flowrate above 12.6 kg/s (approximately).

![Figure 4. Effect of Oxygen on CGE and Temperature.](image1)

![Figure 5. Effect of Oxygen and Temperature on Component Flow Rates.](image2)
3.5. Effect of Steam on Cold Gas Efficiency and Syngas Composition

Figure 6 represents the effect of steam on the cold gas efficiency (CGE) in the gasification unit. The addition of steam into the gasification unit not only controls the gasification temperature but also contributes towards the H\textsubscript{2} production. The results showed that the steam flow rate has a significant influence on the LHV (lower heating value) of the syngas. The LHV of the gas increases with the steam flow rate because of an increase in the net H\textsubscript{2} content in the syngas. The operational parameters of the gasification units in this study are tuned in order to maximize the syngas production with the higher CGE and LHV. The results revealed that the maximum CGE is achieved at the steam flowrate of 23.5 kg/s and at the temperature of 1165 °C.

![Figure 6. Effect of Steam on CGE.](image)

Figure 7 represents the main constituents of the syngas that contribute to the LHV and CGE calculations. The results showed that the flow rates of the H\textsubscript{2} and the CO\textsubscript{2} increase with the increase in the steam flow rates. Enhancing the H\textsubscript{2}O flow rate, multiple reactions occur in the gasifier simultaneously. As more steam is supplied to the feed, reforming reactions occur in the gasifier and lead to higher concentrations of H\textsubscript{2} and CO in the syngas. However, increasing the steam flow rate decreases the CO concentration in the syngas. This is due to the simultaneous occurring of WGS reactions, which reduce the CO concentration by reacting steam with the CO, leading to the formation of H\textsubscript{2} and CO\textsubscript{2}. Overall, it was seen from the analysis that the H\textsubscript{2}/CO ratio increases with the increase in the steam flow.

![Figure 7. Effect of Steam on Component Flow Rates.](image)
3.6. Process Performance and CO$_2$ Emissions Analysis

This study involves the syngas production from low-rank coal and the effect of different operational parameters on the heating value and the composition of the syngas in the gasification unit. Xi et al. [51] have studied the impacts of coal water slurries, gasifier operational parameters, and the C/O ratio on syngas composition and heating values. The gasification process typically produces a higher amount of CO and a lower amount of H$_2$ in syngas, offering a lower H/C ratio. The process efficiency in this study is calculated by calculating the heating value of the syngas per unit of energy supplied by the feedstock and the energy consumption in the process. Depending on the downstream uses, this design set-up can also provide a wide variety of H$_2$/CO ratios for the syngas by manipulating the gasifier operational parameters. The results showed that the heating value of the syngas (CO + H$_2$) is 468.8 MW$_{th}$ as compared to the feedstock heating value of 871.42 MW$_{th}$, and the process energy consumption is estimated as 27.7 MW$_{th}$. The overall process efficiency for producing the syngas is calculated as 50.86%.

$$\eta_{\text{net}} = \frac{\text{Syngas thermal energy [MWth]}}{\text{Feedstock thermal energy [MWth] + Energy consumed [MWth]}} \times 100\% \quad (7)$$

The CO$_2$ emission is an important indicator to reflect the carbon footprint of the process in terms of the uncaptured CO$_2$ from the process. Equation (8) represents the CO$_2$ leaving the process for each fuel unit manufactured.

$$\text{CO}_2 \text{ specific emission} = \frac{\text{CO}_2 \text{ Emission (kmol / h)}}{\text{CO Production (kmol / h) + H}_2 \text{ Production (kmol / h)}} \quad (8)$$

The efficiency of the carbon-conversion can be assessed on the basis of the amount of carbon present in the feedstock and the quantity of carbon transformed into the product. The results showed that for every unit of molar production of the fuel (CO + H$_2$), the specific CO$_2$ emissions for this case were 0.20. The process performance analysis is summarized in the Table 3 as follows:
Table 3. Process Performance Analysis.

| Parameters                          | Units     | Results |
|-------------------------------------|-----------|---------|
| Gasification Temp                  | °C        | 1165    |
| Steam consumed                      | kg/s      | 25      |
| O$_2$ (95%) consumed               | kg/s      | 13      |
| Cold Gas Efficiency                 | %         | 53.8    |
| Syngas Heating Value (H$_2$ + CO)  | MJ/s      | 468.8   |
| Coal Heating Value                 | MJ/s      | 871.42  |
| Oxygen Consumption Energy           | MJ/s      | 9.8     |
| Steam Consumption Energy            | MJ/s      | 40.43   |
| CO Production                       | kg/s      | 23.92739|
| H$_2$ Production                    | kg/s      | 1.587942|
| Total Fuel Produced (CO + H$_2$)   | kg/s      | 25.51533|
| Energy consumed to produced fuel (H$_2$ and CO) | kg/GJ | 27.68542 |
| Overall Efficiency for syngas (CO + H$_2$) Production | % | 50.86       |
| CO$_2$ Emissions/CO + H$_2$ (mole basis) |           | 0.20    |

4. Process Economic and Production Cost Analysis

4.1. Capital and Operational Expenditure Estimation

CAPEX (capital expenditure) and OPEX (operational expenditure) estimates are usually used to determine the overall project cost. The overall cost needed for the construction of the plant is decided by a variety of parameters, including the size/capability of the plant, the process performance, and the annual operational hours. The fixed CAPEX primarily consists of the cost of the necessary plant equipment and the infrastructure. The power law of capacity is employed in this study to determine the cost of the equipment, and the value of x in this study is taken as 0.6, as represented in equation 9. This study estimates that the cost of equipment using the CEPCI (Chemical Engineering Plant Cost Index) for the current year is 618.

\[
\text{Cost}_{\text{New}} = \text{Cost}_{\text{Old}} \times \left( \frac{\text{Capacity}_{\text{New}}}{\text{Capacity}_{\text{Old}}} \right)^x \times \frac{\text{CEPCI}_{\text{New}}}{\text{CEPCI}_{\text{Old}}}
\] (9)

The CAPEX and OPEX were estimated using some of the economic assumptions listed in Table 4.

Table 4. Economic Assumptions.

| Assumption                  | Value     |
|----------------------------|-----------|
| Coal Price                 | 2.2 EUR/GJ|
| Plant construction time    | Three (03) Years|
| Annual Operating Hours     | 7000      |
| Labor Cost                 | 45,000 EUR/Person |
| Administration             | 30% Labor Cost |
| Waste Disposal             | 10 EUR/t |
| Boiler Feed Water (5% recharge) | 0.33 EUR/m$^3$ |
| Discount rate              | 10%       |
| Plant Life                 | Thirty (30) Years |
| Maintenance                | 3.5% of OPEX |
Table 5 summarizes the CAPEX and OPEX calculations. In this study, the results show that the CAPEX for the project is EUR 521.9 million. On the other hand, the OPEX is categorized into two categories: the fixed OPEX that covers the maintenance, administration, and labor costs, and the variable OPEX which reflects the catalyst, boiler feed water, fuel, and waste disposal cost. The OPEX per year calculated in this study is EUR 88 million. In addition, two economic indicators, including CAPEX/MT and OPEX/MT for each production of fuel (CO + H\textsubscript{2}), were evaluated. The results revealed that the CAPEX and the OPEX per metric tonne are 27 EUR/MT and 137 EUR/MT, respectively.

Table 5. Economic Analysis.

| Units                  | Results     |
|------------------------|-------------|
| CAPEX                  | ME          | 521.9521    |
| OPEX                   | ME/Year     | 88.00207    |
| CAPEX/MT               | EUR/metric tonne | 27.05875 |
| OPEX/MT                | EUR/metric tonne | 136.8646  |
| Total Capex+ Opex per MT | EUR/metric tonne | 163.9234  |
| Discount Rate Addition | 10%         | 16.39234    |
| Selling Fuel Price (H\textsubscript{2} + CO) | EUR/Metric Tonne | 180.3157    |

4.2. Minimum Selling Price and Production Cost

The minimum selling price (MSP) and total production cost of fuel (TPC) are computed for the plant’s entire lifetime. The results of the simulations are used for the assessment of raw material, utility, and catalyst use. The total production cost determined for each metric tonne of fuel generated in this scenario is EUR 163.9, using all of the CAPEX and OPEX calculations. The discount rate is often applied to the costs of production in order to estimate the minimum selling price, and a 10% discount rate is chosen to estimate the sales price of the fuel in this scenario. It can be seen that the MSP of the fuel per metric tonne is EUR 180.31.

5. Conclusions

The demand for syngas production processes has gained a lot of attention due to the potential for conversion into cleaner fuels with lesser emissions. In this study, low-rank coals were selected to generate the syngas, which can be transformed into the FT chemicals or hydrogen to meet the future energy needs. The low-rank coals have been in abundance in nature and cannot be used to generate electricity and heat with the current environmental quality control standards; however, the utilization of low-rank coals to generate the syngas showed a significant potential. This study presents the model for syngas (CO + H\textsubscript{2}) production from low-rank coal followed by its techno-economic feasibility. The gasification model is developed for low-rank coals, and the analyses on key technical parameters were performed to evaluate the conditions in which to produce the syngas with higher LHV and CGE. Moreover, the analyses on syngas yield, process efficiency, CO\textsubscript{2} emissions, total production, and the sales price of fuel were also performed. The following are the major outcomes of this study along with the future research direction:

I. The Cold Gas Efficiency (CGE) for the syngas production from low-rank coals can be as high as 53.8%.

II. The net production rates of H\textsubscript{2} and CO are 1.6 kg/s and 23.9 kg/s, respectively. The hydrogen production can be enhanced by using water gas shift reactions depending on the requirements of the downstream process which are to be focused on in the upcoming research.

III. The net production of fuel (CO + H\textsubscript{2}) is 25.51 kg/s, and the total energy consumption to produce the fuel is 27.68 kg/GJ.
IV. The overall process efficiency for the syngas production for the low-rank coals can be as high as 50.86%, and the CO$_2$ emissions per unit of syngas production are 0.20 on a mole basis.

V. The overall production cost of the syngas (CO + H$_2$) is evaluated as 163.92 EUR/MT, and the selling price of the syngas is estimated as 180.31 EUR/MT.

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Nomenclature

| Abbreviation | Description |
|--------------|-------------|
| ATR          | Auto-thermal reforming |
| CAPEX        | Capital expenditure |
| CGE          | Cold gas efficiency |
| CTM          | Coal to methanol |
| DME          | Dimethyl ether |
| DMR          | Dry methane reforming |
| FT           | Fischer–Tropsch |
| HCR          | Hydrogen to carbon ratio |
| LHV          | Lower heating value |
| MSP          | Minimum selling price |
| OPEX         | Operational expenditure |
| POX          | Partial Oxidation |
| SMR          | Steam methane reforming |
| SNG          | Synthetic natural gas |
| TMR          | Tri-methane reforming |
| TPC          | Total production cost |

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