

Article

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

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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 SO_x, NO_x, CO_x, 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 CO₂ 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 calorific 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 H₂ 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 %)	
Coal Type: Lakra Coal (Low-Rank)	
	Dry Basis
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

Table 2. Syngas Composition and Comparison with the Literature.

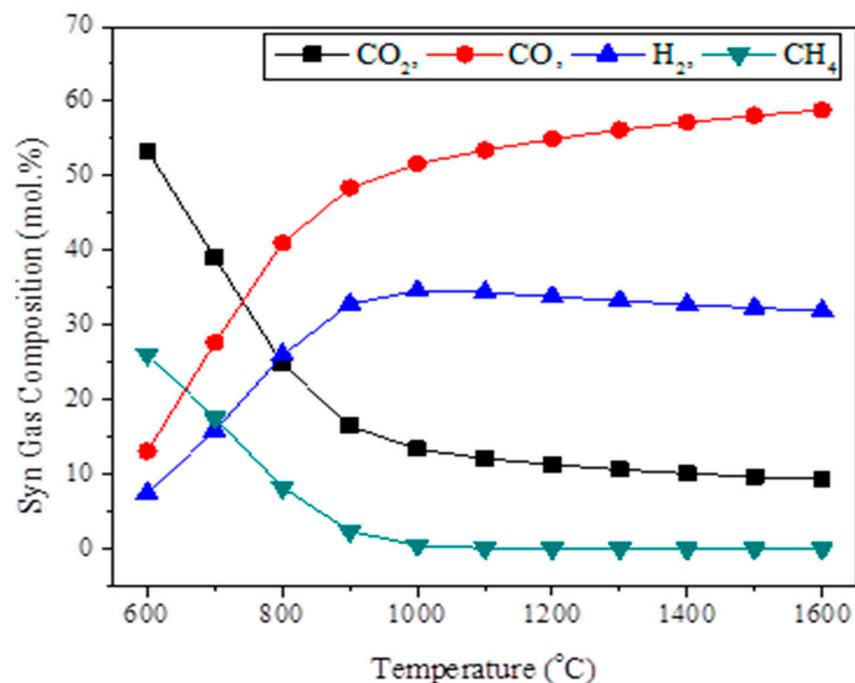
Component	Syngas from Gasifier	Mansouri, et al. [46]	Hyun-Taek, et al. [47]	Kale et al. [48]	Cao et al. [49]	He and Kim [50]	Range
CO	47.40%	48.61%	61.84%	22.40%	31.12%	60.40%	22.4–61.8%
H ₂	30.30%	20.35%	25.05%	29.00%	40.89%	25.40%	25.4–40.9%
H ₂ O	11.35%	18.29%	3.87%	12.08%	-	2.00%	2.0–18.3%
CO ₂	7.26%	3.62%	2.35%	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 preformed 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.

3.2. Effect of Pressure on Syngas Composition

Figure 3 shows the effect of pressure on the gasification products, including the CO and the H₂, 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 H₂ 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 other hand, the values of the CO₂ and the CH₄ 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.

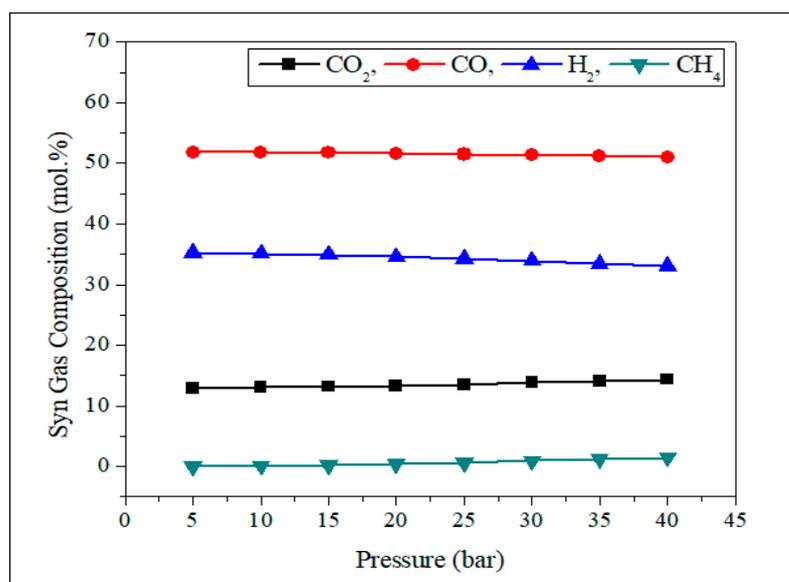


Figure 3. Sensitivity analysis for pressure variation on syngas composition.

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 H₂ and the CO content in the syngas. The increase in the H₂O in the syngas and the conversion of CO into CO₂ 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.

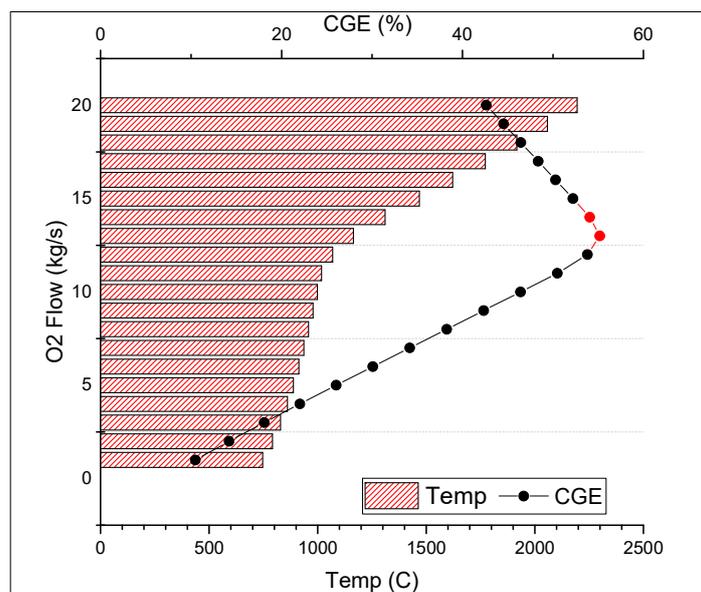


Figure 4. Effect of Oxygen on CGE and Temperature.

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).

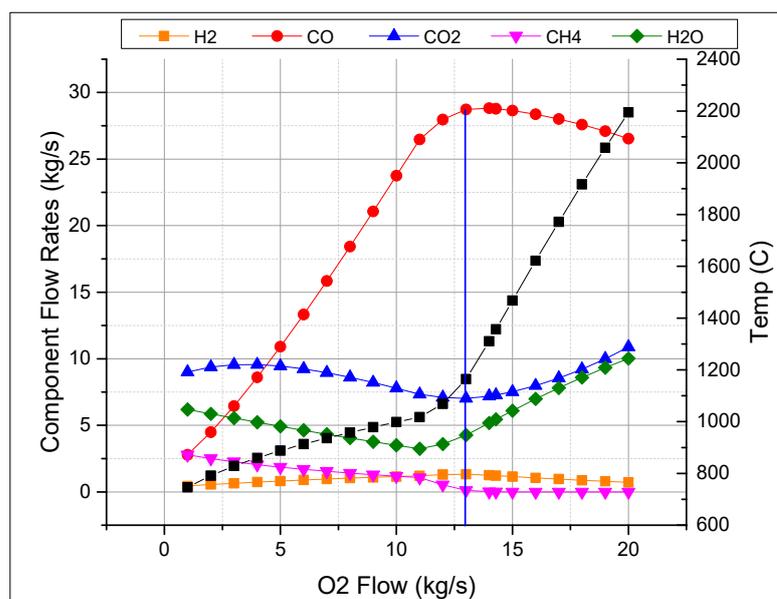


Figure 5. Effect of Oxygen and Temperature on Component Flow Rates.

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_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_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.

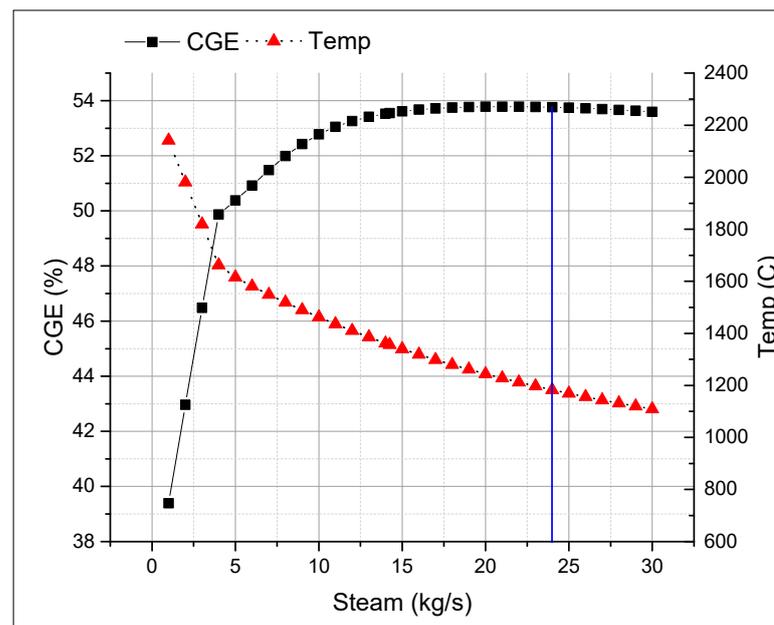


Figure 6. Effect of Steam on CGE.

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_2 and the CO_2 increase with the increase in the steam flow rates. Enhancing the H_2O 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_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_2 and CO_2 . Overall, it was seen from the analysis that the H_2/CO ratio increases with the increase in the steam flow.

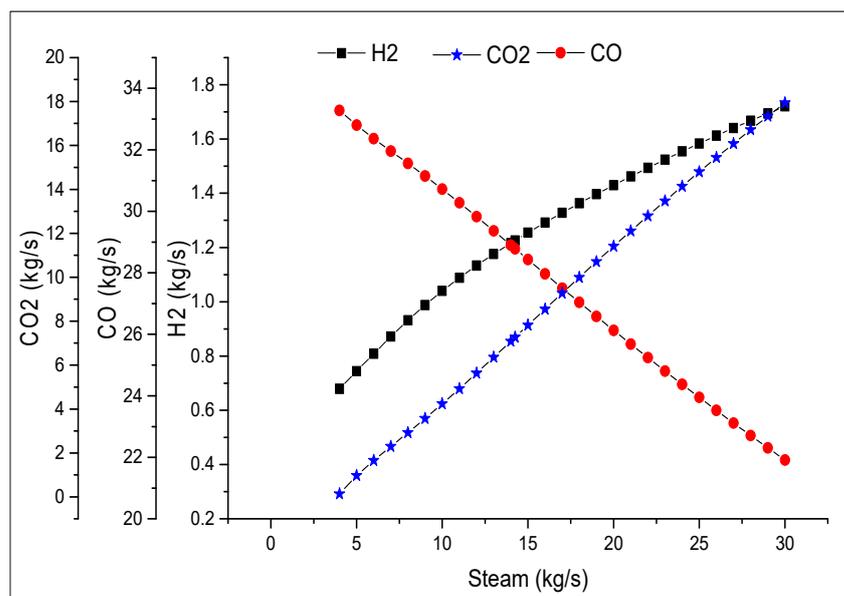


Figure 7. Effect of Steam on Component Flow Rates.

3.6. Process Performance and CO₂ 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 H₂ 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 H₂/CO ratios for the syngas by manipulating the gasifier operational parameters. The results showed that the heating value of the syngas (CO + H₂) 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%.

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

The CO₂ emission is an important indicator to reflect the carbon footprint of the process in terms of the uncaptured CO₂ from the process. Equation (8) represents the CO₂ leaving the process for each fuel unit manufactured.

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

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 + H₂), the specific CO₂ 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.

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

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

Table 4. Economic Assumptions.

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 88 million EUR/yr. In addition, two economic indicators, including CAPEX/MT and OPEX/MT for each production of fuel (CO + H₂), 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 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 + H₂) 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, CO₂ 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 H₂ 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 + H₂) 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 CO₂ emissions per unit of syngas production are 0.20 on a mole basis.
- V. The overall production cost of the syngas (CO + H₂) 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

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

References

1. PricewaterhouseCoopers. *The Indian Coal Sector: Challenges and Future Outlook* Indian Chamber of Commerce; PricewaterhouseCoopers: Barcelona, Spain, 2013; p. 28.
2. International Energy Agency. *Power Generation from Coal 2011*; International Energy Agency: Paris, France, 2011.
3. Kandasamy, J.; Gökalp, I. Pyrolysis and Gasification Characteristics of High Ash Indian and Turkish Coals. *Gasif. Low-Grade Feed.* **2018**. [CrossRef]
4. Grootjes, A.J.; Aranda, G.; Van Der Meijden, C.M.; Drift, A.V.D.; Vreugdenhil, B.J. Gasification of Low Rank Coal. 2015. Available online: <https://publicaties.ecn.nl/PdfFetch.aspx?nr=ECN-M--15-033> (accessed on 22 September 2021).
5. Andrleit, H.; Bahr, A.; Babies, H.G.; Franke, D.; Meßner, J.; Pierau, R.; Schauer, M.; Schmidt, S.; Weihmann, S. Energy Study 2013. 2013, p. 110. Available online: https://www.bgr.bund.de/EN/Themen/Energie/Downloads/energiestudie_2013_en.pdf?__blob=publicationFile&v=2 (accessed on 22 September 2021).
6. Toporov, D.; Abraham, R. Gasification of low-rank coal in the High-Temperature Winkler (HTW) process. *J. S. Afr. Inst. Min. Metall.* **2015**, *115*, 589–597. [CrossRef]

7. Sarkar, J.; Bhattacharyya, S. Application of graphene and graphene-based materials in clean energy-related devices Minghui. *Arch. Thermodyn.* **2012**, *33*, 23–40. [CrossRef]
8. Kalamaras, C.M.; Efstathiou, A.M. Hydrogen Production Technologies: Current State and Future Developments. *Conf. Pap. Energy* **2013**, *2013*, 1–9. [CrossRef]
9. Outlook, E. "International Energy Outlook." Outlook. 2010. Available online: http://www.ourenergypolicy.org/wp-content/uploads/2011/12/2010_07_EIA_InternationalEnergyOutlook.pdf (accessed on 25 September 2021).
10. Cormos, A.M.; Dinca, C.; Cormos, C.C. Multi-fuel multi-product operation of IGCC power plants with carbon capture and storage (CCS). *Appl. Therm. Eng.* **2015**, *74*, 20–27. [CrossRef]
11. Pettinau, A.; Ferrara, F.; Amorino, C. Combustion vs. gasification for a demonstration CCS (carbon capture and storage) project in Italy: A techno-economic analysis. *Energy* **2013**, *50*, 160–169. [CrossRef]
12. Simpson, A.P.; Lutz, A.E. Exergy analysis of hydrogen production via steam methane reforming. *Int. J. Hydrogen Energy* **2007**, *32*, 4811–4820. [CrossRef]
13. Onozaki, M.; Watanabe, K.; Hashimoto, T.; Saegusa, H.; Katayama, Y. Hydrogen production by the partial oxidation and steam reforming of tar from hot coke oven gas. *Fuel* **2006**, *85*, 143–149. [CrossRef]
14. Basile, A.; Tong, J.; Millet, P. Inorganic membrane reactors for hydrogen production: An overview with particular emphasis on dense metallic membrane materials. *Handb. Membr. React.* **2013**, 42–148. [CrossRef]
15. Sengodan, S.; Lan, R.; Humphreys, J.; Du, D.; Xu, W.; Wang, H.; Tao, S. Advances in reforming and partial oxidation of hydrocarbons for hydrogen production and fuel cell applications. *Renew. Sustain. Energy Rev.* **2018**, *82*, 761–780. [CrossRef]
16. Aasberg-Petersen, K.; Hansen, J.H.; Christensen, T.S.; Dybkjaer, I.; Christensen, P.S.; Nielsen, C.S.; Madsen, S.W.; Rostrup-Nielsen, J.R. Technologies for large-scale gas conversion. *Appl. Catal. A Gen.* **2001**, *221*, 379–387. [CrossRef]
17. Emun, F.; Gadalla, M.; Majozi, T.; Boer, D. Integrated gasification combined cycle (IGCC) process simulation and optimization. *Comput. Chem. Eng.* **2010**, *34*, 331–338. [CrossRef]
18. Biagini, E.; Bardi, A.; Pannocchia, G.; Tognotti, L. Development of an entrained flow gasifier model for process optimization study. *Ind. Eng. Chem. Res.* **2009**, *48*, 9028–9033. [CrossRef]
19. Ahmed, U.; Zahid, U.; Jeong, Y.S.; Lee, C.J.; Han, C. IGCC process intensification for simultaneous power generation and CO₂ capture. *Chem. Eng. Process. Process Intensif.* **2016**, *101*, 72–86. [CrossRef]
20. Qiao, Z.; Wang, Z.; Zhang, C.; Yuan, S.; Zhu, Y.; Wang, J.; Wang, S. PVAm-PIP/PS composite membrane with high performance for CO₂/N₂ separation. *AIChE J.* **2012**, *59*, 215–228. [CrossRef]
21. Ahmed, U.; Ha, D.; Shin, S.; Shaukat, N.; Zahid, U.; Han, C. Estimation of Disturbance Propagation Path Using Principal Component Analysis (PCA) and Multivariate Granger Causality (MVG) Techniques. *Ind. Eng. Chem. Res.* **2017**, *56*, 7260–7272. [CrossRef]
22. Ahmed, U.; Ha, D.; An, J.; Zahid, U.; Han, C. Fault propagation path estimation in NGL fractionation process using principal component analysis. *Chemom. Intell. Lab. Syst.* **2017**, *162*, 73–82. [CrossRef]
23. Lee, J.J.; Kim, Y.S.; Cha, K.S.; Kim, T.S.; Sohn, J.L.; Joo, Y.J. Influence of system integration options on the performance of an integrated gasification combined cycle power plant. *Appl. Energy* **2009**, *86*, 1788–1796. [CrossRef]
24. Yilmaz, F.; Ozturk, M.; Selbas, R. Design and thermodynamic analysis of coal-gasification assisted multigeneration system with hydrogen production and liquefaction. *Energy Convers. Manag.* **2019**, *186*, 229–240. [CrossRef]
25. Hasan, A.; Dincer, I. Comparative assessment of various gasification fuels with waste tires for hydrogen production. *Int. J. Hydrogen Energy* **2019**, *44*, 18818–18826. [CrossRef]
26. Al-Zareer, M.; Dincer, I.; Rosen, M.A. Effects of various gasification parameters and operating conditions on syngas and hydrogen production. *Chem. Eng. Res. Des.* **2016**, *115*, 1–18. [CrossRef]
27. Alibrahim, H.A.; SeedAhmed, S.; Ahmed, U.; Zahid, U. Comparative analysis of gasification and reforming technologies for the syngas production. In *Computer Aided Chemical Engineering*; Elsevier B.V.: Amsterdam, The Netherlands, 2019; pp. 1759–1764.
28. Qian, Y.; Man, Y.; Peng, L.; Zhou, H. Integrated process of coke-oven gas tri-reforming and coal gasification to methanol with high carbon utilization and energy efficiency. *Ind. Eng. Chem. Res.* **2015**, *54*, 2519–2525. [CrossRef]
29. Yi, Q.; Feng, J.; Wu, Y.; Li, W. 3E (energy, environmental, and economy) evaluation and assessment to an innovative dual-gas polygeneration system. *Energy* **2014**, *66*, 285–294. [CrossRef]
30. Adams, T.A.; Barton, P.I. Combining coal gasification and natural gas reforming for efficient polygeneration. *Fuel Process. Technol.* **2011**, *92*, 639–655. [CrossRef]
31. Larsson, M. *Global Energy Transformation*; Palgrave Macmillan: London, UK, 2009. [CrossRef]
32. Global warming of 1.5 C An IPCC Special Report on the Impacts of Global Warming of 1.5 C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty. Available online: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_High_Res.pdf (accessed on 25 September 2021).
33. Gas IEA. Gas 2018 Analysis and Forecasts to 2023. Available online: <https://www.iea.org/reports/gas-2018> (accessed on 17 September 2021).
34. DECHEMA; Bazzanella, A.M.; Ausfelder, F. Low carbon energy and feedstock for the European chemical industry. *Eur. Chem. Ind. Counc.* **2017**, 168.

35. Rehfeldt, M.; Worrell, E.; Eichhammer, W.; Fleiter, T. A review of the emission reduction potential of fuel switch towards biomass and electricity in European basic materials industry until 2030. *Renew. Sustain. Energy Rev.* **2020**, *120*, 109672. [[CrossRef](#)]
36. Ahmed, U. Techno-economic feasibility of methanol synthesis using dual fuel system in a parallel process design configuration with control on greenhouse gas emissions. *Int. J. Hydrogen Energy* **2020**, *45*, 6278–6290. [[CrossRef](#)]
37. Chen, J.; Yang, S.; Qian, Y. A novel path for carbon-rich resource utilization with lower emission and higher efficiency: An integrated process of coal gasification and coking to methanol production. *Energy* **2019**, *177*, 304–318. [[CrossRef](#)]
38. Lv, L.; Zhu, L.; Li, H.; Li, B. Methanol-power production using coal and methane as materials integrated with a two-level adjustment system. *J. Taiwan Inst. Chem. Eng.* **2019**, *97*, 346–355. [[CrossRef](#)]
39. Ahmed, U. Techno-economic analysis of dual methanol and hydrogen production using energy mix systems with CO₂ capture. *Energy Convers. Manag.* **2021**, *228*, 113663. [[CrossRef](#)]
40. Ahmed, U.; Zahid, U.; Lee, Y. Process simulation and integration of IGCC systems for H₂/syngas/electricity generation with control on CO₂ emissions. *Int. J. Hydrogen Energy* **2019**, *44*, 7137–7148. [[CrossRef](#)]
41. Ahmed, U.; Kim, C.; Zahid, U.; Lee, C.J.; Han, C. Integration of IGCC and methane reforming process for power generation with CO₂ capture. *Chem. Eng. Process. Process Intensif.* **2017**, *111*, 14–24. [[CrossRef](#)]
42. Ahmed, U.; Zahid, U. *Techno-Economic Assessment of Future Generation IGCC Processes with Control on Greenhouse Gas Emissions*; Elsevier Masson SAS: Issy Les Moulineaux, France, 2019. [[CrossRef](#)]
43. Hamid, U.; Rauf, A.; Ahmed, U.; Shah, M.S.; Ahmad, N. Techno-economic assessment of process integration models for boosting hydrogen production potential from coal and natural gas feedstocks. *Fuel* **2020**, *266*, 117111. [[CrossRef](#)]
44. Cormos, A.M.; Cormos, C.C. Techno-economic assessment of combined hydrogen & power co-generation with carbon capture: The case of coal gasification. *Appl. Therm. Eng.* **2019**, *147*, 29–39.
45. Sikarwar, V.S.; Zhao, M.; Clough, P.; Yao, J.; Zhong, X.; Memon, M.Z.; Shah, N.; Anthony, E.J.; Fennell, P.S. An overview of advances in biomass gasification. *Energy Environ. Sci.* **2016**, *9*, 2939–2977. [[CrossRef](#)]
46. Majoumerd, M.M.; Raas, H.; De, S.; Assadi, M. Estimation of performance variation of future generation IGCC with coal quality and gasification process—Simulation results of EU H₂-IGCC project. *Appl. Energy* **2014**, *113*, 452–462. [[CrossRef](#)]
47. Oh, H.T.; Lee, W.S.; Ju, Y.; Lee, C.H. Performance evaluation and carbon assessment of IGCC power plant with coal quality. *Energy* **2019**, *188*, 116063. [[CrossRef](#)]
48. Kale, G.R.; Kulkarni, B.D.; Chavan, R.N. Combined gasification of lignite coal: Thermodynamic and application study. *J. Taiwan Inst. Chem. Eng.* **2014**, *45*, 163–173. [[CrossRef](#)]
49. Cao, Y.; Gao, Z.; Jin, J.; Zhou, H.; Cohron, M.; Zhao, H.; Liu, H.; Pan, W. Synthesis gas production with an adjustable H₂/CO ratio through the coal gasification process: Effects of coal ranks and methane addition. *Energy Fuels* **2008**, *22*, 1720–1730. [[CrossRef](#)]
50. He, C.; Kim, H. Cleaner Combustion and Sustainable World. *Clean. Combust. Sustain. World* **2013**, 911–916. [[CrossRef](#)]
51. Xie, H.; Zhang, Z.; Li, Z.; Wang, Y. Relations among Main Operating Parameters of Gasifier in IGCC. *Energy Power Eng.* **2013**, *5*, 552–556. [[CrossRef](#)]