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Techno-Economic Assessment of High-Safety and Cost-Effective Syngas Produced by O_2-Enriched Air Gasification with 40–70% O_2 Purity

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Abstract: To strike a better balance between gas quality and production cost of biomass-based syngas, a process for high-safety and cost-effective syngas production is designed and studied, which takes advantage of biomass O_2-enriched air gasification with 40–70% O_2 purity and methanation synthesis. Based on the simulation data, the process is evaluated from techno-economic aspects, including syngas composition, higher heat value (*HHV*), upper and lower explosive limits (*UEL* and *LEL*), toxicity, unit production cost (*UPC*) and levelized cost of energy (*LCOE*). Five kinds of biomass are studied as feedstock. The effects of O_2 purity, methanation pressure, feedstock cost, and plant scale are determined, respectively. The results show that O_2 purity is an important parameter for technical performance, while methanation pressure is a minor parameter except for exergy efficiency. With respect to cost indicators, feedstock cost, and plant scale are crucial variables; by contrast, O_2 purity plays a relatively minor role. This process can generate non-toxic syngas containing 33.2–34.9 vol.% CH_4. The *UEL* and *LEL* are about 34% and 12%, and the average explosive range is about 22%. The *HHVs* of syngas generated from five kinds of feedstock sit between 13.67–14.33 MJ/m^3, and the exergy efficiency achieves 68.68%. The *UPC* varies between 0.05 \$/Nm^3 and 0.27 \$/Nm^3, and the *LCOE* varies between 3.78 \$/GJ and 18.28 \$/GJ. When the plant scale is rational, the process shows strong competitiveness in either *UPC* or *LCOE*. The techno-economic results demonstrate that the studied process offers an alternative and sustainable pathway to supply gaseous fuel for low-income areas.

Keywords: O_2-enriched air gasification; O_2 purity; explosive limit; heating value; exergy efficiency; levelized cost of energy

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1. Introduction

Clean gaseous fuels are highly expected by many undeveloped countries. As biomass is a widely available, renewable, and affordable energy source, gaseous biofuels, such as synthetic natural gas (SNG), biogas, and syngas, are regarded as green alternative fuels that can mitigate global warming and resource depletion issues. Gaseous biofuels can play an important role in sustainable development by substituting conventional natural gas. SNG is the expected product in previous studies, and it can be ejected into a well-developed gas grid [1,2]. However, SNG has relatively higher costs, and its economic competitiveness is lower, especially for low-income areas [3,4]. Gaseous biofuel with low or medium heating value and high safety is significant in low-income areas.

Biogas, without CO_2 removal, can be directly used as an affordable fuel for cooking and heating. Apart from anaerobic digestion, steam gasification is commonly employed for the production of SNG or syngas that is equivalent to biogas. Dual fluidized bed gasifiers are generally used for exothermic steam gasification. In this technology, the gasification and

combustion reactions are conducted in two separate reactors connected by circulating inert or catalytic bed material, which transfers heat from the combustion rector to the gasification reactor. However, these types of gasifiers are complex and difficult to design, operate and maintain. By contrast, air or oxygen-enriched air gasification can be carried out in one reactor, and the process is autothermic, i.e., the heat required by the gasification process can be completely satisfied by oxidation reactions within the gasifier.

The last studies showed that the production cost of syngas is much less than that of SNG, indicating the production cost reduces with the decrease in O_2 purity [5,6]. Specifically, O_2-enriched air gasification (OAG) has an obvious advantage over air gasification in the heating value of producer gas. O_2-enriched air gasification may be a more suitable choice to produce affordable biofuels at a lower cost. With regard to O_2-enriched air gasification, O_2 purity is the key parameter that essentially affects gasification performances. The O_2-enriched air with 30–40% O_2 purity was generally applied to produce low and medium-grade syngas with high N_2 contents and low energy contents [7,8]; meanwhile, the oxygen with a purity of 70% or higher was employed for the production of high-grade syngas with very low N_2 contents and high energy contents [9]. However, the heating value of syngas generated by the gasification with O_2 purity below 40% is commonly low, while the production cost of the producer gas with O_2 purity beyond 80% is a bit high. The O_2-enriched air gasification with 40–70% O_2 purity has not received sufficient attention [10], which may strike a better balance between heating value and production cost.

Furthermore, safety has always been a concern for all fuels under all utilization scenarios. Previous studies show that the producer gas generated by biomass gasification contains plenty of CO, which is harmful to human beings. To lower CO content to a safe level, methanation synthesis is a good upgrading measure [10]. Then, the process integrated with O_2-enriched air gasification with 40–70% O_2 purity and methanation synthesis is a potential pathway to produce cost-effective and high-safety syngas.

To generate high-safety and cost-effective syngas for low-income users, the objective of this work is to design and evaluate a process of syngas production by integrating O_2-enriched air gasification with 40–70% O_2 purity. The process is modeled using Aspen Plus software and then studied from techno-economic aspects, such as explosive limit, toxicity, and production cost. The work offers an alternative pathway of clean and renewable fuel supply for low-income areas lacking natural gas and guides the further development of this practical process.

2. Process Configuration

As shown in Table 1, five kinds of biomass are considered as feedstock, including rice straw (RS), cornstalk (CS), sawdust (SD), sunflower residual (SR), and cotton residual (CR) [11,12]. The syngas production process integrated with O_2-enriched air gasification and methanation synthesis is illustrated in Figure 1. It mainly consists of (1) an O_2-enriched air gasification unit with 40–70% purity oxygen (OAG); (2) a vacuum pressure swing adsorption unit (VPSA); (3) producer gas cleaning unit (PGC); (4) a methanation synthesis unit. (5) Auxiliary devices, including heaters and coolers for heat utilization and an organic Rankine cycle unit for partial power compensation (ORC). The Aspen Plus software (Aspen Plus 10.1) is applied for the process simulation.

(1) O_2-enriched air gasification (OAG)

The feedstock is first dried, and the low-temperature heat used here is recovered within this process. Then, biomass is gasified using O_2-enriched air and steam as gasifying agents. The gasifying agents, the steam (m_{WG}), and O_2-enriched air (m_{OEA}) streams are preheated to 200 °C by the heaters HT_G and HT_{O2}, respectively. A two-stage gasifier is employed in this process, and the second-stage gasifier is constantly operated at 800 °C and atmospheric pressure. All heat recovered from producer gas is used to heat the streams, such as water, O_2-enriched air, and ORC working medium with matched temperatures.

Regarding the simulation of the gasification unit, the pyrolysis and gasification processes are simulated using RYield and RGibbs models with the PR-BM property method,

respectively. The RGibbs model is restricted by chemical equilibrium with temperature approach. Additionally, the STEAM-TA method employed for heating and cooling models is related to water and steam. The following assumptions are adopted in the simulation [5]: (1) The reactors are operated under a steady state with uniform temperature and pressure. (2) The residence times are long enough for the reactions to reach chemical equilibrium. (3) The influence of particle sizes is ignored. (4) Ash in biomass does not participate in the gasification reactions. (5) The carbon conversion efficiency of the feedstock is 98%. (6) The heat loss is assumed to be 3% of the input energy of biomass (*LHV*). Additionally, a Design-Spec function is set to calculate the flow rates of air at a given operating condition based on energy conservation. The simulation of the O_2-enriched air gasification is verified based on Ye et al.'s experimental data [13], and the relative errors of the concentrations of H_2, CO, CH_4, CO_2, and N_2 do not exceed 10%.

Table 1. Composition of five kinds of biomass, in wt.%.

Composition	RS	CS	SD	SR	CR
Proximate analysis [ar]					
Moisture	9.10	9.36	7.89	8.10	5.40
Fixed Carbon	16.75	16.75	14.77	76.40	75.80
Volatile Matter	63.68	70.74	75.78	12.20	12.30
Ash	10.46	3.15	1.56	3.30	6.50
Ultimate analysis [daf]					
Carbon	43.97	44.85	44.24	50.19	42.10
Hydrogen	5.99	5.63	6.20	6.10	6.00
Nitrogen	1.20	0.92	0.99	0.02	3.09
Sulfur	0.17	0.13	0.11	0.00	0.00
Oxygen	48.67	48.47	48.46	43.69	48.80

ar: as received; daf: dry ash free.

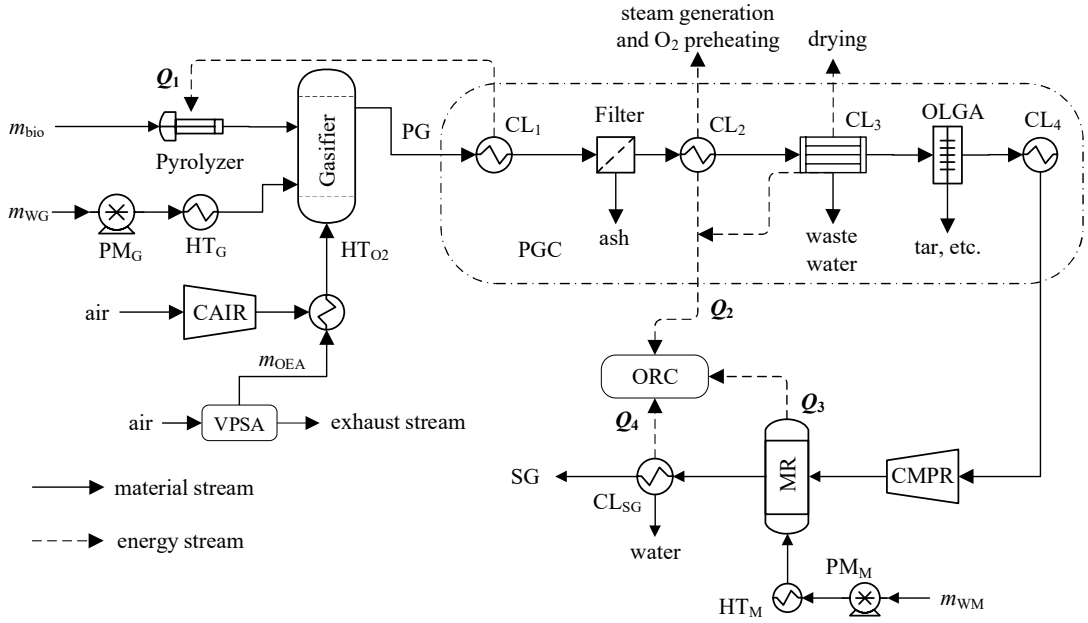

Figure 1. Process flow sheet of the high-safety and cost-effective syngas production process.

(2) Vacuum Pressure Swing Adsorption (VPSA)

Cryogenic distillation is the most common process of air separation for highly pure oxygen production. The VPSA technology is another energy-saving and cost-effective method for air separation. It uses zeolite, a material that adsorbs nitrogen to leave a rich stream of oxygen at ambient temperatures. Standard VPSA equipment packages can

supply oxygen from 40–150 t/h and 80%–93% O_2 purity at pressures to integrate with most applications [14,15], and the specific energy of the 80% O_2 purity product of different manufactures and scales varies from 0.29 to 0.35, in kWh/Nm^3 of pure O_2 [16]. In this study, 80% O_2 purity is employed to simplify the modeling of VPSA. It is assumed that the oxygen purities of 40%, 50%, 60%, and 70% are generated by blending air into 80% purity O_2-enriched air. To simplify the VPSA simulation and focus on electricity consumption, the Compr, Sep, and Heater models in Aspen Plus software are applied [5]. The power consumption of the VPSA unit is calculated by a user-specified FORTRAN subroutine using the specific energy of 0.29 kWh/Nm^3 of pure O_2.

(3) Producer Gas Cleaning (PGC)

The oil-based gas washer (OLGA) technology is integrated to clean the producer gas at low temperatures [17]. The high-temperature producer gas is firstly cooled to about 400 °C by the cooler CL_1. The recovered heat stream (Q_1) is used as the heat source of the pyrolyzer. Then the producer gas first passes through a hot gas filter to remove particles, which operates at 400 °C. Then the gas is cooled to 80 °C in the first OLGA unit, followed by an absorption step in the second unit, during which coolers CL_2 and CL_3 are employed to recover heat. The separation process is simulated by the Sep model in Aspen Plus. The outlet temperatures of CL_2 and CL_3 are set to about 200 °C and 80 °C, respectively. The heat recovered by CL_2 is preferably used to generate steam and preheat O_2–enriched air, while that by CL_3 is firstly used to dry feedstock. Then, the residual heat stream (Q_2) is used by the ORC unit. Finally, the cooler CL_4 is set to adjust the PG temperature for the subsequent compression. All the coolers are simulated by the Heater model in Aspen Plus. The pressure drops over OLGA are less than 50 mbar [18]. The total pressure drop of 5 kPa in PGC is set to simulate the power loss of this unit.

(4) Methanation Synthesis

The clean syngas is compressed by a multi-stage compressor (CMPR) and fed into the methanation reactor (MR). The compressor is simulated by the polytropic model using the ASME method. Then, CO and H_2 are converted into CH_4 and H_2O through the methanation reactions and water–gas shift reactions. Since methane synthesis is highly exothermic, lower methanation temperature is favorable to the synthesis performances. Compared to a fixed bed methanation reactor, a fluidized bed has notable advantages in temperature control and catalyst distribution. This study adopts a single isothermal once-through fluidized bed methanation reactor (MR), which allows for simultaneous methanation and water gas shift reactions [19]. The operation temperature of MR is kept at 300 °C. The heat released by exothermic reactions (Q_3) is mainly used to heat the ORC working medium. A certain amount of water is used for the synthesis reactions to suppress carbon formation. Finally, in the syngas (SG), the output of the methanation synthesis is cooled down by the cooler CL_{SG}, which also removes most vapor in syngas and recovers sensible heat (Q_4) with a temperature above 80 °C for the ORC unit.

The MR is simulated by the RGibbs model and verified based on a case report on conventional SNG production [20]. The heaters and coolers are simulated by the Heater model with a pressure drop of 0.5 kPa and an energy efficiency of 98%. The water pump is modeled with an isentropic efficiency of 85% and mechanical efficiency of 98%. Additionally, the simulation of the ORC unit is simplified, and only the output power is calculated by a user-specified FORTRAN subroutine with a net efficiency of 25%.

3. Assessment Methodology

3.1. Requirements on Syngas

According to the Chinese technical standard [21], natural gas is divided into four classes (3T, 4T, 10T, and 12T) with an *HHV* range of 12.26–45.96 MJ/Nm^3. The *HHVs* of 10T and 12T exceed 34 MJ/Nm^3, which is obviously greater than those of the syngas generated by biomass gasification. In the following analysis, the syngas is compared with the classes 3T and 4T based on *HHVs* (Table 2).

Table 2. Regulations on *HHVs* of different types of natural gas in the technical standard.

Item	*HHV* (MJ/Nm^3)	
Class	3T	4T
Upper Value	14.98	19.04
Standard Value	13.62	17.31
Lower Value	12.26	15.58

The following indicators are studied to demonstrate the technical competitiveness of the process: composition, syngas yield, and *HHV* of the syngas. The syngas yield (Y) is defined as below:

$$Y = \frac{V_{SG}}{m_{bio,daf}} (\mathrm{Nm^3/kg_{daf}}) \quad (1)$$

where V_{SG} is the volume flow rate of syngas, in Nm^3/h; $m_{bio,daf}$ is the mass flow rate of biomass on a dry ash-free basis, in kg/h.

Additionally, syngas contains species that are flammable (mainly CH_4, H_2, and CO) and toxic gases (mainly CO). Both explosivity and toxicity are studied then. The upper and lower explosive limits (*UEL* and *LEL*) of syngas are calculated below [10]:

$$UEL = \frac{(1 - 4.76 \cdot f_O)}{\sum_{i=1}^{n} \frac{f_i}{UEL_i} + 0.01(f_N - 3.76 \cdot f_O)} (\%) \quad (2)$$

$$LEL = \frac{(1 - 4.76 \cdot f_O)}{\sum_{i=1}^{n} \frac{f_i}{LEL_i} + 0.01(f_N - 3.76 \cdot f_O)} (\%) \quad (3)$$

where *UEL* and *LEL* are the upper and lower explosive limits of syngas, respectively, %. UEL_i and LEL_i are the upper or lower explosive limits of flammable component i in syngas, respectively, in %. f_O is the molar fraction of oxygen; f_N is the total molar fraction of inert components (N_2 and CO_2).

The toxicity of syngas can be directly evaluated according to the CO concentration in syngas: Prohibitive (P, CO > 20%), Marginal (M, 10 vol.% < CO $\leq$ 20 vol.%), Good (G, 2 vol.% < CO $\leq$ 10 vol.%) and Excellent (E, CO $\leq$ 2 vol.%) [10].

3.2. Exergy Analysis

The performance of energy conversion is always a concern in this area. This study adopts exergy efficiency to evaluate this performance to include the effect of the product's pressure. The overall exergy efficiency is defined below:

$$\eta_{ex} = \frac{SE_{SG}}{SCE \cdot m_{bio,db} + P_T} \times 100\% \quad (4)$$

where SE_{SG} is the exergy flow rate of syngas (*SG*), including physical and chemical items, in MJ/h [22], and the specific chemical exergies of CH_4, H_2, and CO are 831.69, 236.1, and 275.06, in kJ/mol [6]. $m_{bio,db}$ is the mass flow rate of biomass on a dry basis, in t/h. P_T is the net electrical power required by the process in MJ/h. The specific chemical exergy of biomass (*SCE*) on a dry basis is calculated by the following correlation [23]:

$$SCE = 363.439\mathrm{C} + 1075.633\mathrm{H} + 86.308\mathrm{O} + 4.147\mathrm{N} + 190.798\mathrm{S} + 21.1\mathrm{A}\ (\mathrm{kJ/kg}) \quad (5)$$

where C, H, O, N, S, and A represent carbon, hydrogen, oxygen, nitrogen, sulfur, and ash contents of fuel, respectively, in wt.% on a dry basis.

3.3. Economic Assessment

The unit production cost (*UPC*) is evaluated to demonstrate the economic competitiveness of the process. The *UPC* is calculated based on the cost model involving total capital

investment (*TCI*) and total production cost (*TPC*) [5]. *TCI* includes fixed capital investment (*FCI*) and working capital (*WC*), and the former item includes indirect investment and direct investment. The *TCI* can be estimated based on the *TCI* model and the percentage of each component [5]. The equipment costs (*ECs*) are the key data to estimate *TCI*, which are closely related to the production capacities (*PCs*) of the devices. Table 3 lists the *EC* data of the gasifier, gas cleaning and methanation reactor, etc., in the benchmark year of 2019 [5,6]. The US dollar to Chinese Yuan exchange rate was 6.8985.

Table 3. *PC* and *EC* of the syngas production plant with a plant scale of 25 t/h.

Equipment	Benchmark	*PC*	*EC* (Million $)
Two-stage Gasifier	Biomass	25 t/h	3.266
Gas Cleaning	Syngas	30.7 t/h	2.025
Compressors	Syngas	30.7 t/h	0.494
Methanation reactor	Syngas	30.7 t/h	0.877
Heat exchangers	Water	143 t/h	0.119
ORC	Output	2.39 MW	0.510
VPSA	O_2 stream	2510 m^3/h	0.809

TPC primarily consists of raw materials, utilities, maintenance and operating, depreciation, plant overhead costs, administrative cost, distribution, and selling costs. The investment for utilities is obtained according to the technical data. The depreciation is calculated according to the straight line method with a 4% salvage value and 20 years lifetime. Based on the *TPC* model [5], *UPC* is calculated based on the *TPC* value and annual yield of the product.

Recently the selling price of natural gas in China has varied from 0.348 \$/Nm^3 to 0.406 \$/Nm^3 (2.4–2.8 ¥/Nm^3). It can be used as the reference for the product's *UPC*. However, as there is a significant difference in heating values between syngas and natural gas, the levelized cost of energy (*LCOE*) is applied to compare the costs at the same baseline, and it is defined as below:

$$LCOE = \frac{UPC}{HHV_{SG}} \quad (6)$$

Converted from the selling prices, the *LCOE* of natural gas ranges from 10.32 \$/GJ to 11.61 \$/GJ (71.2–80.1 ¥/GJ).

3.4. Sensitivity Analysis

The sensitivity coefficient of an index to a variable is defined below:

$$\text{sensitivity coefficient} = \frac{\Delta I/I}{\Delta V/V} \quad (7)$$

where I and V are the indicator and variable, respectively, and Δ denotes the change in I or V.

4. Results and Discussion

4.1. Technical Performances

(1) Effects of O_2 purity and methanation pressure

The sawdust is first studied as the representative feedstock. This study mainly focuses on the effects of O_2 purity and methanation pressure, which have a crucial influence on the composition of CH_4-riched syngas [6]. The other parameters, such as steam-to-biomass ratio, gasification temperature, etc., are not concerned in this study since the investigations on these variables are sufficient, and their effects are clear [24,25]. Table 4 summarizes the composition and safety indicators of both producer gas and syngas at constant methanation pressure (10 bar). When the O_2 purity rises from 40% to 70%, the N_2 contents in producer gas and syngas decrease gradually from 14.2 vol.% to 4.8 vol.% and from 20.4 vol.% to

7.3 vol.%, respectively, resulting in increases in the contents of other species. Table 4 shows that the *UEL* and *LEL* of producer gas vary from 60.7% to 63.2% and from 7.5% to 8.2%, respectively, and the explosive range (*UEL–LEL*) is about 54%. By contrast, the *UEL* and *LEL* of syngas range from 32.6% to 36.3% and from 11.4% to 13.0%, respectively, and the explosive range (*UEL–LEL*) is only about 21%. These indicate that the syngas produced by this process has an obvious advantage over the producer gas in explosion risk. Additionally, regarding toxicity performance, all the producer gas with different O_2 purities is rated as "Prohibitive" (CO contents > 20%), while all the syngas is rated as "Excellent" (CO contents < 2%) [10]. These indicate that this process with various O_2 purities can generate high–safety syngas.

Table 4. Composition, explosivity, and toxicity of producer gas and syngas using sawdust as feedstock.

Item	O_2 Purity			
	40%	**50%**	**60%**	**70%**
		Producer gas		
CH_4 (vol.%)	6.7	7.0	7.2	7.4
H_2 (vol.%)	32.9	34.5	35.7	36.6
CO (vol.%)	28.6	30.0	31.1	31.8
CO_2 (vol.%)	17.5	18.3	18.9	19.3
N_2 (vol.%)	14.2	10.0	7.1	4.8
UEL (%)	63.2	62.1	61.3	60.7
LEL (%)	8.2	7.9	7.6	7.5
Toxicity	P	P	P	P
		Syngas		
CH_4 (vol.%)	30.8	33.1	34.9	36.2
H_2 (vol.%)	3.6	3.6	3.6	3.7
CO (vol.%)	0.02	0.02	0.03	0.03
CO_2 (vol.%)	45.2	48.4	50.8	52.6
N_2 (vol.%)	20.4	14.8	10.6	7.3
UEL (%)	36.3	34.6	33.5	32.6
LEL (%)	13.0	12.3	11.8	11.4
Toxicity	E	E	E	E

Furthermore, as shown in Figure 2, when the O_2 purity is fixed, all the concentrations of CH_4, CO_2, and N_2 change slightly with the increase in p_M. Thus, it can be inferred that all the syngas produced with different p_M has excellent safety performances. More specifically, CH_4 concentration increases visibly firstly ($p_M \leq 10$ bar) and then slowly ($p_M > 10$ bar); meanwhile, the CO_2 and N_2 contents increase very slightly. The reason is that the CO methanation reaction leads to a reduction in the number of molecules, then the contents of the three main species rise simultaneously. At any given p_M, the N_2 content decreases correspondingly with the increase in the O_2 purity, resulting in increases in the contents of other constituent species. The sensitivity coefficients of CH_4, CO_2, and N_2 contents to p_M are on average 0.008, −0.006, and 0.08, respectively. By contrast, the sensitivity coefficients of CH_4, CO_2, and N_2 contents to O_2 purity are about 0.26, 0.25, and −1.45, respectively. These indicate that O_2 purity is more crucial than methanation pressure for the syngas composition.

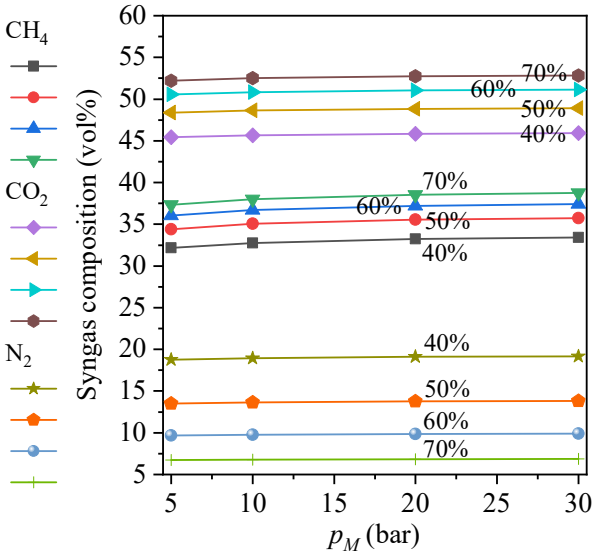

Figure 2. Effects of p_M and O_2 purity on syngas composition of sawdust-derived syngas.

Figure 3a shows that when the O_2 purity is constant, the *HHV* increases visibly firstly ($p_M \leq 10$ bar) and then slowly ($p_M > 10$ bar) with the increase in p_M, which is caused by the variation of CH_4 content. When the p_M is kept unchanged, the *HHV* obviously rises with the increase in O_2 purity since less N_2 is brought into syngas by the gasifying agent. According to the *HHV* range, the syngas cannot meet the requirement of 4T (Table 2). Note that when the p_M exceeds 10 bar, the *HHV* is greater than the upper value of 3T (Table 2), which is indicated by the dashed line in Figure 3a. The syngas with excessive heating value is not recommended considering the interchangeability of gaseous fuels.

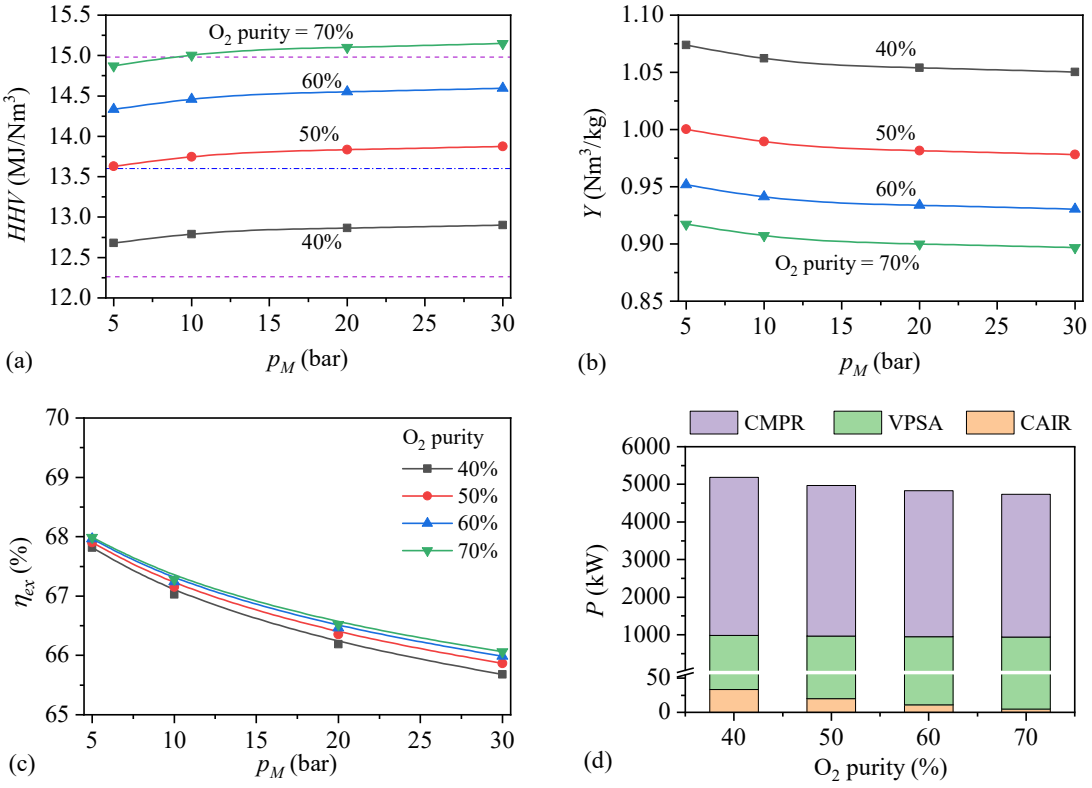

Figure 3. Effects of O_2 purity and p_M on (**a**) *HHV*, (**b**) *Y*, (**c**) η_{ex}, and (**d**) power rates of sawdust-derived syngas.

Figure 3b shows that when the O_2 purity is constant, the Y decreases gradually and then slightly with the increase in p_M due to the volume reduction caused by the methanation synthesis. When the p_M is kept unchanged, the Y visibly decreases with the increase in the O_2 purity.

Figure 3c shows that when the O_2 purity is constant, the η_{ex} gradually decreases with the increase in p_M, which is mainly caused by the increased power of the multi-stage compressor (CMPR). When the p_M is fixed, the η_{ex} visibly rises with the increase in O_2 purity. At the p_M of 10 bar, more O_2-enriched air is needed, and the power of the VPSA unit rises with the increase in O_2 purity; however, the flow rate of inert gas N_2 entering into the process decreases significantly, resulting in the declines in the power rates of the multi-stage compressor CMPR significantly and the fan CAIR, as shown in Figure 3d. Finally, the combined result is that the total power of the process decreases with the increase in O_2 purity.

The sensitivity coefficients of *HHV*, Y_{SG}, and η_{ex} to O_2 purity are, on average, 0.26, −0.24, and 0.007, respectively. While the coefficients to p_M are averagely 0.007, −0.009, and −0.01, respectively. The results indicate that the technical performances (*HHV* and *Y*) except η_{ex} are more sensitive to O_2 purity than methanation pressure. Higher O_2 purity ($\geq$50%) and lower p_M (5–10 bar) are beneficial to this process. Considering the existing outliers in Figure 3a and potential outliers for other feedstock, the effects of O_2 purity and p_M are further analyzed and optimized based on the technical performances using other types of biomass as feedstock.

(2) Syngas properties of different feedstock

The explosive and toxic properties of the syngas produced from other feedstock are similar to those of sawdust-derived syngas. All the syngas are rated as "Excellent," even at the p_M of 5 bar. It should be noted that the purpose of this process is to generate high-safety syngas. It is just good enough to convert CO and H_2 contents to certain low concentrations, and full conversion is not necessary. Additionally, the influences of O_2 purity and p_M on Y and η_{ex} of the syngas produced from other feedstock are also similar to those of sawdust-derived syngas.

The interchangeability of gaseous fuels is closely associated with *HHV*; therefore, the *HHV* has a specific range to meet the interchangeability requirement. Figure 4 shows that the *HHV* of the syngas generated from all feedstock at 5 bar and 10 bar ranges from 12.0–15.1 MJ/m^3, which gradually increases with the increase in O_2 purity. Correspondingly, the *LHV* of the syngas varies from 10.8–13.6 MJ/m^3. According to the *HHVs* in Table 2, this process integrating OAG with 40–70% O_2 purity can only generate syngas that is equivalent to the class 3T. The O_2 purity of 40% or 70% should be carefully used because it may result in outliers beyond the *HHV* range of class 3T, especially at higher p_M, as indicated by Figure 4b. Taking the combined effects of O_2 purity and p_M on *HHV* and η_{ex}, 5 bar is the optimal value of p_M, and the O_2 purity over the range of 50–60% is recommended to be used in the syngas production because the *HHVs* of the syngas are close to the standard value of the class 3T (13.62 MJ/Nm^3). This is beneficial to the compatibility of the existing combustors. Otherwise, 70% O_2 purity can be applied to obtain higher exergy efficiencies. The relative difference of *HHVs* in the technical standard is within ±10% [10], and for the same type of feedstock, the relative differences between *HHVs* with 40%–70% purity and those with 60% purity are within ±6%. Hence, a compromise and conservative choice is to use 60% O_2 purity for all the feedstock.

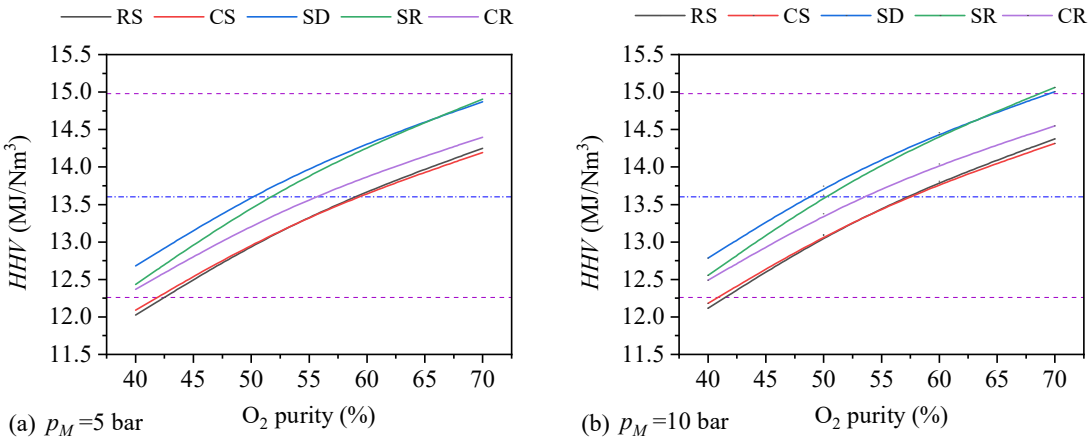

Figure 4. Effects of O_2 purity on *HHV* of syngas produced from five types of feedstock at p_M of (**a**) 5 bar and (**b**) 10 bar.

Table 5 shows the composition, *HHV*, *Y*, and η_{ex} of syngas derived from five sorts of feedstock with 60% O_2 purity and 5 bar p_M. The CH_4 concentration in syngas (33.24–34.89 vol.%) from other feedstock is similar to that from sawdust. The total concentration of inert gases (CO_2 and N_2) is about 62 vol.%. The *HHV*, *Y*, and η_{ex} range between 13.67–14.33 MJ/Nm^3, 0.922–1.088 Nm^3/kg_{daf}, and 66.96–68.68%, respectively. The average values of *UEL* and *LEL* are 34% and 12%, respectively, which also change little with the type of biomass. The explosive range has an average of 22%. Certainly, all the syngas is rated as "Excellent" regarding toxicity.

Table 5. Technical properties of syngas produced from five types of biomass.

Feedstock	Composition (vol.%)			*HHV*	Y	η_{ex}
	CH_4	H_2	CO	(MJ/Nm^3)	(Nm^3/kg_{daf})	(%)
RS	33.28	3.64	0.03	13.69	0.956	66.96
CS	33.24	3.57	0.03	13.67	0.964	67.10
SD	34.89	3.63	0.03	14.33	0.952	67.95
SR	34.80	3.55	0.03	14.28	1.088	68.68
CR	33.80	3.61	0.03	13.89	0.922	67.92

4.2. Economic Performances

(1) Feedstock Cost

In this section, sawdust is chosen as the representative feedstock, and the influence in yield is approximately taken into account by that of feedstock cost (C_{bio}). Additionally, the p_M is fixed at 5 bar. It assumes that the C_{bio} ranges from 14.50 $/t to 72.48 $/t (100–500 ¥/t) [5,26]. Based on the above technical results and the C_{bio} of 43.49 $/t (300 ¥/t), the decreasing order of the top three components in *UPC* is feedstock cost (>50%), O&M (~21%), and depreciation (~9%). Due to the O&M and depreciation being closely related to the fixed capital investment, the plant scale should be analyzed. Additionally, the plant scale is very crucial to the economic performance of biomass conversion projects, which can be represented by the mass flow rate of feedstock (m_{bio}). The plant scale within the range of 5–25 t/h is studied by reference to the scales of a dozen existing biomass-fired power plants in Jiangsu Province, China. Additionally, the electricity cost accounts for less than 10% of *UPC* even when C_{bio} is 14.50 $/t; that is because the specific power consumption of the VPSA technique is quite lower, and it changes little once the O_2 purity is fixed. Thus, the electricity cost is not analyzed in this study.

Figure 5 shows that with the same O_2 purity, both *UPC* and *LCOE* nearly proportionally increase with the increase in C_{bio}. The *UPC* varies between 0.05 $/$Nm^3$ and

0.13 \$/Nm^3 (0.33–0.89 ¥/Nm^3), which is obviously lower than that with an O_2-purity of 80% or higher [5]. Meanwhile, with the plant scale of 25 t/h, the *LCOE* varies between 3.78 \$/GJ and 8.71 \$/GJ (26.08–60.12 ¥/GJ), which is always less than that of natural gas (10.32–11.61 \$/GJ). The results indicate that the syngas generated by this process has strong economic competitiveness.

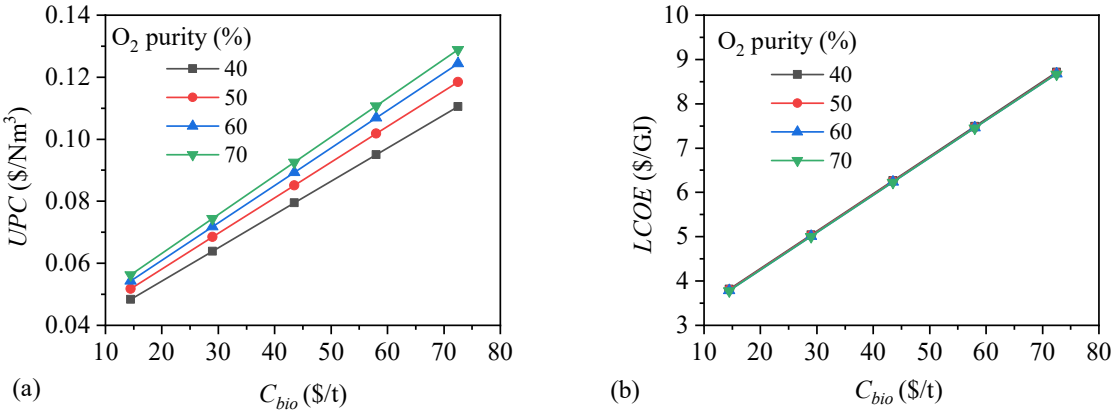

Figure 5. Variations of (**a**) *UPC* and (**b**) *LCOE* with feedstock cost and O_2 purity.

Additionally, with the increase in O_2 purity, the *UPC* with the same C_{bio} visibly increases while the *LCOE* decreases very slightly. When the O_2 purity is improved, both the equipment cost and the power rate of VPSA unit rise, resulting in increases in total equipment cost, fixed capital investment, and production cost. Together, these changes lead to an increase in *UPC*. However, as indicated in Figures 3a and 5a, the variations of *UPC* and *HHV* with O_2 purity have opposite trends, and the combined changes result in the variation of *LCOE* with O_2 purity according to Equation (6). Compared with the effects of O_2 purity on the technical performances, it is a minor variable for economic performances, especially *LCOE*. However, higher O_2 purity is beneficial to both η_{ex} and *LCOE*. This implies that *LCOE* is a more rational indicator than *UPC*, and the later indicator may mislead the decision-makers. It also indicates that VPSA is an attractive technology for O_2-enriched gasification from the perspectives of heating value, exergy efficiency, and cost of the syngas.

(2) Plant Scale

Figure 6a shows that at C_{bio} of 43.49 \$/t (300 ¥/t), the *UPC* decreases sharply firstly and gradually with the increase in plant scale, which sits between 0.08 \$/Nm^3 and 0.27 \$/Nm^3 (0.55–1.87 ¥/Nm^3). In contrast, the changes in *UPC* with O_2 purity are relatively small. Figure 6b indicates that the *LCOE* also decreases sharply firstly and gradually with the increase in plant scale. It sits between 6.23 \$/GJ and 18.28 \$/GJ (42.95–126.11 ¥/GJ) and changes little with O_2 purity. When the plant scale is less than 6 t/h, the *LCOE* is higher than that of natural gas; then the syngas has no economic competitiveness. To obtain syngas that can be competitive with natural gas, the plant scale should be not less than 7 t/h, which is much less than that for SNG production (≥11.25 t/h) [5]. Conservatively, a plant of 10 t/h or larger is recommended.

This process integrating O_2-enriched air gasification offers a way to utilize the biomass residues and supply high-safety, cost-effective and renewable fuel. It is especially attractive in rural areas where there are no natural gas facilities at current, or the cost is high to construct new facilities. The fuel can be used for power and heat generation. It can be applied to build a community with self-sufficiency in energy. Based on the experience of the biomass-fired power plant, the syngas production plant can create about one hundred jobs for local residents.

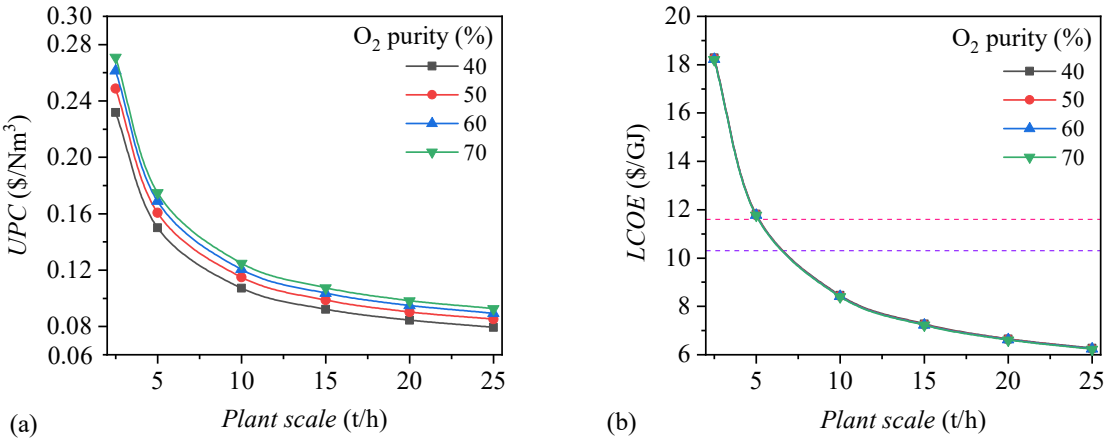

Figure 6. Variations of (**a**) *UPC* and (**b**) *LCOE* with plant scale and O_2 purity.

5. Conclusions

A process integrating O_2-enriched air gasification with 40–70% O_2 purity and methanation synthesis is studied for the production of high-safety and cost-effective syngas. The main findings of the present study are as follows.

O_2 purity is an important parameter to the technical performances of this process, while methanation pressure is a minor parameter except for exergy efficiency. Feedstock cost and plant scale are crucial parameters to economic performances; by contrast, O_2 purity plays a minor role. The O_2 purity of 60% is a compromise and conservative choice for all the feedstock.

This process, with optimal parameters, can generate high-safety syngas containing 33.2–34.9 vol.% CH_4 and approximately 62 vol.% inert gases (CO_2 and N_2). The *UEL* and *LEL* are about 34% and 12%, and the average explosive range is about 22%. Additionally, all the syngas is rated as "Excellent" regarding toxicity. The *HHV* of syngas generated from five types of feedstock sit between 13.67–14.33 MJ/m^3, which is equivalent to that of the medium-*HHV* of city gas.

The exergy efficiency of this process with optimal parameters ranges from 66.96% to 68.68%, indicating strong competitiveness in energy conversion efficiency. The *UPC* varies between 0.05 \$/Nm^3 and 0.27 \$/Nm^3 (0.33–1.87 ¥/Nm^3), and the *LCOE* varies between 3.78 \$/GJ and 18.28 \$/GJ (26.08–126.11 ¥/GJ). When the plant scale exceeds 7 t/h, the syngas has a strong competitiveness in either *UPC* or *LCOE*.

The demonstration of this process, including the development of an O_2-enrich air gasifier, is attractive since the process can generate high-safety and cost-effective syngas with relatively simple process configuration and devices. Additionally, a life cycle sustainability assessment of the syngas produced by this process should be carried out to determine its environmental competitiveness.

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Conflicts of Interest: The authors declare no conflict of interest.

References

1. Bailera, M.; Lisbona, P.; Romeo, L.M.; Espatolero, S. Power to Gas projects review: Lab, pilot and demo plants for storing renewable energy and CO_2. *Renew. Sustain. Energy Rev.* **2017**, *69*, 292–312. [CrossRef]
2. Prussi, M.; Padella, M.; Conton, M.; Postma, E.D.; Lonza, L. Review of technologies for biomethane production and assessment of Eu transport share in 2030. *J. Clean. Prod.* **2019**, *222*, 565–572. [CrossRef] [PubMed]
3. Song, G.; Xiao, J.; Yu, Y.; Shen, L. A techno-economic assessment of SNG production from agriculture residuals in China. *Energy Sources Part B Econ. Plan. Policy* **2016**, *11*, 465–471. [CrossRef]
4. Haro, P.; Johnsson, F.; Thunman, H. Improved syngas processing for enhanced Bio-SNG production: A techno-economic assessment. *Energy* **2016**, *101*, 380–389. [CrossRef]
5. Cui, X.; Song, G.; Yao, A.; Wang, H.; Wang, L.; Xiao, J. Technical and Economic Assessments of a novel biomass-to-synthetic natural gas (SNG) process integrating O2-enriched air gasification. *Process Saf. Environ. Prot.* **2021**, *156*, 417–428. [CrossRef]
6. Song, G.; Wang, L.; Yao, A.; Cui, X.; Xiao, J. Technical and Economic Assessment of a High-Quality Syngas Production Process Integrating Oxygen Gasification and Water Electrolysis: The Chinese Case. *ACS Omega* **2021**, *6*, 27851–27864. [CrossRef]
7. Wang, Z.; He, T.; Qin, J.; Wu, J.; Li, J.; Zi, Z.; Liu, G.; Wu, J.; Sun, L. Gasification of biomass with oxygen-enriched air in a pilot scale two-stage gasifier. *Fuel* **2015**, *150*, 386–393. [CrossRef]
8. Nam, H.; Maglinao, A.L.; Capareda, S.C.; Rodriguez-Alejandro, D.A. Enriched-air fluidized bed gasification using bench and pilot scale reactors of dairy manure with sand bedding based on response surface methods. *Energy* **2016**, *95*, 187–199. [CrossRef]
9. Gu, H.; Tang, Y.; Yao, J.; Chen, F. Study on biomass gasification under various operating conditions. *J. Energy Inst.* **2019**, *92*, 1329–1336. [CrossRef]
10. Song, G.; Xiao, J.; Yan, C.; Gu, H.; Zhao, H. Quality of gaseous biofuels: Statistical assessment and guidance on production technologies. *Renew. Sustain. Energy Rev.* **2022**, *169*, 112959. [CrossRef]
11. Feng, F.; Song, G.; Shen, L.; Xiao, J. Environmental benefits analysis based on life cycle assessment of rice straw-based synthetic natural gas in China. *Energy* **2017**, *139*, 341–349. [CrossRef]
12. Ying, T.; Cao, H. Progress of biomass gasification technology. *Chinese J. Bioprocess Eng.* **2017**, *15*, 57–65. (In Chinese) [CrossRef]
13. Ye, R.; Liu, J.; Li, X.; Zheng, L.; Li, M.; Wang, G.; Zhang, D. Experimental study on biomass of bubbling testbed with steam-oxygen enriched air gasification of directional. *Acta Energiae Solaris Sin.* **2016**, *37*, 1636–1642.
14. Air-Liquide Standard Plants Fully-Packaged Modular Solutions. Available online: https://www.engineering-airliquide.com/sites/activity_eandc/files/2017/04/12/air-liquide-brochure-standard-plants-170418.pdf (accessed on 15 February 2021).
15. Beijing-Peking-University- Pioneer-Technology-Co., -Ltd Vacuum Pressure Swing Adsorption Oxygen Plant (VPSA-O2). Available online: https://www.vpsatech.com/VPSA-Oxygen.html#local (accessed on 15 February 2021).
16. Liu, X.; Dou, Q.; Min, W.; Chen, T.; Xue, Z. Pressure swing adsorption for oxygen generation and its application in EAF steelmaking. *Steelmaking* **2020**, *36*, 6–10.
17. Vilela, C.M.; Boymans, E.; Vreugdenhil, B. Co-production of aromatics in biomass and waste gasification. *Processes* **2021**, *9*, 463. [CrossRef]
18. Zwart, R.W.R.; Boerrigter, H.; Deurwaarder, E.P.; van der Meijden, C.M.; Paasen, S.V.B. Production of Synthetic Natural Gas (SNG) from Biomass. Available online: https://www.biosng.com/fileadmin/biosng/user/documents/reports/e06018.pdf (accessed on 19 September 2021).
19. Seemann, M.C.; Schildhauer, T.J.; Biollaz, S.M.A. Fluidized bed methanation of wood-derived producer gas for the production of synthetic natural gas. *Ind. Eng. Chem. Res.* **2010**, *49*, 7034–7038. [CrossRef]
20. Gassner, M.; Maréchal, F. Thermo-economic process model for thermochemical production of Synthetic Natural Gas (SNG) from lignocellulosic biomass. *Biomass Bioenergy* **2009**, *33*, 1587–1604. [CrossRef]
21. *GB/T 13611-2018*; Classification and Basic Characteristics of City Gas. Technical-Standard; Standards Press of China: Beijing, China, 2018.
22. Szargut, J. *Exergy Method: Technical and Ecological Applications*; WIT Press: Southampton, UK, 2005.
23. Song, G.; Xiao, J.; Zhao, H.; Shen, L. A unified correlation for estimating specific chemical exergy of solid and liquid fuels. *Energy* **2012**, *40*, 164–173. [CrossRef]
24. Watson, J.; Zhang, Y.; Si, B.; Chen, W.T.; de Souza, R. Gasification of biowaste: A critical review and outlooks. *Renew. Sustain. Energy Rev.* **2018**, *83*, 1–17. [CrossRef]
25. Cao, Y.; Wang, Q.; Du, J.; Chen, J. Oxygen-enriched air gasification of biomass materials for high-quality syngas production. *Energy Convers. Manag.* **2019**, *199*, 111628. [CrossRef]
26. Yuan, X.; Chen, L.; Sheng, X.; Liu, M.; Xu, Y.; Tang, Y.; Wang, Q.; Ma, Q.; Zuo, J. Life Cycle Cost of Electricity Production: A Comparative Study of Coal-Fired, Biomass, and Wind Power in China. *Energies* **2021**, *14*, 3463. [CrossRef]