



Mobile Rice Husk Gasifier Performance and Techno-Economic Analysis as Micro Scale Power Generation: Modeling and Experiment

Sarah Pertiwi¹, Yohanes Bobby¹, Marcellino Lorenzo¹, Hafif Dafiqurrohman² & Adi Surjosatyo^{1,3}

¹Department of Mechanical Engineering, Faculty of Engineering, Universitas Indonesia, Kampus UI, Depok 16424, Indonesia

²Department of Mechanical Engineering, Faculty of Engineering, The University of Tokyo, Tokyo 113-8654, Japan

³Tropical Renewable Energy Center, Faculty of Engineering, Universitas Indonesia, Kampus UI, Depok 16424, Indonesia

*E-mail: adisur@eng.ui.ac.id

Highlights:

- Gasifier performance provided by simulation and experimental results.
- Maximum performance was found at an equivalent ratio of 0.25.
- The feasibility of a mobile rice husk gasifier was studied; it is economically feasible as a waste-to-energy technology.

Abstract. Indonesia annually produces significant amounts of biomass waste in the agriculture sector. Rice husk, one of the highest produced agricultural waste materials, has sufficient caloric value to produce syngas in a gasification system to generate sustainable energy. However, the production of tar from rice husk gasification is significantly high, damaging the equipment and internal combustion engine. This study carried out performance analysis on a small-scale rice husk gasifier. A simulation provided a syngas composition overview and showed a maximum LHV value of 6.47 MJ/Nm³ at ER 0.25, and a maximum CGE value of 83% at a temperature of 900 °C. Furthermore, the economic aspect of integrating renewable technology was also considered. The gasifier had an LCOE value ranging from 0.014 to 0.089 USD/kW, depending on the use of the gasifier. The feasibility of using a mobile rice husk gasifier was also inspected, based on net present value, benefit-to-cost ratio, and payback period.

Keywords: *biomass; downdraft; gasifier; techno-economic analysis; waste-to-energy.*

1 Introduction

As an agricultural country, Indonesia relies heavily on biomasses. It is estimated that up to 35.6 GW of energy can be provided by utilizing biomass waste from farm industries, with rice as the primary food in Indonesia, which potentially could deliver 19.41 GW of power from its waste [1]. Xiong, *et al.* (2009) state that 20% of rice production is rice husks, which could produce 3,053 tons cal/ton

Received June 9th, 2022, Revised October 7th, 2022, Accepted for publication October 24th, 2022.

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DOI: 10.5614/j.eng.technol.sci.2022.54.6.8

of energy, while FAO data (2015) shows that Indonesia had 14 million tons of rice husks in 2014, or about 1.5 GJ of energy [2]. This potential energy source is even more useful in remote areas, where access to electricity is limited. Gasification is a thermochemical process that turns organic materials into combustible gas through partial oxidation. The main product is syngas, mainly composed of H_2 , CO, and CH_4 . The side products of the gasification process are ash, biochar, and tar. Gasification has the advantage of simplicity compared to other biomass utilization technologies. Gasification can quickly turn a wide variety of biomasses into combustible fuel and can be applied at various scales. However, tar as a byproduct is an organic compound material that can be harmful to the power generation equipment. Hence, the gasifier must be designed to have high efficiency with low tar production. Among many types of gasifiers, the downdraft gasifier is the clear choice for micro-scale power generation due to its ease of manufacture and operation, and its capability to be used with a wide variety of feedstocks and moisture contents [3]. The downdraft-type gasifier can also be directly integrated into an internal combustion engine (ICE) generator due to the low tar content of the syngas [4]. Gagliano, *et al.* [5] showed that using small-scale downdraft gasifiers in industry is a good and environmentally friendly option. The Biomass Gasification Laboratory of the University of Indonesia has developed a fixed-bed downdraft gasifier, which was designed to provide about 10 kW of electricity. This study assessed the Mobile Biomass Gasifier's performance focused on tar reduction in the syngas. This mobile concept was developed for flexibility so that it can be used in remote areas. Simulations were done to create a benchmark for the experimental result. The goal was to know whether the Mobile Biomass Gasifier could be used in a practical environment. An economic evaluation was also conducted to assess the gasifier's feasibility as an energy generation project.

2 Methodology

2.1 Mobile Rice Husk Gasifier Design

The mobile rice husk gasifier system consists of three main modules: reactor module, tar cleaning system, and power generator (see Figure 1). The reactor module is divided into a feeding system and the reactor itself. The material used for the main reactor is stainless steel AISI 304, while the rest is made of stainless steel SS400. The lower of the part reactor and cyclone are used to separate the syngas from solid waste. The reactor module produces syngas that can be used immediately; however, in practice, the high temperature of the syngas and the high tar content produced when starting up and turning off the gasifier can be harmful to the power generator. To overcome these problems, a gas cleaning system is used, consisting of a condenser and a filter. The condenser module uses water to condensate the tar from the syngas and cools it down to room

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temperature. The condenser can contain 500 L of water, which can be used for many runs. This water-based condenser can keep the outlet syngas temperature at around 30 °C. The filter traps tar that is not perfectly condensated and still lingers in the syngas, cleaning the syngas for a final time before the syngas goes into the generator/burner. Filtering agents used in the filter are rice husk, straw, or biochar. Lastly, the syngas will be collected into a gas tank before being used for electrical or heat generation.

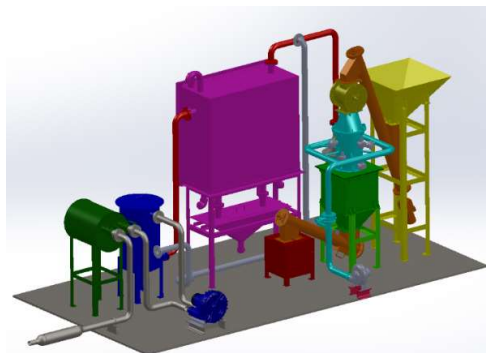


Figure 1 Gasifier model.

2.1.1 Gasification Process

A downdraft-type gasifier is used in this system because of its capability to work with a 10-kWe generator. In this setup, the feedstock goes through the pyrolysis zone before the combustion zone and the reduction zone, so that the pyrolysis products will undergo reactions in the combustion zone. As a result, large organic molecules such as tar will be oxidized to gas. This process can eliminate up to 99% of the tar in the syngas. Downdraft-type gasifiers generally produce 0.015 to 3 g/nm³ of tar. A drawback is that combustible gases such as CO and H₂ formed from the pyrolysis process will also undergo oxidation, which causes the end zone of the downdraft gasifier to generally have a high temperature, causing a decrease in the low heating value (LHV) of the syngas [6]. Chauves, *et al.* [7] combined a downdraft gasifier with an ICE generator. They stated that the syngas produced had a cold gas efficiency of 50 to 70%, and the utilization of heat in the reactor could be increased to 90%. Bhoi, *et al.* [3] developed a mobile downdraft gasifier for small-scale power plants using red cheddar wood and obtained a cold gas efficiency of 60 to 64% using ER 022-0.28. The process of the gasifier is shown in Table 1 [8].

The University of Indonesia's biomass gasification research team has conducted various studies using a fixed-bed downdraft gasifier. The air intake was modified for multi-stage application with a cold efficiency of 30.2% to optimize the

gasification process. The optimum operating temperature of the pyrolysis zone was 500 to 600 °C. Another experiment, with secondary air intake position variation, showed the optimum Z result at position 38 cm from the top of the reactor and the opening of the primary air intake at 45°, with the lowest yield of tar and the highest energy production [9].

Table 1 Gasification reaction inside the reactor.

Zone	Temp.	Reaction	Heat (kJ/mol)	Reaction Name
Drying	100°C	<i>Raw Biomass</i> → <i>Dry Biomass</i>	N/A	Drying
Pyrolysis	500°C	<i>Dried Biomass</i> → <i>Char</i> + <i>H₂</i> + <i>CO₂</i> + <i>CO</i> + <i>CH₄</i> + <i>H₂O</i> + <i>Tar</i>	NA	Pyrolysis
Oxidation	1000°C	<i>H₂</i> + 0.5 <i>O₂</i> → <i>H₂O</i>	-242	H ₂ oxidation
		<i>CO</i> + 0.5 <i>O₂</i> → <i>CO₂</i>	-283	CO oxidation
		<i>C</i> + 0.5 <i>O₂</i> → <i>CO</i>	-111	Char oxidation
		<i>TAR</i> + <i>O₂</i> → <i>CO₂</i> + <i>H₂O</i>	NA	Hydrocarbon oxidation
Combustion	700-900°C	<i>CO</i> + <i>H₂O</i> → <i>CO₂</i> + <i>H₂</i>	-41	Water gas shift
		<i>C</i> + <i>CO₂</i> → 2 <i>CO</i>	172	Boudouard
		<i>C</i> + 2 <i>H₂</i> → <i>CH₄</i>	-75	Methanation
		<i>C</i> + <i>H₂O</i> → <i>CO</i> + <i>H₂</i>	131	Water gas
		<i>CH₄</i> + <i>H₂O</i> → <i>CO</i> + 3 <i>H₂</i>	206	Methane Reforming
		<i>H₂</i> + <i>S</i> → <i>H₂S</i>	NA	H ₂ S formation

The biomass used in this study was rice husk with relative heterogeneity in size. We used biomass from a rice field in Karawang, West Java, Indonesia. The diameter and average length of the rice husks used were 3 mm and 11 mm, respectively. The properties of the biomass are shown in Table 2.

Table 2 Rice husk ultimate and proximate analysis.

Ultimate Analysis	% wt. (dB)	Proximate Analysis	% wt. (dB)
Nitrogen (%)	0.29	Moisture	7.82
Carbon (%)	35.03	Volatile	57.66
Hydrogen (%)	5.46	Fixed carbon	13.91
Oxygen (%)	38.49	Ash	20.61
Sulphur (%)	0.12	Caloric value (kcal/g)	3300

As shown in Figure 2, the reactor model had a diameter of 248.80 mm, a height of 400 mm, and a thickness of 9.27 mm. The reactor was constructed from a 10"

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pipe made of SCH 40 material SUS304 (AISI 304). 150 mm above the grate, there was a lighter hole to turn on the reactor. The reactor used a circular airflow to supply air.



Figure 2 Reactor model.

2.2 Simulation Setup

2.2.1 Gasification Simulation

Aspen Plus has a library database of physical properties used in simulation calculations. It can complete process modules on each block representing zones and provide measures for flow [10]. The Aspen model for the rise husk gasifier is shown in Figure 3.

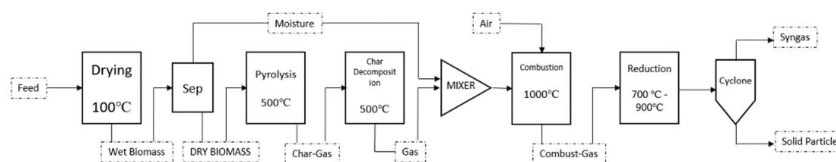


Figure 3 Process simulation flowchart.

The gasification process simulation uses the block diagram shown in Table 3. The feedstock is analyzed by ultimate and proximate analysis. Then its moisture is extracted, after which the biomass feed undergoes chains of chemical reactions as shown. The cyclone is used to separate the ash and the biochar from the syngas. The syngas is cooled using a condenser and is filtered before use [11].

Table 3 Block description.

Block	Model	Description
Drying	RYield	Separate moisture content from the biomass feed.
Pyrolysis	RYield	Simulate the pyrolysis process which decomposes the biomass into char and gases.
Char-dec	RStoic	Simulate the process of char decomposition into C, H ₂ , O ₂ , N ₂ , S.
Combustion	RStoic	Simulate the oxidation process for the stream.
Gasification	RGibbs/RStoic	Simulate the gasification process based on the Gibbs free energy of the stream.
Sep	Sep2	Separate the moisture from the solid feed for the simulation.
Mixer	Mixer	Mix the moisture into the main stream.
Cyclone	Sep2	Separate solid particles from the gas product.
Drying	RYield	Separate moisture content from the biomass feed.

1. Drying and pyrolysis zone modeling

The drying zone is based on the Gibbs reactor's DRYING model. The amount of water (moisture) lost in the drying zone of the rice husk with a temperature of 300 °C, heated with the Gibbs reactor to a temperature of 1000 °C, was determined based on the water content in the proximate analysis of the rice husk. The separation column SEP model was used to separate the dried biomass from the water or the moisture stream because the RSTOIC module has only one single outlet stream. The devolatilization zone, also known as the pyrolysis zone, is the next process. The calculations used in the pyrolysis process were FORTRAN, using the RYIELD block at a temperature of 6270 °C. RYIELD was used to separate the biomass into its essential chemical elements, i.e., as carbon, hydrogen, oxygen, and sulfur as well as ash, water, primary tar, and secondary tar [12]. The primary tars in this model were acetone, toluene, and phenol, while the secondary tars were naphthalene and benzene. The pyrolysis gas was then mixed with air using the equivalence ratio that has been determined.

2. Reduction and combustion zone modeling

In the combustion and reduction zones, primary and secondary tars react with air. The gas produced by pyrolysis and decomposition enters the combustion zone with limited air at a predetermined equivalence ratio. The gas and solid phases flow concurrently in the downdraft gasifier. It enters from above and sinks downwards by gravity through the solid zone.

Based on the above model, a simulation was conducted by varying the equivalence ratio and gasification temperature parameters. For this study, it was assumed that the reactions proceed in a steady state and isothermally; the gasifier worked at ambient conditions at a pressure of 1 atm, and the air was composed

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of 79% N₂ and 19% O₂. A feed of 15 kg/hr was used, and external energy for feeding and air blowing was neglected. The simulation result was in the form of the syngas composition. The LHV and CGE (cold gas efficiency) values were then used to determine the quality of the syngas and the performance of the gasifier [13].

$$LHV = \frac{13.662 CO + 10.788 H_2 + 35.814 CH_4}{100} MJ/Nm^3 \quad (1)$$

$$CGE = \frac{LHV_{Syngas} \times Syngas Flow}{LHV_{Biomass} \times Biomass Flow} \times 100\% \quad (2)$$

2.3 Experimental Setup

The experiment result, shown in Figure 4, resulted in some syngas being collected into special containers and sent to the lab for ultimate and proximate analysis. Proximate, ultimate, and calorific value analyses were done at the Center of Electricity Research & Development, Jakarta, Indonesia. At the same time, a gas composition test was conducted at The Assessment and Application of Technology (BPPT), Jakarta, Indonesia.

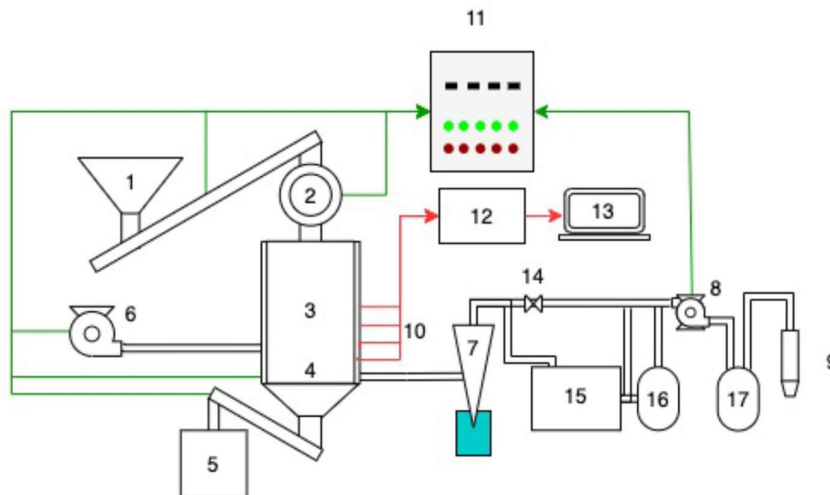


Figure 4 Experimental setup: (1) hopper, (2) double door, (3) reactor, (4) vibrating grate, (5) char box, (6) air supply pump, (7) cyclone, (8) suction pump, (9) burner, (10) thermocouple, (11) PLC, (12) DAQ, (13) laptop, (15) condenser, (16) filter, (17) storage.

The rice husk is fed through the hopper and gasified in the reactor. The system continues; the char is thrown through the vibrating grate and collected in the char box. The syngas produced then goes into the cyclone, is condensed in the

condenser, and filtered in the filter. The burner is used to indicate if syngas is being produced.

2.4 Economic Study

One of the advantages of gasifier technology is the waste-to-energy factor of the gasifier, which allows this technology to be used as a solution to the solid waste problem. Still, this technology must have general capabilities comparable to other power generation technology. There are various kinds of renewable energy technologies in the global market, so innovations must be able to compete with existing technologies. The levelized cost of energy (LCOE) was used in our techno-economic analysis. The LCOE measures the system's total cost for a given period, divided by the amount of energy produced during that period. For this study, the period was one year [14].

$$LCOE = \frac{\text{Annualized Total Cost of the System} \left(\frac{\text{Rupiah}}{\text{year}} \right)}{\text{Total Electrical Load served} \left(\frac{\text{kWh}}{\text{year}} \right)} \quad (3)$$

Some assumptions here were made based on design considerations when developing the gasifier. We used the results of our experiments over the last few months to determine some operating parameters for calculating the annual cost of the gasifier system: (1) the gasifier lifetime was expected to be ten years, with a discount rate of 3.5%, referring to BI (Bank Indonesia); (2) electricity generation has an efficiency of 30%; (3) the gasifier run time is eight hours a day for 360 days, with maintenance scheduled every hundred hours; and (4) no components will be replaced or added during its lifetime.

Biochar is a side product of gasification that can still be used as fertilizer or for making silicon; thus, biochar has a higher market value than the rice husk itself [15]. Rice husk can be considered waste that takes up space for farmers; however, rice husk itself can be helpful and have economic value. Therefore, when calculating LCOE (see Table 4), this gasification technology will be divided into several cases to represent the condition of the users of the gasifier as well as the biomass business opportunity.

Table 4 LCOE scenarios.

Case	Fuel Cost	Biochar Profit
1	Calculated	Not calculated
2	Calculated	Calculated
3	Not calculated	Not calculated
4	Not calculated	Calculated

Financial analysis is one aspect that is considered in building or developing a project. A business is feasible to establish if it can gain economic benefits.

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Analyzing the financial aspect makes it easier to determine investment plans by calculating the expected costs and benefits. The criteria to assess a project's feasibility are the net present value (NPV), the benefit-to-cost ratio, and the payback period (PBP), as shown in Table 5 [15,16].

Table 5 Economic feasibility indicator.

Indicator	Criteria
NPV	NPV > 0
IRR	IRR > discount rate
PBP	PBP > project's lifetime

$$NPV = (\text{Annualized Revenue}) \left(\frac{P}{A}, r\%, n \right) \quad (4)$$

$$PBP = \frac{\text{Capital Cost}}{\text{Annualized income}} \quad (5)$$

A project is deemed feasible if all the indicators are fulfilled. In general, energy use for the generation of either heat or electricity is different; however, since electricity is more widely accepted, the LCOE parameter was analyzed in electricity form. However, from an economic standpoint, it is clear that heat and electricity have different potential users, so that the economic analysis included both.

3 Result and Discussion

3.1 Gasifier Performance

The gasification process can be optimized by varying the conditions inside the reactor. It was obtained that the LHV was increased by increasing the temperature in the reactor with maximum values at 900 °C of 6.89 MJ/Nm³ and CGE at 83%. The tar produced in the simulation was negligible. A high amount of tar could also be made from an uncontrolled reaction at the beginning and toward the end of the operation. The filter was designed to reduce tar using paddy waste such as biochar, rice straw, or rice husk [17]. Figure 5 shows that the gasifier system can be optimized by increasing the combustion zone temperature. This can be achieved by regenerating heat from the exhaust gas or using the secondary air intake [18].

For the experimental result, the temperature profile data was taken when testing for ER 0.18, 0.23, 0.27, and 0.31 on four thermocouples and the reactor temperature profiles were obtained at different equivalence ratios (Figure 6). The thermocouples were approximately located where the gasification process zones are: drying, pyrolysis, oxidation, and reduction. However, this cannot always be

used as a benchmark; even so, the temperature profile of each ER can be known by analyzing the temperature distribution that occurs.

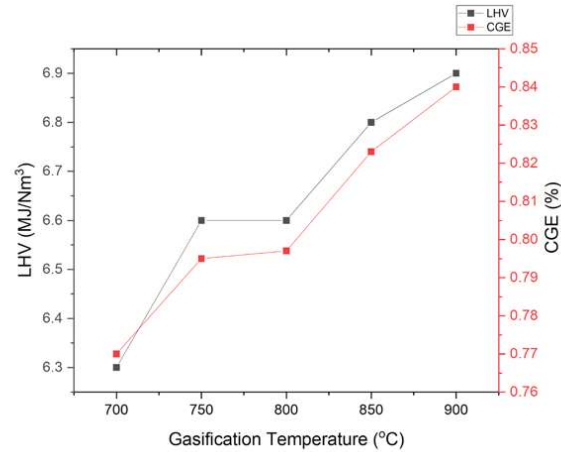


Figure 5 Relation of gasification temperature to LHV and CGE of the syngas.

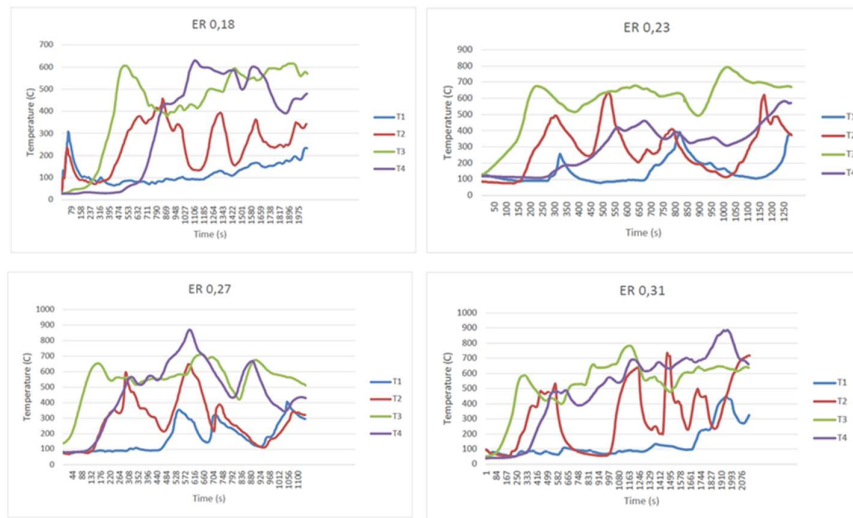


Figure 6 Reactor temperature profiles.

Figure 6 shows that the experimental gasifier temperature was lower than the simulation results, where the combustion zone temperature did not reach 1,000 °C, and the combustion zone did not reach 700 °C. This could be caused by

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several factors, namely the release of heat outside the system or the uneven temperature distribution in each reactor zone.

The percentage volume of the gas composition produced by the GC TCD test was calculated. The hydrogen trend shows an increase to the ER point of 0.27, with a highest value of 3.33%. There was a decrease in hydrogen at ER 0.31 to 2.75%. This is related to the hydrogen oxidation reaction, which increases so that the hydrogen content decreases; there is excess air that can react with hydrogen. It was found that ER 0.27 had a highest cold-gas efficiency of 17.94%. This is because at ER 0.27 there is the highest amount of H_2 and CO compared to other ERs. The gas composition of the gasification products can be seen in Figure 7.

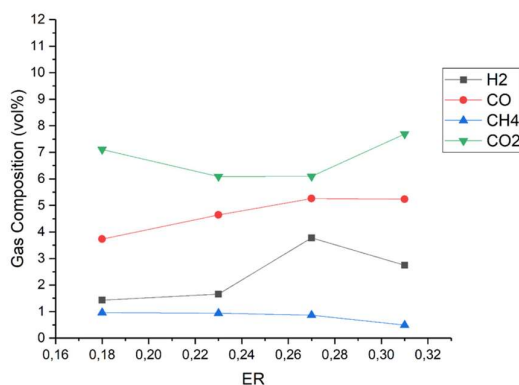


Figure 7 Syngas composition.

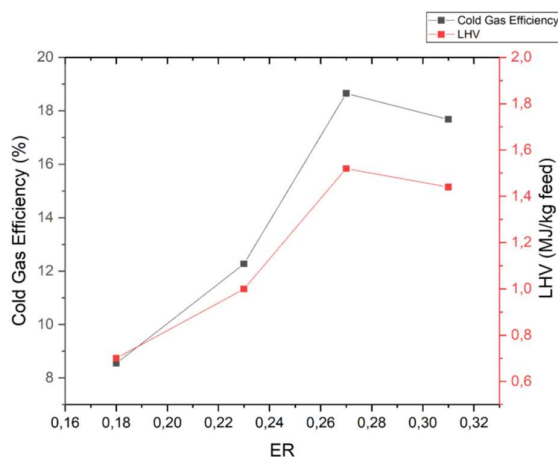


Figure 8 Syngas LHV and CGE values.

The result of the experiment was far lower than that of the simulation, which means that the experiment was not run properly. The leading factor was heat loss to the environment, making the conditions in the reactor unsustainable for gasification reactions. The gasification simulation was rerun with the same reactor condition as the experiment and an ER of 0.27. The result was syngas with an LHV of 1.94 MJ/kg, which is close to the 1.7 MJ/kg from the experiment (see Figure 8). This shows that the gasification process can still be improved by getting closer to the simulation model. Heat loss can be minimized by covering the reactor with an inductor sheath such as rock wool and increasing the gasifier's residence time.

Compared to other studies [19,20], the LHV from rice husk gasification was rather small. The optimum LHV and CGE were 3.13 MJ/Nm³ and 72.73% respectively. However, the LHV can be further increased by increasing the gasification temperature up to 6.89 MJ/Nm³, with CGE also increasing to 83.51%.

3.2 Economic Evaluation

The LCOE value of the gasifier was between 0.015 USD/kWh to 0.89 USD/kWh for electrical generation and 0.004 USD/kWh to 0.025/kWh for heat generation. The LCOE value for heat regeneration was much higher than for electricity because it does not need a generator. On the other hand, the LCOE value of electricity can be used as a parameter to compare the technology with other renewables. The result falls in the range of biomass LCOEs reported by IREA in 2020. The result indicates that in every case the gasifier is comparable to existing biomass technology. The biomass utilization technology also lies in relatively the same range as solar PV, making the technology suitable to be used side by side to reduce the LCOE value by 30 to 50%. Ejiofor, *et al.* [19] conducted a study on power generation using rice husk gasification and obtained an LCOE of 0.086 USD/kWh, which follows the case.

Figure 9 shows that the only feasible option for electrical generation is Case 4, where the rice husk is treated as waste material and biochar is used as an economic tool.

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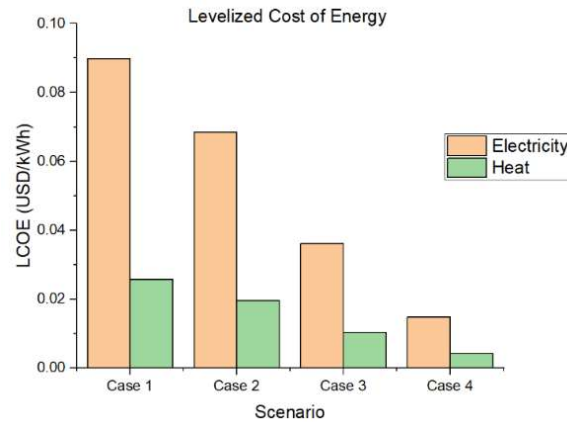


Figure 9 Levelized cost of energy of the gasifier system for each scenario.

In Table 6, Cases 1 and 2, where the fuel cost causes the NPV to be negative, which means the revenue is smaller than the cost, as can be seen at a B/C ratio below 1. However, this depends on the selling price of electricity from the national grid. The price used in this calculation was USD 0.05 per kWh, but the cost of national electricity varies. Stable housing is around USD 1, and one might say that the gasifier is feasible as a substitute for electricity usage [21]. The most profitable scenario is when the gasifier is used as waste treatment technology to produce electricity and yield valuable biochar. However, the most probable case so far is for the gasifier to be used by rice farmer communities to dry paddy while turning the rice husk waste into biochar that can be used as fertilizer in the next season. The best use of the gasifier is for heat generation, such as cooking or drying paddy. Heat generation also cuts the manufacturing cost, since fewer components are required; however, a more elaborated study needs to be done to optimize the gasifier design for this use case.

Table 6 Feasibility result.

Parameters	Case 1	Case 2	Case 3	Case 4
NPV (USD)	-	-	46,602,423	119,276,813
B/C	0.56	0.79	1.37	1.94
PBP (Years)	-	-	18.07	7.06
	Not feasible	Not feasible	Not feasible	Feasible

The power output may decrease or increase depending on the efficiency of the gasification process, which can be seen in Table 7. However, the design will not produce more than 20 kW due to design constraints. Increasing the gasifier volume by 50% is a simple way to double the IRR. This will also mean a higher

feed rate, which benefits the project since rice husk is considered waste and biochar can be sold for money. However, the real limiting design factor is the electricity generator; since the project aims to use an existing electricity generator with a fixed amount of power, modifying the generator to suit the gasifier output will surely be a challenge. It is also important to note that the gasifier's efficiency may drop over time or if the operation is not handled properly. Hence, the O&M activity must be controlled correctly to ensure that the project runs smoothly as intended.

Table 7 Sensitivity analysis of gasification process.

	Power Output	NPV (IDR)	IRR	PBP (Years)	B/C	ROI
25%	5	(207,614,255)	-11%	-11,431	0,746	-25%
50%	10	(37,622,843)	1%	67,935	1,023	2%
75%	15	132.368.569	12%	8,553	1,299	30%
100%	20	302.359.982	23%	4,564	1,575	58%
125%	25	472.351.395	33%	3,112	1,851	85%
150%	30	642.342.808	44%	2,361	2,128	113%
175%	35	812.334.220	54%	1,902	2,404	140%

4 Conclusion

In this study, a mobile rice husk gasifier was assessed on performance and feasibility. The working parameters were a feed of 15 kg/hr, ambient conditions of 25 °C and 1 atm. Gasification simulation with Aspen Plus showed a decline in the amount of H₂ from 29.31% to 21.25% and CH₄ from 0.67% to 0.10%, while CO increased from 22.36% to 29.11% when ER was varied from 0.2 to 0.4. The LHV was at its maximum at ER 0.25 with 6.47 MJ/Nm³. The LHV could be further increased by increasing the gasification temperature up to 6.89 MJ/Nm³, with CGE also increasing from 77.52% to 83.51%. However, the experiment only managed to get an LHV of 18% due to an insufficient temperature zone in the reactor. The simulation was validated using the temperature profile from the experiment, and an LHV of 19% was achieved.

According to the economic analysis, the levelized cost of energy of the gasifier system ranges from 0.015 to 0.89 USD/kWh for electricity generation and 0.004 to 0.025/kWh for heat generation. The optimum case for both energy and heat generation is the same: rice husk is treated as pure waste while biochar is sold as fertilizer. Based on NPV, B/C, and PBP, the gasifier is economically feasible as waste-to-energy technology. The most profitable use is for rice farmers to utilize the system for heat generation. Subsequent development of the mobile rice husk gasifier should be focused on increasing the power output, which can be achieved by enlarging the reactor or simply using fuel with a higher heating value, such as rice husk pellets.

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Acknowledgment

The authors thank the Indonesia Endowment Fund of Education (LPDP), which provided RISPRO LPDP grant [number 510/PKS/WR III/UI/2019 and PRJ-34/LPDP/2019] and JASTIP-NET FY 2020-2021.

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