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Municipal Solid Waste Potential for Indonesian Electrical Energy Sharing: Process Simulation Study

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Abstract. Indonesia's growing energy demand and increasing municipal solid waste (MSW), projected to reach 48.19 million tons by 2027, present significant challenges and opportunities for sustainable energy solutions. This study investigates the conversion of MSW to electricity using validated Aspen Plus® simulations calibrated against real-world operations with one MSW based power plant located in Indonesia. The study evaluated four technologies—air gasification, steam gasification, plasma gasification, and incineration—to assess their electricity generation potential and pollutant emissions. Gasification technologies outperformed incineration, generating 15–27 MW of electricity, with gas engines demonstrating superior efficiency compared to steam turbines due to fewer energy conversion stages. Air gasification increased electricity production with reduced air input but resulted in elevated pollutant emissions, including NH_3 (up to 8 ppm), H_2S (up to 210 ppm), and HCl (up to 1052 ppm). Steam gasification enhanced hydrogen production at optimal steam levels; however, excessive steam inputs reduced efficiency and increased pollutant concentrations, such as NH_3 (14 ppm), H_2S (369 ppm), and HCl (1846 ppm). Plasma gasification maintained stable CO_2 concentrations (~14% vol) but experienced diminishing electricity returns with higher heat inputs. This study also highlights the inefficiency of incineration technology since it produced lower NH_3 and H_2S emissions but notable levels of NO_x, SO_x, and HCl, emphasizing the importance of advanced emission control systems. This study provides valuable insights for optimizing waste-to-energy processes, supporting industrial adoption, and informing sustainable waste management strategies to enhance Indonesia's energy security and environmental sustainability.

Keywords: Gasification, Incineration, Municipal Solid Waste, Process Simulation, Waste-to-Energy

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INTRODUCTION

Energy consumption is critical to economic growth, technological advancement, and improved living standards worldwide. As the global population continues to expand, so does the energy demand. However, this growth is not uniform across countries, and each nation faces unique challenges in meeting its energy needs. In recent years, global energy consumption has exhibited a steady upward trajectory, albeit with variations in growth rates. The world's total energy consumption has been increasing at an average annual rate of approximately 1% to 2% ("Indonesia: Energy Country Profile - Our World in Data," 2021). This rise is driven by urbanization, industrialization, and technological advancements. As societies become more interconnected and reliant on energy-intensive activities, the pressure to find sustainable energy sources becomes even more pronounced.

As a populous and rapidly developing nation, Indonesia plays a significant role in the global energy landscape. Its energy consumption has grown substantially, driven by economic expansion and rising living standards. Notably, Indonesia's electricity consumption increased by 6.15% in 2022, reflecting the recovery of economic activities after the COVID-19 pandemic (Lolla *et al.*, 2021). However, this growth also poses challenges related to energy security, environmental impact, and resource availability. These include a heavy reliance on fossil fuels (particularly coal), inadequate infrastructure for renewable energy integration, and the need to balance economic growth with environmental sustainability.

Indonesia's energy sector currently contributes significantly to greenhouse gas (GHG) emissions, with coal being the dominant source. There were 81 Giga Watts of installed electric generation capacity at the end of 2022 ("Indonesia - Energy," 2024). Of this, PT Perusahaan Listrik Negara (PLN), the state-owned electricity firm, generated 48.04 GW (60.7%), followed by independent power producers (20.18 GW; 26.5%); operating permit holders (5.4%); commercial power utilities (3.58 GW; 5.1%); and the government (55 MW; 0.01%) ("Indonesia - Energy," 2024). According to the recently released National Electric Generation Plan for 2021–2030 (RUPTL), Indonesia's power demand is expected to increase by 4.9% anually. RUPTL projects that 94.1 million consumers will demand 445 terawatt hours (TWh) of electricity by 2030 ("Listrik untuk Kehidupan yang Lebih Baik - PT PLN (Persero)," 2021).

According to the Institute for Essential Services Reform (IESR), Indonesia's greenhouse gas emission reduction targets, as outlined in its Nationally Determined Contributions (NDCs), fall short of the Paris Agreement's ambition to limit global temperature rise to 1.5°C. The unconditional target aims for a 29% to 31.89% reduction by 2030, while the conditional target (with international assistance) increases it to 41% to 43.2% ("Indonesia's Energy Transformation to Zero Emission - IESR," 2023). However, these targets do not align with the urgency of climate change impacts. To achieve compatibility, Indonesia must accelerate its transition to renewable energy sources. The national energy plan sets an ambitious renewable energy target of a 23% contribution to Indonesia's energy mix by 2025, ten percentage points higher than the current 13%. By optimizing this potential, Indonesia can sustainably meet its energy needs achieve zero emissions by 2050. The government's commitment to reducing fossil fuel dependency and promoting renewables is crucial for a greener and more resilient future.

In addition, with its burgeoning population and rapid urbanization, Indonesia grapples with managing municipal solid waste (MSW). The major sources of MSW include residential areas, commercial establishments, and public spaces. The prevailing disposal methods—landfilling and incineration—have significant environmental and social consequences. However, beneath this waste lies a hidden resource waiting to be harnessed. Recent studies reveal that Indonesia's MSW holds immense energy potential. Based on its dry weight of approximately 4530.42 tons per year, MSW could yield around 21,798.98 MWh or 2.49 MW of electrical power ("Waste-to-energy (MSW) in-depth - U.S. Energy Information Administration (EIA)," 2024). This untapped resource can contribute significantly to Indonesia's energy mix, reduce reliance on fossil fuels, and mitigate greenhouse gas emissions.

The potential of MSW potential to electricity generation in Indonesia has been highlighted by several previous researchers (Anshar *et al.*, 2014; Mustafa *et al.*, 2022). Recent Life Cycle Assessment (LCA) studies demonstrate that utilizing MSW for electricity generation can significantly reduce GHG emissions compared to traditional landfill disposal, highlighting its potential as a sustainable energy alternative (Astrup *et al.*, 2015; Dong *et al.*, 2018). Region scale observations have been presented by previous works (Qonitan *et al.*, 2021; Sudibyo *et al.*, 2017b; Sukarni, 2016), which highlighted the important physical and chemical parameters to evaluate the feasibility of MSW conversion to electricity. High moisture contents of MSW from several regions in Indonesia were underlined from previous studies, which could potentially dictate the technological selection since it affects the calorific values and emitted pollutants. Several studies also emphasize the profitability analysis of electricity generation from MSW, which concluded promising economic feasibility by including tipping fee in the WtE plant operation (Azis *et al.*, 2021; Sudibyo *et al.*, 2017a).

Despite growing interest in waste-to-energy (WtE) technologies, several critical gaps persist in understanding municipal solid waste (MSW) potential for electricity generation in Indonesia. Several limitations are still found based on the literature review, i.e., accurate and comprehensive data on MSW composition, calorific values, and seasonal variations from all regions in Indonesia; comparative assessment of conversion technologies; and process optimization of WtE to generate optimum electricity power with less emission. Sudibyo *et al.* (Sudibyo *et al.*, 2017a) has presented a comparison of several technical aspects in WtE from MSW using various technologies, i.e., incineration, air gasification, and plasma gasification. However, the presented method has not thoroughly evaluated the process optimization opportunity to maximize the net power while minimizing several harmful pollutants, i.e., NO_x, SO_x, and CO_2.

The presented study encompasses a comprehensive analysis of potential and characteristics of municipal solid waste for electricity generation in Indonesia. It delves into the technological aspects and performs a thorough emission assessment to ensure environmental compliance and efficiency. Furthermore, the study focuses on process optimization to maximize electricity generation from waste, considering factors such as energy recovery and operational parameters. Finally, it offers recommendations for advancing this technology. It provides an outlook on its future implementation, stressing the importance of policy support, community engagement, and technological innovation to realize the full potential of waste-to-electricity conversion in Indonesia. This holistic approach aims to contribute to the country's energy security while addressing waste management challenges.

METHODOLOGY

MSW Trends and Characteristics Data Collection

This study uses the National Waste Management Information System (SIPSN) to collect and analyze Municipal Solid Waste (MSW) data in Indonesia ("SIPSN - Sistem Informasi Pengelolaan Sampah Nasional," 2024). Developed to address the need for a comprehensive waste management system, SIPSN integrates advanced technology and extensive metrics, providing data on waste generation, recycling, composition, and processing efficiency. Rigorous validation processes, including audits and updates, ensure accuracy, while statistical methods fill gaps for non-reporting areas, creating a robust and comprehensive national waste profile.

Waste characteristics were analyzed to MSW sample from the Yogyakarta Province, Indonesia landfill area. The waste was analyzed using several methods, including proximate analysis, ultimate analysis, and calorific value using a bomb calorimeter (Nugraha *et al.*, 2020). This determines the waste's ability to be processed through thermal treatment (Habibi *et al.*, 2024). Proximate analysis waste analysis aims to determine the moisture content, volatile matter, ash, and fixed carbon. These characteristics were obtained from gravimetric analysis with stoichiometric calculations. The ultimate analysis aims to analyze the percentage of carbon, hydrogen, oxygen, nitrogen, and sulfur elements. Each component of waste, such as organic matter, paper, plastic, and so on, has different percentages of these elements. Meanwhile, the calorific value was generally determined using a bomb calorimeter.

Based on data from the National Waste Management Information System (SIPSN) of the Ministry of Environment and Forestry (KLHK), Indonesia produced 35.93 million tons of waste in 2022, or around 97 thousand tons/day. The daily waste generation rate data are presented in Figure 1 which summarizes

Fig. 1: Daily waste generation rate in Indonesia's provinces in 2022

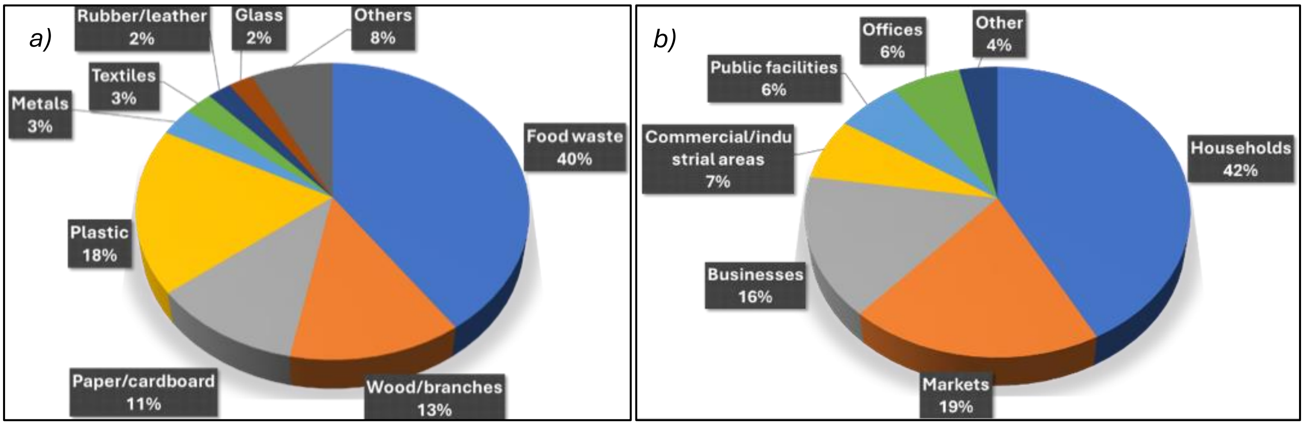

Fig. 2: a) Composition of Indonesian's MSW (b) MSW origin

the total waste generation rate of each province in Indonesia during 2022. Central Java was the largest waste producer at the provincial level, with 5.76 million tons annually or 16.03% of the national waste generation in 2022. East Java ranks second with 4.95 million tons, and West Java ranks third with 4.89 million tons of waste generated. Meanwhile, DKI Jakarta ranks fourth, producing 3.11 million tons of waste yearly.

The MSW characterization needs to be performed to determine the electricity generation potential from MSW. Based on its types, the majority of national waste generation in 2022 consists of food waste, accounting for 40.7% of the total. Other compositions include plastic waste 18%, wood/branches 13%, paper/cardboard 11.3%, metals 3%, textiles 2.6%, glass 2.2%, rubber/leather 2.1%, and other types of waste 7.1%, as depicted in Figure 2a. The majority of national waste generation, amounting to 42%, originates from households as depicted in Figure 2b. Other sources include traditional markets 19%, businesses 16%, commercial/industrial areas 7%, public facilities 6%, offices 6%, and other sources 4%. The distribution of waste composition of the five largest waste producers in Indonesia was summarized in Table 1.

Table 1. Waste composition of five largest provinces in terms of waste production in 2022

Composition	% mass				
	Central Java	East Java	West Java	Jakarta	Banten
Food Waste	41.87	49.20	41.62	25.50	44.78
Wood/Branches	11.34	10.09	12.19	31.59	11.40
Paper/Cardboard	10.45	10.14	10.74	12.17	11.66
Plastic	18.07	16.72	18.16	19.18	17.86
Textiles	2.97	2.36	3.05	0.74	2.27
Rubber/Leather	1.74	1.46	1.31	0.44	1.47
Metals	3.43	2.00	2.33	1.27	2.56
Glass	2.75	1.64	2.69	2.03	2.44
Others	7.38	6.39	7.91	7.08	5.56

Based on the data in Table 1, it was known that organic materials such as food waste, wood/branches, paper, and cardboard have the highest content in the range of 60-65%. In Central Java, East Java, and West Java, the dominant organic material comes from food waste with a content above 40%. Meanwhile, in DKI Jakarta, food waste and wood/branches have almost balanced amounts. Plastic waste composition in each region has a content of 16-20%.

The presented data, derived from SIPSN and supplemented by detailed waste characterization analyses, provides a robust foundation for forecasting the potential of Municipal Solid Waste (MSW) to generate electricity. By offering insights into waste composition, regional variations, and calorific properties, this methodology supports targeted strategies for optimizing waste-to-energy conversion technologies in Indonesia.

Technological Assessment

The analysis of Municipal Solid Waste (MSW) technological assessment to electricity generation incorporates a critical evaluation of emissions alongside the reliability and efficiency of various technologies. Thermochemical conversion was considered the most widely used method in solid fuel decomposition (Nugraha *et al.*, 2021). Based on numerous previous studies and benchmarks of several established industries in Indonesia, the most reliable technologies for converting MSW to electricity via thermochemical conversion are divided into incineration and gasification (Kumar and Samadder, 2017; Murphy and McKeogh, 2004; Varjani *et al.*, 2022). In summary, incineration directly burns MSW, while gasification converts it into syngas for energy production. The assessment is also conducted for electricity generation via the most common technologies, i.e., steam turbines and gas engines (Ogunjuyigbe *et al.*, 2017; Rajaeifar *et al.*, 2017). The current work evaluated these technologies' operational reliability, efficiency, and potential emissions.

In summary, the MSW conversion to electricity generation was divided into four main processes, including:

1. Feed preparation: including size reduction, separation of various MSW components, e.g., organic, glass, metal, etc., and moisture reduction.
2. Thermochemical conversion: conversion of solid fuel into heat for incinerator process and syngas for gasification process.
3. Gas cleaning: reduction of emission and gas conditioning before entering the electricity generation section.
4. Electricity generation: conversion of hot gases or syngas into kinetic energy form to operate a turbine or engine.

Process Simulation and Optimization

The process simulation was conducted using process simulation software Aspen Plus v14® software (AspenTech, USA), which has been proven to be used to simulate the WtE from solid fuel (Aghaalikhani *et al.*, 2019; Mehdi *et al.*, 2023). The entire Waste-to-Energy (WtE) process starts from raw materials. The simulated WtE process technology involves incineration, gasification, and plasma gasification processes. The simulation aims to determine the overall heat and mass balance and the energy potential that can be generated for each feedstock using several alternative waste-to-energy processing technologies. The simulation process stages can also calculate the pollutants formed from each waste-to-energy processing method. Several simulation stages of MSW conversion to electricity and the utilized method in the simulation were described as follows:

Solid Waste Feed using Non-Conventional Properties Method

Non-conventional methods were employed due to the complexity of feedstocks that cannot be approached with pure chemical compounds. The definition of non-conventional was done by inputting the proximate and ultimate compositions obtained from the analysis results. Subsequently, solid' physical and chemical properties can be calculated through the component attributes DCOALIGHT and HCOALGEN in Aspen Plus.

Solid Waste Drying

The feedstock's drying process, i.e., H_2O (l) → H_2O (g), was modeled using the RStoic unit block. The proximate analysis results obtain the amount of water dried in this stage. The main objective of this stage is to determine the total energy required for the drying process. After this stage, it was assumed that water would be completely separated before being introduced to a gasifier or incinerator.

Solid Waste Decomposition

In this stage, the feedstock undergoes decomposition into its constituent compounds. The decomposition products of the feedstock are determined to include solid carbon, hydrogen, nitrogen, oxygen, sulfur, chlorine, and ash. The composition of the decomposition products is calculated based on the ultimate analysis results using a calculator block. In this stage, the ash content in the feedstock will be separated from the mixture before entering the gasifier or incinerator.

Gasification of Solid Waste

The gasification reaction involves reacting the gasifying agent (air or steam) with the decomposed products of the feedstock. The gasification reaction is modeled using the RGibbs block in Aspen Plus. The operating principle of the RGibbs block is to minimize Gibbs free energy. Inputs to the RGibbs block include the composition of the entering compounds, a list of desired outgoing compounds, and operating conditions within the reactor. The RGibbs block will calculate the thermodynamic equilibrium that occurs. It will produce calculations in the form of operating conditions (temperature and pressure) and composition in the outgoing stream of the RGibbs block.

Incineration of Solid Waste

The incineration reaction was approximated using the RGibbs block. This incineration process was carried out by adding air until complete combustion occurs in the reactor. Complete combustion was marked by 100% conversion of the decomposition products. The condition of complete combustion was achieved by adjusting the amount of input air. The input air was adjusted at the air inlet stream, and the excess air was maintained at 20%.

Electricity Generation

Thermal energy conversion in a steam turbine system was performed by heating the steam using the gas exiting the incineration reactor, resulting in an evaporation process. The produced steam was then expanded in a turbine with an isentropic efficiency of 72%. Thermal energy will be converted into mechanical energy.

Meanwhile, for gas engine electricity generation, the synthesis gas resulting from gasification was burned in a gas engine to produce thermal energy. The conversion from thermal to electrical energy was achieved by adding a machine efficiency factor of 38%. The gas engine operates with an input temperature of 50°C and an output temperature of 500°C. The synthesis gas would be burned with 20% excess air. Gas engine modeling was performed using the RStoic block in Aspen Plus.

The Calculator blocks in the simulation automate key processes to ensure accuracy and optimization. The drying calculator block supplies input to separate moisture from feedstock, while the decomposition calculator block breaks feedstock into elemental components (C, H, O, N, S) based on ultimate analysis. The airflow calculator block maintains the air-to-fuel ratio with specified excess air, and the efficiency calculator block calculates net electrical power using thermal-to-electricity efficiency. Lastly, the emission calculator block quantifies gas emissions to evaluate environmental impact, streamlining the simulation for efficient process management.

To maintain simulation accuracy, the simulation validation was performed using the MSW-to-electricity plant operation at one of MSW power plant based in Indonesia. This facility has a capacity of 400 tons per day, with the exhaust gas temperature of the gas engine generator recorded at 525°C, producing approximately 8 MW of electricity.

The optimization of operating conditions was conducted in the incinerator and gasifier. A sensitivity analysis was performed to determine the effect of operating conditions altering on net electricity generation and emissions profile. The electricity presented in this study represents the net electricity production, calculated after subtracting the energy consumed for fluid pumping in the electricity generation section and the energy required for the plasma gasification process in the plasma gasifier. An incinerator's operating condition parameters were explored for air/fuel ratio. The optimum air flow rate was evaluated since a lack of air could potentially result in the unburnt fuel. On the contrary, an excessive amount of air could lower the incinerator temperature due to massive amounts of inert nitrogen. The differences in temperature and combustion completeness could directly affect the emission generated (Amulen *et al.*, 2022)..

In the gasification process, three different technologies will be evaluated, i.e., plasma gasification and air gasification using a downdraft furnace (Mehdi *et al.*, 2023) and steam gasification using a dual fluidized bed (Aghaalikhani *et al.*, 2019). The gasifying agent flow rate was adjusted to assess the net electricity generated and emission profile. Some pollutants generated from gasification will be separated into the simplified gas cleaning units before entering the electricity generation section. Some operating conditions were kept constant for all technology simulations to maintain accurate comparison, which was summarized in Table 2. The exhaust gas temperature in the gas engine system was higher than the validation case to accommodate the design conditions while maintaining high efficiency.

Table 2. Operating conditions used in all simulations

Parameter	Value	Unit
MSW input	400	ton/day
Steam temperature	400	°C
Steam pressure	39	Bar
Excess air in gas engine	20	%
Exhaust gas temperature in gas engine system	350	°C
Turbine discharge pressure	0.5	Bar

This study conducted detailed observations to characterize pollutants generated from gasifier and incineration units. The findings provide valuable insights for the industrial community, providing a foundation for selecting appropriate gas-cleaning processes before entering the electricity generation section. Therefore, chlorine is added proportionally in the ultimate analysis based on data from previous work (Ma *et al.*, 2020). The addition of Cl in the ultimate analysis allows for the prediction of chlorine-based pollutants, e.g., hydrogen chloride (HCl). The other potential pollutants such as NH_3, H_2S, CO, CO_2, NO_x, and SO_x were also included in the analysis since it has been proven to be the major pollutant from the gasification and incineration process (Abdoulmoumine *et al.*, 2015).

RESULTS AND DISCUSSION

MSW Potential for Electricity Generation

Municipal Solid Waste (MSW) is a promising resource for addressing Indonesia's growing energy demands through waste-to-energy (WtE) initiatives. As explained in the methodology section, Indonesia generated 35.93 million tons of waste in 2022, equivalent to approximately 97,000 tons per day, with annual increases projected due to population growth and urbanization. This growing waste volume, with significant calorific potential comparable to low-rank coal, presents a valuable opportunity for electricity generation. The consistent upward trend in waste generation and its energy potential underscores the necessity of strategic WtE implementation tailored to regional waste characteristics and energy needs.

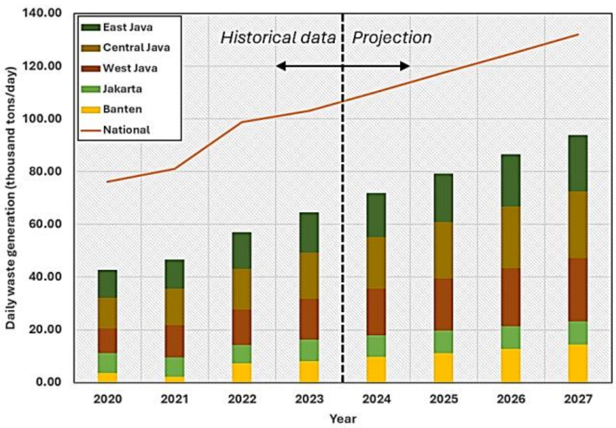

Fig. 3: MSW generation trend and projection and distribution on five largest waste producers

Figure 3 summarizes the historical data of daily MSW generation from 2020 to 2023. The generation projection was also performed to highlight the MSW generation trend up to 2027. The forecasting of MSW generation was based on the linearization of the previous MSW generation trends observed over the past four years. This increasing trend was attributed to population growth. In 2025, the estimated population of Indonesia is projected to be 284.83 million people. The waste generation in Indonesia in 2027 is estimated to be 48.19 million tons, an increase of 46% compared to 2020. This highlights the potential of MSW in terms of total availability, which can be used to forecast its utilization for electricity generation.

The individual assessment of each type of waste was then performed to analyze its chemical composition further. The ultimate, proximate, and heat content analysis was conducted on the sample of MSW from Yogyakarta's landfill. Before the analysis, the sample was divided into nine different, as categorized in Table 1. Based on the individual characterization result, the calculated MSW chemical composition is then performed using MSW regional and national data basis in SIPSN. Table 3 summarizes the calculated chemical properties data regionally and nationally.

Based on Table 3, it can be concluded that Indonesia's MSW contains significant amounts of water content. This highlights the efforts needed to eliminate moisture before entering the main gasification or incinerator reactor. The chemical properties of MSW in Table 3 emphasize a high uniform distribution characteristic throughout Indonesia's province. The MSW's heat content indicates the calorific value of MSW in Indonesia is equal to low-rank coal, lignite, which has an HHV range of around 16 to 24 MJ/kg.

Table 3. The estimated chemical characteristics of MSW in Indonesia

Region	Wet Basis Proximate (% mass)				Ultimate Analysis (% mass)					HHV (MJ/kg)	LHV (MJ/kg)
	Water Content	Volatile Matter	Ash	Fixed Carbon	C	H	N	S	O		
Indonesia	57.40	30.77	6.46	5.37	53.85	7.23	1.50	0.23	37.19	17.86	11.72
Jakarta	54.88	33.28	6.32	5.52	51.49	6.85	1.33	0.23	39.05	18.63	12.44
East Java	59.53	28.45	6.50	5.52	52.88	7.19	1.57	0.23	38.13	18.34	12.15
West Java	57.68	30.48	6.48	5.37	52.96	7.17	1.52	0.24	38.13	18.50	12.30
Bali	54.87	32.96	6.20	5.97	51.31	6.74	1.40	0.22	40.32	17.74	11.61
North Sumatra	56.56	31.47	6.49	5.47	51.41	6.97	1.46	0.24	39.93	17.96	11.81
West Sumatra	58.78	29.25	6.49	5.47	52.86	7.17	1.50	0.23	38.24	18.29	12.11
Lampung	58.70	29.43	6.41	5.47	53.74	7.25	1.59	0.24	37.19	18.98	15.21
South Sulawesi	58.44	29.42	6.50	5.64	52.16	7.06	1.49	0.23	39.07	17.51	11.41
Central Java	57.67	30.50	6.50	5.32	53.17	7.20	1.52	0.24	37.88	18.37	12.18
Banten	51.37	39.42	7.62	1.59	53.08	7.19	1.52	0.23	37.99	18.35	14.58

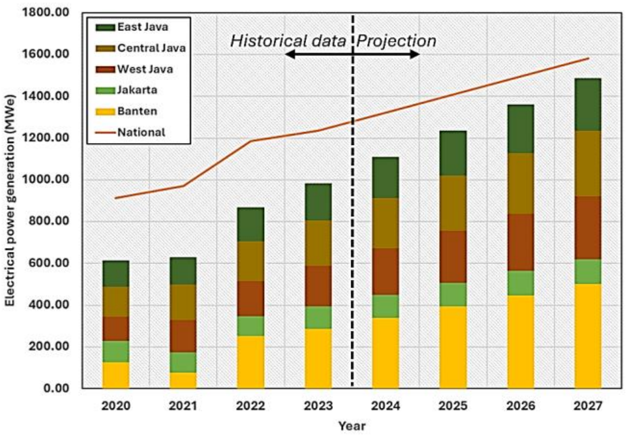

Fig. 3: Electricity power potential trend and projection from MSW

Figure 4 depicts the historical data (from 2020 to 2023) and the projection (up to 2027) of electrical power generation (in MWe) from MSW across several regions in Indonesia. The electricity generation calculation is formulated using LHV data in Table 3 with 25% energy conversion efficiency assumptions. Notably, there is a steady upward trend in electricity generation over the years. This trend reflects the growing emphasis on sustainable energy solutions and the utilization of MSW as a valuable resource. The consistent rise of the historical and projection data promises the potential for waste-to-energy (WtE) initiatives to be executed shortly. Java, the most populous island, contributes significantly to electricity generation from MSW. Its high population density results in substantial waste production. The regional variations emphasize the importance of context-specific waste management strategies. Tailoring approaches to each province's unique characteristics are crucial.

Process Optimization of MSW to WtE

The process optimization of MSW conversion to energy was conducted using process simulation software Aspen Plus v14®. The simulation has been validated against the real-world MSW-to-electricity operation, which records an electricity production of 8 MW using 400 tonnes/day of MSW. The simulation predicts an electricity output of approximately 8.036 MW under the plant's operating conditions, assuming a thermal-to-electricity efficiency of 31%. This low efficiency is attributed to the current operating conditions, as the system has been running for approximately one year without significant maintenance during the operation.

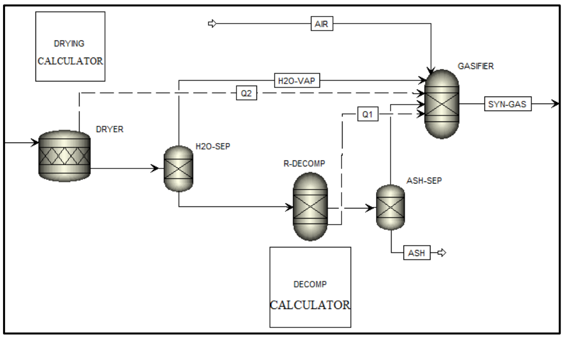

Fig. 5: Simulation flowsheet of air gasification and incineration

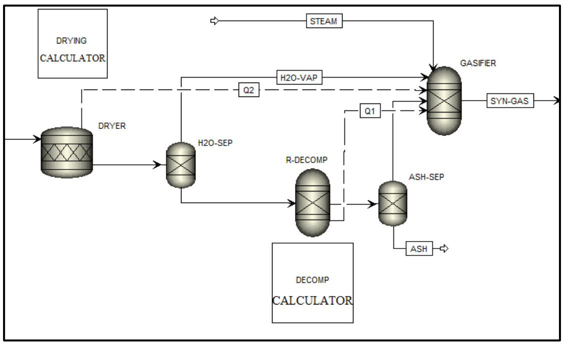

Fig. 6: Simulation flowsheet of steam gasification

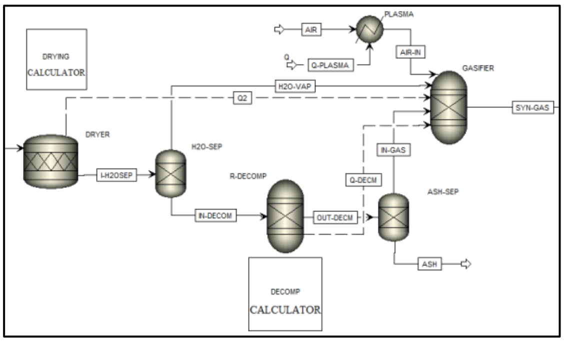

Fig. 7: Simulation flowsheet of plasma gasification

Four different technology alternatives were evaluated to give a comprehensive overview of electricity potential and emission production during WtE conversion, i.e., air gasification, steam gasification, plasma gasification, and incineration. The process flowsheet of each of the four different technologies simulations is depicted in Figure 5 to 7. Moreover, the utilization of steam turbines and gas engine were also compared to find the most optimum net electricity production. The simulation flowsheets of electricity generation from syngas for gasification and exhaust gas for incineration, are depicted in Figure 8.

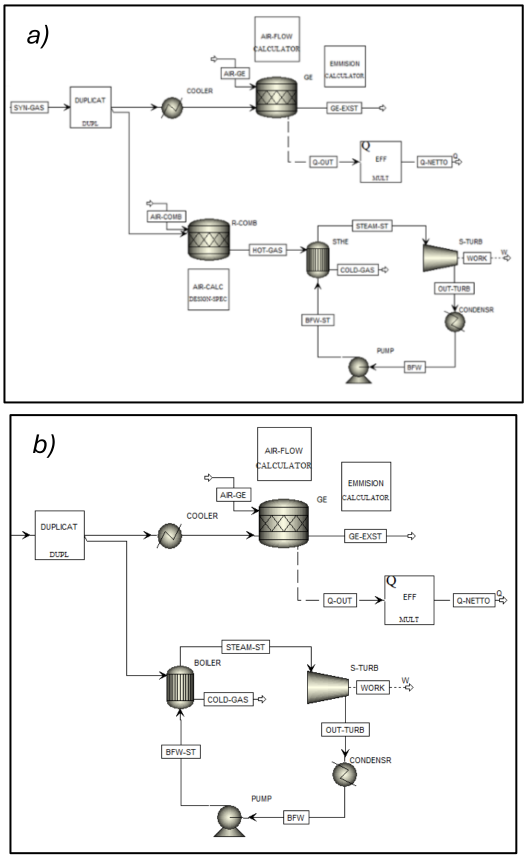

Fig. 8: Simulation electricity generation (a) from syngas produced in gasifier and (b) from exhaust gas produced in incinerator

Simulation is conducted with biomass input to moisture content removal systems in R-DRYER and H_2O-SEP. The water-free biomass is then continued to the R-DECOMP block for further decomposition of biomass into its elemental composition based on ultimate analysis. The ash content is removed in ASH-SEP, and the remaining component is fed to the GASIFIER block. The syngas produced in the Gibbs reactor GASIFIER block is duplicated and distributed to the steam turbine and gas engine system as depicted in Figure 8a. The differences between gasification technologies are whether the GASIFIER block used were air, steam, or direct heat in plasma gasification. In the incineration process, the air is fed to excess to ensure complete hydrocarbon combustion. Therefore, the same system can be used for air gasification and incineration. As shown in Figure 8b, the hot exhaust gas from the incinerator is then fed directly to the boiler for the steam generation process and/or burnt in a gas engine. This highlights the difference between steam turbine systems for gasification and incineration processes.

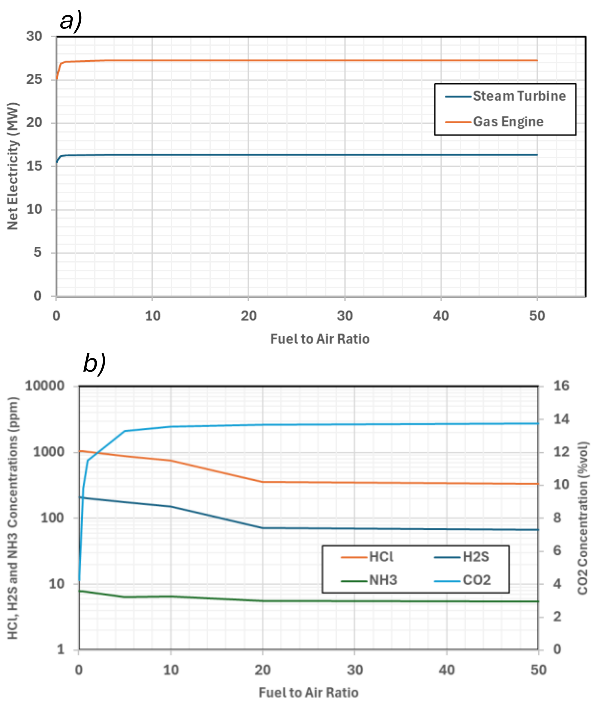

Fig. 9: Sensitivity analysis result of (a) net electricity production and (b) pollutant concentration in air gasification and system as function of fuel to air ratio

Several operating conditions were explored to determine the profile of net electricity production and pollutant concentrations. Figure 9 to 12 summarized the sensitivity analysis results for four different MSW to electricity conversion technologies. Various fuel-to-air ratio levels were evaluated in air gasification and incineration systems, while various fuel-to-steam ratio levels were assessed in steam gasification systems. In the plasma gasification system, the heat supplied in the gasifier was analyzed to generate net electricity and pollutant concentrations profile. Pollutant concentrations are analyzed at the outlet of the gasifier or incinerator, highlighting the mitigation strategies for gas cleaning after the main reactor.

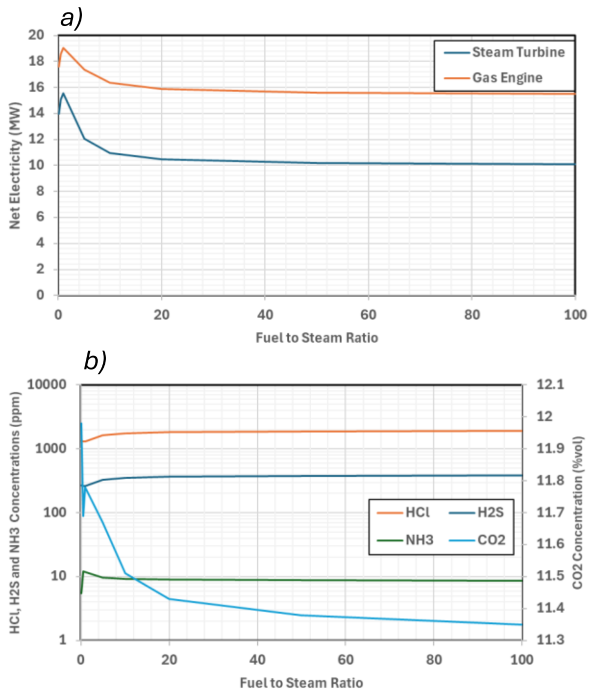

Fig. 10: Sensitivity analysis result of (a) net electricity production and (b) pollutant concentration in steam gasification system as function of fuel to steam ratio

Based on the simulation results presented in Figure 9 to 12, the analysis highlights that gasification technologies provide superior performance compared to incineration in terms of electricity production from 400 tons/day of municipal solid waste (MSW). Specifically, the maximum net electricity production from air, steam, and plasma gasification varied between 15 MW to 27 MW using gas engines. This significant difference underlines the efficiency of gasification, which can extract more energy from MSW by converting it into syngas, subsequently burned in a gas engine with fewer energy losses. Gasification processes, combined with gas engines, exhibit fewer energy conversion stages than steam turbines, which operate through multiple steps of converting syngas into hot gas, steam, and electricity. With fewer conversion stages, the gas engine directly converts syngas to electricity, thus achieving higher efficiency.

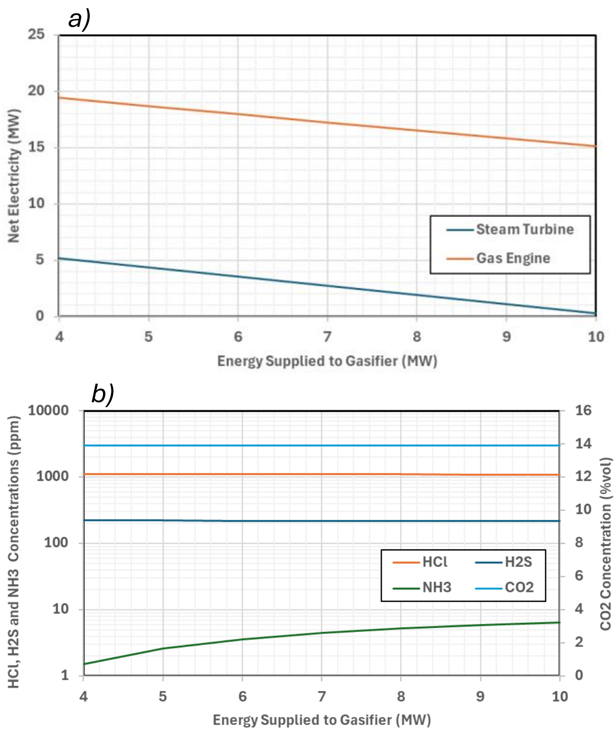

Fig. 11: Sensitivity analysis result of (a) net electricity production and (b) pollutant concentration in plasma gasification system as function of energy supplied to gasifier

In air gasification systems, the results illustrate that reducing the air input increases net electricity output due to decreased combustion of hydrocarbons within the gasifier. This optimization generates greater heat from syngas combustion within the gas engine, increasing the net electricity production. This can be addressed because when more air is used, the nitrogen present reduces the overall temperature in the gasifier, lowering syngas heat content and electricity generation efficiency. Moreover, higher gasifier temperatures favor the production of hydrogen (H_2), a gas with higher energy potential compared to other hydrocarbons such as methane (CH_4) and ethylene (C_2H_4). In addition, the CO_2 concentration was observed to increase, reaching up to 13.77% by volume, with the addition of fuel percentage to the system. Nevertheless, decreasing the fuel-to-air ratio also leads to higher pollutant concentrations, specifically NH_3, H_2S, and HCl. With a higher fuel mass flow rate, pollutant concentrations in syngas can reach up to 8 ppm for NH_3, 210 ppm for H_2S, and 1052 ppm for HCl.

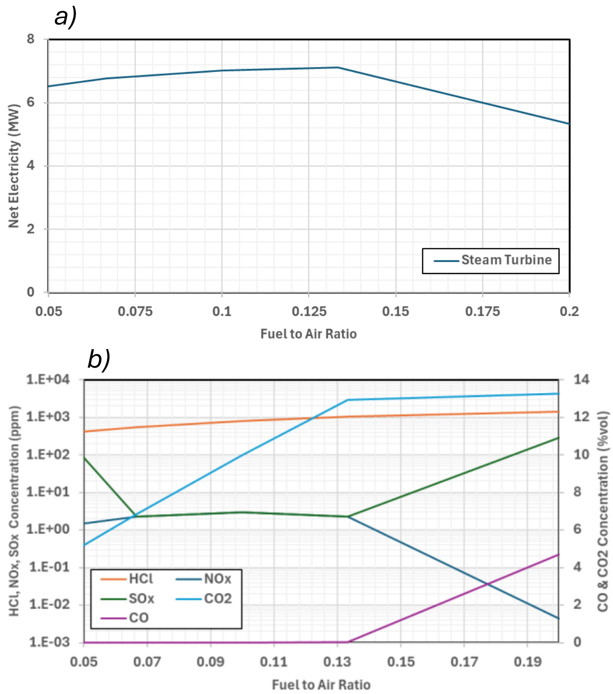

Fig. 12: Sensitivity analysis result of (a) net electricity production and (b) pollutant concentration in incineration system as function of fuel to air ratio

A different trend is observed in steam gasification systems, where increasing the fuel-to-steam ratio initially increases H_2

production, which is beneficial for electricity generation. However, excess steam results in a significant drop in gasifier temperature and an increase in moisture content within the syngas. Higher moisture content reduces the syngas heating value, leading to lower net electricity production. Increasing the fuel-to-steam ratio also leads to elevated concentrations of pollutants in the syngas. For example, the concentrations of NH_3, H_2S, and HCl can rise to 14 ppm, 369 ppm, and 1846 ppm, respectively, highlighting the trade-offs between maximizing electricity production and controlling emissions. The CO_2 concentration remained relatively stable, with a reduction of only 5% across the simulated range of fuel-to-steam ratios.

In the case of plasma gasification, the sensitivity analysis reveals that increasing the heat supplied to the gasifier does not lead to a proportional increase in net electricity production. Although higher energy inputs raise the gasifier temperature, this does not significantly boost H_2 production. Moreover, higher temperatures result in increased emissions of pollutants such as HCl (up to 1113 ppm), H_2S (up to 2227 ppm), and NH_3 (up to 6 ppm). Therefore, while plasma gasification operates at higher temperatures, optimizing heat input is crucial to avoid unnecessary energy consumption and excessive pollutant formation. The CO_2 concentration remained stable at approximately 14% by volume under the simulated conditions of the plasma gasification system. The CO concentration in all gasification systems, including air gasification, steam gasification, and plasma gasification, was very low. Therefore, its contribution to the final emissions can be considered negligible.

For incineration systems, a different profile is observed. Due to the limited syngas generation, steam turbines must be used for electricity production. The sensitivity analysis shows that there is an optimal fuel-to-air ratio that maximizes electricity production. Lower fuel-to-air ratios cause a reduction in incinerator temperature due to an excess of inert nitrogen. In comparison, higher ratios lead to unburnt fuel, decreasing the heat transfer rate in the boiler. Unlike gasification, incineration does not produce NH_3 or H_2S emissions. However, pollutants such as HCl, NO_x, SO_x, CO, and CO_2 are present, with NO_x concentrations peaking at 3.01 ppm, corresponding to the highest electricity production and incinerator temperature. The highest HCl, SO_x, CO, and CO_2 concentrations are recorded at higher fuel-to-air ratios, reaching 1437.5 ppm, 287.4 ppm, 4.70 %vol, and 13.26 %vol, respectively, highlighting the need for effective flue gas cleaning technologies in incineration systems.

The comparative analysis of gasification and incineration technologies for municipal solid waste conversion highlights the superior performance of gasification, particularly when coupled with gas engines, in terms of electricity generation efficiency. However, this comes with trade-offs in pollutant emissions, notably NH_3, H_2S, and HCl, which increase as the fuel-to-air or fuel-to-steam ratios rise. Plasma gasification, while offering high-temperature operation, demonstrates diminishing returns in electricity production at elevated temperatures alongside significant pollutant formation. In contrast, incineration shows lower efficiency in electricity generation but produces fewer hazardous pollutants like NH_3 and H_2S, though NO_x, SO_x, and HCl emissions remain a concern. Optimizing the operating conditions for each technology is crucial to balance maximizing net electricity production and minimizing environmental impact, emphasizing the need for tailored emission control strategies in waste-to-energy systems.

CONCLUSION AND OUTLOOK

This study highlights the significant potential of municipal solid waste (MSW) as a renewable energy source in Indonesia, offering a viable solution to address the dual challenges of growing energy demand and sustainable waste management. Using Aspen Plus® simulation software, the study evaluated four conversion technologies—air gasification, steam gasification, plasma gasification, and incineration—for their electricity generation potential and environmental impacts. Gasification technologies outperformed incineration, generating 15 to 27 MW of electricity from 400 tons/day of MSW, with gas engines proving more efficient than steam turbines due to fewer energy conversion stages. Air gasification showed that lower air utilization increased net electricity production and elevated pollutant levels, such as NH_3, H_2S, and HCl. Similarly, steam gasification initially enhanced hydrogen production at optimal steam levels but suffered from efficiency losses and increased emissions at excessive steam inputs. Plasma gasification demonstrated stable CO_2 concentrations and high operational temperatures but resulted in diminishing returns for electricity production and increased pollutant emissions with higher heat supply.

The study also revealed that incineration, while less efficient than gasification for electricity generation, produced fewer hazardous pollutants like NH_3 and H_2S. However, emissions of NO_x, SO_x, and HCl were notable, particularly at higher fuel-to-air ratios. These findings emphasize the need for tailored operational strategies and emission control systems to optimize performance and mitigate environmental impacts for gasification and incineration technologies. By aligning technological solutions with the diverse characteristics of Indonesia's MSW, this study provides a comprehensive basis for improving waste-to-energy (WtE) conversion systems.

This research offers valuable insights to the industrial community, serving as a guide for optimizing WtE technologies to enhance energy security and support Indonesia's renewable energy goals. It underscores the importance of process optimization, efficient gas cleaning technologies, and regional adaptation of WtE systems to ensure maximum energy recovery while minimizing pollutant emissions. Future research should focus on pilot-scale implementations, advanced pollutant mitigation strategies, and techno-economic analyses to enable the large-scale deployment of sustainable WtE technologies.

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