



Projection of greenhouse gas emission reduction from municipal solid waste management using thermal technology in Surabaya City: A path toward 2050 national climate goals

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ABSTRACT

The continued growth of MSW generation in Surabaya City is projected to reach 939,804.10 tons in 2050, leading to a rebound in GHG emissions, which had previously been reduced after the operation of the gasification unit in 2021. Thermal technology's role in preventing increases in emissions was assessed using an empirical approach within the lifecycle framework, following the IPCC method. The enhancement of gasification capacity induces the net emissions saving, from $-18,015.96$ tons $\text{CO}_2\text{-eq}$ in 2025 to $-22,518.55$ tons $\text{CO}_2\text{-eq}$ and $-26,126.86$ tons $\text{CO}_2\text{-eq}$ in 2035 and 2050, respectively. The city's lowest net GHG emissions from MSW management will reach $-117,401.00$ tons $\text{CO}_2\text{-eq}$ by converting the LFG plant to a 2000 tons per day gasification unit. Surabaya's Gasification expansion plan mirrors the trajectory of the LCCP scenario, meaning that the initiative contributes significantly to the national NZE ambition. The expected result requires overcoming technical, financial, and social barriers through integrated policy frameworks, innovative financing, and enhanced waste management practices. This study may serve as a reference for policymakers, especially in urban areas, in developing a strategic approach to low-carbon MSW management.

Introduction

Climate change remains one of the most urgent environmental and socio-economic challenges of the 21st century. The Intergovernmental Panel on Climate Change (IPCC) underscores that limiting global warming to 1.5°C above pre-industrial levels requires rapid, far-reaching transitions across energy, land, urban infrastructure, and industrial systems (Masson-Delmotte et al., 2021). In response, the Paris Agreement of 2015 established a global framework for climate mitigation, adaptation, and finance, requiring all signatory countries to submit their climate action plans, known as Nationally Determined Contributions (NDCs). As a party to the Paris Agreement, Indonesia has outlined its climate mitigation commitments through its updated NDC. According to the Ministry of Environment and Forestry (MoEF), Indonesia aims to reduce its greenhouse gas (GHG) emissions by 31.89% unconditionally and up to 43.2% with international support by 2030, relative to a business-as-usual (BAU) scenario (Ministry of Environment and Forestry

(MoEF), 2021). These targets encompass various sectors, including energy, forestry, agriculture, and waste. While often under-prioritized in mitigation discussions, the waste sector presents a significant opportunity for emissions reduction.

Municipal solid waste (MSW) contributes considerably to GHG emissions, particularly methane (CH_4), a potent greenhouse gas with a global warming potential 28–36 times that of CO_2 over 100 years (Bogner et al., 2007). Methane is predominantly released from the anaerobic decomposition of organic waste in unmanaged landfills and open dumpsites, which are common in many developing countries, including Indonesia. Surabaya, Indonesia's second-largest city, exemplifies the challenges of urban waste management amid rapid population growth and urbanization. With a population exceeding 2.8 million and ongoing economic development, the city generates 1,500–1,800 tons of MSW daily (Surabaya City Government, 2023). As part of the MSW system, Surabaya has a total of 36 units of intermediate treatment facilities (ITF); however, the calculated recycling rate of the city for the

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year 2020 was only 1.62% making most of the generated waste ends up in the final disposal site (Liem et al., 2024a). Referring to the waste hierarchy concept, reduce–reuse–recycle (3R) is the priority with the least negative environmental impact. Reduction at source, a top preferred action to minimize waste generation, was reported to have crucially reduced the magnitude of GHG emissions and prevented massive natural resource extraction (Gunamantha & Sarto, 2012; Yang et al., 2018). Many studies have confirmed that recycling in the MSW system significantly reduces greenhouse gas emissions (Liem et al., 2023). Further, the increase in the recycling rate was reported to increase the GHG reduction potential (Bernstad Saraiva et al., 2017; Goulart Coelho & Lange, 2018; Premakumara et al., 2018). Despite its vital role, implementing the 3R concept, especially in developing countries, is considered a long-term process, as education is needed to build a new paradigm and positive habits among waste generators (Bagastyo et al., 2023; Taouahria, 2024). A complex network of stakeholders across collection, transportation, segregation, treatment, and disposal, as well as long-term political, organizational, and institutional aspects, is needed to implement an effective recycling practice (Silva de Souza Lima Cano et al., 2022).

In light of these challenges, implementing thermal technologies—such as incineration, gasification, and pyrolysis—has offered a viable solution to reduce reliance on landfills and associated methane emissions. These technologies enable the conversion of waste into energy or inert materials, minimizing environmental footprint and contributing to renewable energy generation (Chicaiza-Ortiz et al., 2024). Several studies have demonstrated that energy recovery from MSW using thermal treatment can significantly reduce GHG emissions compared to landfilling, especially when paired with adequate air pollution controls and energy recovery systems (Liem et al., 2023; United Nations Environment Programme (UNEP), 2019). As in Surabaya, the municipality officially operated a gasification plant connected to the power generation in 2021. This initiative was the implementation of the Presidential Decree on the Development of Environmentally Friendly Waste-to-Energy (WtE) Plants in 12 cities in Indonesia (Presidential Decree on the Development of Environmentally Friendly Waste-to-Energy Plants in 12 Cities in Indonesia, 2018). Together with the biogas treatment plant (sanitary landfill with biogas conversion to electricity, LFG), which has already been implemented, this thermal technology has been reported to cut greenhouse gas

emissions successfully. Initially, the city's MSW management emissions in 2020 were 1,004,951.5 tons CO₂-eq, which then declined by 57.13% after applying a 1,000-ton-per-day waste-to-energy (WtE) conversion process (Liem et al., 2024b). The role of thermal technology in minimizing GHG emissions from MSW management will remain crucial, especially given the national target to achieve net zero emissions (NZE) by 2060 or sooner. However, the increase in MSW generation needs to be anticipated to increase the WtE plant's capacity. Therefore, this study aims to project the potential GHG emission reductions from applying thermal waste management technologies in Surabaya through the year 2050. The projections will be compared against Indonesia's Long-Term Strategy – Low Carbon and Climate Resilience (LTS - LCCR) targets to assess the contribution of the waste sector—specifically thermal MSW treatment—to national climate goals. This research seeks to support urban sustainability planning and inform policy development for climate-resilient waste management by providing a long-term analysis of emission-reduction scenarios.

Methodology

Projection of population and MSW generation

The logical framework for assessing the suitability of thermal MSW treatment for supporting the national climate goals from the waste sector is presented in Fig. 1. Since 2020 is used as the baseline, the total population of 2,874,314 will be projected using the population growth rate (r) from statistical analysis of historical population data from 2005 to 2022. Three different projection approaches, which are arithmetic, geometric, and least-square (equations (1) to (3)), have been tested, and one with the best coefficient correlation value is selected to be used in determining the MSW generation over the years.

$$P_t = P_0(1 + r.n) \quad (1)$$

$$P_t = P_0(1 + r)^n \quad (2)$$

$$Y = a + bX; a = \frac{\sum Y}{n}; b = \frac{\sum XY}{\sum X^2} \quad (3)$$

Where, P_t = future population; P_0 = initial population; r = growth rate; n = number of years; Y = population number; X = time variable

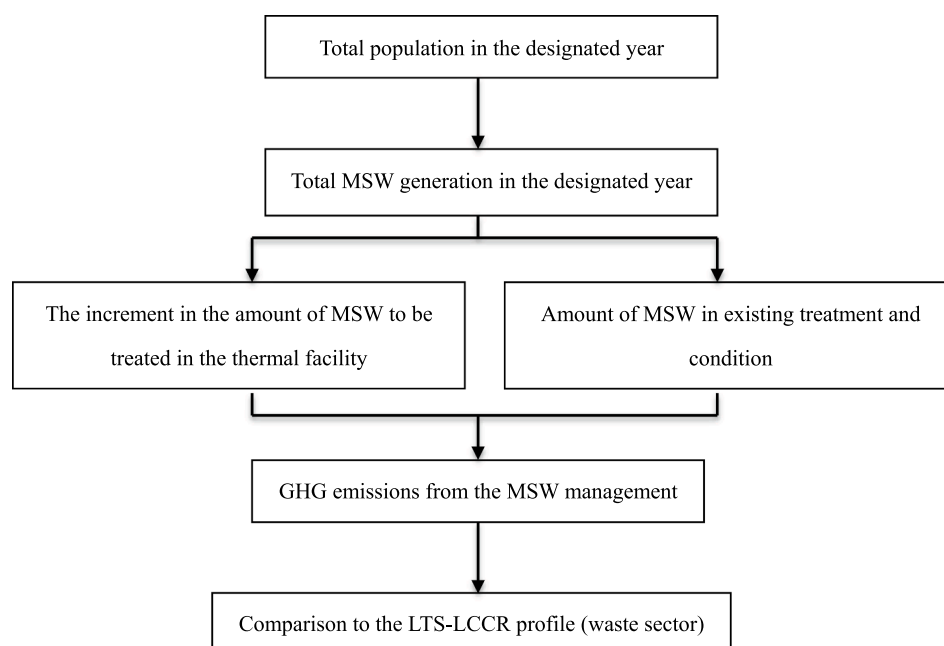


Fig. 1. Logical framework of the study.

(year).

In this case, arithmetic method is selected to project the population number since it has the highest coefficient correlation value (0.877), meanwhile the calculated population growth rate is 0.543%. Background data on MSW management in the study area are described in Liem et al. (2024b). Data on waste production per capita were obtained from the mass balance analysis of MSW management in the city for 2020. Surabaya has a waste generation profile of 0.748 kg per capita per day, which is consistent with the World Bank Report (Kaza et al., 2018). Total waste generation in each year of observation was calculated based on the population and per capita waste production.

Description of scenarios

Scenarios to identify GHG emissions for each measurement year were constructed using several conditions. Four scenarios with time horizons of 2025, 2035, and 2050 have been designed to portray the potential GHG emissions reductions from expanding thermal technology capacity. These three selected years represent (i) the current condition, (ii) at the time when the contract between Surabaya municipality and the private company that operates the WtE will just expire (2032), and (iii) at the due time of LTS – LCCR. The capacity of thermal technology is expanded to 125% and 150% for 2035 and 2050, respectively, relative to current operations. This increment anticipates an increase in MSW generation, while the capacity of other MSW management options (recycling and biogas treatment) remains unchanged. The gradual increase was also set to account for the financial limitations. The 1000-ton-per-day thermal technology unit in Surabaya was built by allocating high capital expenditure (CAPEX) as much as 42,6 million USD (1 USD = 16,500 IDR), excluding the land's investment as it belongs to the government's property (BAPPENAS Under The Project of Emission Reduction in Cities through Improved Waste Management, 2022b). This CAPEX, together with operational expenditure (OPEX), was covered by a private company through a build-operate-transfer (BOT) mechanism. Although it was reported that the payout time (PoT) of WtE implementation in Indonesia is interesting (3 – 5 years), the certainty on the electricity price is still questionable, thus requiring improvement on the WtE financial scheme (Azis et al., 2021). At the same time, the National Government's effort to accelerate the establishment of WtE plants in other targeted cities has led to delays and reduced budget allocation for the expansion plan in Surabaya. Additionally, the progressive increase in capacity anticipates the availability of workforce and advancements in thermal technology.

A scenario representing the operation of a 2000-ton-per-day gasification unit to replace biogas treatment is also established. GHG emissions from MSW management in Surabaya city in 2020 are presented as a baseline for assessing the importance of thermal technology's role in emissions reduction. A description of scenarios for this study is presented in Table 1.

System boundary and data inventory

The recycling rate was set at 30%, as targeted by the National Policy and Strategy for Municipal Solid Waste Management in Indonesia (National Policy and Strategy for Municipal Solid Waste Management (in Indonesia), 2017). Thermal technology, in this case gasification, which is already operational and continually sends about 75% of the produced power to the national electricity grid, is selected as the technology option for MSW management. Meanwhile, transportation emissions were not included in the total GHG emissions calculation. Many studies reported that transportation emissions are considered minimal compared to MSW treatment (Chen & Lo, 2016; Cherubini et al., 2009; Liu, Sun, et al., 2017; Liu, Xing, et al., 2017; Yadav & Samadder, 2018). The contribution of transportation to the overall global warming impact from MSW management was about 1% (Fernández-Nava et al., 2014; D. Wang et al., 2020; Xin et al., 2020a). Besides that, the exclusion in this

Table 1
Description of scenarios.

| Scenario | Recycling Rate | Biogas Plant (LFG) Capacity (ton/day) | Thermal Technology Capacity (ton/day) | Note |
|---------------------|---|---------------------------------------|---------------------------------------|--|
| Scenario – 0 (2020) | <ul style="list-style-type: none"> 0.44% – recyclable^{*)} 6% – organic waste (to be composted) | 500 | – | This baseline scenario refers to the MSW management condition in 2020. Thermal technology has not been implemented, and dependency on landfill was huge (76.51% of total waste ended up in landfill) |
| Scenario – 1 (2025) | <ul style="list-style-type: none"> 30% for both recyclable and organic waste to be composted | 500 | 1000 | A 30% recycling rate is the target based on the national policy and strategy for MSW management in Indonesia |
| Scenario – 2 (2035) | <ul style="list-style-type: none"> 30% for both recyclable and organic waste to be composted | 500 | 1250 | |
| Scenario – 3 (2050) | <ul style="list-style-type: none"> 30% for both recyclable and organic waste to be composted | 500 | 1500 | |
| Scenario – 4 (2050) | <ul style="list-style-type: none"> 30% for both recyclable and organic waste to be composted | – | 2000 | The LFG plant is converted to gasification |

study is intended to avoid bias in the magnitude of GHG emissions across MSW treatment methods. However, calculating transportation emissions is required if information on the total carbon footprint from an established or proposed MSW management system is needed. Optimization of the waste transportation route is another important study to be conducted. This section will be presented in the following phase of this research.

Several data points, both from primary and secondary sources, were used for the calculation. A field measurement, guided by the standard protocol for unprocessed municipal solid waste (ASTM D5231-92), was conducted at the final disposal site in Surabaya (Table 2). Sampling was also performed for each waste fraction prior to proximate and ultimate analysis. Emission conversion factors for each process in MSW management in Surabaya, as provided in Table 3, were adopted from the Prognos–Ifeu–INFU report, IPCC background data, and Breeze (2018), all of which are compatible with the area study's situation (Breeze, 2018; Prognos & Ifeu, 2008). Meanwhile, the GHG emission factor for electricity generation is 870 g CO₂-eq/kWh. This value refers to the national guidance, specifically adopted from the JAMALI (Jawa – Madura – Bali) grid (Ministry of Energy and Mineral Resources, 2019). GHG emissions calculations for the involved processes were conducted following IPCC guidance for the waste sector (IPCC, 2006), as described in (Xin et al., 2020b) and (Wiharja et al., 2025). Several key equations, as follows, were used :

- GHG emissions from landfill (anaerobic decomposition) :

Table 2
Composition of unprocessed MSW in Surabaya City.

| Waste Fraction | Percentage (%) |
|-----------------|----------------|
| Food Waste | 34.48 |
| Garden Waste | 19.09 |
| Plastics | 16.51 |
| • PET | 0.90 |
| • PP | 0.86 |
| • PS | 0.41 |
| • PVC | 0.20 |
| • HDPE | 1.05 |
| • LDPE | 13.09 |
| Paper | 5.89 |
| • White paper | 0.23 |
| • Cardboard | 4.47 |
| • Tissue paper | 1.19 |
| Textiles | 3.46 |
| Rubber, Leather | 1.54 |
| Wood | 1.52 |
| Diapers | 9.77 |
| Glass | 1.01 |
| Aluminum | 0.26 |
| Metals | 0.14 |
| Others | 6.33 |

Table 3
Emission conversion factor for MSW processing (Kg CO₂-eq/ton waste).

| Process | Emission conversion factor |
|---|----------------------------|
| Recycling | |
| • Paper (mixed) | -820 |
| • Plastics (mixed) | -414 |
| • Glass | -480 |
| • Aluminum | -11,100 |
| • Metals | -2025 |
| • Textiles | -2818 |
| Composting | -8 |
| Anaerobic decomposition | -100 |
| Landfill | 1704.2 |
| Landfill with gas collection and electricity production | 1003.9 |
| Thermal process – Gasification | 38.2 |

$$CH_4\text{-generation} = DDOC * F * \frac{16}{12} * (1 - R) * (1 - OX) \quad (4)$$

$$DDOC = W * DOC * DOC_f * MCF \quad (5)$$

$$DOC = \sum_i (DOC_i * W_i) \quad (6)$$

Where DDOC = mass of decomposable waste; DOC = fraction of degradable organic carbon; DOC_f = fraction of DOC that can be decomposed; W = mass of waste that being landfilled; R = CH₄ recovered rate; OX = oxidation factor; MCF = CH₄ correction factor; DOC_i = fraction of degradable organic carbon in a specific waste category; W_i = waste composition with organic carbon

- GHG emissions from thermal process :

$$E_l = E_i - E_e \quad (7)$$

$$E_i = W_i * \sum (f_i * dm_i * CF_i * FCF_{i,t} * OF_w) * \frac{44}{12} \quad (8)$$

$$E_e = AD_e * EF_e \quad (9)$$

Where, E_l = GHG emission in incineration; E_i = direct emission from carbon incineration; E_e = GHG emissions reduction from electricity generation; W_i = mass of waste that is incinerated; dm_i = dry matter content of wet weight; CF_i = DOC content of dry weight; FCF_{i,t} = fossil carbon fraction of total carbon; OF_w = oxidation factor; AD_e = mass of on-grid energy from incineration; EF_e = electricity GHG emissions factor.

- GHG emissions reduction from recycling:

$$E_r = \sum (R_i * EF_i) - \sum (R_i * AE_i) \quad (10)$$

Where, E_r = emissions reduction from recyclables; R_i = amount of recyclable material per category; EF_i and AE_i = emission factor and avoided emission factor per recyclable category material (related to the usage of conventional fuel, coal, for the production of material).

The total GHG emissions were expressed in carbon dioxide equivalent for comparison. Meanwhile, the GHG emissions profile as targeted by the Government of Indonesia to achieve a zero emission condition in 2050 was extracted from the national scenario data (INDONESIA Long-Term Strategy for Low Carbon and Climate Resilience 2050, 2021)

As a modelling study, this paper acknowledges some limitations that may affect the results. Several variables, such as waste composition, recycling rate, and conversion efficiency, may shift due to changes in lifestyle and consumption patterns, as well as technological advancements. Despite better-than-expected results from the adoption of a green lifestyle, this research presents a sensitivity analysis to ensure the model remains reliable for long-term use. The recycling rate, an important factor alongside the application of thermal technology, is used in the sensitivity analysis to assess its impact on GHG emissions in MSW management. Thus, 10%, 20%, and 30% recycling rates are applied in scenario 4 to evaluate how the outcomes may be affected.

Results and discussion

The results of the calculation on the GHG reduction potential from thermal technology advancement, together with relevant discussion, are provided in the following section. The presentation consists of several parts of elaboration, which are (i) projected waste and emissions; (ii) the impact of gasification capacity expansion on GHG reduction; (iii) correlation to the national GHG reduction targets; (iv) model transferability and (v) policy and implementation challenges.

Projected waste and emissions

MSW generation in Surabaya is estimated to rise from 811,255.10 tons in 2020 to 873,378.73 tons in 2035. The increase will continue until 2050, with an increment of up to 15.85% from the baseline, resulting in a total of 939,804.10 tons. Following that trend, the GHG emissions from MSW management will also change. If only the recycling rate rises to 30% while the WtE plants' capacity remains unchanged, GHG emissions will bounce back. As shown in Fig. 2, the operation of the gasification unit with a capacity of 1000 tons of waste/day in 2021 resulted in significant reductions in emissions. Referring to the baseline scenario, this implementation, along with a 30% recycling rate, will reduce GHG emissions from 1,004,951.5 tons CO₂-eq in 2020 to 155,462.45 tons CO₂-eq in 2025. However, the emission level will increase unless MSW management is further adjusted. In 2035, the emissions will increase to 195,568.46 tons CO₂-eq and reach 255,595.81 tons CO₂-eq in 2050. This negative trend is driven by greater reliance on landfilling. Since the capacity of the WtE process and recycling rate remain the same, more MSW will end up at the final disposal site. The MSW portion disposed of in the landfill increases to 41.78% in 2035 and doubles to 2050 compared to 2025 (Fig. 3). This figure is undesirable, as landfills have been identified as the primary source of GHG emissions. GHG emissions from landfills begin after the disposed MSW undergoes decomposition, driven by microbial activity, and may persist for 20 to 50 years after landfill closure (Bogner et al., 2007; Lim et al., 2014; Lou & Nair, 2009). Many studies have reported that among the MSW treatment options, landfill contributes the most significant GHG emissions (Liem et al., 2023). Therefore, dependency on this option should be reduced and shifted to more environmentally friendly treatments. In the Surabaya case, the expansion of landfill area is an unlikely recourse; this is not only due to the difficulty of finding new space, but, most importantly, because of the national commitment. The Ministry of Environment

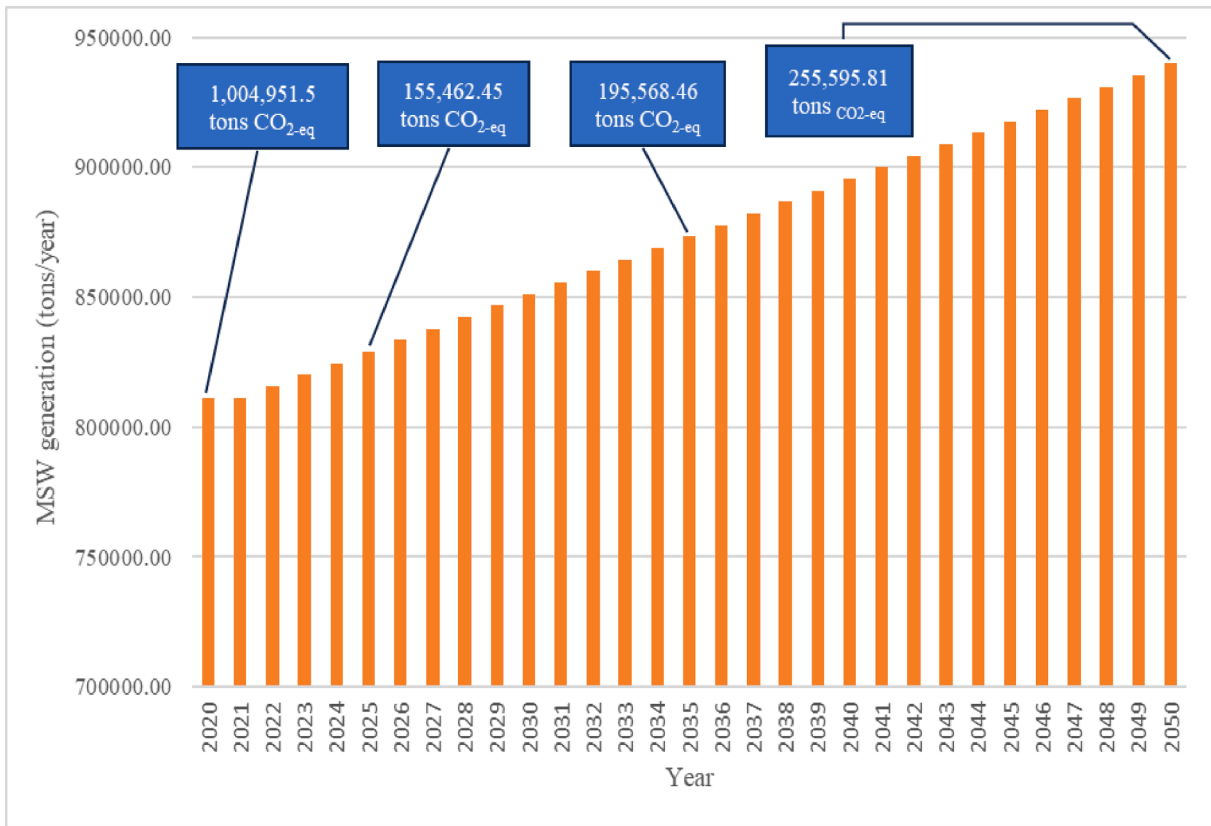


Fig. 2. Projected MSW generation and GHG emissions in Surabaya with no adjustment scenario for the WtE process.

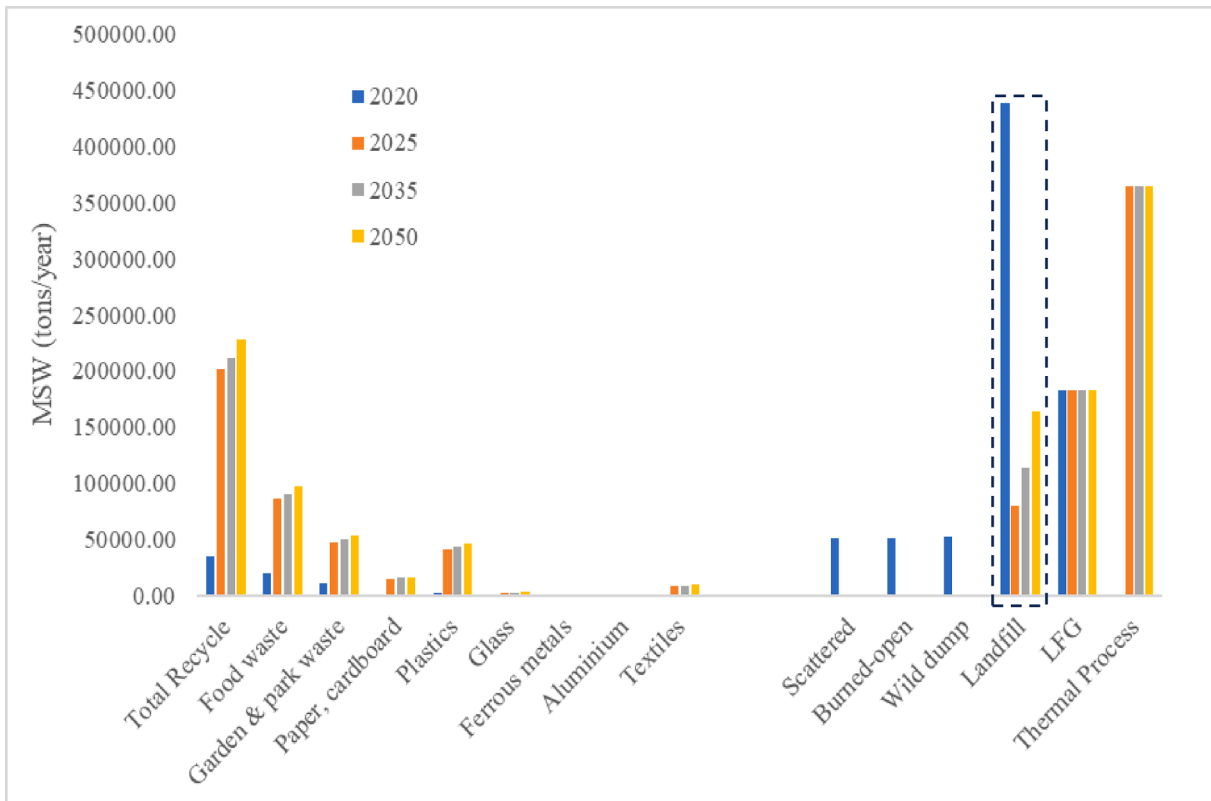


Fig. 3. Transition in the amount of landfilled waste in the no-expansion scheme of the thermal process.

(MoE) has initiated efforts to reinforce Indonesia Law No. 18/2008 by progressively closing 343 open dumping areas starting in 2025 and

limiting landfills to MSW residues only (Ministry of Environmental, 2025).

The impact of gasification capacity expansion on GHG reduction

According to the national policy and strategy for MSW in Indonesia, reducing waste sent to landfills can be achieved by increasing the recycling rate to 30% and the waste treatment rate to 70% (National Policy and Strategy for Municipal Solid Waste Management (in Indonesia), 2017). In this study, the recycling rate was set at 30% for the measurement year; meanwhile, the capacity of the thermal process was increased 25% and 50% from the initial capacity. By doing that, instead of disposing waste to landfill, the amount of waste to the thermal process facility will increase (Fig. 4). Based on this condition, the transition of GHG emissions from MSW management in Surabaya can be seen in Fig. 5. The expansion of thermal process capacity induces the net emissions saving, from -18,015.96 tons CO_{2-eq} in 2025 to -22,518.55 tons CO_{2-eq} and -26,126.86 tons CO_{2-eq} in 2035 and 2050 respectively. In line with this expansion, reducing waste sent to the controlled dump (landfill without a gas collection facility) from 2020 to 2035 will result in a progressive decrease in GHG emissions, reaching zero in 2050, since no more waste will be dumped. The unchanged capacity of the sanitary landfill, with gas collection and electricity production, results in relatively constant emissions of about 141,000 tons CO_{2-eq}. Meanwhile, the perpetual value of the recycling rate results in a slight increase in net emissions savings, from -72,565.21 tons CO_{2-eq} in 2025 to -82,265.77 tons CO_{2-eq} in 2050. This composition prevents the rise in GHG emissions, as illustrated in Fig. 2. Despite the bounce-back effect, the capacity expansion of the thermal process continuously reduces emissions from 155,462.45 tons CO_{2-eq} in 2025 to 71,650.12 tons CO_{2-eq} in 2035, and further to 32,465.04 tons CO_{2-eq} in 2050.

Based on the developed scenarios, selecting a thermal process for electricity production to anticipate rising waste generation over the next 25 years is promising. Since the Indonesian Law No. 18/2008 was enacted, reliance on landfill, especially for untreated waste, is no longer

an option. Given the population growth in Surabaya, the availability of space for landfill area expansion will be difficult. From a GHG-emission-reduction perspective, many studies have reported that landfills emit more GHGs than thermal technologies (Kurniawan et al., 2022; Liem et al., 2023). A case study in the Abruzzo region of Italy found that shifting from landfilling to building a WtE plant had a more positive environmental impact. A 150,000-ton plant operation circumvented 370 Kg CO_{2-eq} per ton treated waste (Cucchiella et al., 2017). Backing up this finding, a specific review evaluating the environmental performance of landfills and incineration found that, in most cases, the thermal process was more favorable (Anshassi et al., 2021).

The greater environmental benefit of the thermal process stems from energy recovery, which offsets energy from fossil fuel sources. The selection of gasification technology in Surabaya is a pioneer at the national level. Currently, 1000 tons per day of MSW is fed into two stages of the combustion system. At first, the waste is pretreated by removing metals and glass, then combusted at 100°C to lower the moisture content. Secondly, the feedstock is burned at 1000°C in the gasifier to produce syngas, which is then supplied to the steam turbine to convert into electricity. The plant's net electrical efficiency is 15%, within the range reported by Arena (Arena, 2012). The electricity output, up to 9 MW per day, is sent to the national electricity grid, while 3 MW is used for internal plant purposes. In terms of emissions, gasification produces less greenhouse gas than incineration. It was reported that, for the same capacity, incineration emissions can be 20 times higher than those from gasification (Ademola, 2022). An intensive comparison of commercial WtE operations in Europe revealed that gasification is more environmentally sustainable, with 5 times greater emission reductions (in a normalized environmental impacts presentation) than incineration (Dong et al., 2018).

Additionally, based on an extensive literature review, a case study to compare gasification and incineration has been conducted to evaluate their environmental performance in treating MSW. The report suggested that gasification is the first option, as its implementation could reduce environmental burdens. Among eight parameters, gasification had a

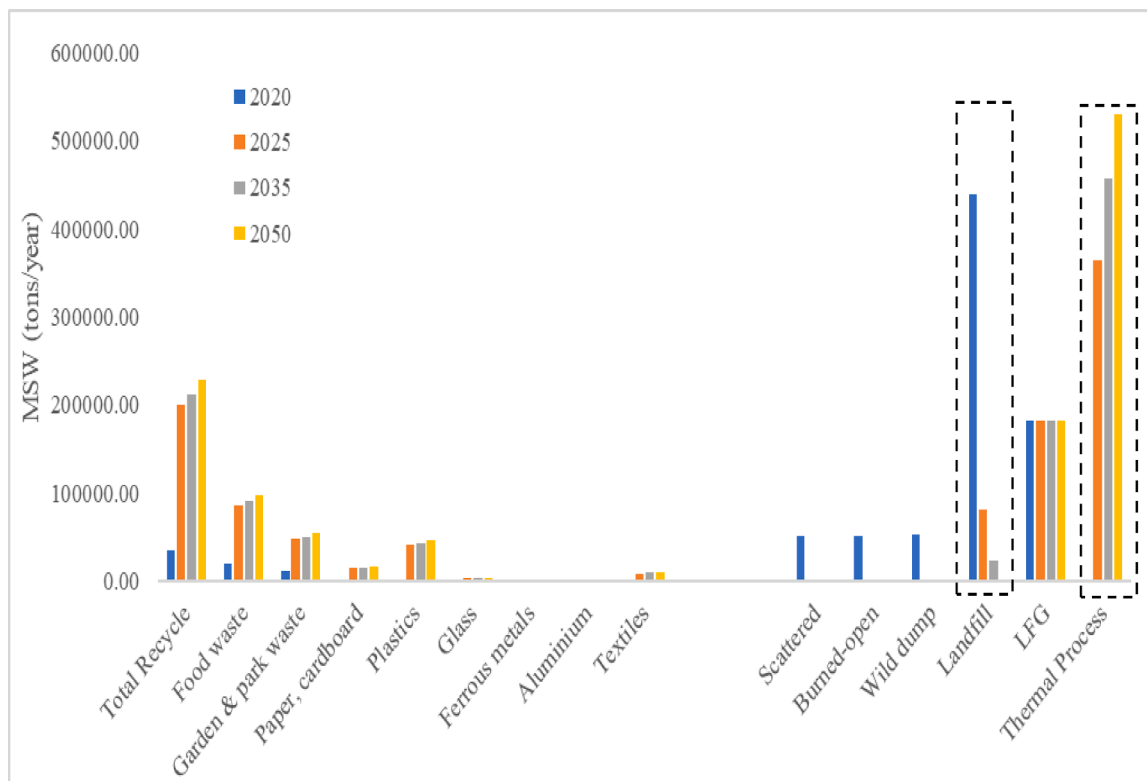


Fig. 4. Transition of the amount of landfilled waste and waste to be treated in the thermal process in all scenarios.

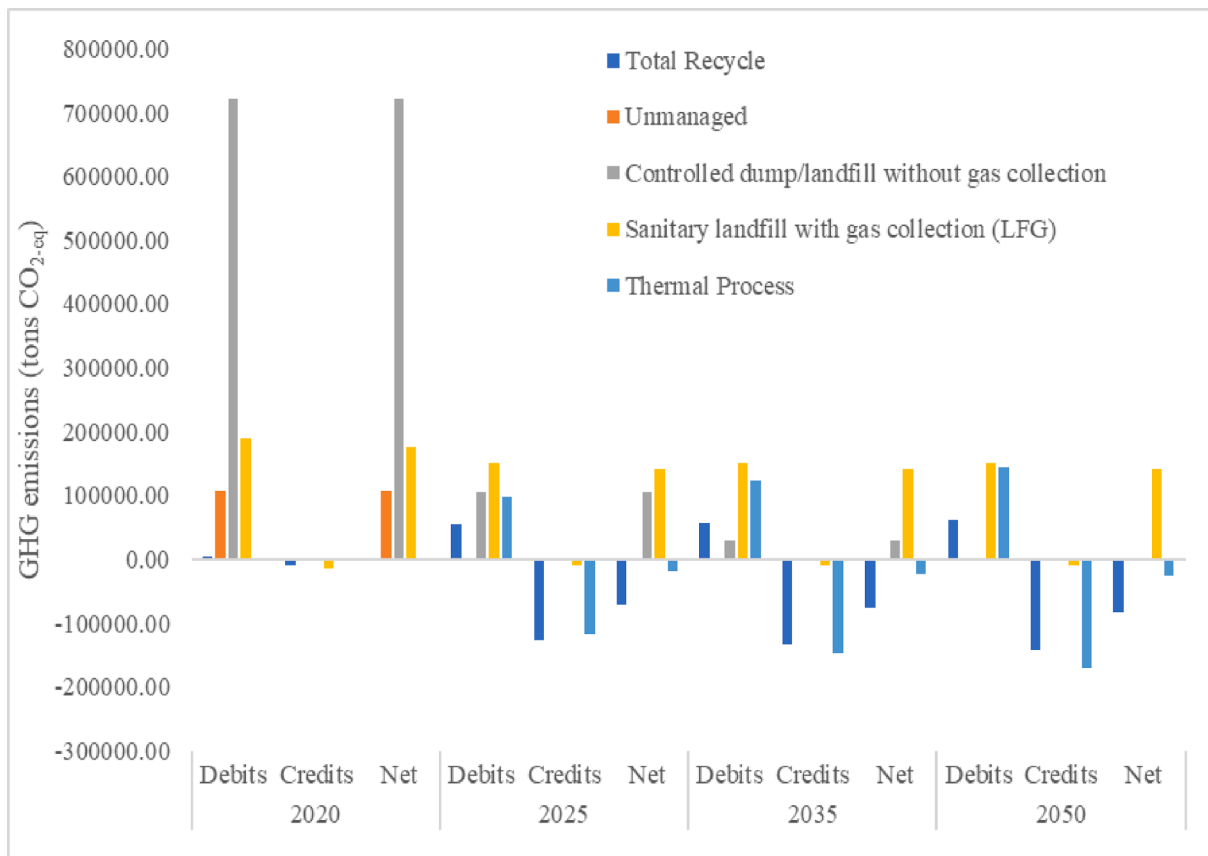


Fig. 5. Transition of GHG emissions from each treatment in the MSW management of Surabaya based on the scenarios.

lower negative environmental impact in seven, including global warming potential (Chicaiza-Ortiz et al., 2024).

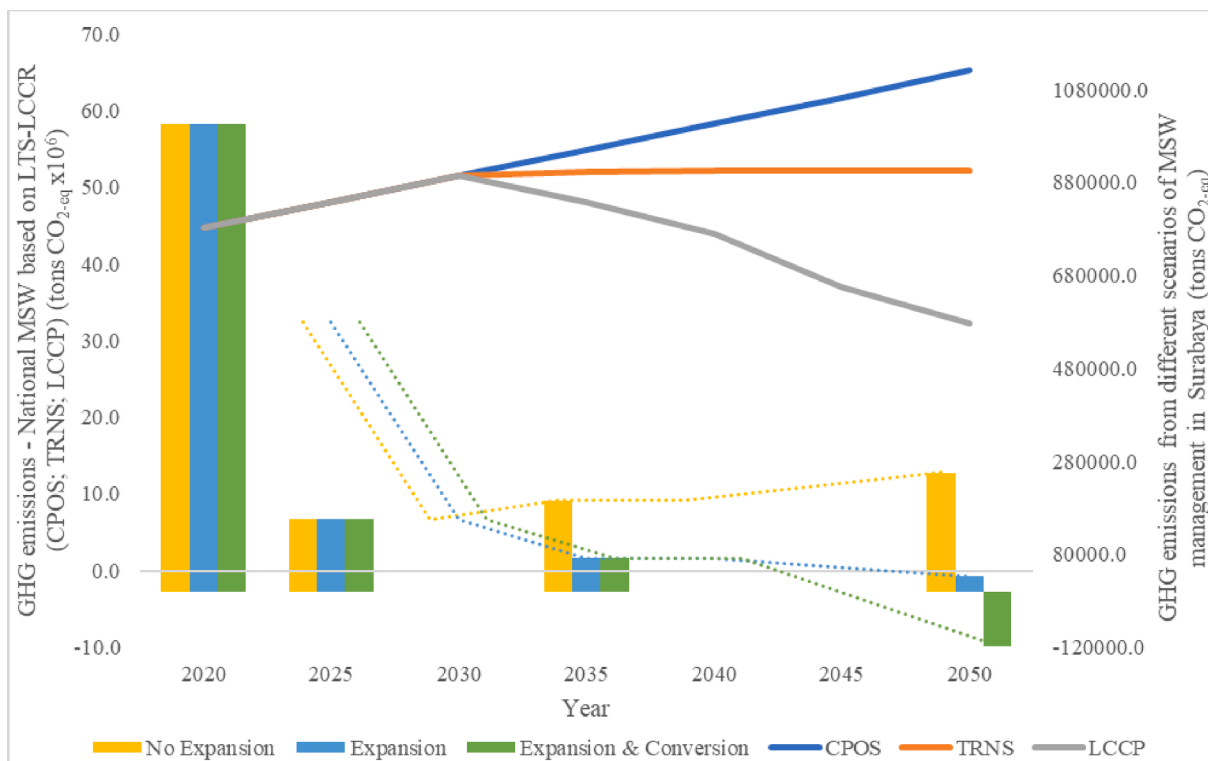


Fig. 6. Correlation between the GHG emissions profile of MSW management of Surabaya and the National LTS-LCCR.

Correlation to the national GHG reduction targets

The Government of Indonesia has developed three scenarios to guide the implementation of LTS-LCCR, namely (i) current policy scenario (CPOS), which is the extension of unconditional commitment of NDC; (ii) transition scenario (TRNS), and (iii) low carbon scenario compatible with Paris Agreement target (LCCP). Fig. 6 (line graph) shows the trend in MSW scenario development at the national level. Under the CPOS scenario, emissions increase progressively from 2020, reaching 65.3 million tons of CO_{2-eq} in 2050. The TRNS scenario decelerates the increase of emissions from 44.8 million tons CO_{2-eq} in 2020 to 52.0 million tons CO_{2-eq} in 2035, followed by a steady condition at 52.1 million tons CO_{2-eq} until 2050. Meanwhile, aggressive mitigation efforts in MSW management will reverse the rise in GHG emissions from 51.5 million tons CO_{2-eq} in 2035 to 32.2 million tons CO_{2-eq} in 2050. The LCCP scenario is an absolute option if the country expects to reach net-zero emissions in the MSW management sector by 2050. In this regard, anticipating an exacerbation of GHG emissions from increased MSW generation, one cannot rely on landfill expansion. Suppose this is the case, even with a 30% recycling rate.

In that case, the emissions level from MSW management in Surabaya will re-inflate following the trend of the CPOS scenario at the national level with a smaller gradient. The capacity-enlargement scenario for gasification units shows a similar trend to the LCCP scenario, bringing GHG emissions below the 2025 level. There is still an opportunity to decrease the city's GHG emissions from MSW management. Based on the calculation shown in Fig. 5, the net emission from LFG remains positive. About 141,000 tons of CO_{2-eq} are emitted to the atmosphere from LFG operations, with 500 tons of waste per day, hindering optimal reduction. Although more cost-effective, LFG installation has drawbacks in operational performance and environmental performance. This technology process requires a long detention time (years) because several conversion steps, steered by specific microorganisms, must occur (Prasanna Kumar et al., 2024). Thus, a larger land area is needed to treat the same waste unit as it proceeds in a thermal installation. The anaerobic decomposition process for dry waste is sensitive to several factors, including temperature, pH, C/N ratio, organic loading rate, and

microbial inoculation. The process may be treated by inefficient mass transfer, ammonia inhibition, and volatile fatty acids accumulation, which need to be balanced by introducing a compound strategy (Z. Wang et al., 2023). The size of waste volume reduction is much smaller than that of a gasification unit, which may achieve 75% - 90%.

Additionally, the LFG system efficiency is reported to be only 10%, while gasification can reach 70% - 80%. In terms of GHG emissions, LFG emits higher, some reports mentioned as much as ten times higher than gasification (Alao et al., 2022; Ouda et al., 2016; Qazi et al., 2018; Yap & Nixon, 2015). Scenario expansion followed by conversion of LFG to a gasification plant in 2050 (Scenario - 4) provides more GHG emissions reduction. The net emission in 2050 becomes -117,401.40 tons CO_{2-eq}, and the pattern of GHG emissions reduction from MSW management in Surabaya is getting closer to the LCCP strategy for MSW management at the national level (Fig. 6). The transformation of WtE technology from a biochemical process to a thermochemical process achieves net zero.

As part of the study, a sensitivity analysis was conducted to evaluate the model's consistency under different parameter values. Fig. 7 presents the results of the analysis for scenario 4 with three different recycling rates. If the targeted recycling rate is achieved (30%), the largest GHG savings of -117,401.63 tons CO_{2-eq} are secured, with contributions of -82,266 tons CO_{2-eq} from recycling and -35,135.63 tons CO_{2-eq} from thermal technology application. The introduction of a 20% recycling rate results in a total of -41,208.98 tons CO_{2-eq} GHG emissions savings. This amount comes from recycling (-54,844.00 tons CO_{2-eq}), thermal process (-31,319.51 tons CO_{2-eq}), and sanitary landfill with gas collection/LFG (44,954.52 tons CO_{2-eq}). The least reduction in GHG emissions, up to 49,590.91 tons CO_{2-eq}, is achieved with a 10% recycling rate. In this condition, emissions from the LFG plant increase as more waste is diverted to the sanitary landfill; meanwhile, the contribution from the thermal process remains the same because the treatment capacity is unchanged.

Model transferability

The proposed model may be adopted to calculate GHG emissions reductions in 12 selected cities, as mandated by the national direction.

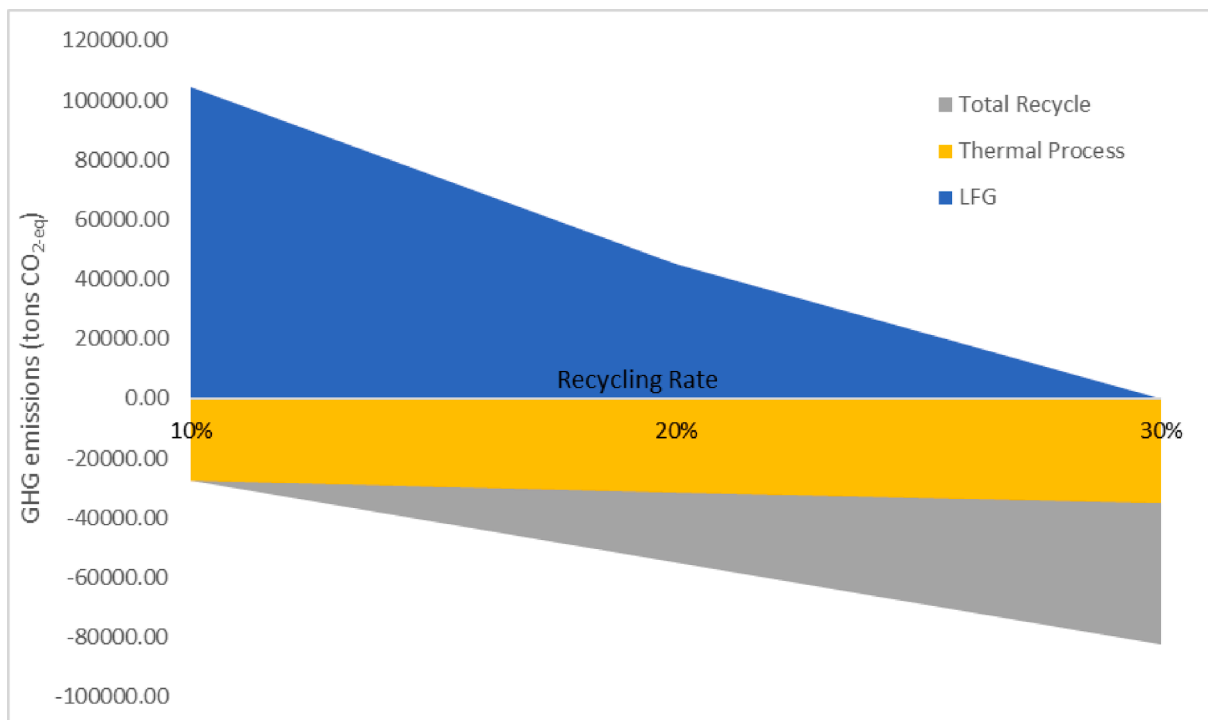


Fig. 7. Comparison of GHG emissions with different recycling rates.

Since some involved parameters have values specific to each city, the adoption should account for those differences. The composition of waste is a key parameter for determining the magnitude of GHG emissions from thermal processes. Among the waste types, thermal technology is suitable for treating organic waste (food and garden waste), plastic waste, paper waste, rubber waste, leather waste, and wood waste (Alao et al., 2022; Rashad et al., 2025). Based on the waste composition information for the designated cities (Table 4), the combustible portion accounts for the majority. The supply of thermal technology is secured, as it is comparable to Surabaya's waste combustible portion. However, differences in the composition and amount of waste to be incinerated may lead to different net GHG emissions. Secondly, the electricity emission factor is used to calculate the GHG emissions benefit. This benefit results from an emission comparison between thermal treatment connected to electricity generation and a conventional power generation unit in the city. The factor for Surabaya (870 g CO_{2-eq}/kWh) is identical to that for Jakarta, Tangerang, Tangerang Selatan, Bekasi, Bandung, Semarang, Surakarta, and Denpasar.

Meanwhile, the factors of 940, 910, and 780 g CO_{2-eq}/kWh are used for the model implementation in Palembang, Makassar, and Manado, respectively (Ministry of Energy and Mineral Resources, 2019). Additionally, the conversion factor for waste combustion to electricity also influences the level of GHG emissions savings. In this case, gasification, the selected technology, is reported to have a higher conversion factor than incineration, as applied in this study (Mayer et al., 2019; Qi et al., 2025; Yousefloo & Babazadeh, 2020). Gasification is considered a new thermal technology for MSW management, especially in Indonesia. In the future, technology maturity is expected to lead to a higher conversion factor, which is positive for climate change mitigation efforts.

Policy and implementation challenges

The Government of Indonesia has encouraged the implementation of WtE technology as a treatment method for managing MSW. Under Presidential Decree No. 35/2018, the government has mandated local authorities (Governors and City Mayors) in 12 cities to facilitate the development of WtE. An ongoing policy (a new Presidential Decree) on national MSW management will soon be released, and one important revision in it is to expand the initiative to build WtE installations in 33 cities with a minimum MSW generation of 1000 tons per day (Malhikmah, 2025). Surabaya is the first city to build and successfully operate thermal technology; however, anticipation over the next 20–30 years is crucial to support the national commitment to achieving the NZE condition. Expanding gasification capacity appears promising for minimizing GHG emissions without compromising the waste management hierarchy. However, several preparations are needed to realize the positive impact of this effort. These preparations include a regulatory framework, financial adjustments, technical aspects, and public-private-community awareness and participation.

Regulatory framework and financial adjustment

The augmentation plan for gasification capacity, as an integral part of MSW management development, must be incorporated into the regulatory framework. In the Long-Term Development Plan 2025 – 2045, the WtE concept (through thermal and/or biological process) is stated as one of the innovation plans in the city's MSW management scheme. Following that, the Mid-Term Development Plan 2025 – 2029 has been put as the guidance for MSW management's annual action plan development. However, a clear description of the WtE innovation plan has not been provided in the documents. As for the innovation of thermal technology, monitoring and measuring the performance of existing plants is required to evaluate and redefine the technical aspects of the extended plant in anticipation of the operational contract's due date (2032) and toward 2050. Therefore, a consistent, continually improved policy is needed to facilitate the realization of the gasification innovation plan up to 2050.

Table 4
Waste composition in the 12 selected cities for WtE installation plant.

| Waste Item | Waste Composition (%) | | | | | | | | | | | |
|--------------|-----------------------|-----------|-------------------|--------|---------|----------|-----------|------------------------|---------|----------|-----------|--------|
| | DKI Jakarta | Tangerang | Tangerang Selatan | Bekasi | Bandung | Semarang | Surakarta | Surabaya ^{*)} | Makasar | Denpasar | Palembang | Manado |
| Food Waste | 49.87 | 57.65 | 45.23 | 65.2 | 44.52 | 60.8 | 38.18 | 34.48 | 52.56 | 27.2 | 56.9 | 47.7 |
| Garden Waste | 3.18 | 0.44 | 16.32 | 7.2 | 3.98 | | 5.64 | 19.09 | 0.06 | 41.12 | 5.4 | 1.14 |
| Plastic | 22.95 | 19.66 | 15.27 | 15.6 | 16.7 | 17.2 | 22.73 | 16.51 | 28.24 | 11.9 | 17.5 | 19.48 |
| Paper | 17.24 | 13.18 | 9.13 | 4.2 | 13.12 | 10.2 | 13.64 | 5.89 | 6.66 | 8.68 | 15.1 | 18.66 |
| Textiles | 0.9 | 2.32 | 1.47 | 6.3 | 4.75 | 4.9 | 7.27 | 3.46 | 1.52 | 1.04 | 2.7 | 1.54 |
| Rubber | 0.7 | 0.8 | 0 | 0.5 | 2.38 | 1 | 0 | 1.54 | 0.19 | 3.16 | 0.3 | 1.49 |
| Wood | | | | | | | | 9.77 | | | | |
| Diapers | | | | | | | | 1.52 | | | | |
| Glass | 1.48 | 0.37 | 0.15 | 0.5 | 1.97 | 1.8 | 0 | 1.01 | 1.45 | 2.04 | 0.8 | 1.85 |
| Aluminum | | | | | | | | 0.26 | | | | |
| Metals | 1.08 | 1.07 | 0.28 | 0.2 | 0.9 | 1.2 | 3.64 | 0.14 | 0.52 | 3.16 | 0.5 | 0.26 |
| Others | 2.6 | 4.51 | 12.15 | 0.3 | 11.68 | 2.9 | 8.9 | 6.33 | 8.8 | 1.7 | 0.8 | 7.88 |
| Combustible | 94.84 | 94.05 | 87.42 | 99 | 85.45 | 94.1 | 87.46 | 92.26 | 89.23 | 93.1 | 97.9 | 90.01 |

Source: Information System for National Waste Management (<https://portal-sipns.kemenvh.go.id/>), ^{*)} except for Surabaya (direct measurement).

The thermal technology option for the expansion plan shall consider economic consequences, mainly investment (CAPEX) and operational–maintenance (OPEX) costs. The initial plant, which operated in 2021, was built with the support of the national government through cooperation between government and business entities. A private company builds the gasification installation and operates the process. After the contract expires, the plant will be handed over to the Surabaya municipality. Meanwhile, the city is responsible for providing the land, sending the MSW to the plant, and paying the tipping fee to the operator. This Build–Operate–Transfer (BOT) concept seems to work effectively, though the tipping fee is an additional burden on the city's budget. While a similar mechanism remains promising for the next 10 to 25 years, Surabaya municipality needs to anticipate alternative sources and optimize current revenues to complement funding. In 2025, the percentage of the budget allocated to MSW management in Surabaya was 3% of the total annual city expenditure. This meets the target value as encouraged by the Ministry of Environment (MoE), since the allotment in most cities/regencies in Indonesia is low, between 0.4–2% of the total annual expenditure ([Dharma Ina Mandiri Under the Project of Emission Reduction in Cities through Improved Waste Management, 2022](#)). However, the allocated funds can only cover routine costs, including collection, transportation, and tipping fees, for the operation of the existing gasification unit. Only a portion is set aside for an intermediate treatment facility (ITF), while the city commits to adding 1 to 2 units each year to support recycling activities. Income for MSW management is obtained from the retribution fee. In this case, the tariff level should be evaluated in accordance with the guidance in the Decree of the Ministry of Home Affairs No. 7/2021 to achieve a more reasonable and feasible adjustment. The retribution fee in most areas of Indonesia is considered very low; the average tariff applied is only 0.06–1 USD, while in Surabaya, it is 0.18–1.45 USD per household per month ([Local Government Regulation No. 7/2023: Local Tax and Retribution for Surabaya City, 2023](#)). Another issue for optimal utilization of the retribution fee is the collection and distribution system. Recently, the fee has been collected manually (door-to-door), especially for lower-income groups.

Furthermore, the collection system is under utility payments (electricity and water bills) and submitted to the city's income post. This system cannot guarantee that the waste retribution fee income can be fully settled for expenditure. Those conditions result in modest effectiveness in budget allocation for MSW management.

As for the tipping fee, this portion may be included in the electrical production cost; thus, the national electrical company covers it in the purchase price. This mechanism shifts the burden from the regency/city, which has a more limited funding capability, to the national government. As important as it, the electricity price from the WtE plant must be competitive when compared to the price of electricity produced with conventional fuels. Therefore, a national guidance for the electricity pricing should be established to assure the sustainability of WtE implementation. From a national perspective, implementing WtE is part of a strategic effort to achieve the energy mix target.

Technical aspect

The main challenge in implementing gasification in Surabaya and Indonesia is achieving more homogeneous waste characteristics. Failure to fulfill this condition will require pre-treatment, which may lead to inefficiency ([Nobre et al., 2020](#)). Gasification is reported to have its best performance for organic fraction, especially food waste and garden waste, which are suitable for Surabaya waste characteristics, where about 53.57% of these two types of waste dominate the composition ([Liem et al., 2024b](#); [Mukherjee et al., 2020](#); [Shareefdeen et al., 2015](#)). However, due to poor segregation efficiency, feeding to the gasification plant is still in mixed condition. Ineffective waste segregation has caused technical problems, reducing gasification thermal efficiency by 20% – 30% ([Srivastava et al., 2025](#)). Besides improving gasification performance, segregation will eliminate hazardous materials that might otherwise cause further contamination if burned in the reactor. As

important as it is, segregation is crucial to recycling activity, significantly reducing GHG emissions. An intensive study in a metropolitan area in Italy found that segregation is indispensable for MSW management to increase the recycling rate and improve other waste treatment performance ([Gadaleta et al., 2022](#)).

Second, the moisture content in MSW is another challenge for the optimal operation of a WtE plant in Indonesia, including Surabaya. The moisture content of the organic fraction in MSW from Surabaya is 52.22%, far above the ideal range requested by the gasification process (15%–30%) ([B. Wang et al., 2023](#)). High moisture content in MSW will cause process instability due to the need for additional heat, potentially damaging equipment. The energy output will be reduced because more energy is required for evaporation, and syngas quality will be compromised as the production of high-calorific gas (CO and CH₄) is blocked ([Arenas, 2012](#)). High moisture content in MSW may arise from waste generator practices and from the collection and transportation processes. Surabaya municipality needs to improve the collection and transportation system in parallel with environmental education to build positive practices at the waste generator level. As important as separate containers, the municipality needs to provide protected waste bins and transporters to prevent contact with water, especially during the rainy season. Furnishing a roof in the unloading area in ITF before loading it to the separation belt conveyor is important to prevent an increase in waste moisture content. Those improvements will ameliorate the level of pre-treatments in the gasification plant.

Public – private – community awareness and collaboration

Community involvement in the MSW management system is crucial. Since waste separation is a key factor for successful recycling and other waste treatment methods, including gasification, the Surabaya municipality may raise concerns about this matter. Segregation at the waste producer level (e.g., home, apartment, office) is considered the most impactful effort to increase overall efficiency in the MSW management system. Several factors were reported to effectively encourage this best practice implementation, such as facile and informative instruction on the packaging for the correct sorting process for consumers, more motivational information in communal places to attract more people in the sorting process, accessible sorting facilities, and continual infrastructure development and promotion ([Sandhi & Rosenlund, 2024](#)). Subsequently, an effective collection mechanism is required to maintain the effectiveness of the waste treatment flow. Currently, collection is beyond the municipality's responsibility; thus, residential/office management sends waste to temporary storage or final disposal sites, increasing the risk of leakage, especially in lower-income areas. The informal sector (waste pickers) is actively involved in collecting recyclable waste from households, temporary storage, and final disposal sites. It is reported that in Indonesia, about 4 million informal workers contribute to acquiring recyclable waste, which is as much as 1.11% of the total waste generation or up to 7.87% of the recyclable group in every regency or city ([BAPPENAS Under The Project of Emission Reduction in Cities through Improved Waste Management, 2022a](#)). Despite their significant role, the informal sector has not been formally acknowledged in Indonesia's MSW management system. Expanding the municipality's scope of responsibility is one thing, and, in parallel, incorporating the informal sector into the waste management chain would be advantageous. The integration of the informal sector and Waste Bank – a community-based unit for collecting recyclable waste – into the circular economy concept in the MSW management system can be achieved by connecting them with the private sector. These groups may act as raw material suppliers for the recycling industry.

The active role of the private sector should be accommodated through mechanisms such as Extended Producer Responsibility (EPR). EPR has been recognized as a vital contributor to increased recycling rates, especially of plastic, in many countries worldwide ([Tumu et al., 2023](#)). However, implementation in Indonesia, and in Surabaya in particular, remains plodding since it was enshrined in Indonesian Law

No. 18/2008. Surabaya Mayor Circular No. 660.1/7953/436.7.12/2019 introduced an initiative to reduce single-use plastic use but it has not linked producers to the collection system. While awaiting national guidance on the mandatory implementation of EPR, building a collaboration framework among the municipality, the private sector, producers (especially fast-moving consumer goods), and the community, including the informal sector, will provide a strong foundation for optimal EPR implementation in the city. Increasing the recycling rate is a top priority for an efficient MSW management system. Developed countries in Europe have set a target to achieve a 60% recycling rate by 2030 and 65% by 2035, the United States pledged to obtain a 50% recycling rate by 2030, and China planned to increase organic waste recycling up to 35% and city area recycling up to 90% (EPA, 2020; Europarl, 2018; Tai et al., 2011). Indonesia's target to reach a 30% recycling rate by 2030 is essential to supporting superior MSW management. The achievement of GHG emissions reduction through expanding gasification treatment capacity in this study is possible only if the targeted rate is met.

Conclusion

Total MSW generation in Surabaya is projected to grow from 811,255.10 tons in 2020 to 939,804.10 tons in 2050. Based on current MSW management practices, GHG emissions rebound to 255,595.81 tons in 2050, neglecting the significant reduction following the operation of the WtE plant in 2021. This study has assessed the potential for reducing emissions by expanding thermal process capacity, particularly the gasification unit. A progressive increase in treatment capacity from 1250 tons/day in 2035 to 1500 tons/day in 2050 results in a decrease in net emissions from MSW management from 71,650.12 tons CO_{2-eq} to 32,465.04 tons CO_{2-eq}. A more aggressive scenario, converting the landfill gas (LFG) plant to a 2,000-ton/day gasification unit by 2050, achieves a net emission of -117,401.40 tons CO_{2-eq}, approaching the Low Carbon Compatible Pathway (LCCP) scenario at the national level. Sensitivity analysis results portray that the model may be adopted for other areas with adjustment on several parameters. Despite its potential, challenges such as high moisture content (52.22% in organic waste), poor waste segregation, and inadequate funding hinder optimal performance. Technical improvements and the emphasis on adequate segregation should be prioritized, as they will affect the determination of the required pre-treatment level in the gasification process. Regulatory enhancements, such as providing clear WtE innovation plans in the 2025–2045 Long-Term Development Plan, followed by the Medium-Term Development Plan every 5 years, are essential to guide the legal implementation. Financial adjustments, including optimizing retribution fees and integrating tipping fees into electricity costs, are critical to sustain expansion. As for the investment, a BOT model has been proven to deliver the initial plant successfully and can thus be considered for reapplication. Public-private-community collaboration, including formalizing the informal sector and implementing Extended Producer Responsibility (EPR), is vital to achieve the 30% recycling target and maximize GHG reductions. The initiative to expand gasification treatment capacity in Surabaya without compromising the recycling rate target contributes significantly to the national NZE ambition.

CRedit authorship contribution statement

Yunus Fransiscus Liem: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Aulia Ulfah Farahdiba:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Aditya Prana Iswara:** Writing – review & editing, Methodology, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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