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Municipal Solid Waste (MSW) Reduction through Incineration for Electricity Purposes and Its Environmental Performance: A Case Study in Bantargebang, West Java, Indonesia

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Abstract: The incineration of municipal solid waste (MSW) effectively reduces waste and has a side product, such as electricity. The waste-to-energy (WTE) power plant in Bantargebang is the first national pilot plant facility in Indonesia using moving grate incinerator (MGI) technology, with a 100 tons/day design capacity and a maximum design of electricity power output of 750 kW. The main challenge of WTE in Indonesia is high moisture content (MC) and unsorted waste. Hence, it is imperative to include the pre-treatment facility through waste drying and sorting. In this work, over 241 working days from January to December 2022, approximately 15,451.35 tons of MSW (averaging 70.55 tons/day) have been incinerated at an average temperature of 613.8°C. Waste pre-treatment alleviates waste MC from 20.13% to 8.59%. This process achieves a significant waste mass reduction of 81.52-96.50%. In addition, the system generates superheated steam at maximum values of 5000 kg/h, 340°C, and 38-39 barA. The total electrical energy generated (956.04 MWh) is used to supply the electrical energy demand of the internal plant operation (1368.78 MWh). Moreover, the wastewater and flue gas in this WTE have successfully been processed by the pollution control systems to meet national standards. The fly and bottom ash from MSW incineration have proven harmless and suitable for construction material or cement admixture. This work conclusively shows that WTE Bantargebang provides positive implementation in almost all aspects, encompasses a significant amount of waste reduction, satisfying incineration performance, a significant amount of electricity generated, and the environmental performance does not harm the surroundings. Related to the performance deficiencies found is expected can be a valuable input for WTE development in Indonesia.

Keywords: Waste-to-energy; Incineration; Flue gas; Moisture; Electricity

1. Introduction

Indonesia's population growth and economic activity have led to problems in managing municipal solid waste (MSW), such as a low service level and difficulty acquiring the area for final disposal (landfill) [1,2]. Most large cities in Indonesia use a landfill system for waste management. However, this approach accelerates the lifetime of the landfill due to the increase in waste caused by population growth. This problem is compounded by the difficulty of finding suitable land for waste landfill [3–6]. Despite efforts to reach the goal of waste minimization at the source and landfill, the high waste generation rate has still led to a low level of national waste reduction [7].

In 2022, the Indonesian population reached 261 million, and the MSW generation was 0.4 kg/person/day. This leads to an estimated national MSW generation of 104,000 tons/day [1]. The Ministry of Environment and Forestry (MoEF) predicts that the MSW generated will reach 71.3 million tons/year by 2025. In response, the government has set targets through the National Strategic Policy to achieve 100% waste management by 2025 [8].

There are various methods of treating waste, which include physical and mechanical processing [9], biological processing such as anaerobic digestion, composting, and landfilling [10], and also thermal processing, including gasification, pyrolysis, and incineration [11]. Incineration is a promising waste treatment method because it can convert thermal energy into electrical energy, providing an opportunity to reduce waste amount in a short time while generating surplus electricity for own consumption [12–14].

Three main processes are involved when MSW is converted into electrical energy using the incinerator, i.e. boiler-incinerator system, energy conversion, and flue gas treatment [10]. This concept is known as waste-to-energy (WTE) which takes some attention and considers positive environmental aspects. Beyond waste reduction, it can reduce the massive dependence on fossil resources [15,16]. Therefore, WTE is believed can support the goal of being environmentally friendly and sustainable.

Currently, the most popular technology for WTE plants is the moving grate incinerator (MGI), which is employed by over 1,000 plants worldwide [17]. Over 90% of WTE plants in Europe use MGI technology [18]. The MGI technology is efficient in MSW processing in developed countries without pre-treatment. However, the pre-treatment facility in Indonesia is required due to unsorted waste of various kinds and sizes and high moisture content (MC) of 50-60%. The latest innovations to improve energy efficiency are combined with heat and power technology [12,19].

In 2018, the WTE Bantargebang project in Indonesia was designed as the first national pilot plant to convert MSW into electrical energy using the MGI technology with a design capacity of 100 tons of MSW/day. The maximum design is aimed at generating 750 kW of electricity power. The plant is located in Bekasi, West Java Province, Indonesia.

The primary objective of the WTE is to conduct MSW management research and development using the MGI technology. This WTE is the pioneer in using the MGI technology equipped with a pre-treatment facility. This facility controls MSW to achieve size homogenization, segregation of non-combustible waste, and increased calorific value. Thus, the MSW treated in the pre-treatment facility is able to meet the requirement condition of the MGI technology. Furthermore, the success of the WTE is expected to contribute to its development and accelerate its implementation with the same technology to reduce significant national waste in Indonesia's big cities.

To assess the operating performance of the MGI equipped with a pre-treatment facility, several parameters such as waste incinerator and power generation, flue gas emissions, ambient air quality, fly ash and bottom ash (FABA), wastewater quality, and noise intensity were measured.

2. Materials and methods

2.1 Raw material and pre-treatment process

MSW utilized as fuel waste was transported by trucks to WTE Bantargebang. A wet (high MC) or a bulky MSW such as household equipment, wrapped waste in plastic, and non-incinerable materials were separated and not to be used. They were immediately set aside and collected as waste beyond the criteria.

Figure 1 reveals processes conducted in the pre-treatment facility. Upon transportation of the waste by trucks to the WTE plant, it underwent a trommel screen process for sorting. The sorted waste was then separated manually, followed by storage in the bunker before being burned.

The Trommel screen has a diameter of 1.96 m, a screen length of 6 m, a rotation velocity of 22 rpm, and a waste screening capacity of 5 tons/h. Trommel screening was operated for 8 h/day, which one person conducted for three shifts/day. The total manpower in pre-treatment and those who supported the WTE operation for three shifts were 24 people.

During manual separation, bulky waste was sorted and chopped. Subsequently, sorted waste that meets the criteria was collected in storage. Air drying was subjected to suppress the moisture contained in the sorted waste. Afterward, sorted waste ready to be incinerated was transported to the bunker (30 m × 10 m × 10 m) at 2.94 tons/h.

At the bunker, while waiting to be put into the incinerator, the air drying process of sorted waste was also implied by utilizing natural convection for 30 to 60 mins at the pre-treatment area by utilizing natural convection.

Fig. 1: Waste sorting process prior to incineration.

2.2 Waste incineration and power generation

The incinerator start-up was operated the same as the boiler as usual. However, to prevent waste accumulation at the grate, the 2.94 tons/h of sorted waste was fed into the incinerator slowly and sequentially. Fire ignition was then provided using diesel oil. Air was gradually supplied using a primary fan, initially from 15-25% air until the composition of air and fuel was balanced. The amount of air was then escalated to 25-50%, 50-75%, and 75-100% according to incineration conditions until the incinerator temperature reached 300^{o}C. The ratio of air and fuel should be balanced to guarantee that the flame evenly propagates and that incineration is not hampered.

Waste was resupplied when the incinerator temperature dropped. Other than that, the feeding was stopped when waste was accumulated until it descended and was evenly distributed first. Air supply from the secondary fan as much as 20-50% was supplied to generate turbulence mixing. If much smoke was produced, the IDF was turned on to suck the smoke out of the incinerator to be processed in flue gas treatment.

The generated incineration energy was converted through Rankine Cycle, as in Fig. 2. The operation units involved were boilers, steam turbines, condensers, deaerators, pumps, and generators [17–20]. The boiler was manufactured by PT. Indomarine has a maximum steam capacity of 8,000 kg/h, with a maximum pressure of 40 bar and a maximum superheated steam temperature of 390^{o}C. The maximum electricity generation from the steam turbine was 750 kW, but it was only operated at 36% of capacity (270 kW). Thermal energy from waste was used to heat boiler feed water (BFW) to superheated steam. BFW's raw material was sourced from a deep well reservoir, which processed it first. The oxygen content also cannot be significant in BFW, so it must be processed in a deaerator.

The steam turbine type used in this work is an extractive type manufactured by Triveni Turbine Ltd., India having a maximum capacity rotation of 9,804 rpm. The steam turbine was coupled with a gearbox system to convert mechanical energy into electrical energy by reducing the turbine rotation to 1500 rpm [21]. The turbine had one shaft with a generator. A part of the steam was expanded to heat the deaerator. The rest was fully condensed to sub-cooled water, which was then pumped back into the boiler.

Raw water from the deep well was pumped by a pump with a capacity of 10 m^3/h and stored in a sediment tank. Water was first filtered using a multimedia filter before being accommodated in a clean water tank. Subsequently, the clean water tank was injected with chemicals for softening. The next stage was filtration with a cartridge filter, followed by reverse osmosis. The filtered water was finally treated with mixed bed adsorption, and the results were stored in demineralization tanks as BFW. In the reverse osmosis process, the retentate was also produced, which was applied to domestic and processed water.

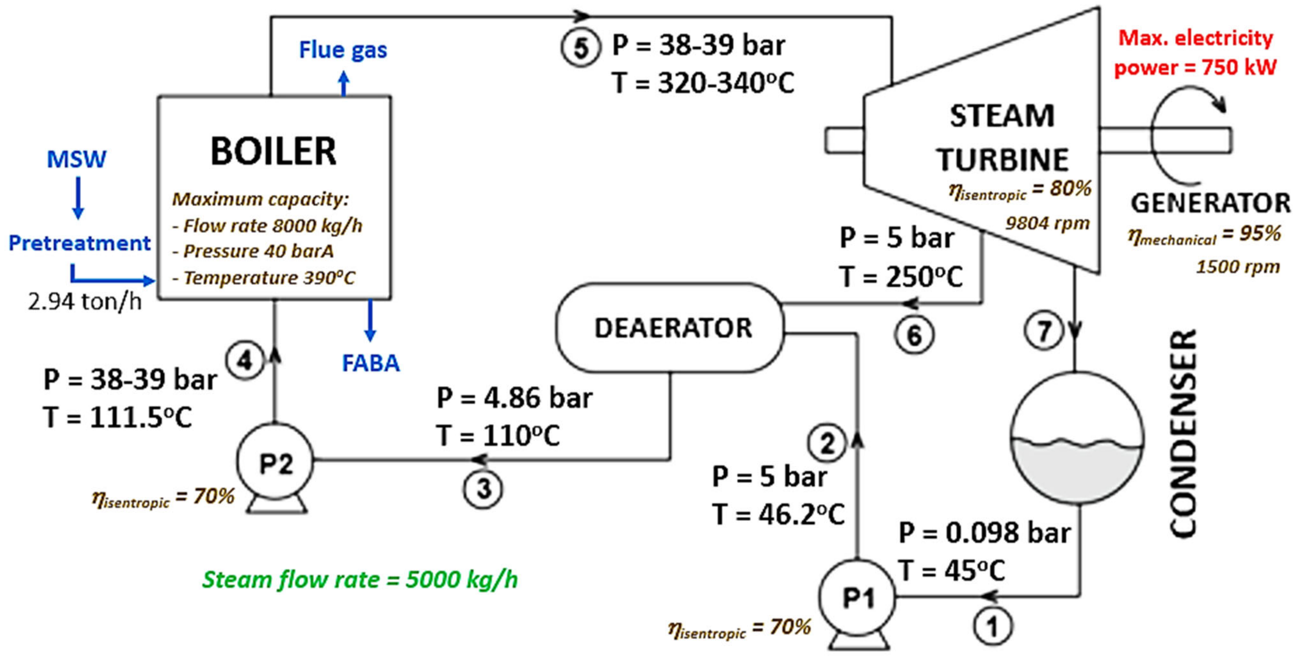

Fig. 2: Electricity generation of WTE Bantargebang through Rankine cycle.

2.3 Characterizations and environmental parameters

Proximate and ultimate analyses were carried out on raw waste, waste after sorting, and waste after air drying in bunkers. The proximate analysis followed ASTM D3173-03 for MC, ASTM D3175-07 for volatile matter, ASTM D3172-07a for fixed carbon, and ASTM D3174-02 for ash content. The MC during the operation was recorded using a moisture meter with a 1-75% measurement range. The ultimate analysis referred to ASTM 3172-3175 for C, H, O, N, and S elements. Meanwhile, the calorific value was measured by ASTM D5865-13 using a bomb calorimeter.

Apart from thermal energy, the WTE also generated waste from flue gas, ash, and wastewater. The WTE was equipped with air, solid, and water pollution control systems to keep the surrounding environment safe. One technology often used to process flue gas combines quenching [22,23], chemical adsorption using slacked lime and activated carbon, and bag filtering [24]. Quenching and chemical adsorption function to reduce the level of acid substances, whereas the bag filter functions to filter out particulates carried by flue gases before being discharged into the environment through the chimney [25].

In the quencher, flue gas flowed from the bottom up in the opposite direction to the sprayed water (counter-current). It has a maximum capacity of 1,100 m^3/min of flue gas, with an inlet temperature of 2000°C, and an outlet temperature of 1800°C. After leaving the quencher, the flue gas stream was injected with slaked lime, $Ca(OH)_2$, to neutralize the sour gases [26].

Heavy metal (Hg) and dioxin content were found in the gas stream containing fly ash. For this reason, the effort was to inject an absorber in the form of activated carbon. Furthermore, the flue gas will enter the inlet bag filter and undergo filtration. The bag filter was operated at 1800°C with a maximum amount of dust at the outlet of 120 mg/Nm^3. Fly ash and other fine particulates were collected under a bag filter to be accommodated in a silo before utilization or final processing. Flue gas that has been processed then flows through a chimney with a height of 30 m and a diameter of 1.2 m, and the monitoring point or sampling hole was located at 9.6 m from the bottom of the chimney.

The flue gas analyzed from the incinerator was NO_X, SO_2, HCl, HF, CO, dioxins/furans, Hg vapor, and particulate matter (PM_{10} and $PM_{2.5}$). The ambient air around the plant measurement was carried out at four locations (in front of the generator room, outside of the front office, chimney side, and backyard area) by isokinetic sampling using a probe that has an emission measurement sensor. Noise intensity measurement was performed every night using a portable sound level meter. It was conducted in two locations close to residential areas.

On the one hand, residue from incineration in the form of FABA was collected in silos, whereas flue gas was formed from incineration. The amount of mineral content in FABA was determined by X-ray fluorescence (XRF) following the ASTM D6349-13 method. Afterward, the toxicity characteristic leaching procedure (TCLP) method was used as a standard for solid waste examination to scrutinize the potential for hazardous chemicals from the inorganic element contained in fly ash. It was recorded using the atomic absorption spectroscopy (AAS) technique.

Further, the wastewater was treated in a wastewater treatment plant (WWTP). Water analysis from WWTP processing included pH, biological oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), total nitrogen, and metals such as mercury and cadmium.

3. Results and discussion

3.1 Performances of incinerator

The proximate and ultimate analysis of the MSW is outlined in Table 1. Raw waste's MC is higher than raw waste MC of the sorted waste and air-dried waste. The raw waste from the source has an average MC of 20.13%-wt (air-dried basis) or 67.46%-wt (as received) which can lead to low efficiency of the incineration process. It can also be implied that the higher MC alleviates calorific value. This results in hardening the incineration process, where a lower calorific value reduces the incineration efficiency and vice versa [27,28].

The sorting process removes the wet waste, reducing the MC to 18.22%-wt (air-dried basis) or 66.22%-wt (as received). Afterward, air drying also evaporates the MC in sorted waste until 8.59%-wt (air-dried basis) or 29.14%-wt (as received). Drying increases waste calorific value from 14.08 MJ/kg to 23.77±2.31 MJ/kg. This value is in line with other MSW characteristics, which lie in Malaysia [29], Nigeria [30], Thailand [31], and Pakistan [32,33]. It can be seen that this waste is combustible due to its low ash content and significant carbon content [34,35]. The content of N and S in the waste is also below 5%-wt, so the potential for N-based and S-based in flue gas is not expected to stand out [36,37]. However, the MC recorded from proximate analysis is the laboratory result which does not represent the MC during the operation measured by the moisture meter.

Table 1. Proximate and ultimate analysis of MSW in WTE Bantargebang compared to other countries.

	Malaysia	Nigeria	Thailand	Pakistan	WTE Bantargebang (Indonesia)		
					Raw Waste	Sorted Waste	Air-Dried Waste
Proximate analysis							
Moisture Content (%)	14.6	48.74	5.51	3.3	20.13*	18.22*	8.59*
					67.46**	66.22**	29.14**
Volatile Matter (%)	69.35	34.39	76.23	79.7	63.78	67.46	75.6
Fixed Carbon (%)	9.00	10.01	14.87	7.2	1.44	1.58	2.77
Ash Content (%)	7.05	6.86	3.39	9.1	14.65	13.77	13.03
Calorific Value (MJ/kg)	18.99	21.58	16.42	15.98	14.08	14.60	23.77
Ultimate analysis							
C (%)	45.00	50.09	44.48	63.6	50.32	48.43	53.82
H (%)	N/A	6.98	5.67	8.19	6.65	8.06	8.94
O (%)	N/A	30.15	49.83	27.0	22.20	25.62	31.46
N (%)	N/A	1.56	N/A	0.4	1.37	0.71	1.33
S (%)	N/A	1.23	N/A	0.1	0.44	0.35	0.21
Refs.	29)	30)	31)	32,33)	This work		

* air dried basis ; ** as received

During operation, the average MC of waste is 65.59±10.57%-wt with fluctuations presented in Fig. 3. Fluctuations occur due to the dynamic characteristics of waste incinerated. The significant MC significantly affects the incineration temperature, so it needs to be a focus of attention in its operation. It causes waste to clump and further clog the feeding line. Besides, the temperature can also decrease drastically and cause adverse incineration performance. If these cannot be avoided, a burner must be operated to maintain the incinerator temperature and steam flow rate.

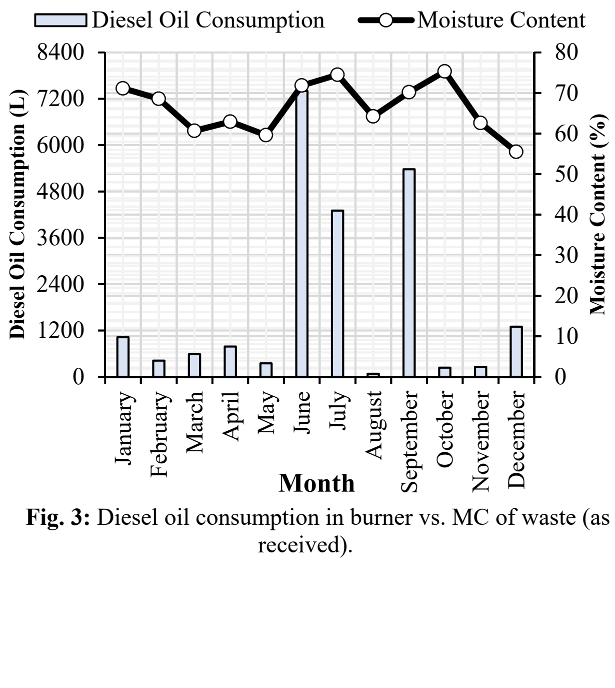

Fig. 3: Diesel oil consumption in burner vs. MC of waste (as received).

Figure 3 also reflects the amount of diesel oil consumed in the burner. The increased pattern in MC due to the rainy season is in line with the significant enhancement of diesel oil consumption. It can be seen that the most significant burner usage (surpassing 1300 L) is found in June, July, and September. During this rainy season, waste is difficult to incinerate since the MC increases to 70%. To reduce diesel oil consumption and to improve the incineration process, additional waste from landfills with lower MC is employed.

Beyond MC, problems are also found in large-sized waste in the incinerator. If large-sized waste escapes and enters the incinerator, the waste becomes challenging to incinerate and easy to drag out along with the bottom ash. Incinerating large-sized waste causes problems such as clogging, unequal waste loading, blockage of the bottom ash channel, and scraper damage in the incinerator. The incinerator temperature should be routinely maintained until the flame remains stable to anticipate them. If a lot of large-sized waste amount of waste enters the incinerator, it should immediately be removed before it falls into the bottom ash channel.

The incinerator's performance is strongly affected by the MC of the waste. During the operation, it was found that the incinerator start-up time requires only ±3 hours in the dry season. However, it can take longer during the rainy season, 5-8 h hours, due to the waste's MC reaching more than 60%-wt. After start-up, the incinerator temperature takes 3-4 hours to reach 400-500ºC. After over 5 hours, the temperature reaches 500-600ºC, then slowly rises to 700ºC.

In the early stages of incineration, especially when the waste still has a high MC, a lot of smoke and soot is produced due to the waste not being completely incinerated [38]. In this condition, the dominant phenomenon that occurs is the drying process and release of volatile materials [39]. The thermal cracking of volatile materials tends to form polyaromatic hydrocarbons, which lead to the formation of smoke and soot [40,41]. During operation, smoke and soot are black and produced in the first 18 s with the longest recorded being 12 mins.

During January-December 2022, the WTE carried out operational activities for 241 working days and 124 days of maintenance activities. During the operational period, the total incinerated waste was 15,451.35 tons, and the total FABA was 1,121.24 tons. Likewise, the average waste reduction during the total operation is 81.52-96.50% of the initial waste weight. The weight of FABA from this work is still 2.5%-wt of the number of waste as fly ash and 20%-wt as bottom ash [42].

The performance of waste incineration in the WTE during this period is shown in Fig. 4. It is indicated that FABA production amount fluctuations are the same as incinerated waste amount fluctuations. It is seen that the steep alleviation of waste reduction occurs in February, July, and October. It is due to the incinerator maintenance activities.

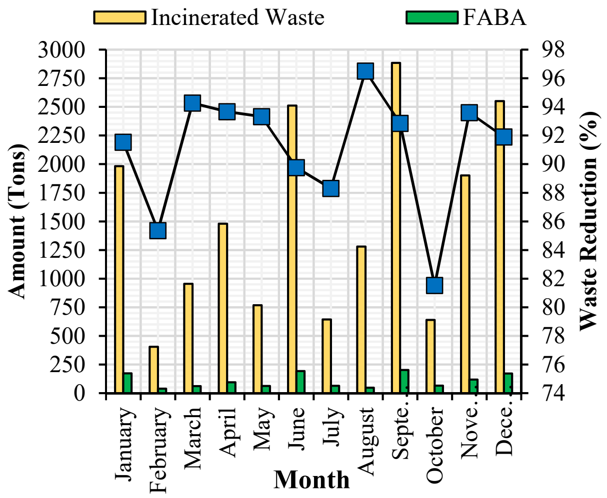

Fig. 4: Waste incineration performance in WTE Bantargebang.

3.2 Potential of power generation

Water consumption for BFW from the deep well is plotted in Fig. 5. When the power plant is entirely operated for 24 hours, the total water consumption reaches 396.7 m^3 daily. A series of water treatments generates a maximum of 118.3 m^3 of demineralized water daily. During January-December 2022, the total water consumption was 47,979.41 m^3, whereas the total demineralized water production was 10,940.6 m^3. Demineralized water is produced in the range of 18.42-35.36%-wt from raw water from a deep well. The rest is used for domestic water and processed water. The distribution per month is depicted in Fig. 5.

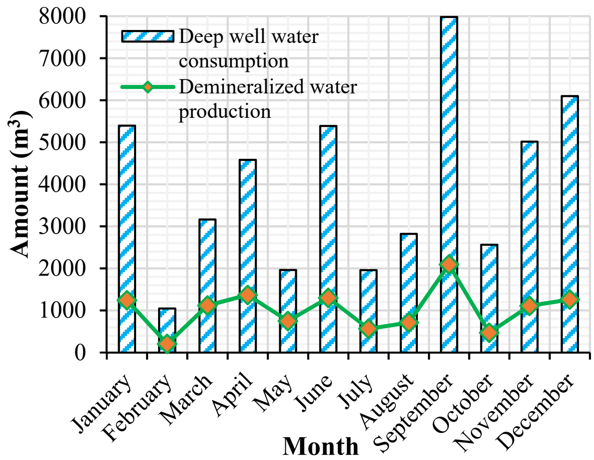

Fig. 5: Deep well consumption vs. demineralized water production for BFW.

Inside the power generation section, there is a deaerator that functions to remove excess oxygen levels as well as to upgrade the efficiency of the Rankine cycle [43,44]. The deaerator obtains heat energy from superheated steam from the expansion of extractive turbines.

Following the boiler operation data, the superheated steam temperature is strongly influenced by incinerator temperature. The average incinerator temperature is

613.8°C with a maximum value of 928°C, and the average steam temperature is 201.1°C with a maximum value of 340°C. The superheated steam condition reaches 38-39 barA with an average of 17.25-19.35 barA.

Based on the number of operational days, the total electricity generated from the steam turbine achieves 956.04 MWh. This electricity potential is entirely used for the internal needs of the plant operation, 1368.78 MWh. Actually, the electrical energy involved in the WTE sources from the State Electricity Company, emergency generator, and electricity generated from the steam turbine. The use of electrical energy sources depends on the ongoing process.

During operation, by synchronizing the rotation of the turbine, the primary source of electricity is generated from the turbine and generator in the plant. During operation without synchronizing turbine rotation, the source of electricity is supplied from external sources (the State Electricity Company and the emergency generator). Operations without turbine synchronization include turbine maintenance, plant shutdown, and plant start-up.

The pattern of fluctuations in the amount of electricity generated (black line) follows the pattern of incinerated waste amount (yellow bar chart), as shown in Fig. 6. The fluctuation of generated electricity from the steam turbine, 7.99-192.99 MWh, follows fluctuations in the WTE internal electricity consumption. In fact, the generated electricity is also used for office lighting and the waste sorting process. The biggest electricity demand is to drive the crane which is used to stir the waste in the pit storage and put the waste into the boiler.

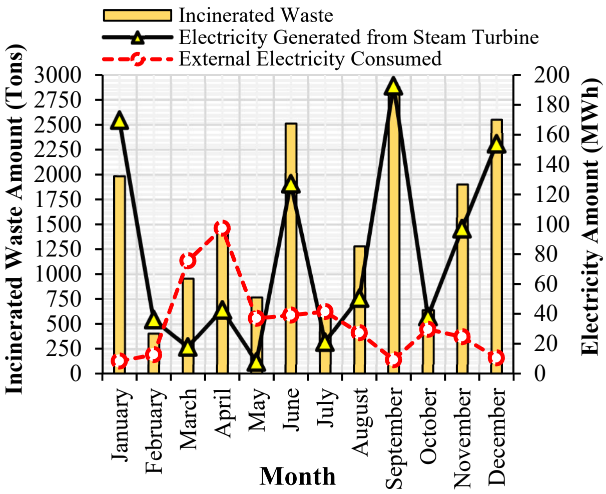

Fig. 6: The pattern of electricity amount and incinerated waste in MSW power plant.

Besides, the WTE's internal electricity supply will be replaced by the State Electricity Company when maintenance is carried out on the boiler. It was aimed at cleaning the scale and dirt that remained on the boiler grid from combustion waste. This boiler cleaning is carried out every month, reducing the WTE factor capacity by up to 14.55%.

The ratio of incinerated waste to generated electricity ranges from 11.22 to 96.06 tons/MWh. This ratio is low compared to the previous study [45]. The WTE has a mass reduction ratio of 81.52-96.50%, which is relatively higher compared to the previous study ratio, of 70% [46].

Total electricity consumption for the WTE operations in 2022 from the State Electricity Company is 409.83 MWh, and from the emergency generator is 2.91 MWh. It should be noted that the electricity from the State Electricity Company is only intended for plant maintenance activities including boiler and turbine maintenance and from the emergency generator only in times of start-up and shutdown processes. Due to those conditions do not always happen, the amount of external electricity consumption from both the State Electricity Company and the emergency generator varies (changes) from month to month.

The ratio of electricity generated from the steam turbine to external electricity consumed has a value of 20.34 in January, 2.85 in February, 3.26 in June, 1.86 in August, 20.86 in September, 1.29 in October, 3.95 in November, and 14.66 in December. In contrast, the highest use of electricity from external sources occurs in March, April, May, and July with values of 4.25-fold, 2.28-fold, 4.62-fold, and 1.96-fold greater than electricity generated from the steam turbine, successively. It happened because there were turbine and ejector system maintenance activities in March, April, May, and July in order to avoid frequent power trips. The comparison of electricity amount from three sources can be seen in Fig. 7.

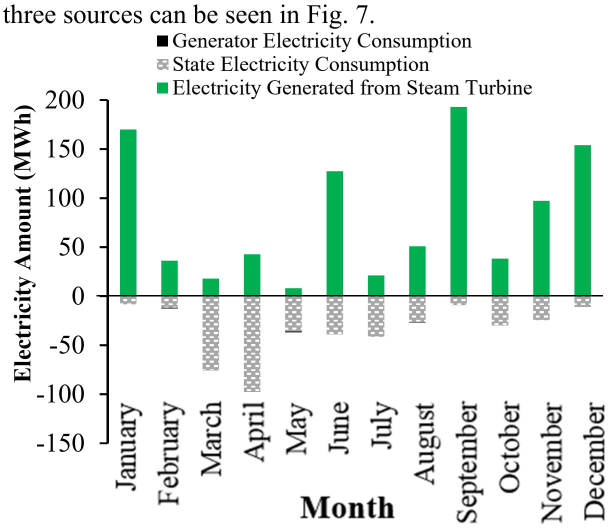

Fig. 7: Comparison of electricity amount (electricity generated is indicated as a positive sign, electricity consumption is indicated as a negative sign).

3.3 Environmental performance

3.3.1 Flue gas characterization results

Flue gas from the incineration process has temperatures of 80.4-148°C. However, the characteristics of flue gas emission depend on the incinerated waste conditions and characteristics. The emissions generally contain gases such as NO_X, SO_2, HCl and HF, CO, dioxins/furans, and

Hg vapor (from waste-containing metal) and particulates (PM_{10} and $PM_{2.5}$) [47,48]. Gas emissions should be suppressed in number by creating near-perfect incineration conditions [49]. It can be realized by adding the amount of air to create a turbulence effect (mixing waste and air) and improve the incineration system [50–53]. The quencher decreases the flue gas temperature by transferring sensible heat to the water until it evaporates. Lowering the temperature of the flue gas can prevent the formation of dioxins through de novo synthesis and reduce some particulates [54,55]. If emissions are still being produced, slacked lime and activated carbon injection are chosen to aid pollution prevention [26,56].

NO_X arises from the content of N elements in the waste. The formation is strongly influenced by the oxygen concentration in the air, incineration chamber temperature, and residence time [57]. With so many potential emissions and dangers to health, flue gas processing is vital in this MSW power plant. On the other hand, SO_2, HCl, and HF amounts are directly related to sulfur, chlor, and fluor content in waste such as paper, plastic, PVC, and used Teflon [58]. Excess oxygen causes SO_2 and SO_3 formation, whereas a lack of oxygen induces the formation of hydrogen sulfide (H_2S) and carbonyl sulfide (COS) [59]. The presence of these gases in the atmosphere results in poor visibility, corrosion of materials, irritation of human and animal organs, and generation of acid rain [60].

The CO concentration in flue gas is an indicator to measure incineration efficiency. CO emissions occur when waste is not completely oxidized to CO_2 [27]. Oxygen concentration, primary to secondary air ratio, incineration chamber temperature, and residence time are several factors that affect CO formation [61]. Additional air (oxygen) reacts with these gases into CO_2 and H_2O. Unfortunately, if there is too much air, it lowers the incineration temperature, which has an impact on slowing down the oxidation reaction [62]. If the air supply is too low, the mixing becomes incomplete and augments CO concentration. In addition, high CO content generally correlates with high emissions of dioxins and furans in the flue gas [54].

Particulate matter derives from inorganic, organometallic, and incomplete waste incineration [63]. Most inorganic materials exit the system through the ash disposal, and a small part is dragged into the flue gas [64]. Organometallic materials oxidize at high temperatures and occur as inorganic oxides in the flue gas, generally as metal oxides, chlorides, and metal mercury, released as a vapor [65]. Cadmium is produced from discarded batteries and electronic equipment [66]. Mercury can emerge from electronics and thermometers [67].

The formation of particulates in waste incineration depends on waste characteristics, waste feeding method, air velocity, incineration temperature, mixing and residence time of flue gas, and incinerator design [55,68]. Greater incineration temperature and longer residence time cause particle incineration to be more complete, thereby reducing particle size. The longer residence time of flue gas also results in more extensive and heavier particulates falling to the bottom of the incinerator [69]. Thus, it is imperative to do waste sorting, as has been exemplified in this work.

To demonstrate its performance, the flue gas emission was measured and the results are summarized in Table 2. It is exhibited that all parameters are met with the national standards. The parameters of SO_2, HCl, HF, CO, and Hg vapor show values far below the detection limit. The performance of the adsorption process using slake lime and activated carbon can be considered quite successful in neutralizing NO_X, SO_2, HCl, and HF, which is reflected by the reasonably low values in the results of these parameters. The results indicate that the bag filter performance is effective. In the meantime, the low CO emission demonstrates that the incineration process runs quite perfectly. Besides, the waste sorting process can be declared successful in separating materials containing Hg, as evidenced by the least Hg vapor content.

Table 2. Flue gas emission measurement results.

Parameter	Result	Standard*	Unit
NO_X	212.9	470	mg/Nm^3
SO_2	<2.6	210	mg/Nm^3
HCl	<0.01	10	mg/Nm^3
HF	<0.1	2	mg/Nm^3
CO	<1.1	625	mg/Nm^3
Dioxins/Furans	0.02	0.1	ng/Nm^3
Hg Vapor	<0.0003	3	mg/Nm^3

*National Quality Emission Standard referring to the Regulation of MoEF Number P.15/2019

After flue gas treatment, it can be vented into the atmosphere as ambient air. Based on the average results of ambient air quality measurements, no air quality parameters exceed the quality standard, as tabulated in Table 3. All parameters are entirely in accordance with Government Regulation Number 41/1999 concerning air pollution control.

Table 3. Average measurement results of ambient air at four sampling locations.

Parameter	Measured Value				Standard Value
	Location 1	Location 2	Location 3	Location 4	
NO_X*	0.0111	0.0159	0.0164	0.0231	400
SO_2*	0.0116	0.0152	0.0263	0.0108	900
CO*	0.31	0.37	0.31	0.33	30000
PM_{10}**	33.75	45.20	69.54	42.82	150
$PM_{2.5}$**	24.12	32.97	27.18	30.13	65

* unit in ppm ; ** unit in mg/m^3

Besides emissions, the WTE location is close to local residential areas. Noise has been generated during the operation. Indeed. The community reports evidence of this. Especially at night. Based on the results of noise intensity measurements. The daily noise level does not exceed the threshold value (60 dB). The average noise intensity during operation is measured at 50.04-50.60 dB with a maximum value of 56.9-59.1 dB. Several sources of noise have been identified. i.e., from generators and venting safety valves. Several actions to reduce noise are minimizing the opening of the venting safety valve and installing the silencer.

3.3.2 Fly ash and bottom ash (FABA)

FABA is generated as a solid residue from the incineration process. Bottom ash has a larger particle size and higher weight than fly ash, so it tends to sediment to the bottom of the incinerator. The physical properties of bottom ash can be observed based on its color. The lighter the ash color, the incineration occurs in a complete conversion, and it also indicates high CaO content and low carbon [70]. Bottom ash usually recovers about 20%-wt from waste input amount [71].

In the meantime, fly ash is a fine particulate of waste incineration residue entrained in the flue gas stream. Fly ash occupies 2.5%-wt of the waste amount, and has a melting point and density of 1300°C and 2.58 g/cm³, respectively [72,73]. The color of fly ash is affected by the incineration duration and generally has a dark grey color [70]. Fly and bottom ash should not be disposed of into the environment. It contains a high concentration of toxic substances, including metals and dioxins [74].

According to the XRF results in Table 4, SiO_2 occupies the largest mineral content and is followed by CaO, Al_2O_3, and Fe_2O_3. The minerals of SiO_2, CaO, Al_2O_3, and Fe_2O_3 were similar to other countries, while other oxides cannot be compared since other countries do not provide them. Beyond the aforementioned minerals, fly ash from this work contains 2.20% P_2O_5, 2.19% MgO, 1.72% TiO_2, 1.18% K_2O, 0.46% Na_2O, 0.11% SO_3, and 0.19% MnO_2. Meanwhile, bottom ash from this work contains 2.55% P_2O_5, 1.73% MgO, 0.83% TiO_2, 0.91% K_2O, 0.55% Na_2O, 0.42% SO_3, and 0.14% MnO_2.

Table 4. XRF result of FABA obtained from this work and other countries.

Fly Ash						
Minerals	Unit	This work	Tarragona, Spain [75]	Jeonju, Korea [72]	Jiangsu, China [76]	Harbin, China [73]
SiO_2	%	31.62	8.09	2.05	38.51	27.51
CaO	%	29.03	35.90	28.8	2.29	23.25
Al_2O_3	%	16.24	9.08	0.47	24.35	7.12
Fe_2O_3	%	5.48	0.91	0.35	1.85	5.11
Bottom Ash						
Minerals	Unit	This work	Wijster, Netherlands [77]	Punjab, India [78]	Taiwan [79]	Poland [80]
SiO_2	%	43.44	54.2	54.43	53.8	35.7
CaO	%	20.94	13.4	18.71	18.3	13.9
Al_2O_3	%	13.04	7.9	10.11	4.0	8.6
Fe_2O_3	%	6.32	13.8	5.29	3.3	16.8

The handling of FABA from WTE plants in Indonesia should comply with the MoEF Regulation No. 26 of 2020, where TCLP of fly ash must be analyzed for its elements and carried out solidification/stabilization before being utilized or dumped. Meanwhile, bottom ash has no set quality standard and can be used directly or dumped in landfills. This fly ash can be consolidated into cement admixture or paving blocks for construction materials [81], while bottom ash is directly dumped in the Bantargebang landfill. The TCLP results of element analysis in fly ash and its quality standard are served in Table 5.

Table 5. Inorganic elements in fly ash at WTE Bantargebang.

Parameters	Aug	Nov	Dec	Standard*	Unit
Ar (Arsen)	<0.07	1.04	<0.07	0.5	mg/L
Ba (Barium)	0.30	0.47	0.33	35	mg/L
Be (Berilium)	<0.03	<0.03	<0.03	0.5	mg/L
Cd (Cadmium)	<0.01	<0.01	0.19	0.15	mg/L
Cl (Chlorine)	587	2361	601	12.500	mg/L
Cr(VI) (Chrom)	<0.01	<0.01	<0.01	2.5	mg/L
Cu (Copper)	0.02	0.12	0.05	10.0	mg/L
Hg (Mercury)	<0.018	<0.018	<0.018	0.05	mg/L
Ni (Nickel)	<0.03	<0.03	0.21	3.5	mg/L
Pb (Lead)	<0.06	<0.06	<0.06	0.5	mg/L
Se (Selerium)	<0.13	<0.13	<0.13	0.5	mg/L
Zn (Zinc)	0.11	0.02	2.36	50.0	mg/L

*Reg. of MoEF Nr. P26/2020

3.3.3 Wastewater effluent

WTE Bantargebang has wastewater treatment facilities by means of WWTP to treat process wastewater. Table 6 reports the quality of water resulting from processing. Based on the results, the water quality processed by WWTP has met the quality standards that refer to Regulation of the MoEF Nr. P59/2016. This characteristic was similar to the leachate from WTE plants in China [82]. The results showed that the WWTP was able to treat the leachate, and the effluent met the standard.

Table 6. Leachate quality before and after treatment in WWTP.

Parameter	Units	Inlet	Outlet	Standard Value[1]
pH	-	7.5	7.7	6-9
BOD	mg/L	8.99	75	150
COD	mg/L	17.99	149	300
TSS	mg/L	24	21	100
Total Nitrogen	mg/L	120.5	24	60
Mercury	mg/L	0.0015	<0.0005	0.005
Cadmium	mg/L	0.085	<0.015	0.1

[1]Regulation of the MoEF Nr. P59/2016

3.3.4 Improvements and advice for future studies

Nowadays, the operation of WTE Bantargebang using MGI technology equipped with the pre-treatment facility is the pioneer in using waste incinerators for energy in Indonesia. From a year of operation, the results were that the mass ratio reduction could reach a maximum of 96.5%. However, the WTE performance parameters such as a capacity factor of 14.55% and the low conversion ratio of incinerated waste to kWh were low, indicating that WTE performance needs to be improved.

Also, the sorting capability of the pre-treatment needs to be improved so that the waste that enters the boiler is flammable, not bulky, and more homogeneous. The sorting capability can also ensure the stability of the calorific value of the waste entering the boiler.

These deficiencies and improvements demanded in the WTE facility performances can be valuable information, and also additional operation know-how and knowledge for the development of WTE in big cities in Indonesia.

4. Conclusions

During one year of operation, the WTE Bantargebang power plant using the MGI technology equipped with a pre-treatment and an environmental treatment facility has achieved success in reducing 81.52-96.50% of unsorted waste from the source. It is also able to demonstrate environmental performance that meets the national standard. The electricity generated from the steam turbine can supply the WTE internal electricity demand. Moreover, flue gas emissions and ambient air quality meet national standards after flue gas treatment. It even includes dioxins, which many people are concerned about the issue. Likewise, the XRF and toxicity tests from FABA reflect that it is not hazardous and proper for construction materials or cement mixtures. The domestic and process wastewater performance, after treatment as well as noise, also does not exceed the quality standard thresholds. Despite the satisfactory performance of MSW incineration in the WTE, the waste pre-treatment facility still requires improvement to prevent wet and large-sized waste not being carried into the incinerator. In addition, the generated electricity should be utilized up to 750 kW to reduce the purchasing cost of diesel oil and electricity from the State Electricity Company. The maintenance schedule should also be organized more effectively, with working days in mind. By improving the weak points of the WTE plant operation and pre-treatment facility function, the obtained know-how in this work should be implemented to improve the WTE operation performance in the following work. In conclusion, the experience and know-how gained from the WTE plant operations are expected to support the development of similar WTE in the 12 planned cities as part of the national plan to address the large volume of MSW in Indonesia.

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