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Carbon Footprint and Energetics of a 25-kW Direct Combustion Waste-to-Energy System for Municipal Solid Waste

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ABSTRACT

The Philippines faces dual challenges of a mounting energy crisis and an increasing volume of municipal solid waste (MSW). Waste-to-energy (WTE) technologies have emerged as a potential solution to address these issues. One related initiative is the government-funded project on the establishment of a 25-kW WTE facility utilizing a direct combustion process for the treatment of MSW located at the University of the Philippines Los Baños (UPLB) in Laguna, Philippines. To evaluate the technology's potential as a sustainable and environmentally sound alternative for waste disposal in the country, the carbon footprint and energetics performance of the WTE system using life cycle assessment (LCA) approach were evaluated. The assessment was conducted using Aspen Plus® for process simulation and SimaPro® for LCA. The system boundary included the MSW transportation, sorting, and processing. The carbon footprint analysis was based on the functional unit- disposal of 1 kg of MSW, enabling comparative analysis with landfilling as the business-as-usual scenario. The modeled facility generated approximately 27 kW gross power for a feed rate of 50 kg h^{-1} of combustible MSW, achieving a plant capacity factor of 84%. The total greenhouse gas (GHG) emissions of the WTE system was 1.55 kg carbon dioxide equivalent (CO_2e) kg^{-1} MSW, significantly lower than the 3.11 kg CO_2e kg^{-1} MSW associated with landfilling. This translates to a GHG reduction of approximately 1.56 kg CO_2e kg^{-1} MSW, or about 50%. Accounting for avoided emissions due to electricity generation and by-products like precipitated calcium carbonate, the net carbon footprint of the WTE system could be reduced to -0.24 kg CO_2e kg^{-1} MSW. The carbon debt from facility fabrication and installation was calculated at 1.40×10^5 kg CO_2e, which could be offset in approximately 0.20 years based on the system's carbon savings. The system achieved an operational power efficiency of 0.54 kWhr kg^{-1} MSW, comparable to the typical range of 0.30-0.70 kWh kg^{-1} MSW which was reported as the overall power generation rate in a WTE plant. These findings underscore the potential of the WTE system to contribute to sustainable solid waste management and energy generation in the Philippines. Future studies are recommended to explore commercial-scale feasibility to further strengthen the country's drive toward sustainability and energy independence.

Keywords: *bioenergy, biomass, carbon footprint, direct combustion, energetics, incineration, life cycle assessment, municipal solid waste, thermochemical conversion, waste-to-energy*

INTRODUCTION

In recent years, the global and local climate are continuously changing. Current climate trends reveal that the Philippines is not spared from the drastic impacts of climate change due to its archipelagic nature and geographic location. Observed rising temperatures, extreme rainfall, sea level rise, and increased frequency of tropical cyclone occurrence are some of the indications of the country's vulnerability to these impacts (*PAGASA 2011*). According to the United States Agency International Development (*USAID 2016*), the Philippines' total GHG emissions of about 157.6 Mt of carbon dioxide equivalent (CO_2e) comprises 0.33% of the world's total CO_2e emissions. The *Intergovernmental Panel on Climate Change* (*IPCC*) (*2022*) revealed that most of the country's GHG emissions in 2019 were dominated by five major contributors, namely the energy sector (34%), industry (24%), agriculture, forestry, and other land use (22%), transport (15%), and buildings (5.6%).

Within the energy sector, electricity and heat production, transportation, and manufacturing and construction are the subsectors that are predominantly contributing to the increasing carbon dioxide emissions (*USAID 2016*). Generally, the top source of the total primary energy supply of the Philippines based on 2022 figures was oil (32.2%), followed by coal (31%), and geothermal sources (14.6%). Traditional biomass sources accounted for 12.6% while natural gas contributed 4.2% of the primary energy supply. Other renewable energy sources accounted for 5.5% (*Department of Energy Philippine Energy Plan 2023-2050*). Notably, about 46% of the country's total primary energy supply is consumed as fuel by the power sector. Heavy reliance on fossil fuels and imported energy poses significant challenges, with coal power plants alone projected to emit an average of 92 Mt of CO_2 annually (*Mondal et al. 2018*). To address these issues aiming to strengthen the country's energy security as well as provide cleaner and sustainable alternative energy, the National Renewable Energy Program (NREP), in accordance with the Renewable Energy Act of 2008, targets to increase the country's renewable energy generation capacity by three-fold from 5,438 MW in 2010 to 15,304 MW by 2030.

The waste sector, through its waste management activities such as landfilling and wastewater treatment, is also identified as one of the leading contributors to the country's GHG emissions (*Paul 2009*). Due to rapid population growth, urbanization, and economic development, the steadily increasing waste generation has become a significant concern in the Philippines as the country's solid waste per day is projected to reach 77,776 Mg by 2025, having a doubled MSW generation per capita of 0.9 kg d^{-1} from 0.5 kg d^{-1} in 2012 (*Hoornweg and Bhada-Tata 2012*). Over the years, the Philippines has been implementing several laws and regulations to improve its solid waste management. However, despite these laws and regulations, the country is still facing pressing issues on solid waste due to concerns about the implementation of the law leading to a relatively low status of compliance at a rate of only 4.64% in 2012 (*Castillo and Otoma 2013*). In 2018, it was reported that 304 illegal dumpsites are still operational, while only 165 sanitary landfills have been established in the country (*EMB 2019*). These issues are further compounded by factors such as the scarcity of new landfill sites, as many existing facilities have reached full capacity and are forced to close. For instance, Los Baños, Laguna in the Philippines, has struggled to comply with waste management regulations due to the lack of available public land for landfill development (*Los Baños Ecological Solid Waste Management Program 2005*).

Landfills are not only a logistical challenge but also a significant environmental concern. The decomposition of organic material in landfills produces landfill gas, which is a notable source of GHG emissions. Globally, the disposal of MSW through landfilling is considered one of the largest anthropogenic methane emission sources (*Powell et al. 2015*). In the Philippines, emissions from solid waste management are estimated at 7–10 Mt CO_2e yr^{-1} (*Soyez and Paul 2014*).

The rising challenges of waste management and energy security underscore the importance of exploring possible solutions such as waste-to-energy (WTE) technologies. According to the World Energy Council report on World Energy Resources-Waste to Energy in 2016, thermal WTE technologies were the leading technologies that accounted for 88.2% of total market revenue in 2013. The significant growth of the WTE market is driven by factors such as a decline in the number of disposal sites such as landfills, depletion of energy resources, and a rapidly growing demand for energy. Globally, around 1700 thermal WTE facilities process over 216 Mt MSW each year (*Chim 2019*). Regions like North America, Europe, and Asia Pacific have successfully adopted WTE technologies, including direct combustion, gasification, pyrolysis, and anaerobic digestion, to convert MSW into energy (*Gumisiriza et al. 2017*).

Recognizing the potential of WTE technologies, the Philippine Department of Environment and Natural Resources (DENR) released guidelines in 2019 to facilitate the establishment and operation of WTE facilities. One of the related research initiatives was the Department of Science and Technology (DOST)-funded project titled "Establishment of a 25-kW Waste-to-Energy Facility via Direct Combustion Process for Municipal Solid Waste" implemented by the University of the Philippines Los Baños (UPLB). Technical, economic, and environmental studies to evaluate the feasibility of WTE as a viable and environmentally sound option for waste management in the Philippines were conducted. It focused on assessing the carbon footprint and energetics of the 25-kW direct combustion WTE system for MSW using LCA. By analyzing the system's inflows, outflows, and emissions, the aim was to evaluate the potential of WTE as a sustainable solution to the solid waste management crisis in the Philippines and contribute to the broader discourse on renewable energy and climate action.

MATERIALS AND METHODS

Design Basis

The waste-to-energy demonstration facility, with a throughput capacity of 50 kg h^{-1} and a gross power-rated capacity of 32.8 kW served as the design basis (**Figure 1**). The process began with pre-sorted combustible wastes manually loaded into the combustion chamber, where they underwent direct combustion at temperatures ranging from 900 to 1100°C. A simple fixed-bed reactor facilitated this combustion. During start-up, an electronic igniter within the chamber was used to initiate the burning process, while a fan supplied oxygen by blowing air into the chamber. The resulting bottom ash accumulated at the chamber's base and was periodically removed.

The produced combustion gases were treated in a two-step scrubbing process using calcium hydroxide and activated carbon to eliminate acidic or toxic gases.

Figure 1. 25-kW Waste-to-Energy (WTE) Integrated System in the University of the Philippines Los Baños in Laguna, Philippines.

Following this, the gases passed through a cyclone dust collector and a bag filter to capture coarse and fine particles. The cleaned gases were then released into the atmosphere through a chimney. The heat from the flue gases was recovered using a heat resolver, producing hot water at 120°C, which was utilized in an Organic Rankine Cycle (ORC) system to generate electricity.

Process Simulation of WTE System

The WTE system was modeled using Aspen Plus ® software. The overall process flow diagram consisted of a direct combustion system, a flue gas cleaning system, and an ORC system for power generation (**Figure 2**). Unlike the conventional steam cycle, the ORC system, which uses an organic working fluid with higher vapor pressure and lower boiling point than water, allows energy recovery from low-temperature heat sources (*Hoffschmidt et al. 2012*). The ideal property method, which was reported as suitable for solids processing such as in coal processing, was applied in the simulation (*Aspen Plus eLearning, n.d.*). Proximate and ultimate analysis data of the MSW feedstock, based on the study of *Yang et al.* (*2018*), were used as input for the simulation (**Table 1**).

Direct Combustion System. The direct combustion system was modeled using RYield and RGibbs reactors in Aspen Plus ®. Specifically, the RYield reactor allows the decomposition of non-conventional feed such as MSW into its constituent elements, resulting in an easier combustion modelling and simulation using the RGibbs

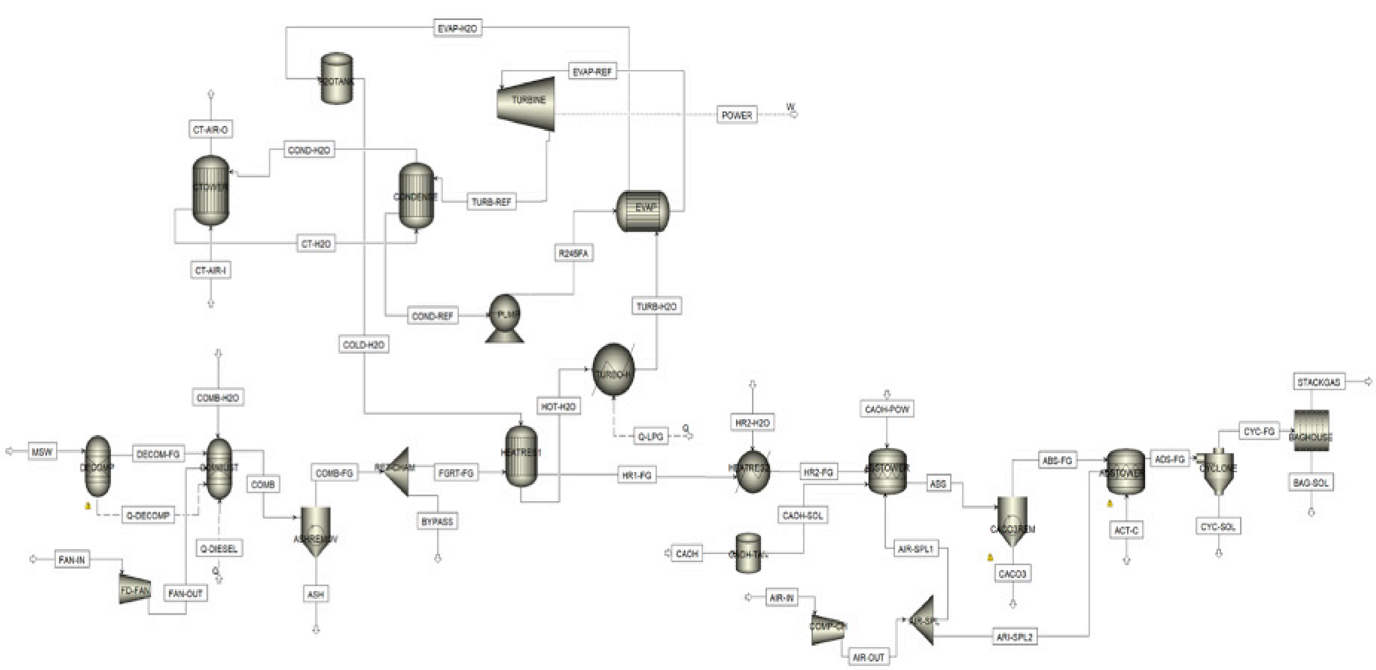

Figure 2. Overall process flow diagram of the waste-to-energy system.

Table 1. Ultimate and proximate analysis of municipal solid waste feedstock.

Ultimate Analysis[a]	Value (%)	Proximate Analysis	Value (%)
C	35.1	Moisture[b]	45.8
H	4.7	Volatile Combustible Matter	51.1
O	16.1	Fixed Carbon	6.3
N	1.4	Ash	42.6
S	0.1		
Ash	42.6		

[a]Presented on an oven-dried mass basis
[b]Moisture content is presented on a wet mass basis

reactor. This reactor modelled equilibrium by minimizing Gibbs free energy (*AspenTech n..d.*). Products of direct combustion at 1,050°C then entered the flue gas retention chamber to facilitate initial decomposition of the organic toxic gases. Subsequently, the combustion gases were blown into an economizer/heat resolver, where useful heat was recovered for power generation (**Figure 3**).

Flue Gas Cleaning System. Flue gas exiting the economizer at 600°C underwent multiple processes, starting with the second heat resolver which allowed further cooling of flue gas from 600 to 250°C before entering the absorption tower. The abrupt cooling of flue gas prevents the maximum formation of dioxins and furans which occurs at 350°C (*Cunliffe and Williams 2008*).

In the absorption tower, calcium hydroxide reacted with carbon dioxide in the flue gas to produce calcium carbonate precipitate. The absorption process using calcium hydroxide was assumed to capture carbon dioxide from flue gas following the chemical reaction (*Equation 1*). This reaction proceeds rapidly in aqueous solution and remains thermodynamically favorable in a wide range of temperature from ambient to 750 ºC (*Han et al. 2011*).

$$Ca(OH)_{2(s)}+CO_{2(g)}\leftrightarrow CaCO_{3(s)}+H_2O_{(l)} \quad (1)$$

Flue gas then entered the dry scrubbing process through the adsorption tower for further removal of toxic gases using activated carbon as adsorbent. According to the study of *Srenscek-Nazzal et al.* (*2015*), about 8.07 mmol of CO_2 can be adsorbed per gram of activated carbon. This value was adopted in the system's simulation study to accurately model the adsorption process. Solid particles were then separated from the flue gas using gas-solid separators such as cyclone dust collector and baghouse filter. Finally, the cleaned stack gas was released through the chimney (**Figure 4**).

Organic Rankine Cycle System for Power Generation. The ORC system employed R245fa as the working fluid, which is suitable for low-temperature heat sources due to its lower boiling point and higher vapor pressure compared to water (*Hao et al. 2020*). From the direct combustion system, the flue gas heats up the cool water via the economizer or heat resolver. The heated water from the heat resolver then directly flows into the ORC evaporator to vaporize the working fluid, driving power generation. A turbo-heater is used to ensure a stable and efficient heat source for the ORC system. Waste heat is then dissipated using a cooling tower (**Figure 5**).

To address the formation of harmful dioxins and furans, known challenges in WTE systems, a

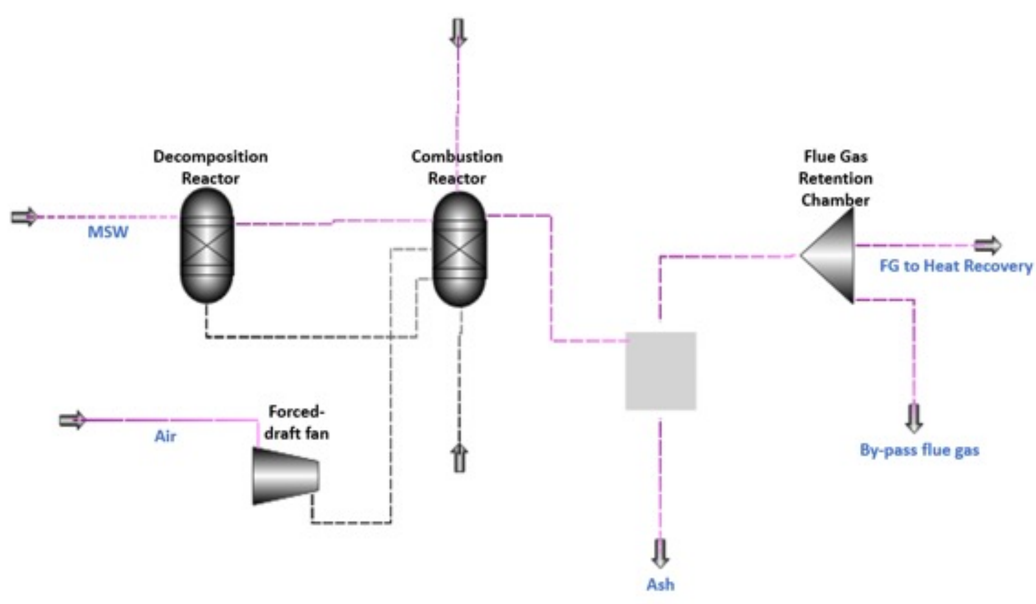

Figure 3. Process flow diagram of the direct combustion system.

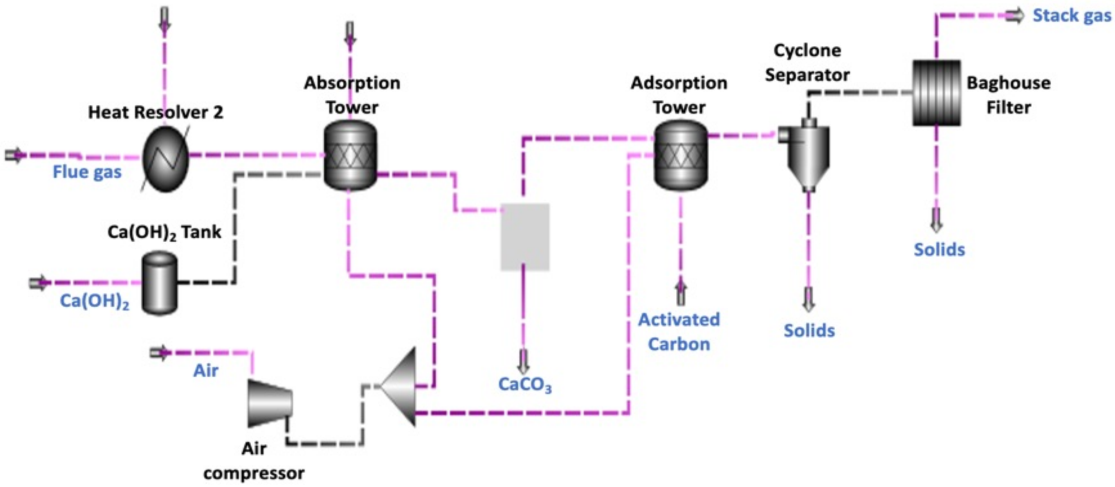

Figure 4. Process flow diagram of the flue gas cleaning system.

combination of optimized combustion practices and robust end-of-pipe treatments in the process design (*Mukherjee et al. 2016*) were incorporated. Good combustion practices included maintaining a combustion temperature of around 1000°C with sufficient residence time to ensure complete breakdown of carbonaceous particles, as well as post-combustion cooling to 200°C to rapidly lower the temperature and inhibit dioxin and furan reformation.

The end-of-pipe treatment system comprised a series of advanced steps designed to mitigate toxic emissions effectively. A quenching tower was employed for rapid cooling of the flue gas, followed by a wet scrubber to remove acidic and water-soluble pollutants. Particulate matter was captured using a bag filter, while activated carbon dosing was introduced to adsorb residual pollutants, including trace amounts of dioxins and furans. This integrated approach ensured comprehensive flue gas treatment while minimizing environmental impacts associated with incineration. Chemicals and consumables used in the WTE system have different flow rates (**Table 2**).

Carbon Footprint Assessment

The environmental performance of the WTE system was analyzed using SimaPro® 9.0.0.35, employing the Ecoinvent database for emission factors. The assessment methods included IPCC 2013 GWP 100a for global warming potential and Cumulative Energy Demand (LHV) for energetics. All material and energy inflows and outflows within the system boundary—municipal solid waste transportation, sorting, and processing—were analyzed (**Figure 6**). Key parameters

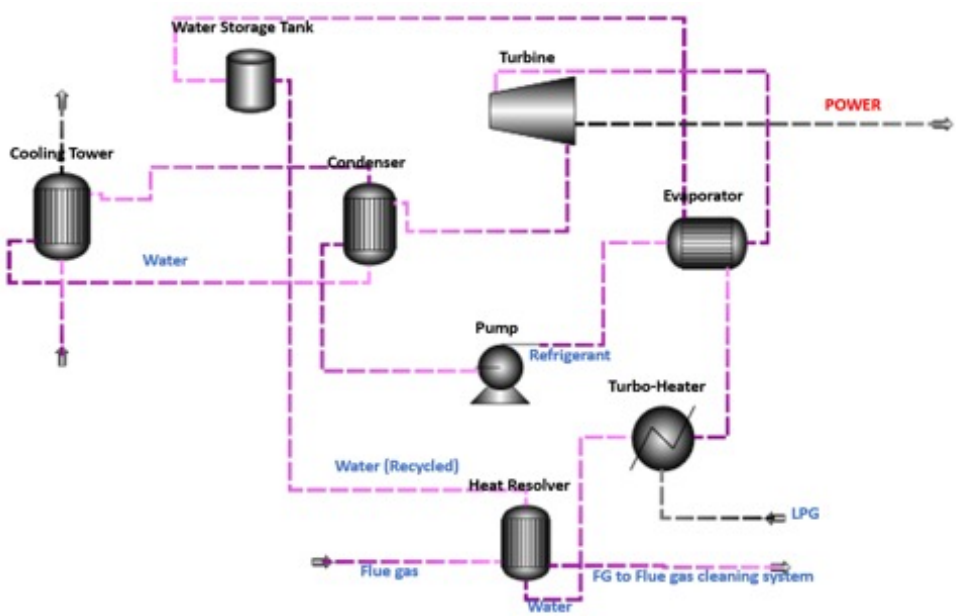

Figure 5. Process flow diagram of the Organic Rankine Cycle (ORC) system for power generation.

Table 2. Chemicals/Consumables of the Waste-to-Energy (WTE) Integrated System.

Chemical	Flow Rate (kg hr^{-1})
Diesel	5.0
Liquefied Petroleum Gas	13.0
Calcium Hydroxide Powder	33.9
Activated Carbon Powder	0.5
Refrigerant[a]	3600

[a]Refrigerant (organic working fluid) is assumed to be replenished every year.

included were: Carbon Debt- the total amount of carbon emitted by the system during plant construction before it started production or operation; Carbon Savings - the difference in carbon emissions of the system under study as compared to other existing systems or baseline scenarios. In this case, it pertained to the total possible reduction in emissions of the WTE system as compared to the baseline landfilling scenario; Carbon Payback Period- the time or period necessary for recuperating all the carbon emitted by the system during plant construction. It indicated the length of time it took for the power plant to recover its carbon emissions before it started production through the carbon savings of the system.

Carbon Debt Analysis. The carbon emissions in the construction of the WTE facility was accounted as carbon debt. The pre-operation inventory included the emissions from equipment fabrication, delivery/transportation, and installation of the WTE system on site. The data on the materials of construction, gross weight, and sourcelocation of each equipment in the system was gathered from the supplier. The transport of equipment, weighing about 30.671 tons in total, from the source supplier was assumed to be via freight shipping by sea for 1,245 nautical miles (equivalent to 2,305.74 km) from Hanoi, Vietnam to Manila, Philippines. Freight shipping by land for 72.9 km was accounted for the transport of equipment from Manila, Philippines to the WTE site in UPLB. The emissions during the installation and integration of the individual equipment were referred to as metal working. Likewise, the electricity consumption for the installation and integration of the WTE system on site was assumed to be 100 kWhr d^{-1} for 30 operating days, which was the estimated average based on the actual site installation of the demonstration facility (**Table 3**).

Carbon Savings Analysis. Carbon savings were calculated by comparing the WTE system with the business-as-usual scenario of landfilling without energy recovery, reflecting the typical practice in the country where most landfill facilities lack provisions for gas recovery. The calculation also accounted for the transport of MSW from the material recovery facility to the Pilotage Trading and Construction Landfill in San Pedro, Laguna.

The assessment of carbon emissions for the WTE system was within the defined system boundary that included MSW transport and the plant operation proper. For MSW transport, it was assumed that the feedstock was sourced from two primary locations: UPLB and Barangay Putho-Tuntungin in Los Baños, Laguna. These sites were identified as the actual waste generators supplying the established demonstration facility. However, emissions from the collection and transport of MSW within UPLB and Barangay Putho-Tuntungin were excluded due to the difficulty of quantifying contributions from diverse waste sources without precise data on waste volumes and routes. Instead, the analysis focused on the transport of 182 tons of MSW annually over a 5.9 km distance

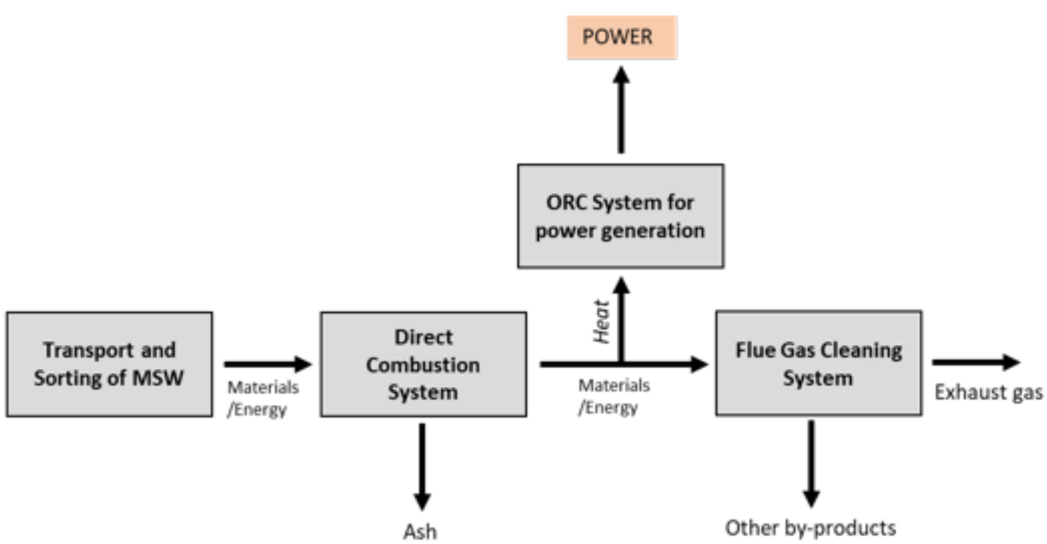

Figure 6. Overall system boundary for carbon footprint assessment.
Note: MSW – Municipal Solid Waste ; ORC – Organic Rankine Cycle

Table 3. Inputs for the carbon debt analysis.

Input	Amount	Unit
Steel	29,231	kg
Aluminum alloy	140	kg
Glass fibre reinforced plastic	1,200	kg
Copper	100	kg
Transport (sea)	70,719.35	ton-km
Transport (road)	2,235.92	ton-km
Metal working for aluminum alloy	140	kg
Metal working for steel	29,231	kg
Metal working for copper	100	kg
Electricity	3000	kWh

from Barangay Putho-Tuntungin's material recovery facility to the WTE site.

Consequently, carbon emissions from plant operations were assessed based on material and energy balances derived from process simulation. It was assumed that the WTE plant operates for 365 d yr^{-1} and 24 hr d^{-1}. Inputs included the chemicals and consumables required for operation, as well as their transport over a distance of 72.9 km. The plant's power consumption was estimated at 9.6 kW, representing approximately 30% of its rated power output.

For the baseline landfilling scenario, carbon emissions were estimated using the IPCC default method for methane emissions from solid waste disposal. This method employs a simple mass balance calculation, assuming that all methane generated by decomposing waste is released in the same year the waste is disposed of (*Ghosh et al. 2018*).

Carbon Payback Period. The carbon payback period was computed as the ratio of carbon debt to annual carbon savings. This parameter signifies the length of time required to offset construction emissions through carbon savings.

Energetics Assessment

Energetics assessment used the Cumulative Energy Demand method to evaluate relevant parameters such as: Energy Debt - the total amount of energy consumed by the system during plant construction before it has started production or operation; Energy Savings- the difference in energy requirement of the system under study as compared to the baseline scenario of landfilling; Energy Payback Period - the time or period necessary for recuperating all the energy consumed by the system during plant construction. It indicates the length of time it takes for the power plant to recover the energy invested before it has started production using the energy savings of the system; Energy Ratio (ER)- an indicator also known as Energy Return on Energy Invested (EROEI). It is a value of output energy divided by the input energy.

Energy Debt Analysis. The energy debt of the WTE system was calculated using an approach similar to the carbon debt analysis. This involved accounting for the energy consumed during equipment fabrication, transportation, and installation (**Table 3**).

Energy Savings Analysis. Energy savings were determined through a direct comparison of the energy consumed versus the energy generated by the WTE system during plant operation. Specifically, energy savings were calculated as the difference between the system's gross energy output and the energy required for plant operation. Consistent with the carbon emissions assessment during WTE operation, the energy associated with all inflows and outflows during operation was evaluated using material and energy balances derived from process simulation.

Energy Payback Period. The energy payback period, representing the time required for the WTE system to recover the energy expended during plant construction and installation, was calculated after determining the energy debt and savings. This parameter highlights how quickly the system can offset its initial energy investment and begin yielding net energy gains.

Environmental Hotspot Analysis

An environmental hotspot analysis was conducted to identify process stages contributing significantly to global warming and energy use. This analysis provided insights into critical areas of improvement, enabling the recommendation of targeted measures and strategies to enhance sustainability and minimize the environmental impact of the 25-kW direct combustion WTE system for MSW.

RESULTS AND DISCUSSION

A gross power of 27.0645 kW is generated by the system for a 50 kg hr^{-1} input of MSW with a calorific value of 5,000 kcal kg^{-1}. Compared to the existing facility's average output of 23 kW, the simulated system showed comparable performance. From the 50 kg hr^{-1} input of MSW with specified composition, the resulting decomposed feed comprised of 50.18 %wt H_2O, 0.83 %wt N_2, 0.06 %wt O_2, 2.79 %wt H_2, 20.84 %wt C, and 25.30 %wt ash. The cleaned stack gas, with a flow rate of

775.9073 kg hr^{-1}, had the following composition (w/w): 61.38% H_2O, 31.54% N_2, 5.35% O_2, 1.71% CO_2 and trace amounts of NO_2, NO, CO, H_2, and particulates. Identified by-products included ash, calcium carbonate, and used activated carbon (**Table 4**).

Carbon Footprint and Energetics

Carbon Debt. The total GHG emissions during the construction of the WTE facility amounted to 1.4 x 10^5 kg CO_2e. Steel production and metal working processes contributed the largest share of about 42.63% and 45.64%, respectively, as most equipment components were made of steel (**Figure 7**).

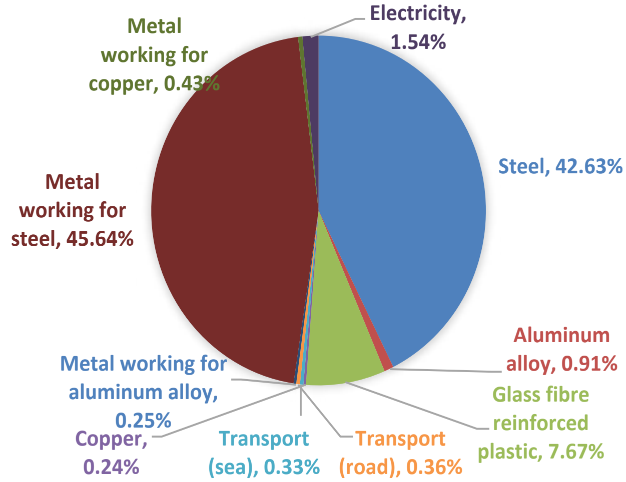

Figure 7. GHG emissions distribution for waste-to-energy (WTE) facility construction.

Carbon Savings. The WTE system was compared to the business-as-usual scenario of landfilling to estimate its GHG reduction potential. During WTE operations, the system emitted 1.55 kg CO_2e kg^{-1} MSW, with lime usage being the largest contributor to emissions (**Table 5**).

To mitigate these environmental impacts, calcium carbonate, a by-product of the reaction between calcium hydroxide and carbon dioxide in the flue gas, can be recovered and repurposed. This recovered calcium carbonate has potential applications as fillers, additives, and reinforcements in industries such as paper, plastics, and cement, qualifying it as an avoided product.

By incorporating this recycled material into other processes, the system could achieve a GHG reduction of approximately 1.54 kg CO_2e kg^{-1} MSW. Similarly, the surplus power generated by the WTE facility, when compared to landfilling without energy recovery, can also be classified as an avoided product. This surplus energy contributes an additional potential GHG emission reduction of 0.254 kg CO_2e kg^{-1} MSW. When considering all process emissions alongside the potential GHG reductions from these avoided products, the WTE system's net GHG emissions could reach as low as -0.24 kg CO_2e kg^{-1} MSW.

When compared to landfilling, the WTE system revealed a significantly lower environmental impact in terms of carbon footprint. Landfilling exhibited higher GHG emissions, with methane (CH_4), a potent greenhouse gas, being the primary contributor. Using

Table 4. Stream summary of outflows from the Waste-to-Energy (WTE) system.

Stream Name	Unit	Ash	Bypass	$CaCO_3$	CYC Solids	Bag Solids	Stack gas
Temperature	°C	1053	1053	150	140	140	140
Pressure	bar	10	10	5	5	1	5
Mass Vapor Frac		0	0.9971	0	0	0	1.000
Mass Liquid Frac		0	0	0	0	0	0
Mass Solid Frac		1	0.0029	1	1	1	1.2E-05
Mass Flows	kg hr^{-1}	11.3835	42.9529	46.9520	0.2527	0.2431	775.9073
H_2O	kg hr^{-1}	0	10.7560	0	0	0	455.0505
N_2	kg hr^{-1}	0	24.6526	0	0	0	262.0369
O_2	kg hr^{-1}	0	3.5871	0	0	0	44.4791
NO_2	kg hr^{-1}	0	0.0003	0	0	0	0.0027
NO	kg hr^{-1}	0	0.0118	0	0	0	0.1064
H_2	kg hr^{-1}	0	0.0000	0	0	0	0.0000
CO	kg hr^{-1}	0	0.0000	0	0	0	0.0000
CO_2	kg hr^{-1}	0	3.8186	0	0	0	14.2218
Ash	kg hr^{-1}	11.3835	0.1265	1.1384	0	0	0
$CaCO_3$	kg hr^{-1}	0	0	45.8137	0	0	0
AC-ADS	kg hr^{-1}	0	0	0	0.2527	0.2431	0.0100
Volume Flow	m^3 hr^{-1}	0.0033	18.4826	0.0173	0.0001	0.0001	251.2889

Note: Refer to Figure 2 for the stream names in the overall process flow diagram.

Table 5. GHG emissions of the Waste-to-Energy (WTE) system per kg of municipal solid waste (MSW) treated.

Input	Without Avoided Products	With Avoided Products
	GHG Emissions* (kg CO_2e kg^{-1} MSW)	GHG Emissions* (kg CO_2e kg^{-1} MSW)
Diesel	0.045	0.045
LPG	0.154	0.154
Lime	0.609	0.609
Activated Carbon	0.0847	0.0847
Refrigerant	0.148	0.148
Transport of chemicals	0.149	0.149
MSW Transport	0.00322	0.00322
Emissions	0.361	0.361
Calcium carbonate, precipitated	-	-1.54
Electricity, medium voltage {Ph}	-	-0.254
TOTAL	1.55	-0.24

*Emission factors are based on Ecoinvent database in SimaPro

the IPCC default method for emissions estimation, the total methane emissions from landfilling 438,000 kg MSW were calculated to be approximately 40,040.99 kg CH_4 yr^{-1}. Including emissions from transporting the waste to the landfill which is 0.03 kg CO_2e kg^{-1} MSW, this resulted in a total carbon footprint of 3.11 kg CO_2e kg^{-1} MSW landfilled.

The GHG emissions from the WTE system were approximately 1.56 kg CO_2e kg^{-1} MSW lower than those from landfilling, representing considerable GHG savings of about 50%. Clearly, a much higher GHG savings can be obtained by accounting the potential GHG avoidance from the system's avoided products.

The results of the study align closely with the findings of *Demetrious and Crossin* (*2019*), who utilized the LCA approach to examine the environmental impacts of various waste management technologies in Australia. Their research focused on individual waste streams, such as mixed paper and mixed plastic wastes, instead of mixed MSW. Using SimaPro 8.0.4 software, the study evaluated three scenarios: landfilling, incineration, and gasification combined with pyrolysis. The functional unit was defined as the treatment of 1 kg of mixed paper waste, composed of 10% newspaper and 90% packaging paper, with an average moisture content of 11.2%, a carbon composition of 40%, a nitrogen composition of 0.3%, and a sulfur composition of 0.1%. These waste characteristics were found to be comparable to those used in the process simulation component of the study. *Demetrious and Crossin* (*2019*) reported that mixed paper waste is more suitable for incineration and gasification-pyrolysis than for landfilling, with GWPs of 1.03 and 1.02 kg CO_2e kg^{-1} waste, respectively. These findings are similar to the total GHG emissions of the WTE system analyzed, which amounted to approximately 1.55 kg CO_2e kg^{-1} MSW.

Further analysis in the study, which accounted for all emissions from process inputs and potential GHG avoidance from displaced products, revealed a net GHG emission of -0.24 kg CO_2e kg^{-1} MSW. This result is comparable to the findings of *Ramos and Rouboa* (*2020*), who used GaBi software to perform an LCA comparing incineration, conventional gasification, and two-stage plasma gasification for MSW treatment. Using a functional unit based on the thermal treatment of 1 tonne of MSW, their study reported negative GWP values for incineration (-0.1709 kg CO_2e kg^{-1} MSW) and plasma gasification (-0.31 kg CO_2e kg^{-1} MSW), indicating environmental credits. Similarly, *Maghmoumi et al.* (*2020*) reported negative GWP values for MSW incineration, with net GHG emissions of -0.0857 kg CO_2e kg^{-1} MSW. These findings collectively highlight the environmental benefits of thermal treatment technologies over landfilling in terms of GHG reduction and validate the robustness of the results obtained in the study. Considering the substantial volume of waste managed through landfilling, adopting WTE systems presents a significant opportunity for GHG mitigation, contributing to the broader goals of sustainable development.

Carbon Payback Period. In line with the obtained high carbon savings for the comparison between WTE system and traditional landfilling, a short payback period of 0.20 years was estimated. In this case, the carbon reductions from avoiding methane emissions at the landfill, coupled with the energy produced from the WTE process, significantly outweighed the emissions generated during the construction and operation of the WTE facility.

Energetics Studies

Aside from assessing the direct combustion WTE system in terms of its carbon footprint, the energy performance of this technology was also studied. Similarly, energy debt, energy savings, energy payback period, and energy ratio were calculated.

Energy Debt. Similar to the carbon debt analysis, the energy debt evaluation encompassed the energy required for the production of materials, the fabrication and transportation of equipment, and the installation and integration of the WTE system on-site. The total energy demand for the construction of the WTE facility was found to be 1.65 x 10^6 MJ.

The majority of the energy consumption is attributed to the production and processing of steel, a key material in the construction of the system. Specifically, steel production and metal working processes accounted for the largest portions of the total energy demand, contributing approximately 38.52% and 46.66%, respectively (**Figure 8**).

Energy Savings. Based on process simulation, the WTE system generated a gross power output of 27.0645 kW at a feed rate of 50 kg hr^{-1}. After accounting for the system's running power consumption of 9.6 kW, a positive net power output of 17.4645 kW was achieved. Given the target operating conditions of 365 d yr^{-1} and 24 hr d^{-1}, the resulting energy savings from the positive net power equates to 152,989.02 kWhr yr^{-1} or 550,760.47 MJ annually.

When compared to the average monthly household energy consumption in the Philippines, which is approximately 210 kWhr, the energy savings from this facility would be sufficient to meet the electricity needs of about 167 households annually. This calculation is based on the typical net electrical efficiency of 23% for combined heat and power (CHP) systems (*Tolis et al. 2010*).

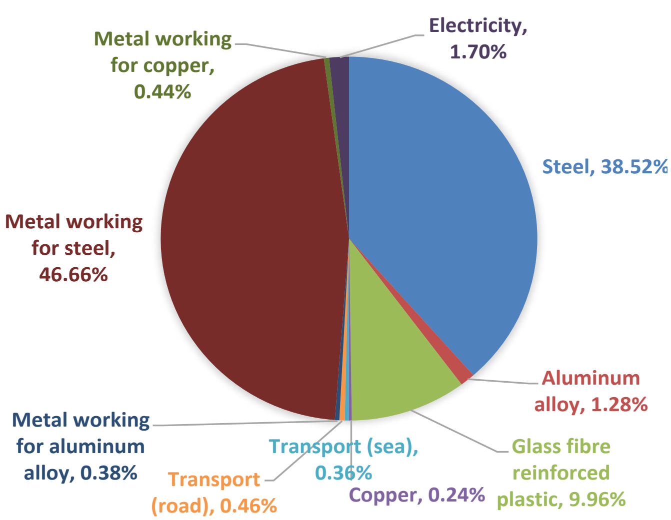

Figure 8. Energy demand distribution for waste-to-energy (WTE) facility construction.

Energy Payback Period and Energy Ratio. In line with the substantial energy savings, the system demonstrated an energy payback period of approximately three years and an energy ratio of 2.82. This indicates a favorable energy return on investment. Furthermore, the operational power efficiency of the system was calculated to be 0.5413 kWhr kg^{-1} MSW, which aligns closely with the typical overall power generation rates observed in conventional WTE plants, ranging from 0.3 to 0.7 kWh rkg^{-1} MSW (*Tsai 2019*). These results underscore the efficiency of the WTE system in energy recovery.

Environmental Hotspots Analysis

The environmental hotspots which are the specific stages within the process that contribute significantly to global warming were also evaluated to identify improvement opportunities and to better recommend strategies to reduce the environmental impacts of the WTE system. Lime used in the absorption process during flue gas cleaning contributed the highest GHG emissions, primarily because of the intensive lime production that causes emissions from processes such as quarrying and combustion (**Figure 9**). To reduce the carbon footprint of the WTE system, one potential strategy is the utilization of the byproduct, $CaCO_3$, in various industrial applications, which could be considered as an avoided product and thus help offset emissions. The use of alternative chemicals such as $Ca(OH)_2$, NaOH, KOH, $Ba(OH)_2$ for flue gas cleaning- particularly for the absorption of CO_2 in flue gas- could also be explored as a potential strategy to reduce environmental impacts (*Blum and Cote 2009*).

In terms of energetics, the use of liquefied petroleum gas (LPG) in turbo heater accounted for the largest contribution to the total energy demand of the system considering the high heat duty required in this process which was about 628,020 kJ hr^{-1} (**Figure 10**). To minimize this impact, it is suggested that heat which can be recovered from the produced higher temperature flue gas from the economizer be used in place of LPG as heating element to maintain the desired temperature of water as heating liquid to the refrigerant in the ORC system. Since the maximum heat duty in the second heat resolver is 837,360 kJ hr^{-1} which was not recovered in the initial process design, it is sufficient to supply the energy demand in turbo-heater thereby completely displacing LPG.

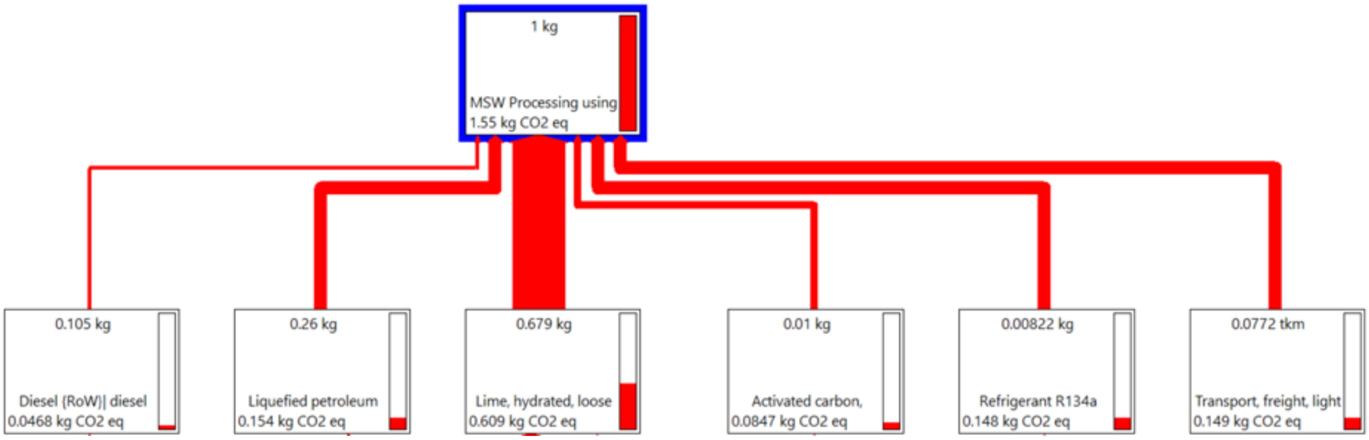

Figure 9. Process network of WTE system in terms of carbon footprint.

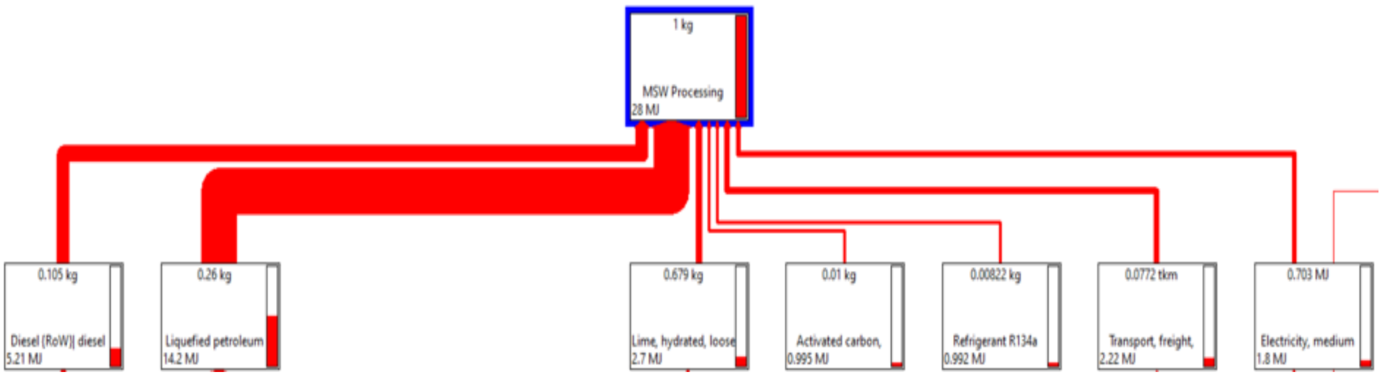

Figure 10. Process network of waste-to-energy (WTE) system in terms of energy demand.

Other by-products of the system such as ash can also be analyzed and characterized in order to assess its possible utilization into various applications. One of which is its potential use as additives or fillers in concrete and cement production. Exploring various desorption methods for possible recovery of used activated carbon can also be studied to further minimize the impact of waste flows from this system.

CONCLUSION AND RECOMMENDATION

The global aim for sustainable development has driven the adoption of cleaner and more sustainable technologies. Waste-to-energy (WTE) technologies have gained significant attention worldwide as potential alternatives to address the mounting challenges of solid waste management, energy security, and rising greenhouse gas (GHG) emissions. However, the intensive material and energy demands associated with constructing and operating WTE facilities necessitate comprehensive evaluation of their carbon footprint and energy performance to assess their viability as sustainable and environmentally benign solutions, particularly in developing countries.

This study evaluated a 25-kW direct combustion WTE system for MSW using the Life Cycle Assessment (LCA) approach to assess its carbon footprint and energetics. Process simulation, based on actual design parameters and defined system boundaries, was performed to analyze all inflows, outflows, and emissions associated with the system. Results indicated that the WTE system's total GHG emissions amounted to 1.55 kg CO_2e kg^{-1} MSW, representing a 50% reduction compared to the business-as-usual scenario of landfilling, which has a carbon footprint of approximately 3.11 kg CO_2e kg^{-1} MSW. The system also demonstrated a carbon-negative profile, equal to -0.24 kg CO_2e kg^{-1} MSW, when accounting for GHG avoidance from byproducts such as precipitated calcium carbonate and surplus electricity generation.

Energy analysis revealed that the WTE system achieved a positive net power output of approximately 17.4645 kW and an operational power efficiency of 0.5413 kWhr kg^{-1} MSW. This is comparable to typical WTE plants, which report power generation rates range from 0.3 to 0.7 kWhr kg^{-1} MSW (*Tsai 2019*). The system's potential energy savings, calculated a 152,989.02 kWhr or 550,760.47 MJ annually, could supply the electricity needs of approximately 167 households per year, assuming a combined heat and power (CHP) efficiency of 23% (*Tolis et al. 2010*).

Environmental hotspot analysis identified lime use during flue gas cleaning as the largest contributor to GHG emissions due to the energy-intensive lime production processes, such as quarrying and combustion. The utilization of calcium carbonate byproducts in alternative applications is recommended to further reduce the WTE system's carbon footprint by accounting for it as an avoided product. Use of alternative chemicals for flue gas cleaning can also be explored to further minimize the system's environmental impact.

In terms of energetics, the use of liquefied petroleum gas (LPG) in the turbo-heater contributed significantly to the system's total energy demand, given the high heat duty required. To mitigate this, it is recommended to recover heat from the higher-temperature flue gas exiting the economizer to replace LPG as the heating medium. Results indicated that the recovered heat wa s sufficient to meet the turbo-heater's energy demand, thereby completely displacing LPG and improving the system's energy efficiency.

This study, which provides valuable insights for the environmental viability of adopting WTE technologies via direct combustion, can inform action plans and policy recommendations to encourage the integration of WTE technologies in the Philippines. However, further research on the economic feasibility of WTE systems is essential to assess their potential for commercial deployment. Additionally, since this study was based on a specific MSW feedstock composition, sensitivity analyses should be conducted to evaluate the impact of varying MSW compositions on power generation and GHG emissions. A scaled-up analysis is also encouraged to examine the GHG emissions and energetics of WTE systems at larger capacities, providing a more comprehensive perspective on their performance and applicability.

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